Using Task Analytic Behavior Modeling, Erroneous Human Behavior Generation, and Formal Methods to Evaluate the Role of Human-automation Interaction in System Failure

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Matthew L. Bolton

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This dissertation is submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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Matthew L. Bolton

Approved:

Ellen J. Bass (Advisor)

Stephen D. Patek (Chair)

Gregory J. Gerling

Westley Weimer

Margaret L. Plews-Ogan

Accepted by the School of Engineering and Applied Science:

James H. Aylor (Dean)

August 2010

Abstract

Failures in complex, safety-critical systems often arise as a result of interactions between the elements of the system, including its human operator. Two sub-disciplines, human-automation interaction (from human factors engineering) and formal methods (from computer science) have attempted to address these types of problems from two different directions. Human-automation interaction researchers use tools such as task analysis and models of erroneous human behavior to investigate the way human operators interact with automation in order to design systems that facilitate safe, human work. Formal methods researchers use well defined mathematical modeling and proof techniques to verify that system models (often with concurrent interacting processes) do or do not exhibit desired properties. Model checking is a particular type of formal verification which proves that a system does or does not exhibit a specified property by searching for a violation in a system's entire statespace. It returns a counterexample (execution trace) illustrating any violation it discovers.

This work shows that it is possible to automatically predict the contribution of both normative and automatically generated erroneous human behavior to failures in human-automation interactive systems using formal verification. We have developed a computational method which utilizes task analytic models, formal system modeling, model checking, and taxonomies of erroneous human behavior to automatically incorporate erroneous human behavior patterns into normative task models, allowing analysts to formally verify system safety properties with both normative and erroneous human behavior. As part of this research, we developed a novel human task behavior modeling language (called the Enhanced Operator Function Model (EOFM)) with a defined formal semantics and a visual notation for graphical display. This allows normative human behavior to be modeled as a hierarchy of activities and actions, where actions can be sequenced using a superset of the temporal relationships supported by similar modeling paradigms. We have also developed two erroneous human behavior generation methods which allow instantiated EOFMs to be systematically manipulated in order to encompass erroneous human behavior consistent with Hollangel's phenotypes of erroneous human behavior and Reason's attentional slips. In order to allow instantiated EOFMs (either normative or erroneous) to be formally verifiable, we have developed a translator which converts instantiated EOFMs into the formal modeling language of the Symbolic Analysis Laboratory, thus allowing task behavior models to be formally verified. We have also developed an architectural framework for formally modeling human-automation interactive systems which coordinates the behavior of formal models of (translated) human task behavior, human mission goals, device automation, the human-device interface, and the operation environment. Finally, we have developed a novel visualization which uses the architectural framework and the EOFM's visual notation to convey the information contained in a model checker counterexample.

We describe the motivation and design for each element of our method. We provide validation testing results which confirm that our method is behaving as we intended. We present benchmarks that show how our method scales. We also demonstrate the different ways in which our method can be used to evaluate human-automation interactive systems with several realistic applications: a patient controlled analgesia pump, an automobile with a cruise control, a radiation therapy machine, and an aircraft on approach. These applications are used to show how the method can be adapted to verify systems that require different elements of our architectural framework. They are also used to demonstrate how different instantiations of architectural elements can be incorporated into application system models to facilitate different analyses, the evaluation of different designs, and the exploration of design interventions for correcting problems discovered using our method.

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A	The “All” path quantifier.
E	The “Exists” path quantifier.
F	The “Future” temporal operator.
G	The “Global” temporal operator.
U	The “Until” temporal operator.
X	The “Next” temporal operator.
Δ	Indicates a change in a variable’s value.
ϕ	A temporal logic proposition about a state or path in a formal model.
ψ	A temporal logic proposition about a state or path in a formal model.
$\bigoplus$	A generic boolean logic operator.
/=	Not equal binary operator in the expression notation of the Symbolic Analysis Laboratory.
<=	Less than or equal to binary operator in the expression notation of the Symbolic Analysis Laboratory.
>=	Greater than or equal to binary operator in the expression notation of the Symbolic Analysis Laboratory.

Chapter 1

Human-automation Interaction and Formal Verification*

Complex, safety-critical systems involve the interaction of automated devices and goal-oriented human operators in a dynamic environment. Failures in such systems are often not due to a single component, but rather elements of the system (including human operators) interacting in unexpected ways. The human-automation interaction is particularly important to the operation of safety critical systems as poor human-automation interaction has contributed to failures in complex systems in a number of domains including aviation [12, 80, 105], process control [146], and medicine [125]. For example human-automation interaction has played an important role in the crashes of American Airlines Flight 965 [126] and China Air 140 [168]; the grounding of the Royal Majesty cruise ship [144]; the disaster at Three Mile Island [158]; and the death of medical patients with the Therac-25 [130].

Human factors researchers have developed methods for characterizing, analyzing, and experimenting with human-automation interaction in order to help make automated systems safe for human work. Computer science researchers have developed mathematically

*This chapter is derived from [32]

robust modeling languages, algorithms, and methods for finding computer hardware or software design flaws, even those resulting from the interaction of concurrent processes. Formal methods encompass one such set of technologies. Both human-automation interaction and formal methods are discussed next to set the stage for a discussion of the intersection of these two fields.

1.0.1 Human-automation Interaction

The field of human-automation interaction is concerned with the design of automated systems to facilitate safe, human work [171]. Problems with human-automation interaction can occur for a number of different reasons. Automation can be brittle [176] in that the device automation and/or the human-device interface does not work correctly, does not perform as efficiently, or does not behave as intended under certain environmental or operational conditions (as was the case in the crash Air France Flight 296 [50]). These issues arise because operational conditions or device behavior were not anticipated by the designer; the device automation design was simplified due to schedule, economic, or technological limitations; or the device automation and/or human-device interface were not implemented in accordance with the design [176].

Human-device interfaces may not provide enough feedback about the state of the device automation [143] and/or the human operator may not properly understand how the automation works [165]. This mode confusion, where the human operator is unable to keep track of the state or mode of the device automation, is dangerous because it can result in automation surprise, where the operator's situation awareness is disrupted by the device automation behaving in an unexpected way [151, 165]. Further, mode confusion can lead to the human operator either performing inappropriate actions (errors of commission) or omitting necessary ones (errors of omission) [165]. Thus, operators of complex, automated systems must work to maintain mode awareness in order to avoid such errors [71]: a task that can be very difficult for human operators given the large number of mode combinations, variety of behaviors a given mode can exhibit, and the range and quantity of information displayed in some systems [165].

As systems become more automated, this can change the tasks of the human operator: where he supervises the system rather than control it directly. In such situations, human operators may not have been trained in the tasks necessary to administer the automation [86]. They may fixate on a specific task while neglecting others, such as passively monitoring the system [11, 141, 166, 170, 183]. They may also alter their task behavior such that they become too dependent on automation (a condition known as automation bias) and therefore acquire and evaluate system information less vigilantly [140, 152].

Issues can also arise as a result of incompatibilities between the behavior of the device (both its automation and human-device interface) and the cognition of the human operator. Many erroneous human behaviors have predictable cognitive causes [159] which can relate to human working memory, human knowledge, human perception, or human physical coordination. It is possible to prevent some human errors through changes to the behavior of the device's automation and human-device interface [22, 45, 61, 62].

Thus, problems with human-automation interaction can arise as a result of interactions between the different elements that make up the system: the goals, cognition, and task behaviors of the human operator; the automated system and its human-device interface; and the constraints imposed by the operational environment. Researchers have addressed these issues from different directions. Cognitive work analysis is concerned with identifying constraints in the operational environment that shape the mission goals of the human operator [179]; cognitive task analysis is concerned with describing how human operators normatively and descriptively perform goal oriented tasks when interacting with an automated system [124, 167]; and modeling and analytic frameworks use this information to make predictions about human performance [123], look for discrepancies between human mental models and device automation behavior [69], and design human-device interfaces that reveal accurate device and environmental information while requiring reduced human operator cognitive effort to interpret [179].

1.0.2 Formal Methods

Formal methods are a set of "well defined" mathematical languages and techniques for the modeling, specification, and verification of systems [182]. Systems (often computer software or hardware) are modeled using mathematically based languages, specifications are formulated to describe desirable system properties, and a verification process mathematically proves whether or not the model satisfies the specification. Formal methods have been used successfully in a number of applications, especially computer hardware and software. While there are a number of different ways in which models can be both manually and automatically verified, two particular computer software technologies, automated theorem provers and model checkers, have proven useful for the formal verification of large complex systems.

Theorem proving is a deductive technique that closely resembles the traditional pencil-and-paper proof activity: from a set of axioms, using a set inference rules, one builds theories and proves theorems to verify correctness claims about the system under investigation, with the help of a proof assistant program. While theorem proving cannot be fully automated in practice for the most expressive logics (such as higher order logics), some smaller fragments are more amenable to mechanized proofs. Satisfiability (SAT) solvers [64] and satisfiability modulo theories (SMT) solvers [66] are equipped with powerful decision procedures able to solve very complex problems from areas such a propositional logic and linear algebra.

Model checking is a highly-automated approach used to verify that a formal model of a system satisfies a set of desired properties (a specification) [56]. A formal model describes a system as a set of variables and transitions between variable states. Specification properties are usually represented in a temporal logic (discussed below) using the formal system model variables to construct propositions. Verification is performed automatically by exhaustively searching a system's state space in order to determine if these propositions hold. If there is a violation, an execution trace called a counterexample is produced. This counterexample depicts a model state (the value of the model's variables) corresponding to a specification violation along with a list of the incremental model states leading up to the violation.

A temporal logic is a set of rules and symbols that allows time to be expressed and reasoned about as part of a logical framework: where time is represented by a sequence of states [79]. For model checking purposes, a temporal logic formula is composed of boolean propositions about the model variables and modal operators. Modal operators usually specify the temporal relationships between propositions. The two most common temporal logics (Linear Temporal Logic (LTL) and Computation Tree Logic (CTL)) make use of the modal operators described in Table 1.1. There are a variety of different specification languages and/or modal logics of which these operators represent the most common concepts. See Emerson [79] for more detail.

1.0.3 Analysis Types to Date

Because both human factors and formal methods are concerned with the engineering of robust systems that will not fail under realistic operating conditions, researchers continue to merge techniques from the two fields in order to use the powerful verification techniques offered by formal methods to analyze human-automation interaction. This chapter next

Table 1.1: Frequently used temporal logic operators.

Operator Type	Name	Usage	Interpretation
Path Quantifier	**A**ll	$\mathbf{A}\,\psi$	Starting from the current state, all future paths satisfy ψ.
	Exists	$\mathbf{E}\,\psi$	Starting from the current state, there is at least one path that satisfies ψ.
Temporal Operator	Ne**X**t	$\mathbf{X}\,\psi$	ψ is true in the next state of a given path.
	Future	$\mathbf{F}\,\psi$	ψ is eventually true in some future state of a given path.
	Global	$\mathbf{G}\,\psi$	ψ will always be true in a given path.
	Until	$\phi\,\mathbf{U}\,\psi$	ϕ will be true until ψ is true for a given path.

Note. In all of the above, a path is taken to mean a valid temporally ordered sequence of states for a given model. ϕ and ψ are two propositions about either a state or path in the model that can evaluate to either true or false.

reviews the research conducted in the intersection of these two areas and addresses how formal verification can be used to inform analyses of human-automation interaction. This work can be categorized based on the type of analyses the formal methods have been used to support. These are: formal verification of human-device interfaces; the detection and prevention of mode confusion and automation surprise; formal verification of human task and workflow as part of a system model; and formal verification of human cognition as part of a system model.

1.1 Formal Verification of Human-device Interfaces

Some work has focused on how to model human-device interfaces using formal constructs so that their correctness can be evaluated using formal verification. While these analyses do not consider human models as part of the process, they provide guarantees that the human-device interface will behave in the way it was intended and/or in ways that support safe human-automation interaction.

Human-device interfaces are formally modeled as finite state transition systems [153]. There are many different ways in which this has been accomplished. Statecharts are formal transition systems that support hierarchies, parallelism, and communication that have been used model interfaces [68]. Interactors are object-oriented interface building blocks that have an internal state and communicate by generating and responding to events [93]. Physiograms are used exclusively for modeling physical device interfaces [74]. Table and matrix specification paradigms like the Operational Procedure Model (OPM) [173] and ADEPT [172] define interfaces based on their input-output behavior. Abstractions have been developed for formally modeling human computer interfaces (HCIs) defined in software development environments such as Visual Basic and Java Swing [76, 77]. Despite the diversity of modeling techniques, all generally treat the interface as having a specific state (a specific valuation of variable values) that can transition to different states based on human operator actions, device automation, and/or environmental factors. Some paradigms (such as the interactor) specifically model the rendering of information on the interface display and thus explicitly model what information is available to the operator in any given interface state.

Generic temporal logic property patterns have been developed for specifying desirable properties of human-device interfaces. Campos and Harrison [46] identified four related categories of properties that could be expressed in temporal logic and thus formally verified for human-device interface models: reachability, visibility, task related, and reliability. Reachability properties make assertions about the ability of the interface to eventually reach a particular state. Visibility properties assert that visual feedback will eventually result from an action. Task related properties describe human behaviors that the interface is expected to support: usually the ability to achieve a particular goal represented by a state or set of states in the interface model. Reliability properties describe desirable interface properties that support safe human-automation interaction. Within each of these categories, specific patterns have been identified for checking specific properties (see Table 1.2 for some examples).

Table 1.2: Formally verifiable interface specification properties.

Category	Property	Informal Description
Reachability	State inevitability	It will always be true that a specific interface state will eventually be reached [2].
	Weak reachability	A specific action will always result in a change in the interface state [154].
	Strong reachability	A specific action will allow for the possibility of a future change in interface state [154].
Visibility	Feedback	A specific action will always result in a change in interface state that is available to the human operator [48, 154].
	Continuous feedback	All human operator actions must produce a change in interface state that is available to the human operator and must do so before any additional actions can be performed [154].
Task related	Weak task completeness	There is at least one action sequence from a specific initial interface state that will eventually achieve a specific goal [2, 154].
	Strong task completeness	For any given possible sequences of actions from a specific initial interface state, there is a set of additional actions which will eventually achieve a specific goal [2].
	Weak task connectedness	From any interface state, there is at least one action sequence that will achieve a specific goal [2].
	Strong task connectedness	From any interface state, there is at least one action sequence that will eventually achieve a specific goal with a specific final action [2].
	Undo / Reversibility	The effects of a specific action can be undone with a single additional action or eventually undone with at least one sequence of actions [2, 48, 154].
Reliability	Behavioral consistency	A specific action will always result in a change in interface state that adheres to a specific characterization [48].
	Rule set connectedness	There is at least one situation in which the interface supports the ability to perform a specific action through the interface (such as clicking a button) [2].
	Deadlock freedom	The interface will never reach a state that will never accept human operator input [2].
	State floatability	There is a sequence of actions that can cause the interface to go from one specific interface state to another without ever reaching an undesirable state [2].

Note. In the above, a goal describes a specific interface state or a predicate representing a set of interface states. Temporal logic patterns for formally specifying each of these properties can be found in the cited literature.

This work has been extended to heuristically assess usability using formal verification or the output of formal verifications. Hussey et al. [106] identified four usability properties (from [135]) that could be evaluated in this way: task efficiency, reuse, robustness, and flexibility. Task efficiency describes how efficiently a human operator can perform a task as measured by the number of actions taken to reach a goal state (information that can by extracted from a counterexample). An interface that supports reuse will allow human operators to achieve multiple goals using similar behaviors. This has been formally measured by comparing execution traces that achieve different goals and looking for shared action sequences between them. An interface that is robust will help prevent human operators from making errors and will allow them to recover should one occur. This has been evaluated by formally verifying properties such as deadlock freedom, state floatability, and undo/reversibility (Table 1.2). A flexible system allows the human operator to achieve goals in different ways, formally measured by the number of alternate action sequences the human operator can use to achieve a goal.

Kamel and Aït-Ameur [117] showed how four usability properties (originally from [59]) specific to multimodal human-device interfaces could be evaluated formally: complementarity, assignation, redundancy, and equivalence. Complementarity asserts that the human operator will be able to reach a given state from a specific initial state using different modalities. A modality can be considered assigned to a specific state (assignation) if it is the only modality capable of reaching that interface state. Two or more modalities are equivalent if both allow the interface to reach a specific state. Two or more modalities are redundant if they are equivalent and can be used in parallel to reach a specific state. Kamel et al. [118] also provided temporal logic patterns for verifying the “adaptability” of a multimodal interface: for a give initial state (which may encompass a condition where a particular modality is not available), the human operator will always be able to eventually find a way to reach a goal state.

1.2 Formal Verification and Mode Confusion

Researchers have investigated how formal verification can predict and help prevent mode confusion and automation surprise.

1.2.1 Using Formal Verification to Identify Mode Confusion

There are several general approaches for using formal verification to detect potential mode confusion. The first explicitly models the device automation's behavior along with the human operator's abstracted mental model of how that automation works. The two models are then checked (either manually or using model checking) to find inconsistencies between the two models: when the human operator's mental model state does not match the automation model state. Degani, Heymann, Oishi and colleagues [67, 68, 147, 148] showed how inconsistencies could be algorithmically discovered between state chart representations of the human operator's mental model and device automation in a variety of applications including an aircraft autopilot [68], a cruise control system [67], and an aircraft auto-land system [147]. Sherry et al. [174] used matrix-based representations of both the device automation's input-output behavior and the human operator's mental model of that input-output behavior and showed how they could be algorithmically compared to find inconsistencies for an aircraft's mode control panel. These types of analyses have be performed automatically using model checkers. Rushby et al. [163, 164] used Murϕ [73] and Buth [41] used FDR2 [85] to find known mode issues with the MD-88 autopilot.

Another approach assumes a formal model of the human-device interface and the device automation. These models are systematically searched for display conditions and automation behaviors hypothesized to cause mode confusion. Leveson et al. [131] showed how system requirements modeled using state machine languages could be systematically examined for such properties. They illustrated their method with a robot control system.

This process has been automated using a variety of model checker and automated theorem provers [42, 116, 134] to find potential mode confusion problems in a flight guidance system. Campos and Harrison [47] showed how human operator expectations about the behavior of a system (an aircraft mode control panel) could be encoded in temporal logic, and violations of those expectations could be found using the Symbolic Model Verifier (SMV) [138] model checker for a formal system model consisting of a human-device interface (written using interactors) and a device automation model.

A third approach encodes the human operator's knowledge about how he accomplishes goals with the system through the human-device interface. This is accompanied by a human-device interface and device automation model. All are checked for conditions where the interface will not allow the human-operator to accomplish any given goal. Wheeler [181] illustrated how such a method could be performed manually for an alarm clock example. Bredereke and Lankenau[36, 37] automated this type of evaluation using Communicating Sequential Processes (CSP) [99] and the FDR2 model checker [85]. Doing this, they were able to find a number of potential mode confusion issues with an electric wheel chair. Javaux [108] showed how implicit learning could be used to model how the knowledge represented in a human operator's mental model (modeled formally) degrades over time due to a lack of repeated exposure to all of the automated device's modes. Javaux showed how this can lead to mental models that facilitate mode confusion and automation surprise in an autopilot system.

1.2.2 Generating Human-device Interfaces that Prevent Mode Confusion

Researchers have proposed ways of generating human-device interfaces that do not exhibit properties associated with mode confusion. These methods assume that the human operators must have the information necessary to maintain a correct mental model through the human-device interface. Thus, a mental model representing an abstraction of the system's device automation that does not facilitate mode confusion becomes a specification for the information content and behavior of the human-device interface. Crow et al. [60] discussed how mental models constructed through results from questionnaires given to human operators can be progressively abstracted and/or refined and checked with a model checker until a "safe minimal mental model" is found: the least complex mental model that does not facilitate mode confusion. Heymann and Degani [97] proposed an algorithmic means of achieving such a model. First, a state chart representation of the system's automation is constructed. Then, each state is assigned to one of several specification classes: aggregate states that the analyst hypothesizes the human operator must distinguish between. This model is then systematically reduced by combining states within specification classes in a way that avoids inconsistencies indicative of mode confusion. Combéfis and Pecheur [57] showed how such a process could be performed automatically without the need for specification classes.

1.3 Formal Verification and Task Analytic Models

Task analytic models are generated as part of a task analysis and can be used to model human task behavior as sequences of activities with respect to the fulfillment of goals. Task analytic models do not encompass sophisticated models of human cognition, and thus are not concerned with modeling cognitive concepts such as human attention and the mechanisms involved in human long- and short-term memory. They can, however, model abstractions of these in order to model human behavior as a simple input-output system where inputs can come from the human mission, the operation environment, or human device interfaces; and outputs are human actions.

These models have been used in the evaluation of single and multiple operator systems for a variety of purposes including intent inferencing [40], usability evaluation [110, 129], intelligent tutoring [53], timing analysis of human tasks [110], alerting systems [16], and controlling agents in simulations [87]. Because of their widespread use, researchers have attempted to use formal methods to verify that the human behavior encompassed by task analytic models will always accomplish the desired goals and/or avoid dangerous system operating conditions. Extensions of this work allow erroneous human behavior to be incorporated into task models so that its impact can be evaluated as part of the formal verification.

1.3.1 Formal Verification with Task Analytic Models of Normative Human Behavior

Some researchers have modeled human tasks in the native formal notation utilized by the analysis package they are employing. Degani et al. [70] incorporated human task models into state chart models of a human-device interface and used them to explore human operator behavior during an irregular engine-start on an aircraft. Basnyat et al. [14, 15] used a Petri net-based formalism called Interactive Cooperative Objects (ICO) to model human task behavior as part of larger system models (a waste fuel delivery plant and a satellite control system) to verify properties critical to the system's safe operation. Resolutions to discovered problems came in the form of barrier systems to monitor the system and prevent it from transitioning to unsafe states [14] or through modification to operator training materials [15]. Gunter et al. [89] encoded patterns of human task behavior into CSP concurrently with system and environment models (also encoded in CSP) to verify safety properties of a portable Automated Identification and Data Capture (AIDC) device used to identify and record data about patients and equipment in the hospital. They showed that a "protection envelope" could be incorporated into the system's automation to ensure that the modeled normative human task behavior would never result in situations where incorrect or corrupted data could be entered into the AIDC device.

To facilitate model development and analyses that make use of task analytic models, researchers have used task analytic modeling notations to model human tasks which are then translated into the needed formalism. Palanque et al. [150] showed how task models written in User Action Notation (UAN) [94] could be translated into ICO and used to verify task behaviors for interacting with an automated teller machine (ATM). Fields [82] developed a custom notation for modeling hierarchies of activities in human tasks along with the temporal relationships between them. Aït-Ameur et al. [3, 4] and Paternò et al. [155, 157] have translated ConcurTaskTrees [156] into formal models and performed formal verification with larger system models. Aït-Ameur's work used a theory prover (called event B) to verifying human interaction with a software dialog box for converting currencies. Paternò et al. translated CTT models of multiple human operators managing runway traffic into LOTOS [78] and then into a formal model where it could be checked as part of a system model encompassing the behavior of the interface, its automation, and the environment being managed.

1.3.2 Formal Verification with Models of Erroneous Human Behavior

Rather than look for specification violations that occur with normative human behavior models, Fields [82], [17], and Bolton and Bass et al. [25, 34] have investigated how patterns of erroneous behavior (based on the phenotypes of erroneous actions [100]) can be manually incorporated into formal task analytic models. These models could then be integrated with the analyses described above in order to use formal verification to investigate whether these errors impact the fulfillment of specification properties.

1.4 Formal Verification and Cognitive Models

Instead of modeling human tasks, researchers have modeled human cognition as part of a formal system model for use in formal verification. The goal is to model the cognitive process the operator employs to decide what actions he will use to interact with the system. These methods let the analyst to formally verify that the system will always allow the operator to achieve his goals with a set of cognitive behaviors. These methods can identify situations where the human operator fails to achieve his desired goals or drives the system into dangerous operating conditions.

Lindsay and colleagues [51, 128, 132] have investigated the use of the Operator Choice Model (OCM) in such an analysis. The OCM describes the process human operators use to scan or search human-device interfaces for information, determine if that information is worthy of additional interest, decide how to proceed in light of the assessed information, and execute a plan of actions. This method was used to model the human operator's cognitive process for identifying and attempting to resolve conflicts in a simple air traffic control task. Patterns of human behavior were encoded into temporal logic and a model checker was used to check that these behaviors were cognitively valid (were compatible with their cognitive model) and would not result in the operator failing to resolve a conflict or accidentally creating a conflict between aircraft.

Blandford, Curzon, and colleagues have focused on creating Programmable User Models (PUMs) [184] that capture the knowledge and cognitively plausible behavior that an operator might use when interacting with an automated system and implementing them as part of a formal system model [21, 23, 44]. PUMs encompass the goals the operator wishes to achieve with the system, his beliefs and knowledge about the operation of the system, the information available to him from the human-device interface, and the actions he can use to interact with the system. When executing, the human operator model must use knowledge about the system and the currently available information to select actions to fulfill its goals. Such models have been used with human initiated systems (where system behavior is solely driven by its human operator) [23] and evaluated using formal verification with both theorem provers [43] and model checkers [160].

These formal PUM analyses have been used to obtain different insights about systems. Butterworth et al. [43] showed how specification properties related to system safety, liveness, and usability could be investigated using PUMs and formal verification for a simple web browsing task. Butterworth et al. [43] used PUMs and formal verification with the same application to identify the type of knowledge a human operator requires in order to successfully fulfill his goals. PUMs and formal verification have been used to identify cognitively plausible errors based on a human operator model interacting with an automated system. These include repetition of actions, omission of actions, committing actions too early, replacing one action with another, performing one or more actions out of order, and performing an unrelated action [61]. Means of identifying post-completion errors (special types of omission errors in which the operator forgets to perform actions that occur after the completion of a high level goal) have also been identified and illustrated using a model of a vending machine [62]. Design rules were applied to address these errors, and their effectiveness was evaluated using the same formal verification process [61, 62]. Work has also investigated using PUMs to model different classes of human operator (expert vs. novice) [63] in order to investigate when different types of operators may perform different errors when interacting with an ATM. Keystroke-level timing analysis (similar to that used by KLM-GOMS [110]) have also been added into their framework and used to evaluate timing performance of a human operator interacting with the ATM [162]. PUM models have also been extended so that formal verification can investigate how humans might make errors due to issues related to salience, cognitive load, and cognitive interpretation of spatial cues [160, 161], illustrated with the same ATM model. Basuki et al. [19] used heuristics for modeling human operator habituation, impatience, and carefulness and showed how they could be used to find human errors for interacting with the vending machine model from Curzon and Blandford [62].

1.5 Limitations of Current Techniques and Technologies

1.5.1 Limitations of Formal Verification

Despite its power, there are a number factors which limit what formal verification can do.

1.5.1.1 Limitations of Model Checking

One of the challenges facing model checking verification is the state explosion problem. As the complexity of the modeled system increases, the memory and time required to store the combinatorially expanding state space can easily exceed the available resources. One way this has been addressed is through the development of extremely efficient means of representing a system's state space, referred to as symbolic model checking [39]. Other techniques allow select portions of the state space to be searched without compromising the accuracy of the verification. The best known of these depend on partial order reduction [103], symmetry [88] and abstraction techniques such as abstract interpretation [58] and counterexample-guided abstraction refinement [55].

A second major limitation of model checking is the expressive power of its modeling formalisms. Traditional model checking is applied to systems that can be modeled with discrete variables. However, complex systems can have continuous quantities. While the field of hybrid systems has been developed to address this issue [95], current techniques can handle systems models with no more than a half-dozen continuous variables. With respect to the modeling of time, discrete-state models can be augmented with a set of clocks [96]. While this technique can be used to model clock synchronization problems in digital systems, only very simple models can be fully verified.

One of the most compelling outputs of a model checker is a counterexample: an execution trace illustrating exactly how a specification was violated. In most analysis environments this is a list of the model variables and the values they assume at each step in the execution trace. This output can be cumbersome to interpret. There have been a few attempts to remedy this problem. Traviando [119] uses message sequence charts to visualize model checker counterexamples. Loer and Harrison [133] used a table to display counterexample information, where changes in variable values were highlighted. A number of animations and sequence diagrams have also been discussed [3, 133].

1.5.1.2 Limitations of Automated Theorem Proving

In principle, theorem proving does not suffer from the same limitations as model checking. However, theorem proving is not a fully automated process: the analyst guides the proof while exploiting automation to reuse routine proof techniques. The more expressive the logic used to model and reason about the system, the less automation is possible. Thus, theorem proving requires significant effort by highly trained experts who guide the verification process. Further, because the proof process must be guided, theorem proving is less likely to find emergent features that are not anticipated by the analyst.

1.5.1.3 Examples in the Literature

These limitations are reflected in the covered literature as the majority of the applications of formal verification in human-automation interaction are very simple: franc to euro currency converters [3, 4], interface widgets [5, 38], automated teller machines [63, 149], aircraft mode control panels [47, 68, 163, 174], and air conditioner programming interfaces [57] to name a few. Work by Bolton and Bass [27, 31] and Blandford et al. [23], who both attempted to representatively model more complex systems (such as a patient controlled analgesia (PCA) pump and calender program respectively), ultimately resorted to a series of model compromises and abstractions in order for the verification process to be tractable. There have also been very few attempts at evaluating hybrid systems (see [147] and [148]).

1.5.2 Tradeoffs Between Formal Human-automation Interaction Verification Techniques

Each of these approaches has advantages and disadvantages. The human-device interface verification and mode confusion work does not explicitly describe human operator behavior (treating them as unbounded) and thus must be used to evaluate very simple and/or heavily abstracted representations of device automation in order to avoid being limited by the size of the system model. Because human behavior is not explicitly modeled, these techniques can only be used to find system conditions theorized to be preconditions to erroneous human behavior.

The cognitive modeling work avoids some of these limitations by bounding human behavior based on models of cognition. By explicitly modeling the cognitive processes human operators use to interact with the system, formal verification can be used to find unsafe system operating conditions, and predict when the system facilitates erroneous behavior. By constraining the system around plausible human behavior, higher fidelity models can be evaluated.

The task modeling work similarly constrains operator behavior. The task analytic models used in these analyses only describe the explicit human behavior (not the cognition). Thus processes that use them can make use of more complex system models than those used in the cognitive modeling techniques. However, any erroneous human behavior the analyst wants to consider must be manually incorporated into the task analytic models.

1.5.3 General Limitations of Formal Verification of Human-automation Interaction

There are also several general limitations for the use of formal verification for evaluating the safe operation of human-automation interactive systems. Firstly, the task behavior models used either rely on the formal modeling notation [14, 15, 70] or on notations not common in the human factors literature [3, 4, 82, 155, 157] which do not support all of the different ordinal and parallel relationships that can exists between actions in human task behavior. Secondly, none of the existing work utilizes an architectural framework capable of allowing system models to be constructed around all of the human-automation interaction concepts: the human task behavior, the human mission or goals, the device automation, the human device interface, and the operational environment. Thus none of the discussed analyses allow for easy interchange of different models of these elements in order to perform multiple analyses while exploring a design. Thirdly, little of the discussed literature addresses the computational limitations of the analysis techniques making it difficult for practitioners to determine the scalability of the analyses. Finally, all the work discussed which incorporates erroneous human behavior requires either modeling cognition (which adds complexity) [51, 61, 62, 128, 132, 160, 161] or manual intervention to apply erroneous behavior patterns to task analytic models (which may miss many potential erroneous behaviors) [17, 82].

The remainder of this document discusses a research effort that addresses these issues.

1.6 Research Objectives: A Method to Evaluate the Role of Human-automation Interaction in System Failure

1.6.1 Operation Concept

This work is focused on extending the analyses that can be performed using formal verification and task analytic models. If an analyst is interested in evaluating how human behavior may contribute to system failure (the violation of system safety properties) then he will want to be able to evaluate realistic normative and erroneous human behavior in light of varying goals or missions and different system operating conditions and behaviors. Further, he may wish to run multiple analyses in order to assess how different human goals or behaviors from the human affect system safety. He may also wish to evaluate the safety implications for different human-device interfaces, device automation designs, or environments either to evaluate different designs, operating conditions, or to identify potential interventions that can fix problems discovered during formal verification.

An infrastructure capable of supporting these analyses should have a number of features. It should allow task analytic models of human behavior to be represented in a way characteristic of existing task analytic modeling constructs in order to allow task analysis experts (mostly human factors engineers) to implement these models. Task models should be capable of supporting the temporal orderings and parallelism from existing task modeling paradigms. Task models should also have a formally defined semantics which would ensure that a model's meaning would be unambiguous and capable of being implemented in a formal modeling notation.

The human task behavior model should be able to be integrated with a larger system model encompassing other system components of interest to an analyst such as human operator goals or missions, device automation behavior, the human-device interface, and the operational environment. Thus the task model should be capable of interfacing and coordinating its behavior with the other system components. Because a human-device interface is, by definition, the means by which a human operator can perform actions that impact the system, the human-task behavior model should have information about the human-device interface necessary for performing the task such as what actions the interface can receive (such as button presses) and what information it provides.

Analyst may want to run multiple analyses using different task behavior models, human missions, human device interfaces, device automation behaviors, or operational environments in order to evaluate different designs or to identify potential interventions that may eliminate discovered problems. Thus the formal system model should facilitate the ability to easily incorporate alternative configurations of any of these elements.

Because erroneous human behavior can occur in unexpected circumstances, the ability to generate erroneous human behavior for use in formal verifications is advantageous. Thus, there should be a theoretically driven means of systematically altering the structure or interpretation of task analytic models so that they would be capable of generating realistic erroneous human behavior. This allows erroneous human behavior to be systematically included in formal verifications with task behavior models without the need for low level detailed cognitive models.

Task model constructs should be used to present formal verification results to analysts so that they can be interpreted using the same representation in which the models were developed.

Finally, because of the restrictions formal verification places on the complexity of system models, analysts should have access to information which allows them to interpret how task behavior modeling impacts system model complexity, and thus potentially limits what can be formally verified.

1.6.2 The Method

To address these issues we have developed a method (Figure 1.1) which extends the model checking verification process. In it, a human analyst examines documentation and other information gleaned from the evaluation of a target system. He creates models of the normative human task behavior using a novel task analytic representation. This task model can then run through an automatic human erroneous behavior prediction process in order to produce an erroneous human behavior model capable of generating erroneous human behavior. The analyst can choose whether he wants to use the erroneous or normative human behavior model in the remaining process. Our automated process, the task model translator, then converts the chosen human task behavior model into a formal human task model which can be incorporated into a larger formal system model. The analyst creates (or uses existing) formal system models of the mission, human-device interface, device automation, and environment. He also creates temporal logic specifications representing the system qualities he wants to be true. The formal system model and the system specification are run through the model checker which produces a verification report. If a violation of a specification is found, the report will contain a counterexample. The counterexample and the original human task behavior model can then be processed by our automated visualizer which illustrates the sequence of human behaviors and related system states that led to the violation.

1.6.3 Contributions

This method is capable of both formally verifying and discovering problems in human-automation interactive systems while incorporating models of both normative and generated erroneous human behavior. We demonstrate this with a number of different applications which show how the method can be adapted to verify systems that require different

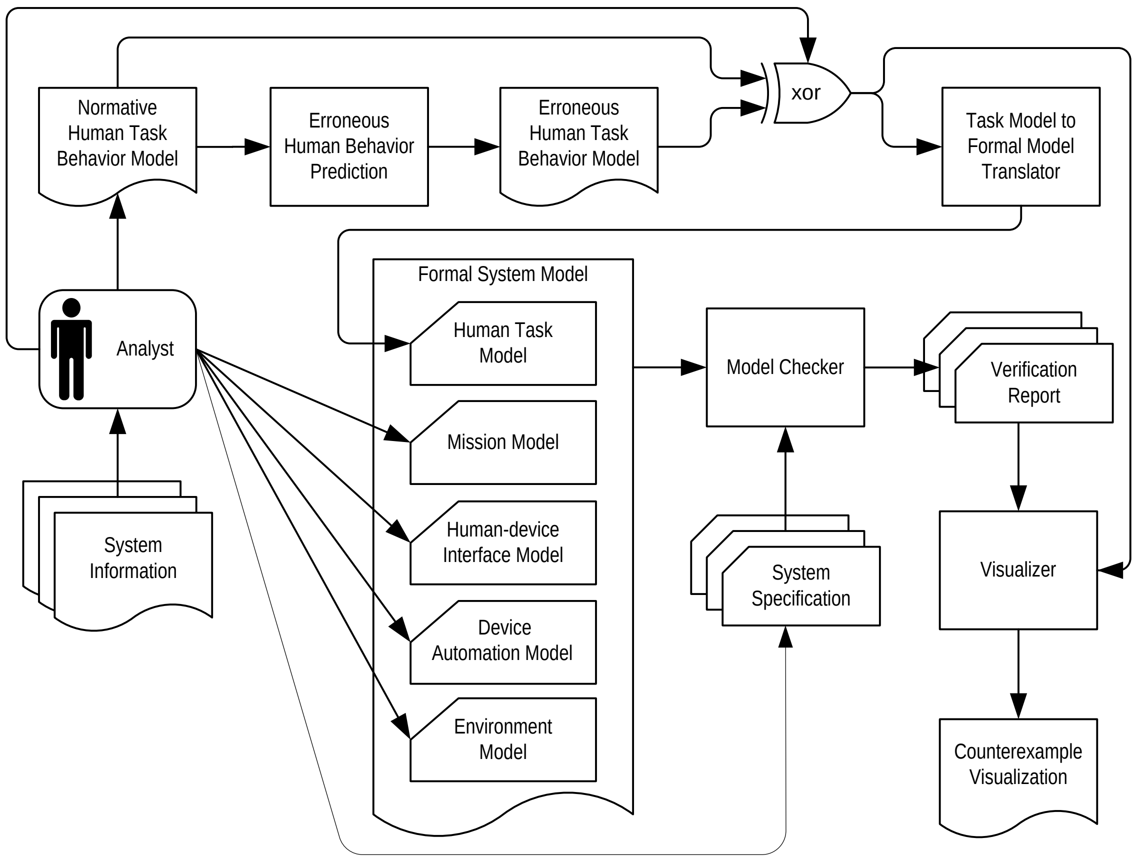

Normative Human Task Behavior Model
Erroneous Human Behavior Prediction
Erroneous Human Task Behavior Model
xor
Task Model to Formal Model Translator
Formal System Model
Human Task Model
Mission Model
Human-device Interface Model
Device Automation Model
Environment Model
Analyst
System Information
Model Checker
Verification Report
System Specification
Visualizer
Counterexample Visualization

Figure 1.1: Method for predicting how both normative and erroneous human behavior may contribute to system failure using model checking.

elements of our architectural framework, and how different instantiations of architectural elements can be incorporated into application system models to facilitate different analyses and the exploration of different designs. In several situations, we illustrate how the architecture can be exploited in order to identify potential interventions that correct problems discovered with the method. The following chapters discuss each of the method's elements in detail and discusses how they satisfy the goals from the operational concept. When appropriate, benchmarks are given to provide insights into the scalability of the method. Chapters also illustrate the use of the method in the evaluation of the different applications. Each chapter discusses future work that could be conducted to extend concepts and technologies discussed in the chapter.

Chapter 2 introduces the EOFM: a hierarchical, generic, platform independent, XML-based, task analytic modeling language. We present the syntax of EOFM which incorporates features from Operator Function Model [139] and extends them with additional task sequencing options. The EOFM's visual syntax is illustrated using an example of programming a digital alarm clock. We also present the EOFM's formal semantics which represents a mathematically based, unambiguous interpretation of the meaning of the EOFMs modeling constructs. The potential future extensions of the language are discussed.

Chapter 3 discusses the goals and rationale behind the formal system modeling architectural framework which was composed of independent models of the human mission, human task behavior, human-device interface, device automation, and operational environment. The chapter discusses the coordination that is required to allow EOFM task models to interact with other components of the architecture. Finally it presents a PCA pump example which includes models of the operator's mission and task behavior as well as device automation and the human-device interface. These verification procedures demonstrate the use of our method to verify a human-automation interactive system using both an unconstrained human task behavior model and normative human task behavior. The PCA pump model required multiple revisions before it was small enough to be fully verified. This application represents a realistic upper bound on the complexity of models our method can handle for the computation resources available to us. This application's use in the analyses also demonstrates a tradeoff between model complexity and verification time between unconstrained human operator models and that controlled by formal representations of EOFM task behavior.

Chapter 4 shows how the EOFM's formal semantics were used to construct an automated process for translating an instantiated EOFM into the formal modeling language of SAL. This allows instantiated EOFMs to be automatically incorporated into a formal system model which can be used in formal verification. We use formal verification to validate that the translator is producing SAL code that conforms to the EOFM's formal semantics (see Appendix B). We also report on an evaluation of the scalability of the translation algorithm. We then present an automobile cruise control example to illustrate how an instantiated EOFM can be integrated into a larger system model that includes the human operator's mission, device automation, human-device interface, and operation environment. Using our method, we were able to identify a problem with the system and formally verify that a solution which, with modifications to the human-device interface and task behavior model, corrected it.

While there is a plethora of literature on erroneous human behavior (see [115]), the two most prominent perspectives are those offered by Hollnagel [100] and Reason [159]: where Hollnagel classifies erroneous human behavior based on how the observable manifest (their phenotypes) and Reason classifies them based on their cognitive causes (their genotypes). Chapters 5 and 6 show how these two perspectives on erroneous human behavior can be used to generate erroneous human behavior by either permuting an instantiated EOFM's task structure to generate Hollnagel's phenotypes using the instantiated EOFM's information about the human device interface (Chapter 5) or by modifying the formal semantics of the instantiated EOFM to generate Reason's attentional slips (Chapter 6). In both chapters, the error generation process is described and the chapter discusses how the erroneous human behavior generation was incorporated as an option to be automatically generated by the EOFM to SAL translator. Each chapter also presents an application that illustrate the types of system problems that can be found using the particular erroneous behavior generation technique (a radiation therapy machine in Chapter 5 and the PCA pump in Chapter 6). Both examples included models of the operator's mission and task behavior as well as device automation and the human-device interface. In both applications, safety properties verified to true when the normative human behavior model was used. However, violations were discovered with the system models containing the generated erroneous human behavior models. In Chapter 5 this was corrected by changing the device automation. In Chapter 6 the correction occurs through changes to the human-device interface. Chapter 6 discusses the tradeoffs between the two erroneous behavior generation techniques.

In Chapter 7, we present a novel visualizer which allows counterexamples produced by SAL for models utilizing translated EOFM task behavior models using the EOFM's visual notation, the architectural framework, and concepts from general counterexample visualizers. The chapter discusses the rationale and operation concept for the visualizer and presents a design prototype. The chapter then demonstrates how the visualizer communicated information relevant to diagnosing problems in the cruise control application, the radiation therapy machine, and the PCA pump. Thus the chapter demonstrates the capabilities of the visualizer for diagnosing problems in formal system models containing normative human behavior as well as both types of generated erroneous behavior.

Chapter 9 presents an extended application of the method: an aircraft on approach. This application's formal system model contained all elements of the architectural framework: human mission, human task behavior, device automation, human-device interface, and environment. In this example we show how the flexibility of the method and architectural framework can be exploited to investigate the design of a system by interchangeably using different instances of architectural elements between analyses. In doing this, the system is evaluated with multiple normative human task behaviors, multiple erroneous human task behaviors, and multiple device automation behaviors. In the latter case, the analyses show how the impact of degraded and/or erroneous automation behavior can be evaluated with our method. In all analyses, solutions to discovered problems are discussed, some of which involve formal verifications with models containing new or modified human missions, automation behaviors, or human task behaviors.

Finally Chapter 9 discusses the contributions of this work and outlines how future work could evaluate and extend the method. It also discusses how the formal verification of human-automation interaction could be further developed in general.

Chapter 2

The Enhanced Operator Function Model: Syntax and Formal Semantics[*]

When designing for human-automation interaction, human factors engineers generally do not use formal models, but rather task analytic methods to represent human operator behaviors. Task analytic models represent descriptive and normative human behavior for interacting with an automated system as sequences of activities with respect to the fulfillment of goals [124, 167]. These types of models have been used in the specification, implementation, and analysis of single- and multi-operator systems [16, 28, 53, 87, 110, 129, 178]. Such models are heterarchical as there can be a number of independent goals and strategies to achieve them. They can be hierarchical in that goals decompose into lower level activities and ultimately atomic actions. Further, conditions specify constraints under which activities and actions can execute. Logical operators can also be used to control how many activities or actions can execute and what temporal relationship exists between them. Information from external sources (the operational environment, the human operator's mission, human-device interfaces, other human team members, etc.) can be used in the definition of conditions.

[*]This chapter is derived from [28] and [33]

This chapter present the EOFM language, its syntax, and its formal semantics all of which are used in a variety of examples in subsequent chapters.

2.1 Enhanced Operator Function Model

There are several task analytic modeling paradigms such as Operator Function Model [139], ConcurTaskTrees (CTTs) [154], hazard networks [16], User Action Notation (UAN) [98], and several varieties of Goals, Operators, Methods, and Selection rules (GOMS) [110]. Collectively these techniques encompass the following features [28]:

- Activities can be modeled as sequences of actions or as part of more complex hierarchies of activities which can ultimately decompose into atomic actions.
- Observable human actions (such as pushing a button, turning a wheel, or flipping a switch) are supported by all techniques but some also support human cognitive or perceptual actions (such as remembering a number or noticing an alarm).
- Different cardinalities for how many sub-activities or actions can execute in a given decomposition: zero or more, one or more, exactly one, or all.
- Different temporal orders that control when sub-activities and actions can execute in relation to each other: in sequence with no overlap in any order, in sequence with no overlap in a particular order, synchronized, or executed in parallel with any potential overlapping or interleaving.
- Different ways to represent strategic knowledge and/or conditions that control when activities can execute, when they are completed, and when they can repeat.
- Different analysis environments and platforms.

- Support for graphical notations that help to convey the modeled behavior.

By extending the OFM [139], the Enhanced Operator Function Model (EOFM) [28] is a generic task analytic modeling language to support the features described above. The OFM supports a visual and object-oriented means of representing task models. It uses state and derived variables to specify model behavior including its handling of input and output. It models goal-level behaviors as activities. Each activity may include conditions that describe under what conditions it can be undertaken. Activities are decomposed into lower-level sub-activities and, finally, actions. Operators on each decomposition specify the cardinality of and the temporal relationships between the sub-activities or actions. The EOFM standardizes the type of conditions that modify activities and supports the full cross set of the cardinalities and temporal orderings discussed above. The EOFM language is XML-based, thus making it platform independent and easy to parse. A more in depth discussion of the design decisions that went into the EOFM can be found in [28].

2.2 Language Description

The EOFM language supports modeling the human operator as an input/output system. Inputs may come from several sources including: the human-device interface, environment, mission goals, and other human operators. Output variables are human actions. The operator's task model describes how human actions may be generated based on input and local variables.

Each human operator model is a set of EOFM task models that describe goal-level activities. Activities decompose into lower level activities and eventually atomic actions. Decompositions are controlled by decomposition operators that specify the cardinality of and temporal relationship between the sub-activities or actions; allowing zero or more, one or more, exactly one, or all to execute with all of the task analytic modeling supported options for ordered, sequential, parallel, or synchronized execution. Activities can have preconditions, repeat conditions, and completion conditions (Boolean expressions written in terms of input, output, and local variables as well as constants) which specify what must be true before an activity can execute, when it can repeat execution, and what is true when it has completed execution respectively. Atomic actions are either an assignment to an output variable (indicating an action has been performed) or a local variable (representing a perceptual or cognitive action). All variables are defined in terms of constants, user defined types, and basic types; described below.

2.2.1 Syntax

The EOFM language's XML syntax is defined using the Relax NG standard [54]. The specification of its syntax, graphically depicted in Figure 2.1, has been modified from [28] in order to support more standardized terminology and an XML structure that more closely represents the EOFM graphical notation.

XML documents contain a single root node whose attributes and sub-nodes define the document. For the EOFM specification, the root node is called *eofms*. The next level of the hierarchy, has zero or more *constant* nodes, zero or more *userdefinedtype* nodes, and one or more *humanoperator* nodes. The *userdefinedtype* nodes define enumerated types useful for representing operational environment, human-device interface, and human mission concepts. A *userdefinedtype* node is composed of a unique name attribute (by which it can be referenced) and a string of data representing the type construction (the syntax of which is application dependent). A *constant* node is defined by a unique name attribute, either a *userdefinedtype* attribute (the name attribute of a *userdefinedtype* node) or *basictype* attribute.

The *humanoperator* nodes represent the task behavior of the different human opera-

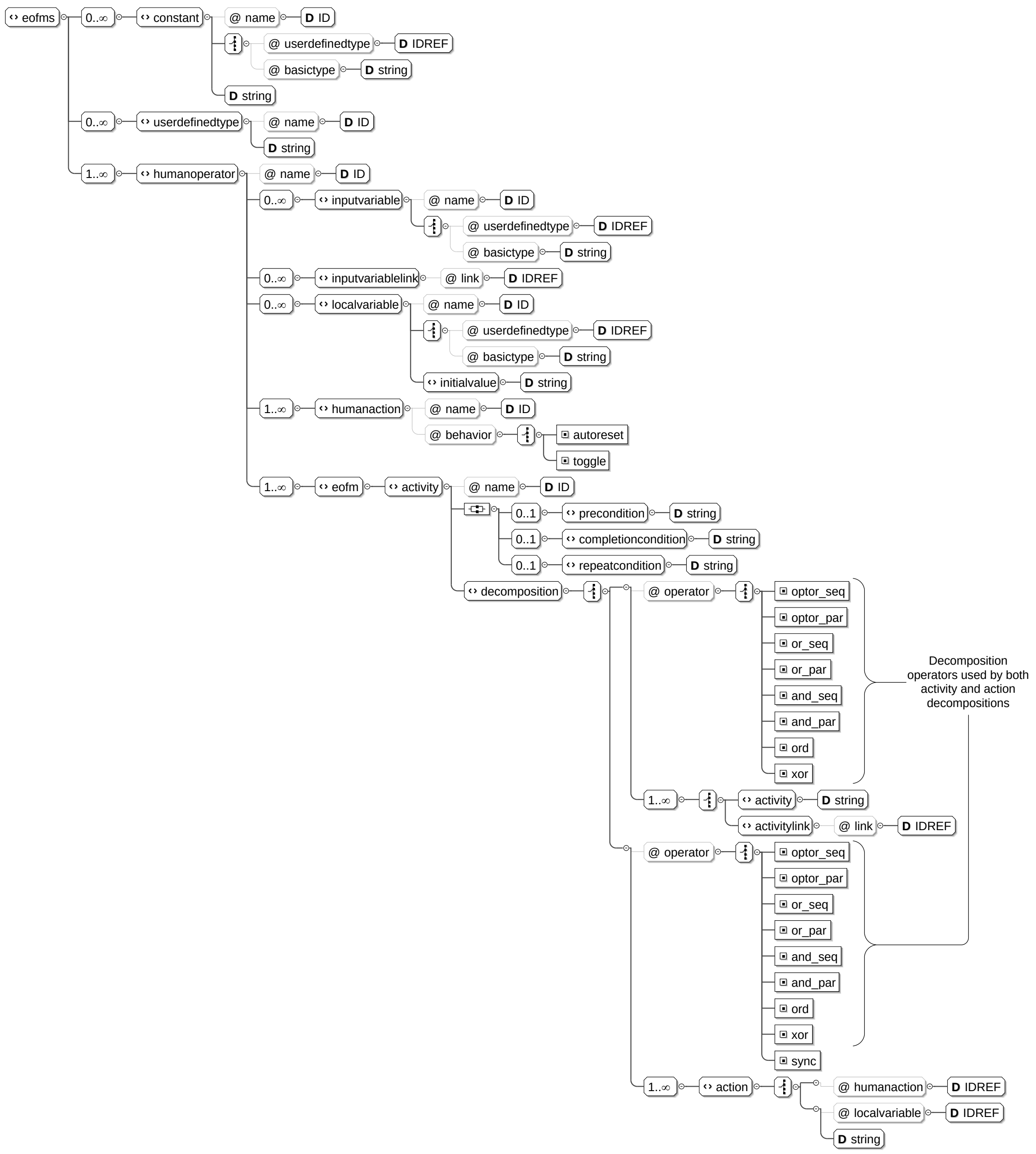


Figure 2.1: The EOFM Relax NG Language Specification

tors. Each *humanoperator* has zero or more input variables (*inputvariable* nodes and *inputvariablelink* nodes for variables shared with other human operators), zero or more local variables (*localvariable* nodes), one or more human action output variables (*humanaction* nodes) and one or more task models (*eofm* nodes). A human action (a *humanaction* node) describes a single, observable, atomic act that a human operator can perform. A *humanaction* node is defined by a unique *name* attribute and a *behavior* attribute which can have one of two values: *autoreset* (for modeling a single discrete action such as flipping a switch) or *toggle* (for modeling an action that must be started and stopped as separate discrete events such as holding a button down and then releasing it).

Input variables (*inputvariable* nodes) are composed of a unique name attribute and either a *userdefinedtype* or *basictype* attribute (defined as in the constant node). To support the definition of inputs that can be perceived concurrently by multiple human operators (for example two human operators hearing the same alarm issued by an automated system) the *inputvariablelink* node allows a *humanoperator* node to access input variables defined in a different *humanoperator* node using the same input variable name. Local variables are represented by *localvariable* nodes, themselves defined with the same attributes as an *inputvariable* or *constant* node, with an additional sub-node, *initialvalue*, a data string with the variable's default initial value.

The task behaviors of a human operator are defined using *eofm* nodes. One *eofm* node is defined for each goal directed task behavior. The tasks are defined in terms of *activity* nodes. An *activity* node is represented by a unique *name* attribute, a set of optional conditions, and a *decomposition* node. Condition nodes contain a boolean expression (in terms of variables and human actions) with a string that constrains the *activity*'s execution. The following conditions are supported:

- *precondition*: criterion to start executing;
- *repeatcondition*: criterion to repeat the execution; and
- *completioncondition*: criterion to complete execution.

An activity's *decomposition* node is defined by a decomposition operator (an *operator* attribute) and a set of activities (*activity* or *activitylink* nodes) or actions (*action* nodes). The relative position of *activity* and *action* nodes to eachother in the XML hierarchy directly corresponds to their position in an the task modeling hierarchy. The *decomposition* attribute specifies a decomposition operator that controls the cardinal and temporal execution relationships between the sub-*activity* and *action* nodes (referred to as sub-acts). In order to support the required cardinalities and temporal orders, the EOFM language implements the following decomposition operators: *and*, *or*, *optor*, *xor*, *ord*, *sync*. Each of these operators have two modalities: sequential (suffixed *_seq*) and parallel (suffixed *_par*) (Table 2.1). For the sequential mode, the sub-acts must be executed one at a time. In parallel mode, the execution of sub-acts may overlap in any manner. For the *xor*, *ord*, and *sync* decomposition operators there is no need to include both modalities: *xor* and *ord* are always sequential and *sync* is always parallel.

Table 2.1: Decomposition operators

Operator		Modality	
Type	Semantics	Sequential	Parallel
and	All of the sub-acts must execute	*and_seq*	*and_par*
or	One or more of the sub-acts must execute	*or_seq*	*or_par*
optor	Zero or more of the sub-acts must execute	*optor_seq*	*optor_par*
xor	Exactly one sub-act must execute	*xor*	—
ord	All sub-acts must execute in the order they appear in	*ord*	—
sync	All sub-acts must be executed at the same time	—	*sync*

The *activity* nodes represent lower-level or sub-activities and are defined identically to those higher in the hierarchy. Activity links (*activitylink* nodes) allow for reuse of model structures by linking to existing activities via a *link* attribute which names the linked *activity* node.

The lowest level of the task model hierarchy is represented by either observable, atomic human actions or internal (cognitive or perceptual) ones, all using the *action* node. For an observable human action, the name of a *humanaction* node is listed in the *humanaction* attribute. For an internal human action, the valuation of a local variable is specified by providing the name of the local variable in the *localvariable* attribute and the assigned value within the node itself [1].

2.2.2 EOFM Visualization

The structure of an instantiated EOFM's task behaviors can be represented visually as a tree-like graph structure (an example appears in Figure 2.2) where actions are represented by rectangular nodes and activities by rounded rectangle nodes. In these representations, conditions are connected to the activity they modify: a *precondition* is represented by a yellow, downward pointing triangle connected to the right side of the activity; a *completioncondition* is presented as a magenta, upward pointing triangle connected to the left of the activity; and a *repeatcondition* is conveyed as a recursive arrow attached to the top of the activity. These standard colors are used for condition shapes to help distinguish them from each other and the other task structures. Decompositions are presented as arrows, labeled with the decomposition operator, extending below an activity that points to a large rounded rectangle containing the decomposed activities or actions.

2.2.3 EOFM Formal Semantics

We now formally describe the semantics of the EOFM language's task models: explicitly defining how and when each activity and action in a task structure executes.

[1] An example of an instantiated EOFM's XML code for the automobile driver discussed in Chapter 4 can be found in Appendix A

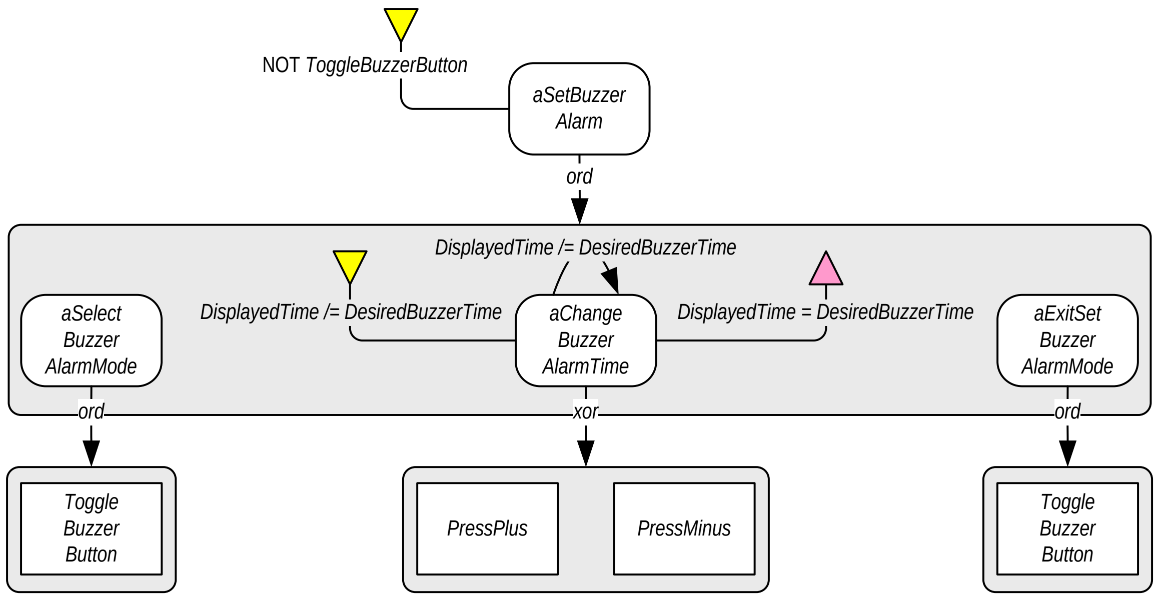


Figure 2.2: An example EOFM for programming the buzzer time into a digital alarm clock. The activity for setting the buzzer alarm time (*aSetBuzzerAlarm*) can execute if the precondition specifying that the buzzer alarm button is not toggled is satisfied (NOT *ToggleBuzzerButton*). The activity is executed by performing three sub-activities in sequential order (the *ord* operator): selecting the mode for setting buzzer alarm time (*aSelectBuzzerAlarmMode*), changing the buzzer alarm time (*aChangeBuzzerAlarmTime*), and exiting the mode for setting the buzzer alarm time (*aExitSetBuzzerAlarmMode*). The mode for setting the buzzer alarm time is selected by toggling the buzzer button (*ToggleBuzzerButton*). The buzzer alarm time can be changed (a precondition), and continue to be changed (a repeat condition), if the displayed time does not match the desired time (DisplayedTime /= DesiredBuzzerTime). The activity executes by pressing either (the *xor* decomposition) the plus or minus buttons (*PressPlus* and *PressMinus* respectively). The activity completes (a completion condition) when the displayed time matches the desired buzzer alarm time (*DisplayedTime* = *DesiredBuzzerTime*). The activity for exiting the mode for setting the buzzer alarm time executes when the operator toggles the buzzer button (*ToggleBuzzerButton*).

An activity's or action's execution is controlled by how it transitions between three discrete states:

- *Ready*: the initial (inactive) state which indicates that the activity or action is waiting to execute;

- *Executing*: the active state which indicates that the activity or action is executing; and
- *Done*: the secondary (inactive) state which indicates that the activity has finished executing.

While *precondition*s, *repeatcondition*s, and *completioncondition*s can be used to describe when activities and actions transition between these execution states, three additional conditions are required. These conditions support transitions based on the activity's or action's position in the task structure, the execution state of its parent, sub-acts (activities or actions into which the activity decomposes), and siblings (activities or actions contained within the same decomposition).

- *startcondition*: implicit condition that triggers the start of an activity or action defined in terms of the execution states of its parent and siblings.
- *endcondition*: implicit condition to end the execution of an activity or action defined in terms of the execution state of its sub-acts.
- *reset*: implicit condition to reset an activity (have it return to the *Ready* execution state).

For any given activity or action in a decomposition, a *startcondition* is comprised of two conjuncts: one stipulating conditions on the execution state of its parent and the other on the execution state of its siblings based on the parent's decomposition operator, generally formulated as:

$$(parent.state = Executing) \wedge \bigwedge_{\forall siblings\ s} (s.state \neq Executing)$$

This is formulated differently in the following circumstances. If the parent's decomposition operator has a parallel modality, the second conjunct is eliminated. If the parent's decomposition operator is *ord*, the second conjunct is reformulated to impose restrictions only on the previous sibling in the decomposition order: $(prev\_sibling.state = Done)$. If it is the *xor* decomposition operator, the second conjunct is modified to enforce the condition that no other sibling can execute after one has finished:

$$\bigwedge_{\forall siblings\ s} (s.state = Ready)$$

An *endcondition* is also comprised of two conjuncts both related to an activity's sub-acts. Since an action has no sub-acts, an action's *endcondition* defaults to *true*. The first conjunct asserts that the execution states of the activity's sub-acts satisfy the requirements stipulated by the activity's decomposition operator. The second asserts that none of the sub-acts are executing. This is generically expressed as follows:

$$\left(\bigoplus_{\forall subacts\ c} (c.state = Done)\right) \wedge \bigwedge_{\forall subacts\ c} (c.state \neq Executing)$$

In the first conjunct, $\bigoplus$ (a generic operator) is to be substituted with $\wedge$ if the activity has the *and_seq*, *and_par*, or *sync* decomposition operator; and $\vee$ if the activity has the *or_seq*, *or_par*, or *xor* decomposition operator. Since *optor_seq* and *optor_par* enforce no restrictions, the first conjunct is eliminated when the activity has either of these decomposition operators. When the activity has the *ord* decomposition operator, the first conjunct asserts that the last sub-act has executed.

The *reset* condition is *true* when an activity's or action's parent transitions from *Done* to *Ready* or from *Executing* to *Executing* when it repeats execution. If the activity does not have a parent, implying that it is at the highest level of an EOFM task model's decomposition hierarchy, *reset* is *true* if that activity is in the *Done* execution state.

The *startcondition*, *endcondition*, and *reset* conditions are used with the *precondition*, *repeatcondition*, and *completioncondition* to define how an activity or action transitions between execution states. This is presented in Figure 2.3 where states are represented as nodes (rounded rectangles) and transitions as arcs. Guards are attached to each arc.

The transition criteria for an activity (Figure 2.3(a)) are described in more detail below:

- An activity is initially in the inactive state, *Ready*. If the *startcondition* and *precondition* are satisfied and the *completioncondition* is not, then the activity can transition to the *Executing* state. However, if the *startcondition* and *completioncondition* are satisfied, the activity moves directly to *Done*.

- When in the *Executing* state, an activity will repeat execution when its *endcondition* is satisfied as long as its *repeatcondition* is true and its *completioncondition* is not. An activity transitions from *Executing* to *Done* when both the *endcondition* and *completioncondition* are satisfied.

- An activity will remain in the *Done* state until its *reset* condition is satisfied, where it returns to the *Ready* state.

The transition criteria for an action is simpler (Figure 2.3(b)) since an action cannot have a *precondition*, *completioncondition*, or *repeatcondition*. Note that because actions do not have any sub-acts, their *endcondition*s are always *true*.

2.3 Discussion

The EOFM language supports a superset of the features of other task analytic modeling languages:

- Activities (*activity* nodes) are modeled as sequences of actions and/or more complex hierarchies of activities which can ultimately decompose into atomic actions.

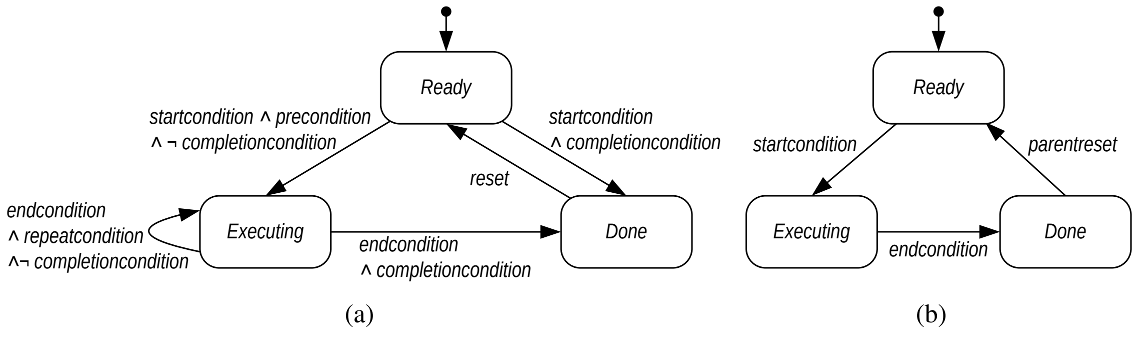


Figure 2.3: (a) Execution state transition diagram for a generic activity. (b) Execution state transition diagram for a generic action.

- Observable human actions are modeled as *action* nodes which can either represent an observable human action (*humanaction*) or human cognitive or perceptual action (the assignment to a *localvariable*).
- The decomposition operators support all of the following cardinalities for how many sub-activities or actions can execute in a given decomposition: zero or more, one or more, exactly one, or all.
- The decomposition operators support all of the following temporal orders that control when sub-activities and actions can execute in relation to each other: in sequence with no overlap in any order, in sequence with no overlap in a particular order, synchronized, or executed in parallel with any potential overlapping or interleaving.
- *precondition*, *repeatcondition*, and *completioncondition* nodes represent strategic knowledge that control when activities can execute, when they are complete, and when they can repeat.
- The use of XML makes the EOFM language platform independent.
- EOFM supports a graphical notation that can help convey the modeled behavior.

The EOFM language specifically extends OFM [139, 178] in several ways. Firstly, EOFM allows the analyst to explicitly define the input-output relationship between the human task behavior and the system: defining inputs (input variables), outputs (human actions with specified behavior), and internal state (local variables and task structure). OFM only explicitly defines the task structure from which the input and output information must be inferred. Secondly, OFM only supports the equivalent of EOFM's *and_seq*, *or_seq*, *xor*, and *ord* decomposition operators. Thus, EOFM extends OFM by supporting optional execution (the *optor* decomposition operators) and parallelism (operators with the *_par* suffix and the *sync* operator). Finally, OFM does not have a formal semantics to explicitly define how a model instantiated in it is to be interpreted, EOFM does. This is a significant contribution in that the EOFM's formal semantics have been used as the basis of a translator which converts instantiated EOFMs into a model checking language (see [33]) which allows them to be subject to formal verification. This is discussed in greater depth in Chapter 4.

Because the EOFM language is specified in RELAX NG and implemented in XML, the language should be easy to parse with existing code libraries. The wide support of these technologies also means that analysts can make use of a number of existing tools when working with the EOFM language. For example, we have used existing XML parsing technology in the creation of both our java-based EOFM to SAL translation process (see [28] and Chapter 4) and a Microsoft Office-based EOFM renderer (see [30] and Chapter 7). We have also successfully used the RELAX NG specification with the oXygen xml editor[2] which allows EOFM instantiations to be implemented in an environment that supports code completion, code highlighting, and dynamic syntax checking.

[2]http://www.oxygenxml.com/

2.3.1 Language Extensions

The EOFM language has been used successfully in a number of human-automation interaction analyses (see [26],[31],[29] and latter chapters). However, there are ways it could be improved.

One feature that is supported by UAN [98] and CTT [155] is the ability for activities to be interrupted when a higher priority activity becomes relevant due to a change in the human-device interface or environmental conditions. For example, an automobile driver may need to respond to traffic that has cut him off even in the midst of responding to a light further down the road. After the higher priority activity has been addressed, UAN and CTT support means of restarting, resuming, or abandoning any interrupted activities. Future work should investigate how such feature can be incorporated into the EOFM.

The current implementation of the EOFM does not enforce a specific syntax for type constructions, initial values, and condition Boolean expressions nor does it specify a standard set of basic types for defining its variables. These must conform to the syntax supported by the infrastructure the model is integrating with. Relax NG offers a variety of ways in which standards for these modeling concepts could be enforced such as additional XML structures and regular expressions for data formatting. Future work should investigate how these might be used to further specify EOFM syntax.

The current EOFM implementation assumes that all root activities are temporally related with the equivalent of a *optor_seq* decomposition operator. Future work should determine if this is descriptive enough, or if more options are necessary.

Although the EOFM has been designed to support multiple operators, to date it has only been used to model single operator systems [25–28, 31, 34]. There are a number of systems that depend on multiple human operators interacting with automation.

The current EOFM language supports the ability for multiple *humanoperator* nodes to share input information via *inputvariablelink* nodes. While this accomplishes the desired goal, it requires that all inputs be defined within a given *humanoperator* node. This results in a strong coupling between humanoperator nodes and associates the input exclusively with a human operator rather than the source of that input like the environment or a human-device interface. Similarly, multiple human operators may be able to interact with a human-device interface that they share, allowing each to submit identical human actions to system automation. The current implementation of the EOFM language supports this, but requires that these human actions be defined using different names in the associated *humanoperator* nodes. Thus it is the job of the modeler to ensure that these human actions are treated the same when the language is interpreted. Finally, multi-human operator systems may support direct communication between human operators that does not occur through a human-device interface. The current implementation of the EOFM does not support this feature.

These limitations could be resolved by modifying the EOFM semantics so that *inputvariable* and *humanaction* nodes as well as communication channels between human operators could be defined independently of the *humanoperator* nodes, and referenced where appropriate in these nodes. Future work will investigate how these features might be incorporated into EOFM.

Another limitation comes in the way task structures (activity and action hierarchies) can be reused between *humanoperator* nodes. In the current implementation, activities must be defined in one *humanoperator* node and referenced in others using *activitylink* nodes. This too results in strong coupling and does not support good objected-oriented design. Their are a variety of different architectures that might be supported in a multi-operator system: there may be multiple operators with a mixture of shared and discrepant task structures, and there may be shared or discrepant human-device interfaces. Object-orient concepts such as inheritance, interfaces, and polymorphism may allow these types of relationships to be more easily and flexibly instantiated in EOFM. Future work should investigate how this might be accomplished.

Chapter 3

Human-automation Interaction Formal Modeling Architectural Framework*

Chapter 1 showed that a significant amount of work has been done in the interaction of human-automation interaction and formal methods. While this has produced useful results, the models have not included all of the components necessary to analyze human-automation interaction. For human factors engineering (HFE) analyses of human-automation interaction, the minimal set of components are the goals and procedures of the human operator; the automated system and its human interface; and the constraints imposed by the operational environment. Cognitive work analysis is concerned with identifying constraints in the operational environment that shape the mission goals of the human operator [179]; cognitive task analysis is concerned with describing how human operators normatively and descriptively perform goal oriented tasks when interacting with an automated system [124, 167]; and modeling frameworks such as [69] seek to find discrepancies between human mental models, human-device interfaces, and device automation. In this context, problems related to human-automation interaction may be influenced by the human operator's mission, the human operator's task behavior, the operational environment,

*This chapter is derived from [31]

the human-device interface, the device's automation, and their interrelationships.

We have developed a computational framework (Figure 3.1) for the formal modeling of human-automation interaction. This framework utilizes concurrent models of human operator task behavior, human mission (the goals the operator wishes to achieve using the system), device automation, and the operational environment which are composed together to form a larger system model. Inter-model interaction is represented by variables shared between models. Environment variables communicate information about the state of the environment to the device automation, mission, and human task models. Mission variables communicate the mission goals to the human task model. Interface variables convey information about the state of the human-device interface (displayed information, the state of input widgets, etc.) to the human task model. The human task model indicates when and what actions a human operator would perform on the human-device interface. The human-device interface communicates its current state to the device automation via the interface variables. The human-device interface receives information about the state of the device automation model via the automation state variables.

For broader applicability, the analysis framework should support modeling constructs

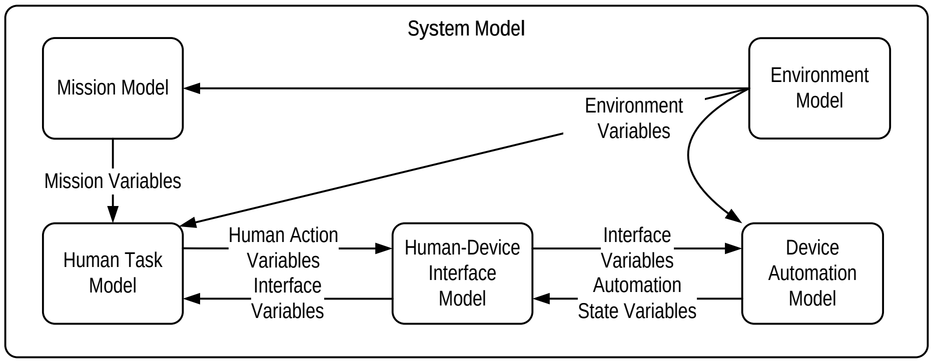


Figure 3.1: Framework for the formal modeling of human-automation interaction. Arrows between models represent variables that are shared between models. The direction of the arrow indicates whether the represented variables are treated as inputs or output. If the arrow is sourced from a model, the represented variables are outputs of that model. If the arrow terminates at a model, the represented variables are inputs to that model.

useful to the human factors engineer in order to allow him to effectively model human missions, human tasks, and human-device interfaces. Because an engineer may wish to rerun verifications using different missions, task models, human-device interfaces, environments, or automation behaviors, these components should remain decoupled (as is the case in Figure 3.1). Finally, the modeling technique must be capable of representing the target systems with enough fidelity to allow the engineer to perform the desired verification, and do so in a reasonable amount of time (this could mean several hours for a small project, or several days for a more complicated one).

This chapter describes an instantiation of this framework using a model of a Baxter Ipump Pain Management System [20], a patient controlled analgesia (PCA) pump that administers pain medication in accordance with constraints defined by a health care technician (described in section 3.1.1). Models were developed in two phases. The first phase involved the construction and debugging of the human-device interface, device automation, and human mission models (an environmental model was not included because of the general stability of the environment in which an actual pump operates) with an unconstrained human task model serving as a placeholder for a more realistic human task model. The protocol necessary for coordinating behavior between the human task behavior and the other system elements was also developed in this phase. The second extended the model produced in Phase 1 with a realistic model of the human task, completing the framework.

Even though the target device in this modeling effort was seemingly simple, the system model that was initially developed in Phase 1 (Phase 1a) was too difficult for the model checker to process quickly and too complex for it to verify. Thus a number of revisions were undertaken [27]. In Phase 1b a reduced and abstracted model of the Baxter Ipump was produced which, while capable of being used in some verifications, did so at the expense of limiting the number of goals represented in the human mission model. This Phase 1b model limited the usefulness of incorporating human task behavior in Phase 2. Thus, in Phase

1c, the system model was reduced to encompass the programming procedure for a much simpler PCA pump. In Phase 2, the incorporation of the more realistic human task behavior actually resulted in a reduction of the total system model's complexity, but did so at the expense of an increase in verification time. This chapter discusses these modeling phases, the verification results produced in them, and their associated compromises in relation to the goals of the modeling architecture.

3.1 Methods

3.1.1 The Target System

The Baxter Ipump is an automated machine that controls delivery of sedative, analgesic, and anesthetic medication solutions [20]. Solution delivery via intravenous, subcutaneous, and epidural routes is supported. Medication solutions are typically stored in bags locked in a compartment on the back of the pump.

Pump behavior is dictated by internal automation, which can depend on how the pump is programmed by a human operator. Pump programming is accomplished via its human-device interface (Figure 3.2) which contains a dynamic LCD display, a security key lock, and eight buttons. When programming the pump, the operator is able to specify all of the following: whether to use periodic or continuous doses of medications (i.e. the mode which can be PCA, Basal + PCA, or Continuous), whether to use prescription information previously programmed into the pump, the fluid volume contained in the medication bag, the units of measure used for dosage (ml, mg, or μg), whether or not to administer a bolus (an initial dose of medication), dosage amounts, dosage flow rates (for either basal or continuous rates as determined by the mode), the delay time between dosages, and one hour limits on the amount of delivered medication.

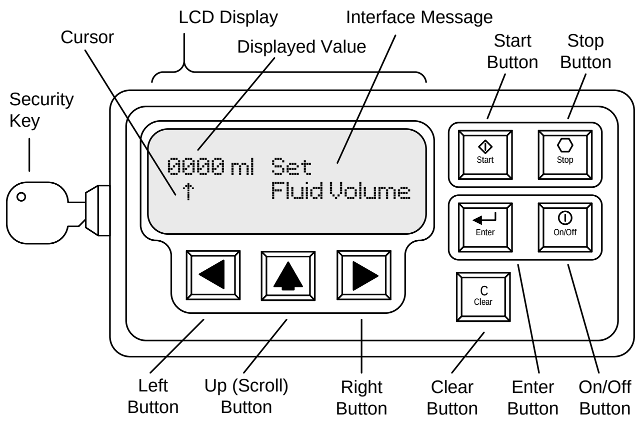


Figure 3.2: A simplified representation of the Baxter Ipump's human-device interface. Note that the actual pump contains additional controls and information conveyances.

During programming, the security key is used to lock and unlock the compartment containing the medication solution. The unlocking and locking process is also used as a security measure to ensure that an authorized person is programming the pump. The start and stop buttons are used to start and stop the delivery of medication at specific times during programming. The on-off button is used to turn the device on and off.

The LCD display supports pump operation options. When the operator chooses between two or more options, the interface message indicates what is being chosen, and the initial or default option is displayed. Pressing the up button allows the practitioner to scroll through the available options.

When a numerical value is required, the interface message conveys its name and the displayed value is presented with the cursor under one of the value's digits. The practitioner can move the position of the cursor by pressing the left and right buttons. He or she can press the up button to scroll through the different digit values available at that cursor position. The clear button sets the displayed value to zero. The enter button is used to confirm values and treatment options.

Aside from the administration of treatment, the pump's automation supports dynamic checking and restriction of operator entered values. Thus, in addition to having hard limits on value ranges, the extrema can change dynamically in response to other user specified values.

3.1.2 Apparatus

All formal models were constructed using the Symbolic Analysis Laboratory (SAL) language [65] because of its associated analysis and debugging tools, and its support for both the asynchronous and synchronous composition of different models (modules using SAL's internal semantics). The task model representations described next were translated into the SAL language as a single module using a custom-built java program [33]. All verifications were done using SAL-SMC 3.0, the SAL symbolic model checker[1]. Verifications were conducted on a 3.0 gigahertz dual-core Intel Xeon processor with 16 gigabytes of RAM running the Ubuntu 9.04 desktop.

Human task models were created using EOFM [28, 33] (see Chapter 2).

3.1.3 Verification Specification

Two specifications were employed in each of the modeling phases: both were written in linear temporal logic and evaluated using SAL-SMC. The first (3.1), used for model

[1]Some model debugging was also conducted using SAL's bounded model checker. See Chapter 4 for a more in depth discussion of SAL.

debugging, verifies that a valid prescription could be programmed into the pump:

$$\mathbf{G}\neg\left(\begin{array}{l} \mathit{iInterfacemessage} = \mathit{TreatmentAdministering} \\ \wedge\ \mathit{Mode} = \mathit{PrescribedMode} \\ \wedge\ \mathit{FluidVolume} = \mathit{PrescribedFluidVolume} \\ \wedge\ \mathit{PCADose} = \mathit{PrescribedPCADose} \\ \wedge\ \mathit{Delay} = \mathit{PrescribedDelay} \\ \wedge\ \mathit{BasalRate} = \mathit{PrescribedBasalRate} \\ \wedge\ \mathit{1HourLimit} = \mathit{Prescribed1HourLimit} \\ \wedge\ \mathit{Bolus} = \mathit{PrescribedBolus} \\ \wedge\ \mathit{ContinuousRate} = \mathit{PrescribedContinuousRate} \end{array}\right) \tag{3.1}$$

Here, if the model is able to enter a state indicating that treatment is administering (*InterfaceMessage* = *TreatmentAdministering*) with the entered (or programmed) prescription values (*Mode*, *FluidVolume*, ..., *ContinuousRate*) matching the prescription values generated by the mission model (variables with the *Prescrived* prefix), a counterexample would be produced illustrating how that prescription was programmed.

The second specification (3.2) represented a safety property that was expected to verify to true, thus allowing the model checker to traverse the entire state space of each phase's model. Because such a verification allows SAL to report the size of a model's state space, verifications using this specification would provide some means of comparing the complexity of the models produced in each phase.

$$\mathbf{G}\neg\left(\begin{array}{l} \mathit{InterfaceMessage} = \mathit{TreatmentAdministering} \\ \wedge\ \mathit{Mode} \neq \mathit{Continuous} \\ \wedge\ \mathit{Delay} = 0 \end{array}\right) \tag{3.2}$$

Here, the specification is asserting that the model should never enter a state where treatment is administering in the PCA or Basal + PCA modes (*Mode* $\neq$ Continuous) when there is no delay between doses[2]. Thus, if 3.2 verifies to true, the pump will never allow a practitioner to enter prescriptions that would allow patients to continuously administer PCA doses to themselves [20].

3.2 Phase 1a: A Representative Model of the Ipump

3.2.1 Model Description

An initial model was created to conform to the architectural and design philosophy represented in Figure 3.2: the mission was represented as a set of viable prescriptions options; the mission, human operator, human-device interface, and device automation were modeled independently of each other; and the behavior of the automated system and human-device interface models was designed to accurately reflect the behavior of these systems as described in the user's manual [20] and observed through direct interaction with the device. An unconstrained human operator was constructed that could issue any valid human action to the human-device interface model at any given time. Because the PCA pump generally operates in a controlled environment, away from temperature and humidity conditions that might affect the performance of the pump's automation, no environmental model was included. Finally, because documentation related to the internal workings of the pump was limited, the system automation model was restricted to that associated with the pump programming procedure: behavior that could be gleaned from the operator's manual [20], correspondences with hospital staff, and direct interaction with the pump.

[2]A delay can only been set when the PCA or Basal + PCA modes have been selected by the human operator. There are no delays between doses when the pump is in the Continuous mode.

3.2.2 Model Coordination

Model infrastructure was required to ensure that human operator actions were properly recognized by the human-device interface model. In an ideal modeling environment, human action behavior originating from the human operator model could have both an asynchronous and synchronous relationship with the human-device interface model. Synchronous behavior would allow the human-device interface model to react to user actions in the same transition in which they were issued/performed by the human operator model. However, both the human operator and human-device interface models operate independently of each other, and may have state transitions that are dependent on internal or external conditions that are not directly related to the state of the other model. This suggests an asynchronous relationship. SAL only allows models to be composed with each other asynchronously or synchronously (but not both). Thus, it was necessary to adapt the models to support features associated with the unused composition.

Asynchronous composition was used to compose the human operator and human-device interface models. This necessitated some additional infrastructure to prevent the human operator model from issuing user inputs before the human-device interface model was ready to interpret them and to prevent the human operator model from terminating a given input before the interface could respond to it. This was accomplished through the addition of two Boolean variables: one indicating that input had been submitted (henceforth called *Submitted*) and a variable indicating the interface was ready to receive actions (henceforth called *Ready*). This coordination occurred as follows:

- If *Ready* is true and *Submitted* is false, the human operator module sets one or more of the human action variables to a new input value and sets *Submitted* to true.
- If *Ready* and *Submitted* are true, the human-device interface module responds to the values of the human action variables and sets *Ready* to false.

- If *Ready* is not true and *Submitted* is true, the human operator module sets *Submitted* to false.
- If *Ready* and *Submitted* are both false and the automated system is ready for additional human operator input, the human-device interface module sets *Ready* to true.

3.2.3 Verification Results

Attempts to verify this model using the specifications in 3.1 and 3.2 resulted in two problems related to the feasibility and usefulness of the verification procedure. Firstly, the SAL-SMC procedure for translating the SAL code into a binary decision diagram (BDD) took more than 24 hours, a time frame impractical for debugging such a limited model. Secondly, the verification process which followed the construction of the BDD eventually ran out of memory, thus not returning a verification result.

3.3 Phase 1b: A Reduced Baxter Ipump Model

As a result of the failed verification of the model produced in Phase 1a, significant revisions were required to make the model more tractable. These are discussed below.

3.3.1 Representation of Numerical Values

In order to reduce the time needed to convert the SAL-code model to a BDD, a number of modifications were made to the model from Phase 1a by representing model constructs in ways more readily processed by the model checker. As such, the modifications discussed here did not ultimately make the BDD representation of the model smaller, but merely expedited its construction.

3.3.1.1 Redundant Representation of Values

Two different representations of the values programmed into the pump by the operator were used in the human-device interface and device automation models. Because the human-device interface required the human operator to enter values by scrolling through the available values for individual digits, an array of integer digits was appropriate for the human-device interface model. However, because the system automation was concerned with dynamically checking limits and using entered values to compute other values, a numerical representation of the actual value was more convenient for the automated system model.

This redundancy burdened the BDD translator. This was remedied by eliminating the digit array representations and using functions to enable actions from the human task model to incrementally change individual digits within a value.

3.3.1.2 Real Numbers and Integers

In the model produced in Phase 1a, all numerical values were represented as real values with restricted ranges. This was done because most user specified values were either integers or floating point numbers (precise to a single decimal point). No data abstractions were initially considered because the nature of the human task (modeled in Phase 2) required manipulation of values' individual digits. However, representing values this way proved especially challenging for the BDD translator. Thus, all values were modified so that they could be represented as restricted range integers. For integer variables representing floating point numbers, this meant that the model value was ten times the value it represented. This representation allowed the values to still be manipulated at the individual digit level, while making them more readily interpretable by the BDD translator.

3.3.1.3 Variable Ranges

In the Phase 1a model, the upper bound on the range of all value-based variables was set to the theoretical maximum of any value that could be programmed into the pump: 99999[3]. However, in order to reduce the amount of work required for the BDD conversion, the range of each numerically valued variable was given a specific upper bound that corresponded to the maximum value it could actually assume in the device.

3.3.2 Model Reduction

In order to reduce the size of the model, a variety of elements were removed. In all cases these reductions were meant to reduce the number of state variables in the human-device interface or Device Automation models (slicing), or reduce the range of values a variable could assume (data abstraction). Unfortunately, each of these reductions also affected what human tasks could ultimately be modeled and thus verified in subsequent model iterations. All of the following reductions were undertaken:

- In the Phase 1a model, the mission model could generate a prescription from the entire available range of valid prescriptions. This was changed so that fewer prescription options were generated in Phase 1b's mission model: that of programming a prescription with a continuous dosage with two options for bolus delivery (0.0 and 1.0 ml) and two continuous flow rate options (1.0 and 9.0 ml/hr). While this significantly reduced the number of model states, it also reduced the number of prescriptions that could be used in verification procedures.

- In the Phase 1a model, the human-device interface model would allow the operator to select what units to use when entering prescriptions (ml, mg, or μg). Only the

[3]All lower bounds were set to 0.

ml unit option was included in the Phase 1b model. This reduced the number of interface messages in the model, allowed for the removal of several variables (those related to the unit option selection, and solution concentration specification), and reduced the ranges required for several numerical values related to the prescription. This eliminated the option of including unit selection and concentration specification task behaviors in the model.

- In the Phase 1a model, both the human-device interface and device automation models encompassed behavior related to the delivery of medication solution during the priming and bolus administration procedures. During priming, the human-device interface allows the operator to repeatedly instruct the pump to prime until all air has been pushed out of the connected tubing. During bolus administration, the human-device interface allows the operator to terminate bolus infusion by pressing the stop button twice. This functionality was removed from the Phase 1b models, thus eliminating interface message states and numerical values indicating how much fluid had been delivered in both procedures. This eliminated the possibility of incorporating task behavior related to pump priming and bolus administration in the model.
- The Phase 1a model mimicked the security features found in the original device which required the human operator to unlock and lock the device on startup and enter a security code. This functionality was removed from the Phase 1b model which reduced the number of interface messages in the model and removed the numerical variable (with a 0-999 range) associated with entering the security code. This eliminated the possibility of modeling human task behavior related to unlocking and locking the pump as well as entering the security code in the model.
- In the Phase 1a model, the interface message could automatically transition to being blank: mimicking the actual pump's ability to blank its screen after three seconds

of operator inactivity. Because further operator inaction would result in the original device issuing a "left in programming mode" alert, a blank interface message could automatically transition to an alert issuance. This functionality was removed from the Phase 1b model, eliminating several interface messages as well as variables that kept track of the previous interface message. Thus, the option of modeling operator task response to screen blanking and alerts was removed from the model.

While these reductions resulted in the Phase 1b model being much smaller and more manageable than the original, the ability to model some of the task behaviors originally associated with the device had to be sacrificed.

3.3.3 Results

The Phase 1b model was able to complete the verification procedure with 3.1 and produce a counterexample with a search depth of 54 in approximately 5.9 hours, with the majority of that time (5.4 hours) used for creating the BDD representation [27]. Not surprisingly, the model checker ran out of memory when attempting to verify 3.2.

3.4 Phase 1c: A Simpler PCA Pump Model

While the model developed in Phase 1b did produce usable results and has subsequently been used in the verification of additional properties (see [26]), this power came at the expense of a reduction in the scope of the mission model. Since the mission directly influences what human behavior will execute, this limited the human task behavior that could ultimately be verified as part of the system model. Further, the fact that the Phase 1b model was too complex for 3.2 to be verified potentially limited any future model development that might add complexity. To remedy these shortcoming, the model produced in Phase

1b was further reduced to one that encompassed the programming of the most basic PCA pump functionality while the ranges of possible values for the remaining mission model variables were expanded to be more realistic.

3.4.1 Model Reduction

To obtain a smaller PCA model, all of the following were removed: the selection of mode and the ability to specify a basal rate, continuous rate, bolus dosage, and fluid volume. As a result, associated interface messages and variables were removed along with the ability to model their programming as part of the human task behavior model. This resulted in a model that only encompassed functionality for programming a PCA dose, programming the delay between PCA doses, turning the pump on and off, and starting and stopping the administration of treatment: functionality compatible with the most basic PCA pump operations (see [9]).

Value ranges were further restricted to reduce the size of the model. Specifically, the upper bound on the acceptable delay between PCA dosages was changed from 240 to 60 minutes. This, coupled with the other reductions, had the added benefit of allowing the number of digits required for the programming of pump values to be reduced to 2 rather than the original 4.

The reductions in other areas allowed the scope of the delays and PCA dosages generated by the mission model to be expanded to a more representative set. For PCA dosages, the full range of values from 0.1 to 9.9 in 0.1 ml increments were supported. For delay between dosages, five options were available: delays of 10, 15, 30, 45, and 60 minutes.

All pump interface functionality was retained from the previous models. Thus, the unconstrained human task model was unchanged as was the human task and human-device interface models' communication protocol.

3.4.2 Results

The Phase 1c model ran the verification procedure for 3.1 (with the eliminated variables removed) in 6 seconds with a search depth of 22, much faster than the model from Phase 1b. The verification of the specification in 3.2 verified to true in 129 seconds with a search depth of 259 and 78,768,682,750 visited states.

3.5 Phase 2: Incorporating Models of Human Behavior

In the second phase of modeling, we expanded our instantiation of the framework by incorporating a more realistic human task behavior model. We therefore replaced the unconstrained human operator in the Phase 1c model with a human task behavior model derived from pump documentation [20] and training materials. This model utilized the EOFM concepts and thus required some additional infrastructure in order to incorporate it into the formal system model. We describe the behaviors that were modeled and report verification results for the produced system model.

3.5.1 Human Task Behavior Modeling and Translation

The pump's materials contained six high-level goal directed behaviors for performing a variety of pump activities relevant to the Phase 1c model:

- Turning on the pump,
- Stopping the infusion of medication,
- Turning off the pump,
- Entering a prescribed value for PCA dosage volumes (in ml)

- Entering a prescribed value for the delay between PCA doses (in minutes), and
- Selecting whether to start or review an entered prescription.

The EOFM models describing each of these behaviors are discussed below.

3.5.1.1 Turning On the Pump

The model for turning on the pump is shown in Figure 3.3. Here, the EOFM can execute if the interface message indicates that the system is off (*InterfaceMessage* = *SystemOff*; a precondition). This high level activity (aTurnOnPump) is completed by performing the action of pressing the on/off button (*PressOnOff*). The *ord* decomposition operator indicates that all of the decomposed activities or actions must be completed in sequential order. The EOFM has accomplished its goal (a completion condition) when the interface message indicates that the pump is no longer off (*InterfaceMessage* /= *SystemOff*).

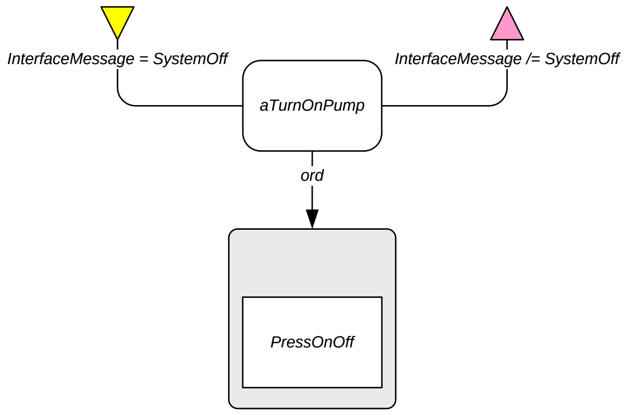


Figure 3.3: The EOFM graphical representation for turning on the pump.

3.5.1.2 Stopping Infusion

Infusion of medication can be stopped (Figure 3.4) if the interface indicates that treatment is administering (*InterfaceMessage* = *TreatmentAdministering*). This is accomplished by pressing the stop button (*PressStop*) twice in quick succession with no other human inputs occurring in between. The process has completed when the interface indicates that treatment is not administering (*InterfaceMessage /= TreatmentAdministering*).

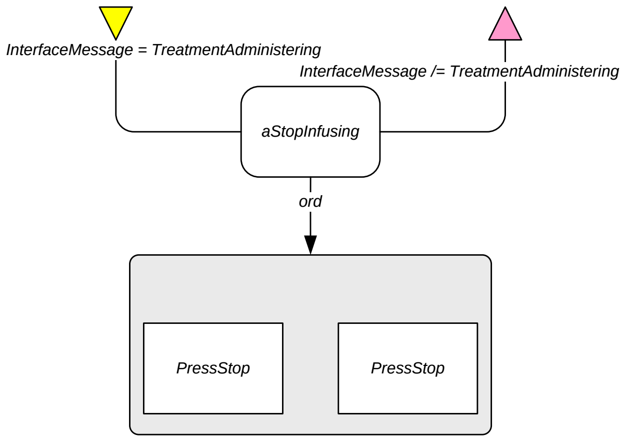

InterfaceMessage = TreatmentAdministering
InterfaceMessage /= TreatmentAdministering
aStopInfusing
ord
PressStop
PressStop

Figure 3.4: The EOFM graphical representation for stopping infusion.

3.5.1.3 Turning Off the Pump

The model for turning off the pump (Figure 3.5) is relevant if the interface message indicates that the system is not off (*InterfaceMessage /= SystemOff*). The pump is turned off by performing two lower level activities in sequential order: stopping infusion (*aStopInfusion*; explained above) and pressing the keys necessary to turn off the pump (*aPressKeysToTurnOffPump*). This latter activity is completed by pressing the on/off button (*PressOnOff*) twice in sequence. The entire process of turning off the pump completes when the interface indicates that the pump is off (*InterfaceMessage = SystemOff*).

3.5.1.4 Programming a Value Into the Pump

The values for PCA dosage volume and delay between dosages can be programmed into the pump using an EOFM patterned after Figure 3.6. Thus, for a given value *X*, the corresponding EOFM becomes relevant when the interface for setting that value is displayed

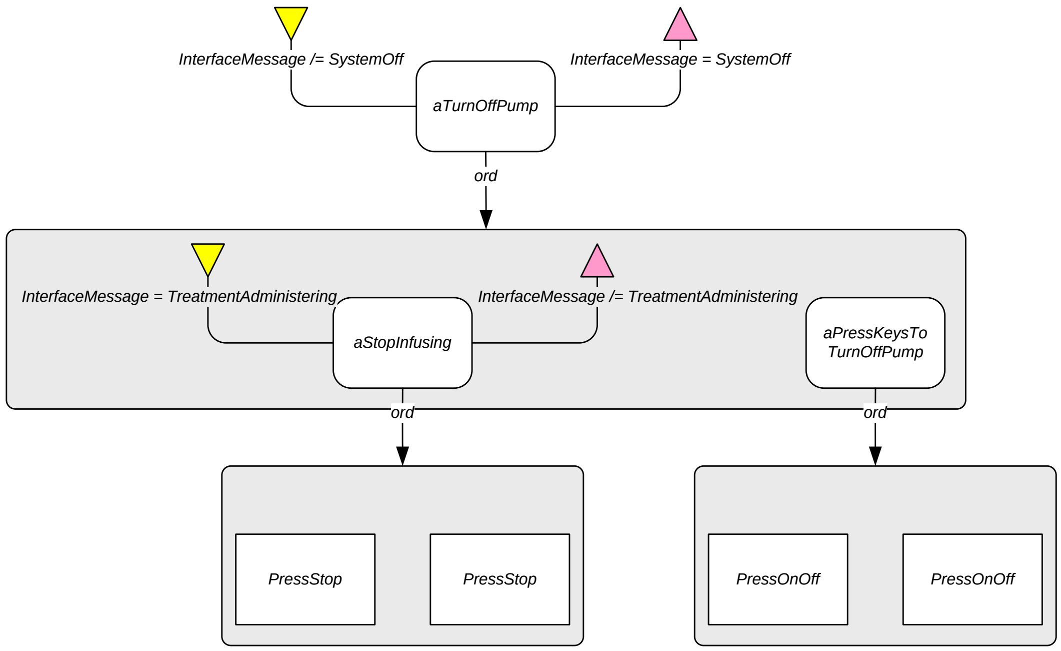

InterfaceMessage /= SystemOff
InterfaceMessage = SystemOff
aTurnOffPump
ord
InterfaceMessage = TreatmentAdministering
InterfaceMessage /= TreatmentAdministering
aStopInfusing
aPressKeysTo TurnOffPump
ord
ord
PressStop
PressStop
PressOnOff
PressOnOff

Figure 3.5: The EOFM graphical representation for turning off the pump.

(*InterfaceMessage* = *SetX*). This is achieved by sequentially executing two sub-activities: changing the displayed value (*aChangeXValue*) and accepting the displayed value (*aAccept*). The activity for changing the displayed value can execute, and will repeatedly execute, if the displayed value is not equal to the prescribed value (*CurrentValue /= PrescribedX*). The value is changed by executing one or more (denoted by the *or_seq* decomposition operator) of the following sub-activities: changing the digit currently pointed to by the cursor (*aChangeDigit*: completed by pressing the up key (*PressUp*)), moving the cursor to a different digit (*aNextDigit*: completed by pressing only one of (the *xor* decomposition operator) the left (*PressLeft*) or right (*PressRight*) buttons), or setting the displayed value to zero (*aClearValue*: completed by pressing the clear button(*PressClear*)). The process of changing the displayed value completes when the displayed value matches the prescribed value (*iCurrentValue* = *iPrescribedX*). The displayed value is accepted by pressing the enter key. The entire process ends when the interface is no longer in the state for accepting *X*.

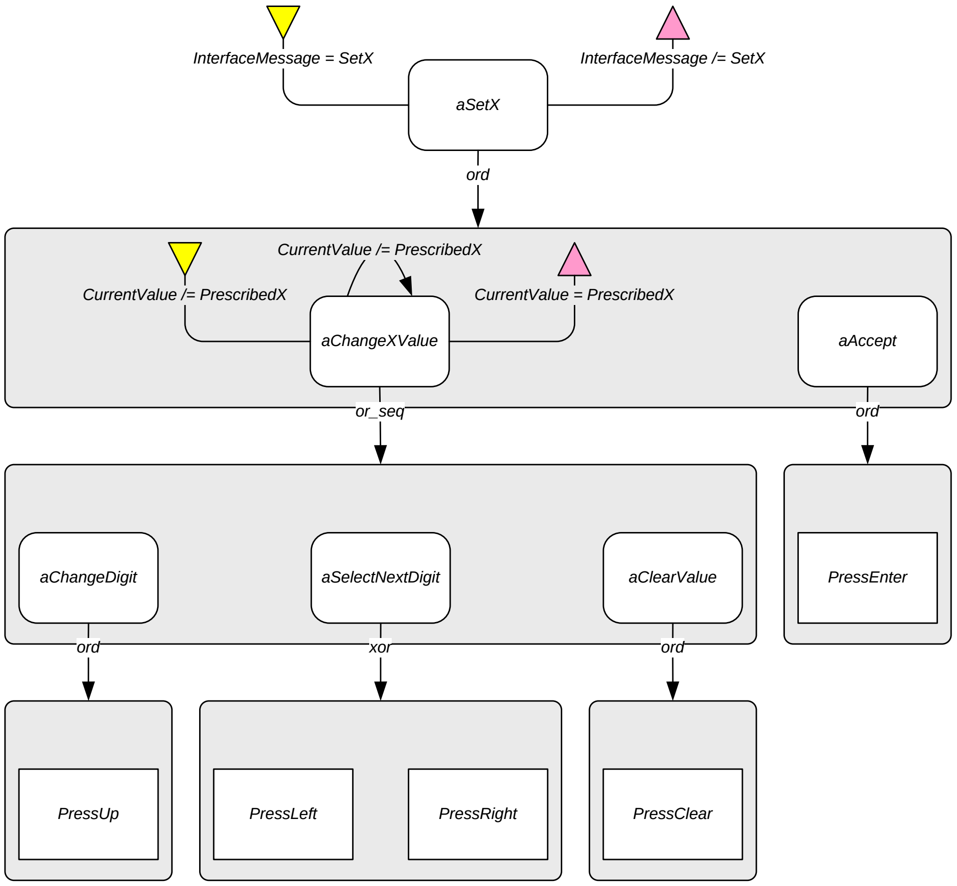


Figure 3.6: The EOFM graphical representation of the pattern for programming a value *X* into the pump.

3.5.1.5 Starting or Reviewing a Prescription

After a prescription has been programmed the human operator is given the option to start the administration of that prescription or to review it (where the operator works through the programming procedure a second time with the previously programmed options displayed at each step). The EOFM for performing this (Figure 3.7) becomes relevant at this point (*InterfaceMessage* = *StartBeginsRx*). It is completed by performing only one of two activities: selecting the option to start treatment (*aStartRx* - performed by pressing the start button (*PressStart*)) or selecting the review option (*aReviewRx* - performed by pressing the enter button (*PressEnter*)).

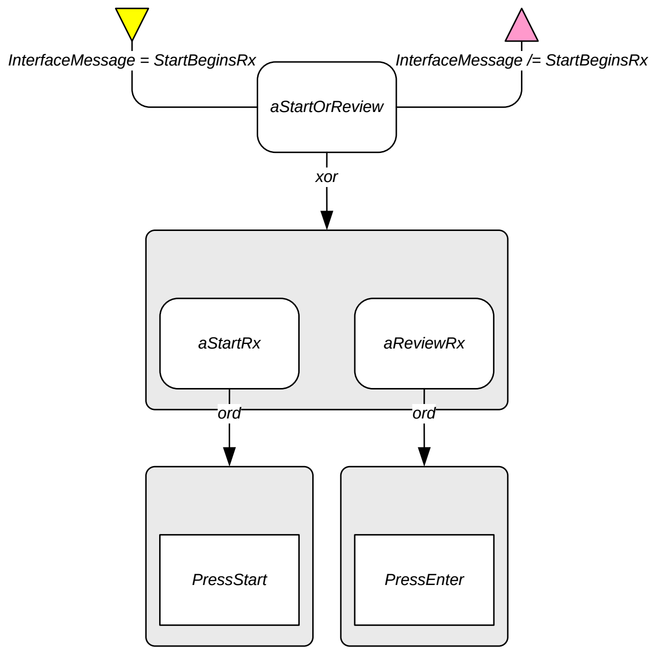

InterfaceMessage = StartBeginsRx
InterfaceMessage /= StartBeginsRx
aStartOrReview
xor
aStartRx
aReviewRx
ord
ord
PressStart
PressEnter

Figure 3.7: The EOFM for choosing to start or review a prescription.

3.5.2 EOFM Translation

The EOFMs representing the human task model were translated into a SAL code module using the EOFM's formal semantics and the process described in Chapter 4.

The instantiated EOFM file contained 168 lines of XML code, its translated version contained 439 lines of SAL code. While the resulting human operator module and its associated unconstrained operator model both had the same inputs and outputs, the logic associated with traversal of the human task structures required 48 additional variables in the human task behavior model.

3.5.3 Results

The specification in 3.1 verified (produced the expected counterexample) in 57 seconds with a search depth of 42. The specification in 3.2 verified to true in 10.6 hours with a search depth of 437 and 1,534,862,538 visited states.

3.6 Discussion

This work has shown that it is possible for human-automation interaction to be evaluated using the architecture in Figure 3.1. However, this came as a result of tradeoffs between the goals the architecture is designed to support:

1. Model constructs need to be represented in a useful form for human factors engineers who will be building and evaluating many of the models;
2. The sub-models should be decoupled and modular (as in Figure 3.1) in order to allow for interchangeability of alternative sub-models; and
3. The constructed models need to be capable of being verified in a reasonable amount of time.

We discuss how each of these goals was impacted and how related issues might be addressed.

3.6.1 Goals 1: Model Representation Usefulness

Many of the model revisions were associated with representing model constructs in ways that were more readily interpretable by the model checker rather than the human factors engineer. These primarily took the form of converting floating point and digit array values into integers in Phase 1b. Further, the extensive model reductions that were undertaken in Phase 1c would be very cumbersome for a human factors engineer.

There are two potential ways to address this issue. One solution would be to improve the model checkers themselves. Given that the modifications would not actually change the number of reachable states in the system, this would suggest that the model checker need only optimize the BDD conversion algorithms.

Alternatively, additional modeling tools could be used to help mitigate the situation. Such tools could allow human factors engineers to construct or import human-device interface prototypes, and translate them into model checker code. This would allow the representations necessary for ensuring a model's efficient processing by the model checker to be removed from the modeler's view.

3.6.2 Goal 2: Decoupling of Architecture Sub-models

Because the protocol used to coordinate human actions between the human-device interface and human task models (discussed for Phase 1a and used in all models produced in all subsequent phases) assumes a particular relationship between variables shared by these models, they are tightly coupled. Unless a model checker can be made to support both asynchronous and synchronous relationships between models more elegantly, this coordination infrastructure cannot be eliminated.

However, a solution may be found in an additional level of abstraction. A toolset for translating a human-device interface prototype into model checking code, could handle the construction of the coordination protocol, making this process effectively invisible to the modeler. Such a process could also allow for more efficient means of coordinating the human-device interface and human task models: one that might not require the use of separate models in the actual model checker code.

While the extensive model reductions from Phase 1 greatly diminished the fidelity with which the model represented the actual PCA pump, this provides some advantages. Since the model from Phase 2 does not suffer from the memory usage problems encountered in Phase 1, this opens the door to the addition of other model constructs to be added allowing for a more complete system analysis.

3.6.3 Goal 3: Model Verifiability

We are predominantly concerned with exploring how formal methods can be used to provide insights into human factors and systems engineering concerns. If our goal were to formally verify properties of the Baxter Ipump, the modeling compromises we made in order to obtain a verifiable model might necessitate a change in modeling philosophy or verification approach.

There are many barriers to the verifiability of models of realistic systems. These include large numbers of parallel processes, large ranges of discrete valued variables, and non-discretely valued variables. The modeling efforts described here were so challenging because the target system was dependent on a large number of user specified numerical values, all of which had very large acceptable ranges. This resulted in the scope of the model being reduced to the point where it could no longer be used for verifying all of the original human operator task behaviors: with the model produced in Phase 1b making minor compromises and the model produced in Phase 1c only allowing for behaviors associated with basic PCA pump functionality.

As was demonstrated in Phase 2, the verifiability of the model actually increased with the inclusion of the human task behavior as indicated by the 98% reduction in the reported state space from the Phase 1c to the Phase 2 model. However, this came at the expense of the verification process taking 284 times as long. Thus, in a context where verification time is less important than the size of the model's state space, the inclusion of the human task behavior model may generally prove to be advantageous in the formal verification of systems that have a human-automation interaction component, irrespective of whether the human behavior is of concern in the verification process. Future efforts should investigate the different factors that affect this tradeoff.

Even exploiting this advantage, the relative simplicity of the device that was modeled in this work makes it clear that there are many systems that depend of human-automation interaction that would be even more challenging to verify, if not impossible, using these techniques. While the use of bounded model checkers may provide some verification capabilities for certain systems, there is little that can be done without either using additional abstraction techniques or future advances in model checking technology and computation power.

It is common practice in the formal methods community to use more advanced forms of data abstraction than those employed in this work to mitigate the complexity of variables with large value ranges (an overview of these methods can be found in [136]). Because the nature of the modeled human task behavior in this work was concerned with the digit level editing of the data values, such abstractions were not appropriate for this particular endeavor. Additionally, automatic predicate abstraction techniques like those used in counterexample-guided abstraction refinement [55] could potentially alleviate some of the complexity problems encountered in this work without requiring changes to the models themselves. Future work should investigate how these different abstraction techniques could be used when modeling systems that depend on human-automation interaction in ways that are more useful to human factors engineers.

It is clear that the multiple, large-value-ranged variables were the source of most of the model complexity problems in the pump example, as shown in the drastic decrease in verification performance time between the models produced in Phases 1b and 1c. Thus, had the target system been more concerned with procedural behaviors and less on the interrelationships between numerical values, the system model would have been much more tractable. Future work should identify additional properties of systems dependent on human-automation interaction that lend themselves to being modeled and verified using the framework discussed here.

Finally, some of the performance issues we encountered can be attributed to our use of

SAL. For example, model checkers such as SPIN [104] do not perform the lengthy process of constructing the BDD representation before starting the checking process. Future work should investigate which model checker is best suited for evaluating human-automation interaction.

3.6.4 Closing Comments

The work presented here has shown that it is possible to construct models of human-automation interaction as part of a larger system for use in formal verification processes while adhering to some of the architectural goals in Figure 3.1 [4]. In making this contribution, this work has utilized a coordination protocol which allows the human task behavior to interact with the other elements of the formal system model. It has also shown that the incorporation of human task behavior models into system models may help alleviate the state explosion problem in some systems that depend on human-automation interaction given the significant reduction in the size of the models statespace between the formal system model containing the unconstrained human operator and the one using normative task behavior defined in an instantiated EOFM. In fact, the use of the two different task behavior models (both the normative and unconstrained) illustrates the flexibility of the architectural framework, given that the two were completely interchangeable. Although the PCA pump application did not include a model of the environment, and no problems with human-automation interaction were discovered, applications in latter chapters address both of these issues.

These successes were the result of a number of compromises that produced a model that was not as representative or modular as desired. Thus, in order for formal methods to become more useful for the HFE community, the verification technology will need to

[4]More successful implementations are discussed in subsequent chapters.

be able to support a more diverse set of systems. Further, new modeling tools may be required to support representations that human factors engineers use. These advances will ultimately allow formal methods to become a more useful tool for human factors engineers working with safety critical systems.

Chapter 4

Enhanced Operator Function Model to Symbolic Analysis Laboratory Translator[*]

Chapter 3 showed that task analytic models can be incorporated into a system modeling framework that also includes models of the human missions, human-device interfaces, device automation, and the environment. This chapter shows how the formal semantics of the EOFM (see [33] or Chapter 2) can be used to create a translator that automatically converts an instantiated EOFM into a formal model that can be formally verified with SAL's symbolic model checker. The translation process is verified to produce code that complies with EOFM's formal semantics. The complexity of the formal representations of EOFM task models are benchmarked. We also present an automobile driving case study illustrating how this process can be used with our method to discover and to analyze a potential intervention to correct safety properties related to the use of the cruise control.

[*]This chapter is derived from [33]

4.1 EOFM to SAL Translation

To be utilized in a model checking verification, instantiated EOFMs must be translated into a model checker supported language. We use the formal semantics ([33] and Chapter 2) to translate instantiated EOFMs into the language of the Symbolic Analysis Laboratory (SAL). SAL is a framework for combining different tools to calculate properties of concurrent systems [65, 169]. The SAL language is supported by a tool suite which includes state of the art symbolic (SAL-SMC), bounded (SAL-BMC), and "infinite" bounded (SAL-INF-BMC) model checkers. Auxiliary tools include a simulator, deadlock checker, and an automated test case generator.

The SAL language is designed for specifying concurrent systems in a compositional way. Constants and types are defined globally within a SAL file. Discrete system components are modeled as modules. Each module is defined in terms of input, output, and local variables. Modules are linked by their input and output variables. Within a module, local and output variables are given initial values. All subsequent value changes occur as a result of transitions. A transition is composed of a guard and a transition assignment. The guard is a Boolean expression composed of input, output, and local variables as well as SAL's mathematical operators. The transition assignment defines how the value of local and output variables change when the guard is satisfied.

The EOFM to SAL translation is automated by our custom built Java program which uses the Document Object Model [127] to parse an instantiated EOFM's XML code and convert it into SAL code.

For a given instantiated EOFM, the translator defines SAL constants and types using the *constant* and *userdefinedtype* nodes. The translator creates a separate SAL module for each *humanoperator* node. Input, local, and output variables are defined in each module corresponding to the *humanoperator* node's *inputvariable*, *localvariable*, and *humanaction* nodes respectively. Input and local variables are defined in SAL using the *name* and type (*basictype* or *userdefinedtype*) attributes from their markup. Local variables are initialized to their values from the markup. All output variables in the SAL module (one for each *humanaction* node) are defined with a Boolean type and initialized to *false*: a value of *true* indicates that the action is being performed.

The translator defines two Boolean variables in the *humanoperator* node's module to handle a coordination handshake with the human-device interface module (see [27], [31], or Chapter 3):

1. An input variable *interfaceReady* that is *true* when the interface is ready to receive input; and

2. An output variable *actionsSubmitted* that is *true* when one or more human actions are performed.

The *actionsSubmitted* output variable is initialized to *false*.

The translator defines a SAL type, *ActivityState*, to represent the execution states of activities and actions: *Ready*, *Executing*, or *Done* (Figure 2.3). As described previously, the activity and action state transactions define the task (Figure 2.3). Each *activity* and *action* in the human operator's node structure has an associated local variable of type *ActivityState*. For activities, in addition to the task model defined *precondition*s, *repeatcondition*s, and *completioncondition*s, three other conditions are required to define the transition guards: *startcondition*s, *endcondition*s and *reset*. The translator defines the *startconditions* based on the execution state of its parent activity, the state of the activity's siblings, and its parent's decomposition operator. The *startcondition* for an activity is *true* when the parent is *Executing*, the activity is *Ready*, and:

1. The decomposition operator is *ord* and all preceding siblings are *Done* (it is the next activity to execute);

2. The decomposition operator is *xor* and all siblings are *Ready* (it is the only activity to execute); or

3. The decomposition operator is *and_seq*, *or_seq*, *optor_seq*, or *sync* and no other siblings are *Executing* (the activity cannot execute when its siblings execute).

The *endcondition* for an activity is true when the activity is *Executing* and:

1. The decomposition operator is *and_seq*, *and_par*, or *sync* and all child activities or actions are *Done*;

2. The decomposition operator is *ord* and the last child activity or action is *Done*;

3. The decomposition operator is *or_seq*, *or_par*, or *xor* and all child activities or actions are not *Executing* with at least one being *Done*; or

4. The decomposition operator is *optor_seq* or *optor_par* and all child activities or actions are not *Executing*.

Because the *reset* occurs when an *activity*'s parent resets, the *reset* transition is handled differently than the others. When a parent *activity* transitions from *Executing* to *Executing*, all of the execution state variables corresponding to its sub-acts (and throughout the hierarchy) are assigned the *Ready* state. Additionally, for each *activity* at the top of a task hierarchy, a guard is created that checks if its execution state variable is *Done*. Then, in the transition assignment, this variable is assigned a value of *Ready* along with the lower level activities and actions in order to achieve the desired *reset* behavior.

Transitions between execution states for variables associated with *action* nodes are handled differently due to the coordination handshake. For each *action*, a *startcondition* is created using execution state variables and written as a guard for the *Ready* to *Executing* transition (Figure 2.3(b)) with the additional condition that *interfaceReady* is *true*. In the transition assignment: the execution variable associated with the given *action* is set to *Executing*; the corresponding *humanaction* output variable is set to the logical negation of its value (*true* or *false*, where the change in variable value indicates that a human action has been performed); and *actionsSubmitted* is set to *true*. Because the *endcondition* for all *action*s is always true, the *Executing* to *Done* transition is handled by a single guard and transition assignment, where the guard accounts for the handshake protocol. Thus the guard specifies that *actionsSubmitted* is *true* and that *interfaceReady* is *false*: verifying that that the interface has received submitted *humanaction* outputs. In the assignment, *actionsSubmitted* is set to *true*; any execution state variable associated with an *action* that has value *Executing* is set to *Done* (it is unchanged otherwise); and any *humanaction* output variables that support the *autoreset* behavior are set to *false*. The *reset* transition occurs as a result of the activity *reset* process discussed above.

Because all of the transitions are non-deterministic, multiple activities can be execute independently of each other when any of the *_par* decomposition operators are used. Multiple human actions resulting from such decompositions are treated as if they occur at the same time if the associated *humanaction* output variables change during the same interval (a sequential set of model transitions) when *interfaceReady* is *true*.

4.2 Validation and Benchmarking

A series of formal verifications were performed in order to validate that the EOFM to SAL translator was working as intended (see Appendix B). To evaluate the complexity and scalability of EOFM task models, we generated EOFM models and investigated the translated models' state spaces and runtimes using SAL.

The EOFM models include a single human operator who presses keys on a human-device interface. The *autoreset* behavior was used for all key press actions. For all cases, the human operator had a single, goal level activity that decomposed into two or more actions via a decomposition operator.

Table 4.1: Translated EOFM instance benchmark experiments

Decomposition	# Subacts							
	2		8		16		24	
Operator	States	Time	States	Time	States	Time	States	Time
and_seq	20	0.15	2,564	0.51	1,179,652	1.82	436,207,620	5.77
or_seq	24	0.15	3,072	0.51	1,310,720	1.85	469,762,048	6.20
optor_seq	26	0.14	3,074	0.50	1,310,722	1.76	469,762,050	6.43
xor	16	0.11	52	0.32	100	1.07	148	3.05
ord	14	0.13	38	0.46	70	1.16	102	2.62
and_par	22	0.12	13,126	0.39	86,093,446	1.75	564,859,072,966	21.48
or_par	26	0.13	13,634	0.41	86,224,514	1.56	564,892,627,394	145.52
optor_par	28	0.13	13,636	0.39	86,224,516	1.91	564,892,627,396	76.42
sync	10	0.11	10	0.21	10	0.37	10	0.67

Note. Time is measured in seconds.

To ensure that the verification process would search a model's entire state space, we created an LTL specification that would not produce a counterexample. This stated that the model could never have an execution state variable indicating that a specific action is executing (*action1State*) without its corresponding human action output (*PressKey1*) being true:

$$\mathbf{G}(\neg(\mathit{action1State} = actExecuting \wedge \mathit{PressKey1} \neq true))$$

Using SAL's symbolic model checker (SAL-SMC) on a single core 2.8 gigahertz machine with 8 gigabytes of RAM running Ubuntu Linux, we ran 9 benchmarking trials. Table 4.1 shows the size of the state-space and runtimes for the entire set of singleton operators. The results are consistent with the interleavings of actions associated with the decomposition operators. For example, there is one more interleaving allowed for *optor* than for *or*[1]. Also, the number of synchronous actions executed at the same time has no

[1]The number of reachable states is multiplied by two, because each interleaving produces an additional

impact on the size of the state space.

In terms of scalability, the symbolic model checker can handle large state spaces (over half a trillion for some of the parallel operators). However the size of the state space, the time to check the LTL query, and the type of decomposition operator interact to impact the runtime. With the *and_par*, *or_par*, and *optor_par* decomposition operators, the statespaces are roughly the same size; however the runtimes vary by a factor of 7 between *and_par* and *or_par*.

4.3 Application: Cruise Control System

To illustrate the use of an EOFM model to find human-automation interaction related problems, we present a formal model of driving with a simple automobile cruise control system (Figure 4.1) in which a car is traveling down a street toward a traffic light. The distance of the car from the light is represented in intervals corresponding to its relative position: Very Very Far, Very Far, Far, Merging, Close, Very Close, and At Intersection. At the Merging interval, a ramp intersects with the road allowing any traffic on the ramp to merge.

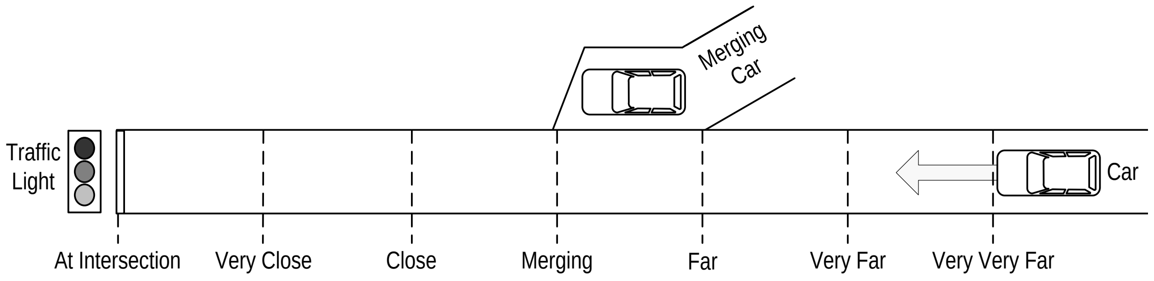


Figure 4.1: Cruise control model scenario.

The driver of the car wants to drive safely down the road. The driver's goal is to drive at his desired speed while avoiding merging traffic and safely responding to traffic lights.

reachable state where the key is pressed and the corresponding action is first *executing* and then transitions to *done*.

He can drive at one of 3 speeds (Slow, Moderate, or Fast) using a gas pedal to increase and decrease the gas. Increasing the gas (pressing the gas pedal) causes the car to accelerate to the next faster speed. Decreasing the gas decelerates the car to the next slower speed. The driver can release the gas pedal (which causes the car to decelerate until it stops) and can press the break. The driver can enable or disable the cruise control using available buttons. Cruise control can also be disabled by pressing the break. When enabled, the cruise control will keep the car moving forward at its current constant speed unless the driver increases the gas. In this situation, the driver controls the car's speed above the cruise speed.

The formal system model architecture [27, 34] includes the human-device interface, device automation, operational environment, and human mission. It also contains the human task behavior which is translated from an instantiated EOFM for the three modeled driving tasks: driving at the desired speed, avoiding merging traffic, and responding to a traffic light. Formal verification is performed on this system model using SAL-SMC to ensure that the driver will never run a red light.

At each interval, the driver can perform a single action, or synchronous set of actions, in response to the information he is receiving from the rest of the model. Once these actions have been committed, the human-device interface, device automation, and environments update: the light is allowed to change, merging traffic may arrive on the ramp, and the car advances one interval down the road if it has not stopped. Next we discuss each component of this system model, how each is modeled formally, and the instantiated EOFM.

4.3.1 Human-device Interface

The human-device interface receives actions from the human operator and provides feedback from the device automation in response. Through the human-device interface, the driver can: increase the gas (*IncreaseGas*), decrease the gas (*DecreaseGas*), release the gas pedal (*ReleaseGas*), press the break (*Break*), press the enable cruise control button (*EnableCruise*), and press the disable cruise control button (*DisableCruise*). The driver receives information as inputs from the human-device interface: the position of the pedal (*Pedal*); the speed of the car (*CarSpeed*); and whether the car has accelerated, decelerated, or remained at a constant speed (*CarAcceleration*).

The driver can directly control the state of the human-device interface's gas pedal (Figure 4.2). The pedal has four different states (*Unpressed*, *PressedToSlow*, *PressedToModerate*, and *PressedToFast*) representing its position. These directly correspond to a car speed (*Stopped*, *Slow*, *Moderate*, or *Fast* respectively). The initial state of the pedal (*PressedToSlow*, *PressedToModerate*, or *PressedToFast*) determines the initial speed of the car. If the human operator increases the gas then the state of the pedal is set to the next higher state. If he decreases the gas, the state of the pedal is set to the next lower state. The pedal transitions to the *Unpressed* state when the driver releases the gas.

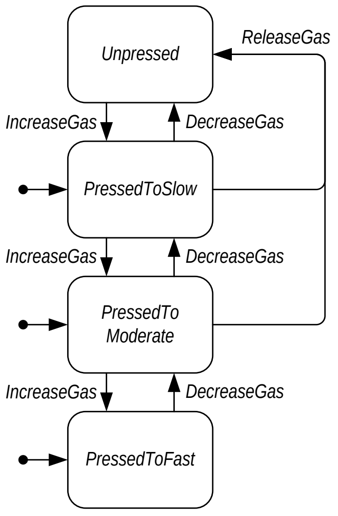


Figure 4.2: State transition diagram depicting the formal model's behavior for the gas pedal (*Pedal*). States are depicted as rounded rectangles. Arcs with Boolean expressions attached represent guards on transitions between states. Arrows with a dot point to valid initial states.

4.3.2 Device Automation

The device automation tracks the status of the cruise control (Figure 4.3). Cruise is *Enabled* when the driver presses the enable cruise button and *Disabled* when he presses the disable cruise button or presses the break.

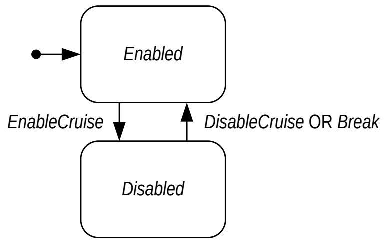


Figure 4.3: State transition diagram depicting the formal model's behavior for the state of the cruise control (*Cruise*). States are depicted as rounded rectangles. Arcs with Boolean expressions attached represent guards on transitions between states. Arrows with a dot point to valid initial states.

Enabling the cruise control also sets the cruise speed in the device's automation (Figure 4.4) where the cruise speed directly corresponds to the speed of the car when cruise is enabled.

Human operator input to the gas pedal and the state of the cruise control also impact how the device automation controls the speed of the car (Figure 4.5): a property visible to the human operator via the speedometer. The driver can increase the car's speed by increasing the gas even when the cruise control is enabled. The application of the break stops the car. When the driver decreases the gas (without applying the break), the car's speed decreases when *Cruise* is *Disabled* or when *Cruise* is *Enabled* and the *CruiseSpeed* is below the car's current speed. When the driver removes his foot from the gas (as indicated by the *Pedal* being *Unpressed*), the car slows by two speed increments below the current speed unless *Cruise* is *Enabled* and at an intermediary speed. In this case, the car will remain at or slow down to the *CruiseSpeed*.

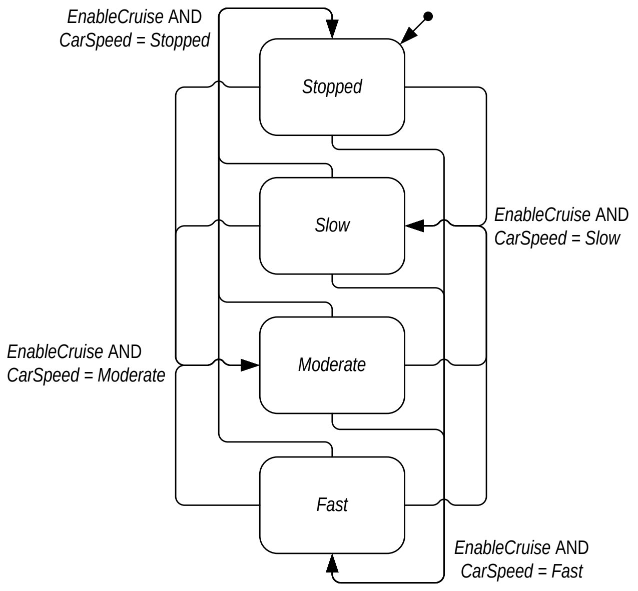

EnableCruise AND *CarSpeed = Stopped*
Stopped
Slow
EnableCruise AND *CarSpeed = Slow*
EnableCruise AND *CarSpeed = Moderate*
Moderate
Fast
EnableCruise AND *CarSpeed = Fast*

Figure 4.4: State transition diagram depicting the formal model's behavior for the state of the cruise speed (*CruiseSpeed*). States are depicted as rounded rectangles. Arcs with Boolean expressions attached represent guards on transitions between states. Arrows with a dot point to valid initial states.

The state of the car's acceleration (Figure 4.6) is directly tied to changes in the state of the car's speed. If the car's speed has decreased then the car has *Decelerated*. If the car's speed has increased then the car has *Accelerated*. If there has been no change in the car's speed, the car has remained at a *ConstantSpeed*.

4.3.3 Operational Environment

The environment model encompasses the state of the traffic light, the state of merging traffic, and the relative position of the car to the traffic light.

The state of the traffic light changes between its three colors in response to a modulo 8 counter (Figure 4.7). The light is *Green* when the counter is between 0 and 3, *Yellow* when the counter is 4, and *Red* when the counter is between 5 and 7. Any counter value is a valid initial state. At every step in the model's execution, when the environment model

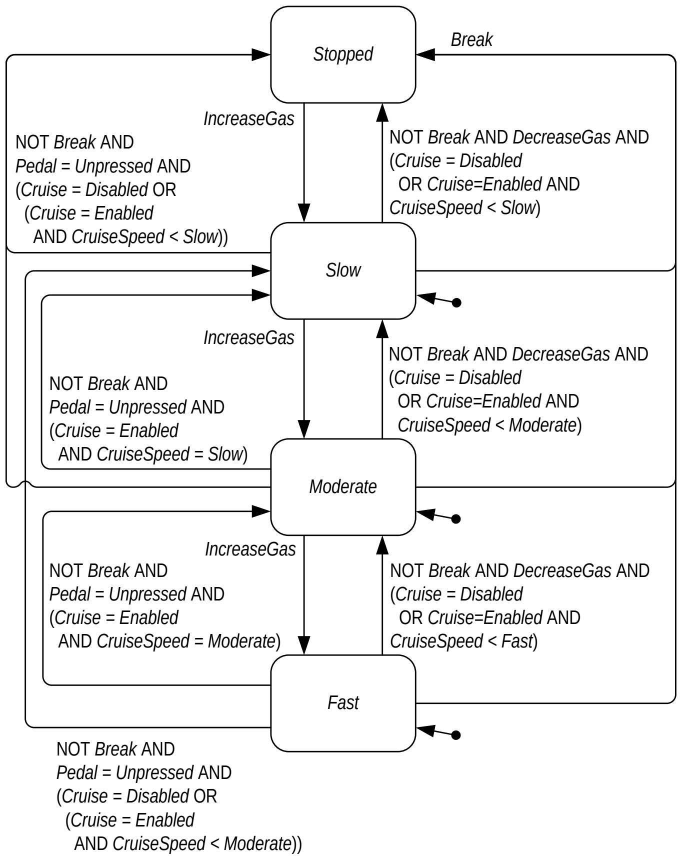

Stopped
Break
IncreaseGas
NOT Break AND Pedal = Unpressed AND (Cruise = Disabled OR (Cruise = Enabled AND CruiseSpeed < Slow))
NOT Break AND DecreaseGas AND (Cruise = Disabled OR Cruise=Enabled AND CruiseSpeed < Slow)
Slow
IncreaseGas
NOT Break AND Pedal = Unpressed AND (Cruise = Enabled AND CruiseSpeed = Slow)
NOT Break AND DecreaseGas AND (Cruise = Disabled OR Cruise=Enabled AND CruiseSpeed < Moderate)
Moderate
IncreaseGas
NOT Break AND Pedal = Unpressed AND (Cruise = Enabled AND CruiseSpeed = Moderate)
NOT Break AND DecreaseGas AND (Cruise = Disabled OR Cruise=Enabled AND CruiseSpeed < Fast)
Fast
NOT Break AND Pedal = Unpressed AND (Cruise = Disabled OR (Cruise = Enabled AND CruiseSpeed < Moderate))

Figure 4.5: State transition diagram depicting the formal model's behavior for the state of the car's speed (*CarSpeed*). States are depicted as rounded rectangles. Arcs with Boolean expressions attached represent guards on transitions between states. Arrows with a dot point to valid initial states.

is allowed to update, the light counter increments.

When the car is at the *Merging* interval, there may be merging traffic based on the transition logic in Figure 4.8. Initially there is no merging traffic. When the car is at the *Merging* interval, there can either be no merging traffic or a single merging car. The *Merging* state will automatically transition back to *NotMerging* when the environmental model next updates.

The environment model tracks the relative distance, or the interval, of the car from the traffic light (Figure 4.9). The car starts at the *VeryVeryFar* interval and proceeds through

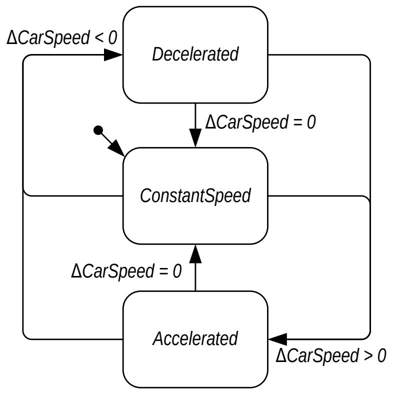


Figure 4.6: State transition diagram depicting the formal model's behavior for the state of the car's acceleration (*CarAcceleration*). States are depicted as rounded rectangles. Arcs with Boolean expressions attached represent guards on transitions between states. Arrows with a dot point to valid initial states.

the intervals incrementally every time the environmental model updates if the car is not stopped. Once the *AtIntersection* interval is reached, the entire system model is at its final state.

4.3.4 Human Mission

The human mission model controls how fast the human operator wants to drive via the *MissionSpeed* variable. It is initialized to *Slow*, *Moderate*, or *Fast*.

4.3.5 Human Task Behavior Model

An instantiated EOFM describes the human driver task behavior using a single *humanoperator*. This human operator driver has access to input variables from:

1. The environment model: the traffic light's color (*TrafficLight*) and its relative interval distance (*TrafficLightDistance*);

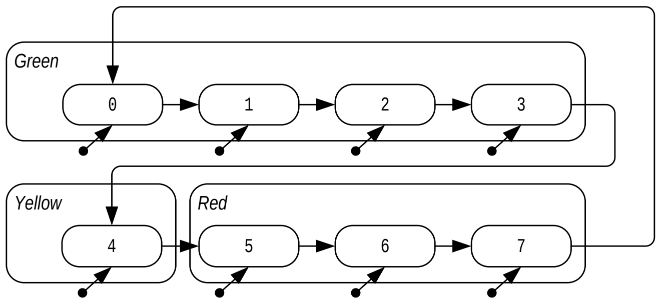


Figure 4.7: State transition diagram depicting the formal model's behavior for the traffic light (*TrafficLight*). States are depicted as rounded rectangles. Arcs with Boolean expressions attached represent guards on transitions between states. Arrows with a dot point to valid initial states.

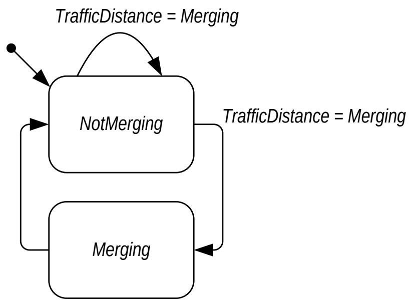


Figure 4.8: State transition diagram depicting the formal model's behavior for the presence of merging traffic (*Traffic*). States are depicted as rounded rectangles. Arcs with Boolean expressions attached represent guards on transitions between states. Arrows with a dot point to valid initial states.

2. The human-device automation and interface models: the car's speed (*CarSpeed*), the car's acceleration (*CarAcceleration*), and the state of the gas pedal (*GasPedal*); and

3. The mission model: mission speed (*MissionSpeed*).

The driver model generates *humanaction* outputs representing actions performed through the human-device interface: increasing the gas (*IncreaseGas*), decreasing the gas (*DecreaseGas*), releasing the gas (*ReleaseGas*), making no change to the gas (*NoChange*), pressing the break (*Break*), enabling the cruise control (*EnableCruise*), and disabling the

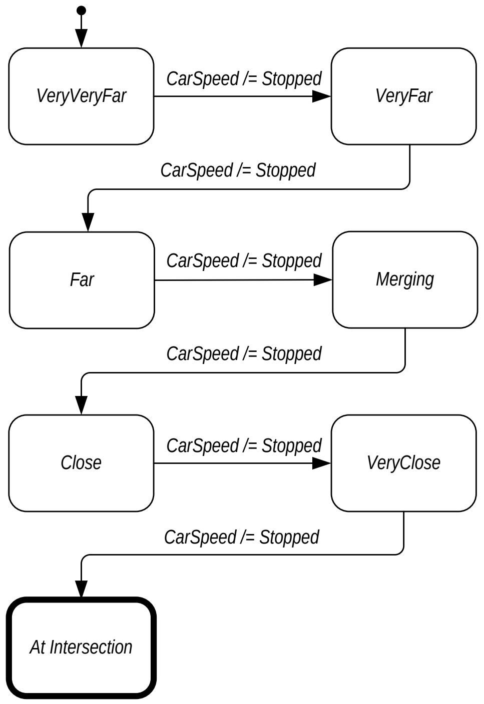


Figure 4.9: State transition diagram depicting the formal model's behavior for the relative distance/interval of the car to the traffic light (*TrafficLightDistance*). States are depicted as rounded rectangles. Arcs with Boolean expressions attached represent guards on transitions between states. Arrows with a dot point to valid initial states. A thick black line around a node indicates a final state.

cruise control (*DisableCruise*).

Three goal directed task models were constructed[2]: one for driving at the desired speed (Figure 4.10), one for avoiding merging traffic (Figure 4.11), and one for responding to the light (Figure 4.12).

The task model for driving at the desired speed (Figure 4.10) has root activity *aDriveAtDesiredSpeed*. This has both a *precondition* and *repeatcondition* that control when it can execute and when it can repeat execution: when there is no merging traffic and either the traffic light is green or the car is not close to the intersection. Execution will stop (*completioncondition*) if the traffic light is not green and the car is close to the traffic light, or if

[2]A full code listing can be found in Appendix A

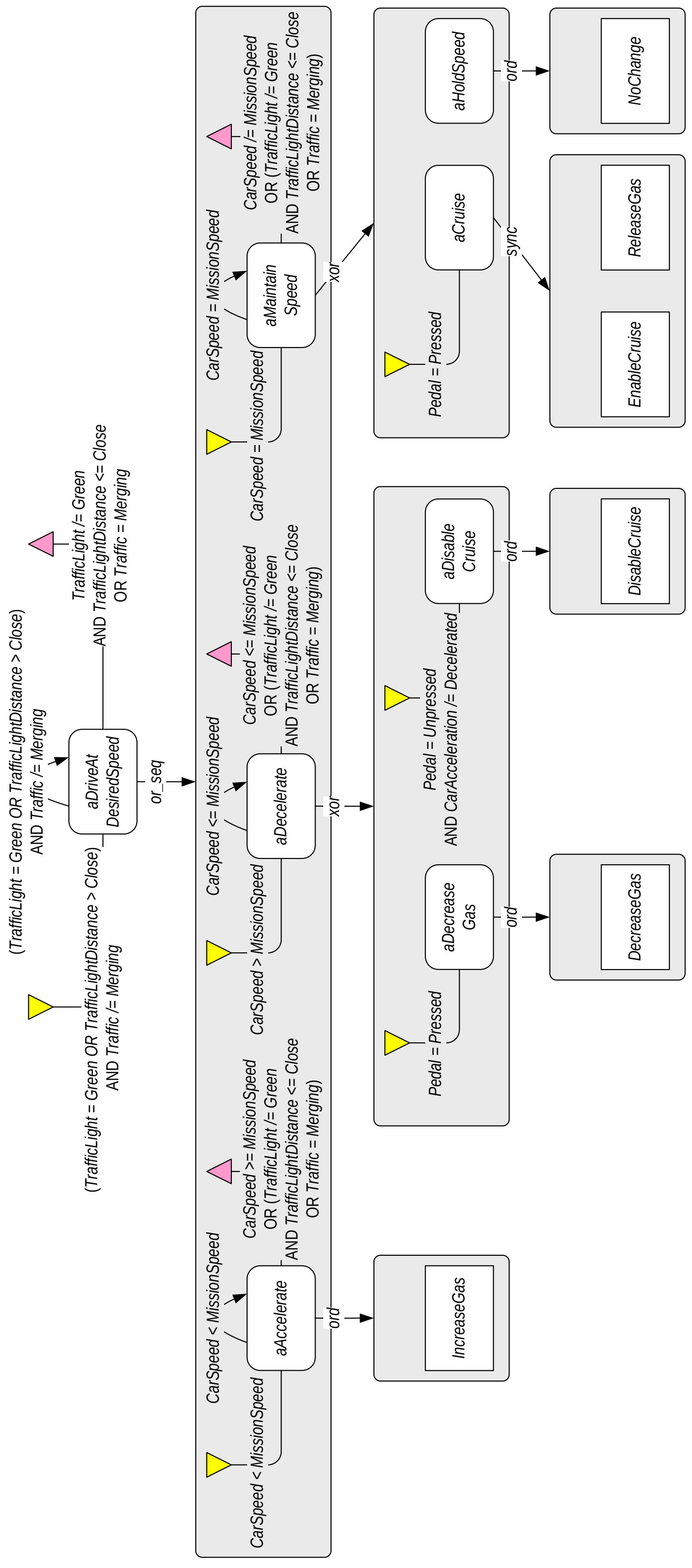

(TrafficLight = Green OR TrafficLightDistance > Close) AND Traffic /= Merging
(TrafficLight = Green OR TrafficLightDistance > Close) AND Traffic /= Merging
aDriveAt DesiredSpeed
TrafficLight /= Green AND TrafficLightDistance <= Close OR Traffic = Merging
or_seq
CarSpeed < MissionSpeed
CarSpeed < MissionSpeed
aAccelerate
CarSpeed >= MissionSpeed OR (TrafficLight /= Green AND TrafficLightDistance <= Close OR Traffic = Merging)
ord
IncreaseGas
CarSpeed > MissionSpeed
CarSpeed <= MissionSpeed
aDecelerate
CarSpeed <= MissionSpeed OR (TrafficLight /= Green AND TrafficLightDistance <= Close OR Traffic = Merging)
xor
Pedal = Pressed
aDecrease Gas
ord
DecreaseGas
Pedal = Unpressed AND CarAcceleration /= Decelerated
aDisable Cruise
ord
DisableCruise
CarSpeed = MissionSpeed
CarSpeed = MissionSpeed
aMaintain Speed
CarSpeed /= MissionSpeed OR (TrafficLight /= Green AND TrafficLightDistance <= Close OR Traffic = Merging)
xor
Pedal = Pressed
aCruise
sync
EnableCruise
ReleaseGas
aHoldSpeed
ord
NoChange

Figure 4.10: Visualization of the EOFM task model for driving at the desired speed. Activities are represented as rounded rectangles, actions by unrounded rectangles, and preconditions as inverted yellow triangles. Boolean expressions in conditions use the syntax supported by transition guards in SAL.

traffic is merging.

The driver performs this activity using one or more methods (the *or_seq* decomposition operator): accelerating (*aAccelerate*), decelerating (*aDecelerate*), or maintaining the current speed (*aMaintainSpeed*). Accelerating can be performed repeatedly if the car's speed is less than the mission speed. This activity completes when the car's speed reaches or surpasses the mission speed, or if the driver must respond to the light or merging traffic. The driver accelerates by increasing the gas (the *ord* decomposition operator indicates a sequential order; but with one action, only the one action is performed).

The driver can start or continue decelerating if the car's speed is greater than the desired (mission) speed. The activity completes when the car's speed is less than or equal to the desired speed, or the driver needs to respond to the light or traffic. Deceleration is accomplished by one of two activities (the *xor* decomposition operator): decreasing the gas (*aDecreaseGas*) or disabling the cruise control (*aDisableCruise*). If the gas pedal is pressed, the driver can decrease the gas. The driver can disable the cruise control if it is enabled: the pedal is not pressed and the car has not just decelerated.

The driver can maintain speed as long as the car's speed matches the desired speed. The activity completes if the car's speed does not match the desired speed, or the driver needs to respond to the light or traffic. The driver maintains speed by either enabling the cruise (*aCruise*) or holding the current speed (*aHoldSpeed*). If the cruise control does not appear to be enabled (indicated by the pedal being pressed), it can be enabled by synchronously performing (the *sync* decomposition operator) the actions for enabling the cruise control and releasing the gas pedal. The driver can tell that the cruise control has been enabled if the car does not decelerate when he removes his foot from the gas pedal. The driver holds the current speed by making no change to the gas pedal.

The driver can avoid merging traffic (*aAvoidMergingTraffic*; Figure 4.11) when traffic is merging by performing one of two activities: if the car is not at its minimum speed, the driver can let the merging traffic go in front (*aLetCarGoInFront*), or if the car is not at its maximum speed, the driver can let the merging traffic in behind (*aLetCarGoBehind*). Letting the traffic pull in front is achieved by (a) decreasing the gas (via *aDecreaseGas*) if cruise is not enabled or (b) disabling cruise (via *aDisableCruise*) if it is enabled. Letting the traffic in behind is achieved by increasing the gas.

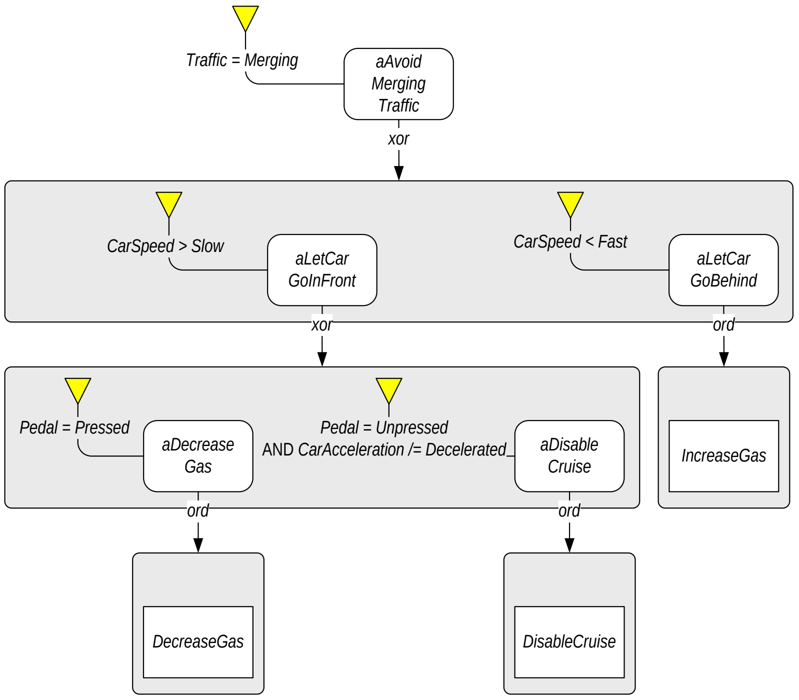


Figure 4.11: Visualization of the EOFM for avoiding to merging traffic.

The driver responds to the traffic light (*aRespondToLight* in Figure 4.12) if the traffic light is not green and the car is close or very close to it by performing one or more of three activities: waiting to respond to the light until the car is closer (*aWaitTillCloser*), performing a break stop (*aBreakStop*), or performing a roll stop (*aRollStop*). If the car is close to the traffic light, the driver can wait until the light is closer by making no change to the car's gas pedal.

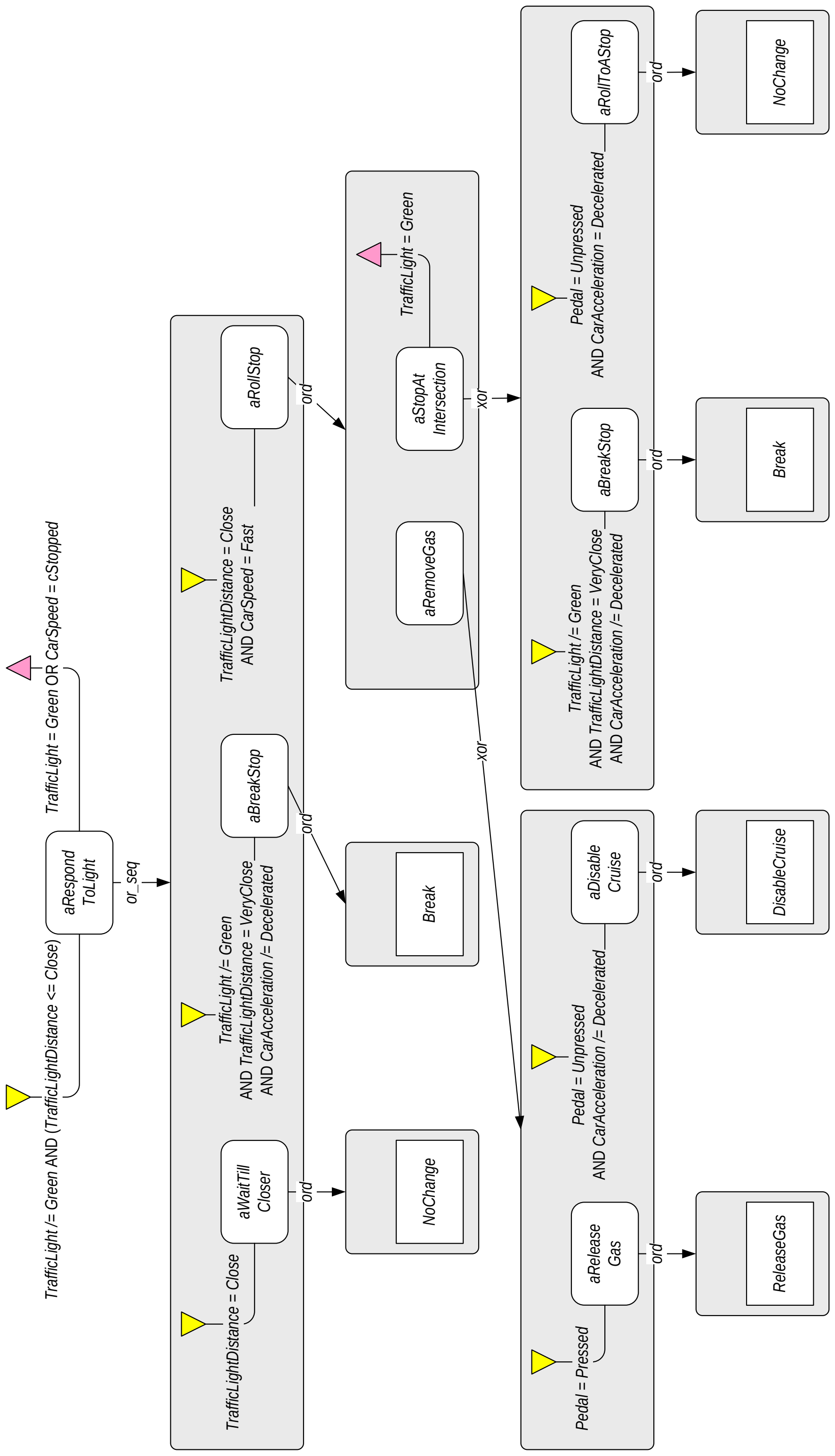

TrafficLight /= Green AND (TrafficLightDistance <= Close)
TrafficLight = Green OR CarSpeed = cStopped
aRespond ToLight
or_seq
TrafficLightDistance = Close
aWaitTill Closer
TrafficLight /= Green AND TrafficLightDistance = VeryClose AND CarAcceleration /= Decelerated
aBreakStop
TrafficLightDistance = Close AND CarSpeed = Fast
aRollStop
ord
NoChange
Break
aRemoveGas
aStopAt Intersection
TrafficLight = Green
xor
Pedal = Pressed
aRelease Gas
Pedal = Unpressed AND CarAcceleration /= Decelerated
aDisable Cruise
TrafficLight /= Green AND TrafficLightDistance = VeryClose AND CarAcceleration /= Decelerated
aBreakStop
Pedal = Unpressed AND CarAcceleration = Decelerated
aRollToAStop
ReleaseGas
DisableCruise
Break
NoChange

Figure 4.12: Visualization of the EOFM for responding to a traffic light.

If the traffic light is not green, the car is very close to the light, and the car has not decelerated, the driver can quickly slow by breaking.

If the car is close to the traffic light and the car is going fast, the driver can let the car slowly roll to a stop by first ceasing to supply gas to the car (*aRemoveGas*) and then stopping at the intersection (*aStopAtIntersection*). He removes the gas supply by either releasing the gas (via *aReleaseGas*) if cruise is not enabled, or disabling cruise (via *aDisableCruise*) if it is.

The driver no longer considers stopping at the intersection when the light is green. Otherwise the driver performs a break stop (via *aBreakStop*) if the car has not decelerated or continues to roll to a stop if it has.

4.3.6 EOFM to SAL Translation

The EOFM instance was translated into SAL code and incorporated into the larger formal system model. In its original XML form, the human task behavior model was represented in 168 lines of code (43 lines were devoted to closing XML tags). The translated SAL version of the model was represented in 439 lines of code (2.6 times more lines of code than the XML EOFM Language representation).

4.3.7 Specification and Verification

To ensure safety, we wanted to check that the car would never reach the intersection while moving when the traffic light was red. This was represented in LTL as follows:

$$\mathbf{G}\neg\left(\begin{array}{l} \mathit{TrafficLightDistance} = \mathit{AtIntersection} \\ \wedge\ \mathit{Car} \neq \mathit{Stopped} \\ \wedge\ \mathit{TrafficLight} = \mathit{Red} \end{array}\right) \tag{4.1}$$

The attempt to verify this specification using SAL-SMC resulted in a counterexample illustrating a violation. This occurred as follows:

1. The car starts *VeryVeryFar* from the traffic light going *Slow* with a *ConstantSpeed* acceleration. The pedal is *PressedToSlow* and cruise is *Disabled*. The traffic light is *Green* and the driver wants to maintain a *Moderate* speed.

2. Because the current speed is too slow, the driver increases his speed by increasing the gas (*IncreaseGas* via the *aDriveAtDesiredSpeed* and *aAccelerate* activities; Figure 4.10). The car proceeds to the *VeryFar* interval having *Accelerated* to a *Moderate* speed.

3. Now at his desired speed, the driver engages the cruise control (synchronously performing *EnableCruise* and *ReleaseGas* via the *aDriveAtDesiredSpeed*, *aMaintainSpeed*, and *aCruise* activities; Figure 4.10). The car thus proceeds to the *Far* position at a *Moderate ConstantSpeed*.

4. The driver makes no changes to the speed of the car (*NoChange* via the *aDriveAtDesiredSpeed*, *aMaintainSpeed*, and *aHoldSpeed* activities). The car proceeds to the *Merging* position at a *Moderate ConstantSpeed*, where traffic is attempting to merge.

5. The driver lets the traffic in behind by increasing the gas (*IncreaseGas* via the *aAvoidMergingTraffic* and *aLetCarGoBehind* activities; Figure 4.11). The car advances to the *Close* interval having *Accelerated* to the *Fast* speed. The traffic light turns *Yellow*.

6. The driver responds to the light by executing releasing his foot from the gas to perform a roll stop (*ReleaseGas* via the *aRespondToLight*, *aRollStop*, *aRemoveGas*, and *aReleaseGas* activities; Figure 4.12). The car proceeds to the *VeryClose* interval having *Decelerated* to the *Slow* speed. The light turns *Red*.

7. Having felt the car decelerate when he released the gas, the driver attempts to continue rolling to a stop at the intersection by making no change (*NoChange* via the *aRespondToLight*, *aRollStop*, *aStopAtIntersection*, and *aRollToAStop* activities; Figure 4.12). However, the car has reached its cruising speed (*Moderate*) and has continued to the *AtIntersection* interval at a *Moderate ConstantSpeed*.

Thus the specification has been violated with the car reaching the intersection without having stopped when the light is red.

4.3.8 Redesign

We can use our methodology to explore potential solutions to the discovered problem. A possible explanation for the above problem is that the driver does not remember that the cruise control is engaged and therefore cannot properly perform a roll stop. In the current implementation, the only way the driver can tell that the cruise control is engaged is if the gas pedal is not pressed and the car is not decelerating.

The car designer can add an indicator light with the state of the cruise control. In the formal model, this can be represented by a new variable (*Cruising*) which indicates whether cruise control is *Enabled* or *Disabled*. The driver's task model then changes to check this variable before executing a roll stop. To model this change a *Cruising inputvariable* node is added to the driver's *humanoperator* node. In the *aDriveAtDesiredSpeed* activity (Figure 4.10) the *precondition*s for *aDecreaseGas* and *aCruise* check that cruising is *Disabled* and the *precondition* for *aDisableCruise* checks that cruise is *Enabled*. In the *aAvoidMergingTraffic* (Figure 4.11) activity, the *precondition* on *aDecreaseGas* and *aDisableCruise* check that cruise is *Disabled* and *Enabled* respectively. Finally, in the *aRespondToLight* (Figure 4.12) activity, the *precondition* to *aReleaseGas* and *aDisableCruise* check that cruise is *Disabled* and *Enabled* respectively. The decomposition of *aDisable-*

Cruise also changes to the *sync* decomposition operator to support the actions for disabling the cruise control and releasing the gas pedal.

An EOFM instantiation modified to reflect these changes was translated into SAL and incorporated into the compatibly modified system model. When SAL-SMC was run using this new model and the specification in 4.1, it verified to true. Thus the minor modifications to the human-device interface and the human task behavior model eliminated the potential human-automation interaction problem discovered in the previous verification.

4.4 Discussion

The EOFM task modeling language is defined formally and its formal description has been used to construct a translator to support model checking. Translated models can be incorporated into larger system models so that they can be formally verified. We have demonstrated that this process can be used to discover and correct problems related to human-automation interaction.

4.4.1 Benchmarking and Model Complexity

The reported benchmarks highlight the tradeoffs associated with modeling different temporal orderings of human behavior. In order to assess this, one must qualify the frequency that each decomposition operator is used in task analytic modeling, and in what contexts each is most appropriate. This will help provide a better understanding of what types of systems are best suited for the analysis presented here.

Bolton and Bass [31] indicate that, rather than add to the complexity of formal system models, the formal representation of the human task models reduces model complexity for systems that depend on human-automation interaction by constraining the reachable state space to that associated with modeled human behavior. This suggests that the decomposition operators associated with higher model complexity in Table 4.1 would simply fail to constrain the system model as tightly as the less complex decomposition operators. This could limit the types of applications that can be formally verified using the method discussed here. Future work should explore this possibility.

There may also be potential for reducing the state space complexity of the translated EOFM models. In the current implementation, the formal model represents every transitional step of an activity's execution state as a single model transition in the formal model. While this accurately adheres to the formal semantics of the language, it necessitates that the formal model has a discrete state for every intermediary transition in the task model hierarchy. These intermediary transitions are of no consequence to the other elements of the system model, which are only concerned with the resulting human actions. Thus, the complexity of the formal task model representation could be reduced by decreasing the number of internal transitions required to traverse an instantiated EOFM's translated task structure during execution. Future work should investigate the feasibility of this.

4.4.2 Compactness of the EOFM Language

The increase in code size between the EOFM language representation and its translated SAL code version illustrates how much more compact the EOFM language is for modeling human task analytic behavior. This coupled with the fact that the EOFM language structure closely mimics the hierarchical nature of the task analytic modeling paradigm suggests that it may be easier to model human task behavior using the EOFM-like languages than with native model checking code. Future work should investigate whether analysts can develop task models more efficiently using EOFM. This is discussed in more thoroughly in Chapter 9.

Chapter 5

Phenotypical Erroneous Human Behavior Generation*

The discussion up to this point has used examples showing how our method can be used with normative human task behavior models to find human-automation interaction related system problems. However, many system failures involving human behavior occur (at least partially) as a result of erroneous human behavior [12, 80, 105, 125, 126, 130, 144, 146, 158, 159, 168]. This chapter discusses the literature on the classification and modeling of erroneous human behavior and discusses a way in which this can be used to describe the erroneous human behavior model generation process from the method, where phenotypes of erroneous human behavior [100] are automatically incorporated into instantiated EOFMs. This allows an analyst who is using our method to evaluate the impact of potentially unpredicted erroneous human behavior on system safety properties. Our implementation is validated, and benchmarks are provided to provide insight into how the analyses may scale in relation to the number of generated erroneous behaviors. The process is also illustrated with a radiation therapy machine application which makes use of the human mission, human task behavior, device automation, and human-device interface. The use of the gen-

*This chapter is derived from [29]

erated erroneous human behavior in the formal system model resulted in a specification violation. Changes to the device automation were able to eliminate this violation even with the inclusion of the erroneous human behavior.

5.1 Erroneous Human Behavior Taxonomies

Erroneous behavior has been classified based on how they arise from human decision making, cognition, and task execution [100, 142, 159]. Many classifications rely on a models of cognition or decision making [142, 159]. However, Hollnagel [100] relies exclusively on the observable manifestation of erroneous human behavior. Instantiated EOFMs do not have to model the low level perceptual, motor, and cognitive processes but do model human task behavior hierarchically down to the atomic, observable action level. Thus they are compatible with Hollnagel's [100] phenotypes of erroneous action.

Hollnagel [100] classified erroneous human behavior based on how it observably manifests as divergence from planned or normative sequences of actions. All erroneous behaviors are composed of one or more erroneous actions, all capable of being detected by observing the performance of a single act in a plan. These "zero-order" phenotypes include: prematurely starting an action, delaying the start of an action, prematurely finishing an action, delaying the completion of an action, omitting an action, skipping an action, re-performing a previously performed action, repeating an action, and performing an unplanned action (an intrusion). Higher order phenotypes are composed of two or more zero-order phenotypes.

The phenotypes for delaying, prematurely starting, or prematurely finishing an action specifically refer to time, not currently supported by formal verification with our method [26]. However, all of the other zero-order phenotypes relate to the performance or non-performance of actions, all supported by the formal semantics and structure of the EOFM.

In this work, we introduce a method that automatically generates these phenotypes as part of an instantiated EOFM that captures normative behavior.

5.2 Automatic Phenotypical Erroneous Human Behavior Generation

The error generation process must be capable of replicating Hollnagel's 1993 zero-order phenotypes of erroneous human behavior for omitting, skipping, re-performing, repeating or intruding an action for each original action in an instantiated EOFM. To allow for more complex erroneous human behaviors, error generation must be capable of chaining zero-order erroneous human acts. Because an unbounded number of erroneous acts could result in an unbounded human task behavior model, the error generation process must support a mechanism for constraining the number of erroneous acts that can be performed in the formally translated erroneous human behavior model. In order to facilitate analysis with our method, the error generation structure should be represented in the EOFM language thus making it compatible with EOFM to SAL translation process and counterexample visulization.

To create and erroneous human behavior model, a pattern for generating zero-order phenotypes for omissions, skips, re-performances, repetitions, and intrusions are incorporated into an instantiated EOFM by replacing each atomic action ($Action^x$) with a customized structure ($Action^x$') (Figure 5.1). This design includes an upper bound on the number of erroneous acts (*EMax*) and a variable (*ECount*) that keeps track of the number of erroneous acts that the task model has performed. Any activity that represents an erroneous act has a precondition asserting that it cannot be performed unless the current number of performed erroneous actions is less than the maximum ($ECount < EMax$). Every time an activity representing an erroneous act executes, *ECount* is incremented by one (*ECount*++).

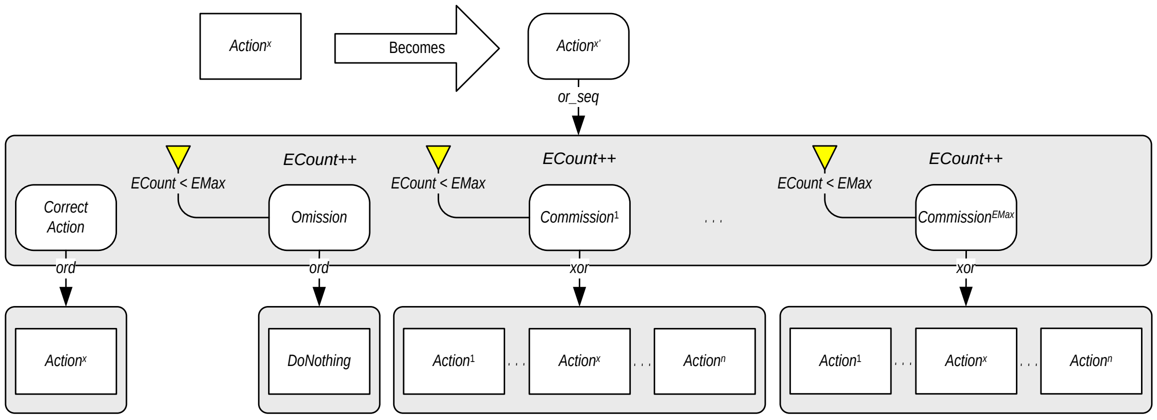


Figure 5.1: Visualization of the EOFM structure used to generate a zero-order phenotypical erroneous human behavior.

Action^x' decomposes into several addition activities, allowing Action^x' to complete execution if one or more of these activities executes (the *or_seq* decomposition operator). *CorrectAction* allows the original correct action (*Action*^{x}) to be performed. The *Omission* activity allows a human operator to perform the erroneous act of omitting the original action, represented as the *DoNothing* action. The *Commission* activities each allow a single erroneous action to be performed (the *xor* decomposition operator), where the set of erroneous actions corresponds to the *n* human actions available to the human operator. There are *ECount Commission* activities, thus allowing up to *ECount* erroneous actions to occur in place of the original action.

This design allows the specified zero-order erroneous behavior phenotypes to be generated and/or considered when the EOFM is evaluated in terms of its formal semantics. Skips and omissions occur through the execution of the *Omission* activity. Repeating the current action, re-performing a previously completed action, or performing an intrusion can occur by executing either the current action, a previously performed action, or some other action respectively through one of the *Commission* activities. Multiple erroneous actions can occur before, after, or instead of the correct action due to the *or_seq* decomposition and multiple erroneous acts can occur between error generating structures for different actions. Thus, the use of this structure allows for single erroneous actions as well as more complicated erroneous behaviors to be generated.

Our Java-based EOFM to SAL translator [33] was modified to optionally incorporate erroneous acts into any instantiated EOFM. The translator takes the maximum number of erroneous acts (*EMax*) as input from the analyst and traverses the EOFM structure, replacing each action with its corresponding error generative structure (Figure 5.1). To accommodate the verification process, the translator represents *EMax* as a constant and the range for the number of possible erroneous acts (0 to *EMax*) as a type. It modifies each human operator by adding a local variable representing the current number of performed erroneous acts (*ECount*) and a *DoNothing* human action.

The translator produces two files as output. The first is an EOFM XML file representing the created erroneous human behavior model (separate from the model of normative behavior). The second is the translated SAL representation of this model, created by the modified translator.

5.3 Testing and Benchmarks

A variety of tests and benchmarks were performed to determine if the error generation process as implemented would generate the desired erroneous human behavior (see Appendix C) and shed light on how the error generation process impacted model complexity.

For the model complexity analyses, a simple instantiated EOFM was constructed in which a single activity (*aParent*) with no conditions decomposes into a single action (*a*) with an ordered (*ord*) decomposition operator. Model complexity was assessed using the translated task model which was incorporated into a formal system model containing a human-device interface that could accept the human operatorŠs action. This was checked against a valid specification using SAL-SMC. Model complexity should vary based on both the number of actions the human operator can perform and the maximum number of erroneous acts (*EMax*). Thus, both were varied (1 to 4 actions, and 0 to 4 maximum erroneous acts) in a full cross product in these tests in order to obtain metrics of complexity (number of states) and verification time. Using SAL's symbolic model checker (SAL-SMC) on a dual core 2.8 gigahertz machine with 16 gigabytes of RAM running Ubuntu Linux, we ran 20 trials (Table 5.1).

Table 5.1: Verification benchmarks (statespace size and verification time) for phenotypical erroneous human behavior generation.

	Maximum Erroneous Acts									
♯ Human	0		1		2		3		4	
Actions	♯ States	Time	♯ States	Time	♯ States	Time	♯ States	Time	♯ States	Time
1	10	0.09	96	0.27	360	0.36	1152	0.44	3360	0.58
2	10	0.09	122	0.29	650	0.41	3042	0.57	13122	0.81
3	10	0.09	148	0.32	1008	0.48	6144	0.74	34816	1.14
4	10	0.09	174	0.34	1430	0.55	10710	0.90	74850	1.49

Note. All times are given in seconds.

Thus, it is clear that both the number of actions the human operator can perform and the maximum number of erroneous acts increase the complexity of the model. Figure 5.2 show that the complexity of the model seems to increase exponentially with the maximum number of erroneous acts, where complexity increase faster as the number of actions the human operator can perform increases.

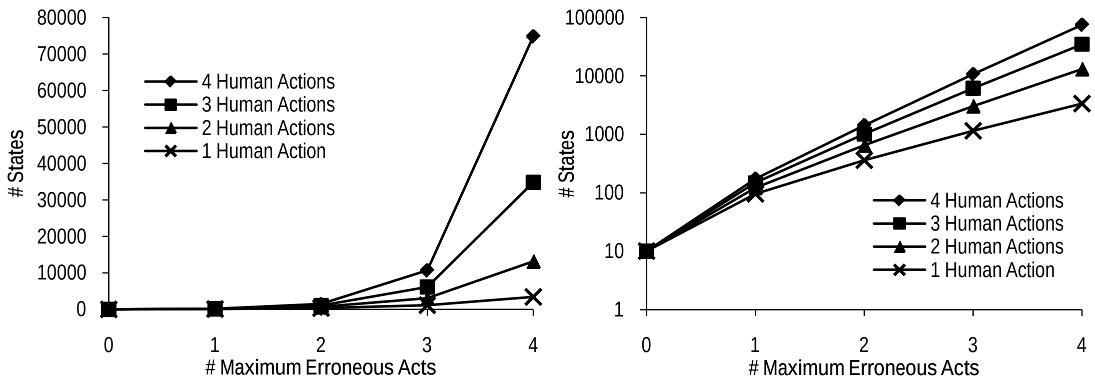


Figure 5.2: Plot of the maximum number of erroneous acts vs. the number of states for EOFMs with 1-4 human actions on both linear-linear and log-linear coordinates.

5.4 Application

To demonstrate how this type of error generation can be used, we evaluate a model of a human operated radiation therapy machine (see for example [130]). This device is a room-sized, computer-controlled, medical linear accelerator. It has two treatment modes: the electron beam mode is used for shallow tissue treatment, and the x-ray mode is used for deeper treatments - requiring electron beam current approximately 100 times greater than that used for the electron beam mode. The x-ray mode uses a beam spreader (not used in electron beam mode) to produce a uniform treatment area and attenuate radiation of the beam. An x-ray beam treatment application without the spreader in place can deliver a lethal dose of radiation.

5.4.1 Human-device Interface

The human-device interface model (Figure 5.3) includes interactions with the 5 relevant keyboard keys (‘X’, ‘E’, Enter, Up and ‘B’) and the information on the monitor. The interface states (*InterfaceState*) starts in *Edit* where the human operator can press ‘X’ or ‘E’ (*PressX* or *PressE*) to select the xray or electron beam mode and transition to the *Confir-*

mXrayData or *ConfirmEBeamData* states respectively. When in the *ConfirmXrayData* or *ConfirmEBeamData* states, the appropriate treatment data is displayed (*DisplayedData*), and the human operator can confirm the displayed data by pressing enter (advancing to the *PrepareToFireXray* or *PrepareToFireEBeam* states) or return to the *Edit* state by pressing up (*PressUp*) on the keyboard. In the *PrepareToFireXray* or *PrepareToFireEBeam* states, the human operator must wait for the beam to become ready (*BeamState*), at which point he can press 'B' (*PressB*) to administer treatment by firing the beam. This transitions the interface state to *TreatmentAdministered*. The operator can also return to the previous data confirmation state by pressing up.

5.4.2 Device Automation

The device automation model (Figure 5.4) controls the power level of the beam (*Beam-Level*), the position of the spreader (*Spreader*), and the firing of the beam (*BeamFireState*). The power level of the beam (*BeamLevel*) is initially not set (*NotSet*). When the human operator selects the xray or electron beam treatment mode, the power level transitions to the appropriate setting (*XrayLevel* or *EBeamLevel* respectively). However, if the human operator selects a new power level, there is a delay in the transition to the correct power level, where it remains in an intermediary state (*XtoE* or *EtoX*) at the old power level before automatically transitioning to the new one. The position of the spreader (*Spreader*) starts either in or out of place (*InPlace* or *OutOfPlace*). When the human operator selects the xray or electron beam treatment mode, the spreader transitions to the appropriate setting (*InPlace* or *OutOfPlace* respectively). The firing state of the beam (*BeamFireState*) is initially waiting to be fired (*Waiting*). When the human operator fires the beam (pressing 'B' when the beam is ready), the beam fires (*Fired*) and returns to its waiting state.

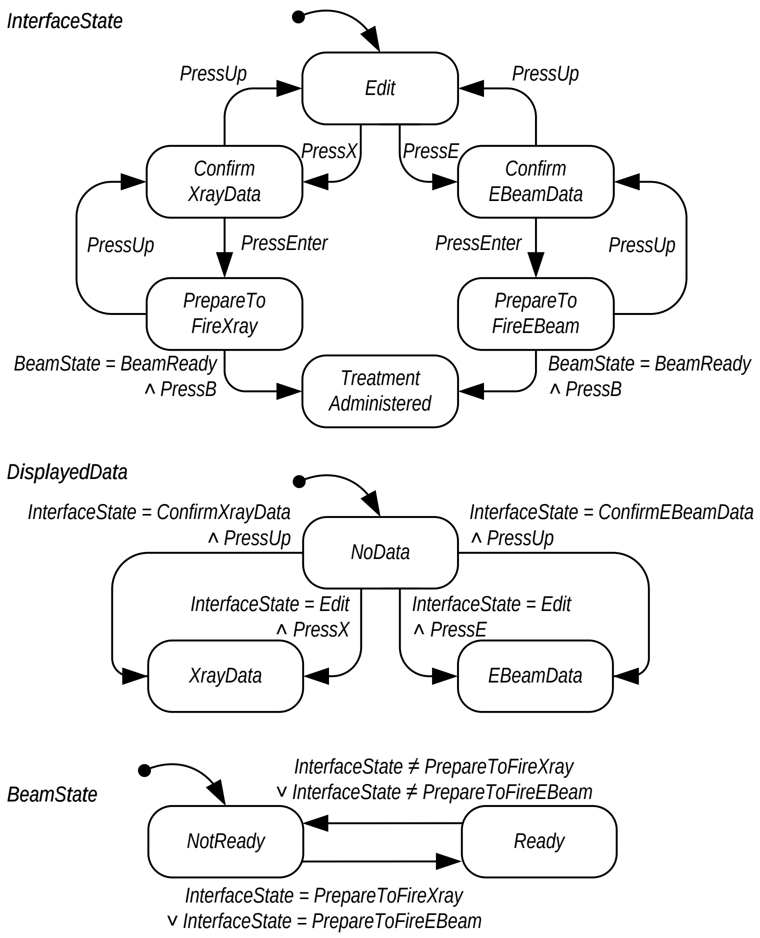

InterfaceState
Edit
PressUp
PressUp
PressX
PressE
Confirm XrayData
Confirm EBeamData
PressUp
PressEnter
PressEnter
PressUp
PrepareTo FireXray
PrepareTo FireEBeam
BeamState = BeamReady ∧ PressB
Treatment Administered
BeamState = BeamReady ∧ PressB
DisplayedData
InterfaceState = ConfirmXrayData ∧ PressUp
InterfaceState = ConfirmEBeamData ∧ PressUp
NoData
InterfaceState = Edit ∧ PressX
InterfaceState = Edit ∧ PressE
XrayData
EBeamData
BeamState
InterfaceState ≠ PrepareToFireXray ∨ InterfaceState ≠ PrepareToFireEBeam
NotReady
Ready
InterfaceState = PrepareToFireXray ∨ InterfaceState = PrepareToFireEBeam

Figure 5.3: State transition representation of the formal human-device interface model. Rounded rectangles represent states. Arrows between states represent transitions. Dotted arrows indicate initial states.

5.4.3 Human Mission

The human mission identifies the desired treatment (*TreatmentType* equaling *Xray* or *EBeam*).

5.4.4 Human Task Behavior

Three goal directed task models describe the administration of treatment with the radiation therapy machine (Figure 5.5): selecting the treatment mode (*aSelectXorE*), confirming

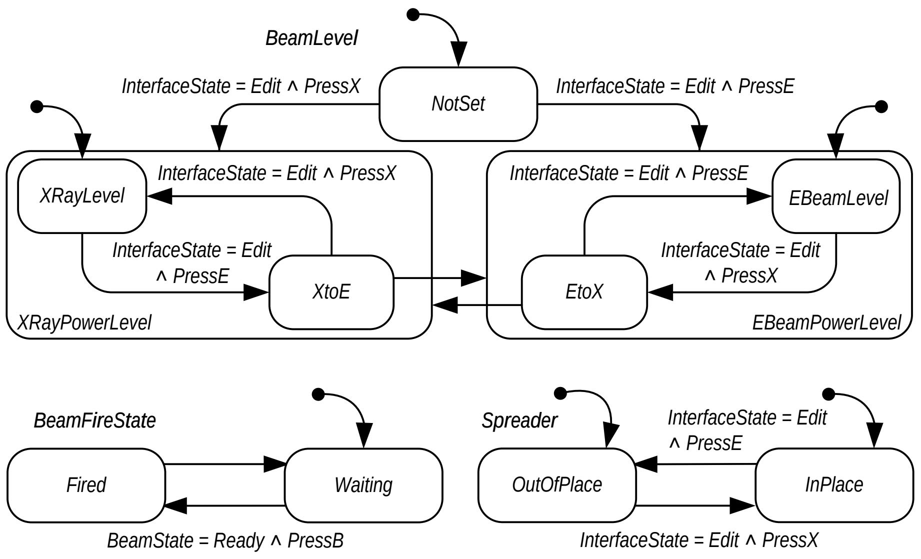

BeamLevel
NotSet
InterfaceState = Edit ∧ PressX
InterfaceState = Edit ∧ PressE
XRayLevel
InterfaceState = Edit ∧ PressX
InterfaceState = Edit ∧ PressE
EBeamLevel
InterfaceState = Edit ∧ PressE
XtoE
InterfaceState = Edit ∧ PressX
EtoX
XRayPowerLevel
EBeamPowerLevel
BeamFireState
Fired
Waiting
BeamState = Ready ∧ PressB
Spreader
InterfaceState = Edit ∧ PressE
OutOfPlace
InPlace
InterfaceState = Edit ∧ PressX

Figure 5.4: State transition representation of the formal device automation model.

treatment data (*aConfirm*), and firing the beam (*aFire*).

These models access input variables from the human-device interface (the interface state (*InterfaceState*), the displayed treatment data (*DisplayedData*), and the ready status of the beam (*BeamState*)) and the mission (treatment type (*TreatmentType*) to generate the human actions for pressing the appropriate keyboard keys.

When the interface is in the edit mode (*aSelectXorE*), the practitioner can select the appropriate treatment mode based on the mission *TreatmentType* by performing either the *PressX* or *PressE* actions. When the interface is in either of the two data confirmation states (*aConfirm*) the practitioner can choose to confirm the displayed data (if the displayed data corresponds to the desired treatment mode) by pressing enter or return to the *Edit* state by pressing up. When the interface is in either of the states for preparing to fire the beam (*aFire*), the practitioner can choose to fire the beam if the beam is ready by pressing ‘B’ or return to the previous interface state by pressing up.

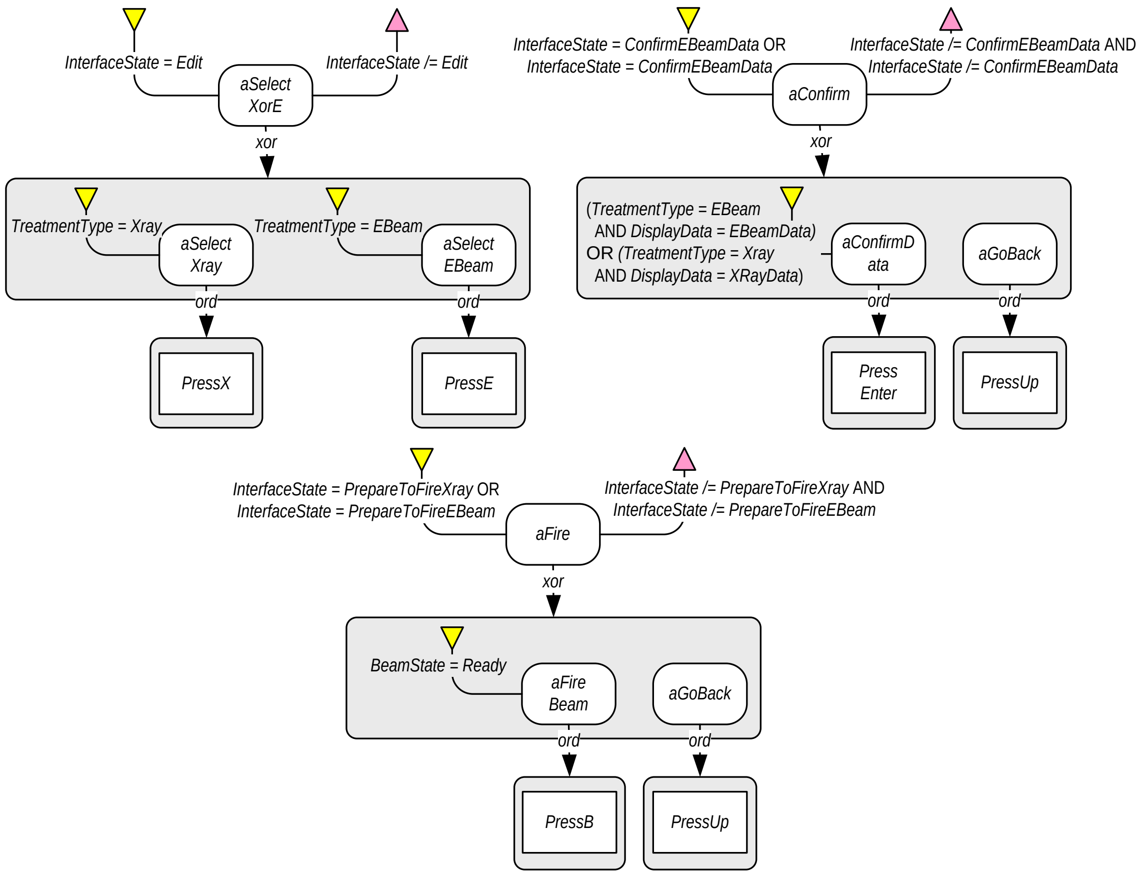

InterfaceState = Edit
InterfaceState /= Edit
aSelect XorE
xor
TreatmentType = Xray
aSelect Xray
TreatmentType = EBeam
aSelect EBeam
ord
PressX
PressE
InterfaceState = ConfirmEBeamData OR InterfaceState = ConfirmEBeamData
InterfaceState /= ConfirmEBeamData AND InterfaceState /= ConfirmEBeamData
aConfirm
(TreatmentType = EBeam AND DisplayData = EBeamData) OR (TreatmentType = Xray AND DisplayData = XRayData)
aConfirmData
aGoBack
Press Enter
PressUp
InterfaceState = PrepareToFireXray OR InterfaceState = PrepareToFireEBeam
InterfaceState /= PrepareToFireXray AND InterfaceState /= PrepareToFireEBeam
aFire
BeamState = Ready
aFire Beam
PressB

Figure 5.5: Visualization of the EOFMs for interacting with the radiation therapy machine: selecting the treatment mode (*aXorE*), confirming treatment data (*aConfirm*), and firing the beam (*aFire*).

5.4.5 EOFM to SAL Translation

The EOFM instance was translated twice into SAL code and incorporated into the larger formal system model: once for normative behavior and once for erroneous human behavior with a maximum of one erroneous act. The normative behavior model's EOFM representation was 74 lines of XML code. Its corresponding formal representation was 166 lines of SAL code. The produced erroneous EOFM model was 240 lines of XML code. Its formal representation was 641 lines of SAL code.

5.4.6 Specification and Verification

We specify that we never want the radiation therapy machine to irradiate a patient by administering an unshielded xray treatment using Linear Temporal Logic as follows:

$$\mathbf{G}\neg\left(\begin{array}{l} BeamFireState = Fired \\ \wedge\ BeamLevel = XRayPowerLevel \\ \wedge\ Spreader = OutOfPlace \end{array}\right) \tag{5.1}$$

When checked against the formal system model with the translated normative task behavior model, it verified to true in less than one second having visited 1648 states.

The formal system model containing the erroneous human behavior model produced a counterexample after 38 seconds illustrating the following failure sequence:

1. The model initialized with the interface in the edit state with no displayed data and the beam not ready; the beam power level not set; the spreader out of place; the beam fire state waiting; and the human mission indicating that the human operator should administer electron beam treatment.

2. When attempting to select the electron beam mode, the practitioner erroneously pressed ‘X’ instead of ‘E’ (via a generated *Commission* activity in *aSelectXorE* from Figure 5.5). This caused the interface to transition to the xray data confirmation state and display the xray treatment data. The spreader was also moved in place and the beam was set to the xray power level.

3. Because the incorrect data was displayed, the practitioner pressed up to return the interface to the edit mode.

4. The practitioner selected electron beam treatment mode by pressing the ‘E’ key. The interface transitions to the electron beam data confirmation state and displayed the

electron beam treatment data. The spreader was moved out of place and the beam prepared to transition to the electron beam power level (XtoE in Figure 5.5).

5. The practitioner confirmed the treatment data by pressing enter and the interface transitioned to the electron beam's waiting to fire state.

6. The beam became ready.

7. The practitioner fired the beam by pressing 'B'. Because the beam power level had not yet transitioned to the electron beam power level, the beam fired at the xray power level with the spreader out of place.

5.4.7 Redesign

One way of correcting this discovered system failure is by modifying when the beam becomes ready in the human-device interface. This can be done by adding the additional constraint that the beam will not transition to ready unless it is set to the correct power level (Figure 5.6).

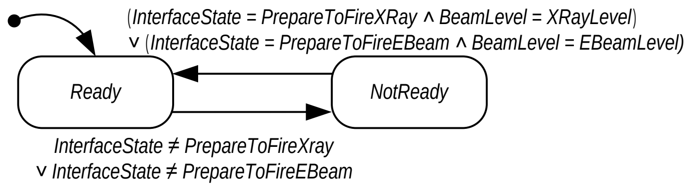

(InterfaceState = PrepareToFireXRay ∧ BeamLevel = XRayLevel)
∨ (InterfaceState = PrepareToFireEBeam ∧ BeamLevel = EBeamLevel)
Ready
NotReady
InterfaceState ≠ PrepareToFireXray
∨ InterfaceState ≠ PrepareToFireEBeam

Figure 5.6: State transition diagram depicting the modified formal model's human-device interface indications of the beams ready state.

When this modified model was incorporated into the system model with the erroneous human behavior model and checked against (5.1), it verified to true in 42 seconds having visited 45290 states.

5.5 Discussion

The generation process meets all of its requirements, allowing it to be integrated into our method for the formal verification of human-automation interaction:

1. Using an EOFM task structure to replace every action in an instantiated EOFM, we are capable of generating zero-order phenotypes of erroneous human action: omitting an action, skipping an action, re-performing a previously completed action, repeating the last performed action, or intruding an action.

2. The use of the structure in each action, and the use of the *or_seq* decomposition operator (which allows one or more sub-activities to execute) in the error generation structure allow multiple zero-order phenotypical erroneous acts to generate all of Hollnagel's first-order phenotypes except for time compression.

3. The number of possible erroneous act is constrained by a maximum and a counter preventing generated errors from making the task behavior model unbounded.

4. The erroneous behavior generation structure is represented in EOFM constructs and is thus compatible with the EOFM to SAL translator and counterexample visualizer.

The radiation therapy machine example illustrates how this process can be used to find potential system problems due to erroneous human behavior in human-automation interactive systems. In fact, the discovered problem is very similar to one discovered in the Therac-25 radiation therapy machine which resulted in the death of several people [130]. Similar problems have also resulted in injury and death with a number of modern radiation therapy machines [24].

5.5.1 Statespace Complexity Optimization

The fact that the complexity of the model increases exponentially with the maximum allowable number of erroneous acts indicates that analysts will be limited in the number of erroneous acts they can introduce in a formal verification.

This is seen in the radiation therapy application in the increase in state space from the system model with normative behavior (1648 states) to the system model with the erroneous human behavior (45290 states) which had 27 times the number of states. For comparison, a system model with an unconstrained human operator had 4400 states, more than the model with normative model, but significantly less than that used by the erroneous human behavior model. All of this suggest that future work should investigate ways to increase the efficiency of the erroneous human behavior model.

In the current implementation there are situations where non-erroneous acts are counted as erroneous. For example, the correct action could be executed through a *Commission* activity without the *CorrectAction* activity executing. Similarly, the current structure allows for the same erroneous acts to be performed in multiple ways. For example, the same erroneous act could be performed through different *Commission* activities. The structure and translation process used to generate erroneous human behavior should be optimized to reduce redundancy and the size of the formal system model.

Given that an unconstrained human operator should theoretically support many more action sequences than an erroneous human behavior model with a maximum of one erroneous act. This would suggest that the intermediary transitions in the implementation of the SAL version of an instantiated EOFM are adding significantly to the complexity to the model. As was discussed in [33] and Chapter 4, it may be possible to eliminate many of the intermediary transitions and variables associated with an instantiated EOFM's SAL representation. Future work should investigate whether these types of improvements will substantially reduce model complexity.

Although the erroneous human behavior model has the distinct disadvantage of producing a more complex formal system model than the unconstrained one, it is important to note that it is still useful in that it provides insights that an unconstrained model does not. For example, the erroneous human behavior model gives analysts context for when an error may occur for a given task, which may suggest particular solutions to discovered problems specifically related to the human-device interface or the human task. Further, the erroneous human behavior model allows analysts to check certain properties that could not be checked with an unconstrained model. For the radiation therapy example, consider a specification asserting that the practitioner will always administer treatment in the mission specified mode. A system model containing erroneous human behavior could verify this for up to the specified maximum number of allowable erroneous acts. However, an unconstrained model could not. Future work should investigate what the tradeoffs are between the use of these two types of models.

5.5.2 Excluding Specific Erroneous Behaviors

Given the nature of formal verification with model checking and the fact that the error generation process is done automatically, it is conceivable that an analyst will receive a counterexample illustrating a system problem involving an erroneous human behavior that he is not interested in or that can not be corrected. In this situation, the analyst may wish to rerun the analysis without considering a specific erroneous behavior.

In the current implementation this can be achieved by modifying the specification to ensure that the unwanted behavior is never executed. This can be accomplished with the following specification:

$$(\mathsf{G}(ErroneousAct = Ready)) \Rightarrow (OriginalSpecification) \tag{5.2}$$

This asserts that, for the EOFM Action or Activity representing the erroneous act the analyst wishes to ignore (*ErroneousAct*) and the original desired specification (*OriginalSpecification*), the erroneous act never executing ($\mathbf{G}(\mathit{ErroneousAct} = \mathit{Ready})$) will imply that the original specification will always be true:

For example, where *PressX_14* represents the action for erroneously pressing 'X' instead of 'E' when selecting the treatment mode, we can apply this to the un-corrected model of the Therac-25 containing the erroneous human behavior model as:

$$(\mathbf{G}(\mathit{PressX\_14} = \mathit{Ready})) \Rightarrow \left(\mathbf{G}\neg\left(\begin{array}{l} BeamFireState = Fired \\ \wedge\ BeamLevel = XRayPowerLevel \\ \wedge\ Spreader = OutOfPlace \end{array}\right)\right) \tag{5.3}$$

This specification verifies to true in 80 seconds having visited 42578 states.

Note that (5.2) can be modified to exclude additional erroneous acts simply by adding them to the expression the left of the implication operator.

Future work will investigate other means of allowing analysts to exclude specific or groups of erroneous acts from formal verifications.

5.5.3 Erroneous Human Behavior Generation

Our method currently does not support Hollnagel's [100] phenotypes for delaying, or prematurely starting or finishing an action. Future work should investigate if these types of erroneous behaviors can be incorporated.

Because Hollnagel's phenotypes only concern observable human behavior, and because our method does not support a realistic model of human memory or cognition, the current implementation only impacts human actions, and does not affect the assignment of local variables which are typically used to model memory actions in instantiated EOFMs. Future work should investigate how memory errors could be incorporated into our method.

Hollnagel's phenotypes generally assume that human behavior is executing sequentially, with no parallelism or synchronization between human actions. For this reason, the current method does not support the erroneous behavior generation for synchronized human actions (those in a *sync* decomposition), and does not support synchronized erroneous actions, such as a human performing two erroneous actions synchronously or performing the correct action synchronously with erroneous actions. Future work should investigate how these types of erroneous acts might be incorporated.

While the process discussed here is well suited to the generation of single erroneous actions, generating more complex erroneous behaviors requires a significant number of erroneous acts. This would greatly increase model complexity, and treats more unlikely action sequences equal to ones that are more cognitively probable (see [159]). Chapter 6 explores an alternative error generation process that begins to addresses this issue.

Chapter 6

Strategic Knowledge-based Erroneous Behavior Generation

Our phenotypical erroneous human behavior generation technique (Chapter 5) is capable of reproducing all of Hollnagel's zero-order phenotypes that relate to the performance or non-performance of actions. While this takes advantage of the EOFM's task structure representation capabilities, it does not address erroneous human behaviors that may arise due to strategic (i.e., conditions under which activities and actions should be considered) knowledge. Reason [159], as part of his Generic Error Modeling System, outlined a set of erroneous behaviors called slips in which a person fails to notice conditions which result in a failure to perform an activity or action normatively due to either inattention or overattention (attending at the inappropriate time). A person can omit an action or high level activity by failing to notice that the necessary conditions for performing the activity are true, possibly due to interruption or not attending to information at the right time. A person may erroneously repeat an action or high level activity after losing his place in a task. A person may also have his attention "captured" by something else (external or internal to the person) which results in him performing (committing) an inappropriate action or activity either in addition to or instead of an appropriate one.

From a completely observable perspective, this means that a slip can manifest as:

- An omission, the failure to perform all or part of an activity;
- A repetition, the repeated performance of an activity or action; or
- A commission, the inappropriate performance of an activity or action.

Our phenotypical erroneous human behavior generation process is particularly well suited to replicating single action slips as it is fully capable of generating omissions, repetitions, and other commissions for single atomic actions, and two or more of these can be chained together to form more complex erroneous behavior. However, replicating these at an activity level of abstraction would require a maximum number of erroneous acts large enough to support the chaining of multiple zero-order phenotypes to replicate the correct execution of activities in an erroneous context. This approach would significantly increase the complexity of the model (see Section 5.3) and it would introduce a number or erroneous action sequences beyond those associated with the above cognitive justifications.

This chapter discusses how the strategic knowledge represented in EOFM conditions can be manipulated to generate Reason's [159] slips at the activity level. We validate our implementation of the process. We also benchmark the process in order to evaluate how the incorporations of erroneous behavior can impact model complexity. The PCA pump example from [31] (Chapter 3) is revisited, and we show how this new erroneous behavior generation process can be used to discover a previously unseen system failure using our method. We show how the human-device interface could potentially be modified to prevent the discovered failure from occurring.

6.1 Automatic Strategic Knowledge-based Erroneous Human Behavior Generation

This erroneous human behavior generation process should be capable of replicating the manifestation of Reason's [159] slips for omitting, repeating, or committing activities or actions based on misapplication of EOFM strategic knowledge contained in pre, repeat, and completion conditions. Because an unbounded number of erroneous acts could result in an unbounded human task behavior model, the error generation process must support a mechanism for constraining the number of erroneous acts that can be performed in the formally translated erroneous human behavior model. In order to facilitate analysis, the EOFM to SAL translation process, and counterexample interpretation, the error structure should be compatible with the EOFM language and translator.

These strategic knowledge-based erroneous behaviors were incorporated into translated EOFM task representations by making changes to the formal semantics (Figure 6.1). In this design, addition transitions (dotted arrows in Figure 6.1) are added to the formal semantics in order to describe erroneous conditions in which an activity can switch between execution states. This design includes an upper bound on the number of erroneous acts (*KMax*) and a variable (*KCount*) that keeps track of the number of erroneous acts that a task model has performed. An erroneous transition can only be undertaken if the current number of erroneous transitions is less than the maximum ($KCount < KMax$). Every time an erroneous transition occurs, *KCount* is incremented by one (*KCount*++).

Each new transition represents the erroneousness analog of a non-erroneous transition, where the erroneous transition is conditioned on the same start or end condition as its analog as well as the negation of any strategic knowledge (pre, completion, or repeat condition) used by any non-erroneous transition.

Omissions can occur when an activity completes its execution too early. An activity can

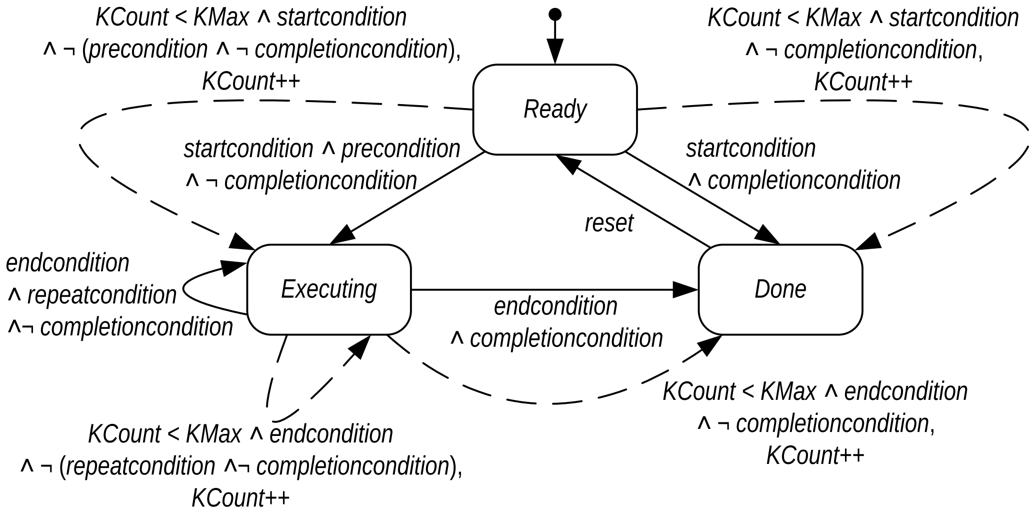

KCount < KMax ∧ startcondition ∧ ¬ (precondition ∧ ¬ completioncondition), KCount++
KCount < KMax ∧ startcondition ∧ ¬ completioncondition, KCount++
Ready
startcondition ∧ precondition ∧ ¬ completioncondition
startcondition ∧ completioncondition
reset
endcondition ∧ repeatcondition ∧¬ completioncondition
Executing
endcondition ∧ completioncondition
Done
KCount < KMax ∧ endcondition ∧ ¬ completioncondition, KCount++
KCount < KMax ∧ endcondition ∧ ¬ (repeatcondition ∧¬ completioncondition), KCount++

Figure 6.1: Modified formal semantics for automatically generating knowledge-based erroneous human behavior. Arrows with solid lines represent the original formal semantic transitions. Arrows with dotted lines represent additional (erroneous) transitions.

erroneously complete (transition from *Executing* to *Done*) if the end condition is *true* and the completion condition is not ($endcondition \wedge \neg completioncondition$)). This transition is eliminated if an activity does not have a completion condition.

Omissions can also occur when an activity fails execute at all. An activity cannot execute (transition from *Ready* to *Done*) if the start condition is *true* and the completion condition is not. This transition persists even if there is no completion condition.

An erroneous repetition occurs when an activity erroneously repeats its execution. An activity can erroneously repeat (transition from *executing* to *executing*) if the end condition is *true* and either the repeat condition is *false* or the completion condition is *true* ($endcondition \wedge \neg(repeatcondition \wedge \neg completioncondition)$). This last clause is removed from the guard when an activity does not have a repeat condition.

A commission can occur when an activity erroneously executes. An activity can erroneously execute (transition from *Ready* to *Executing*) if the start condition is *true* and either the precondition is *false* or the completion condition is *true* ($startcondition \wedge$

$\neg(\textit{precondition} \wedge \neg \textit{completioncondition}))$. This transition is eliminated if the activity does not have a precondition.

Thus, this design allows each of observable manifestations of Reason's [159] slips to be generated when an instantiated EOFM executes. Omissions can occur through an erroneous *Ready* to *Done* transition or an erroneous *Executing* to *Done* transition. Repetitions can occur via an erroneous *Executing* to *Executing* transition. Finally, commissions can occur through an erroneous *Ready* to *Executing* transition.

Our Java-based EOFM to SAL translator [33] was modified to optionally incorporate these erroneous transitions into the translated SAL version of an instantiated EOFM. The translator takes the maximum number of erroneous acts (*KMax*) as input from the analyst. When the SAL file is written, this maximum is represented as a SAL constant, and an enumerated type is created representing the range of the possible number of erroneous transitions. When a human operator's module is written, it is given a local variable representing the count of erroneous transitions (*KCount*). When writing the transition logic for each activity, this implementation adds transitions (guards and variable assignments) associated with each of the dotted lines in Figure 6.1. The variable assignment for each erroneous transition is identical to its non-erroneous counterpart in the SAL code, with the exception that it adds the assignment which increments the erroneous transition count.

6.2 Testing and Benchmarks

Tests and benchmarks were performed to determine if the error generation process as implemented would generate the desired erroneous transition of activity execution state (see Appendix D) and evaluate how the error generation process impacted model complexity.

For the model complexity analyses, a simple instantiated EOFM was constructed in which a single activity (*aParent*) which decomposes into a single action (*a*) with an ordered (*ord*) decomposition operator. This translated EOFM interacts with a simple human-device interface model which can receive all human operator actions. The human operator also receives Boolean inputs (*precondition*, *repeatcondition*, and *completioncondition*) from the human-device interface model which give (*aParent*) access to simulated pre, repeat, and completion conditions that can change between *true* and *false* (or remain unchanged) at each step in a system model's execution. Because model complexity should vary based on the maximum number of erroneous transitions (*KMax*), this was varied in these tests in order to obtain metrics of complexity (number of states) and verification time. Using SAL's symbolic model checker (SAL-SMC) on a dual core 2.8 gigahertz machine with 16 gigabytes of RAM running Ubuntu Linux, we ran 5 trials (with a maximum of between 0 and 4 erroneous transition). The results are reported in Figure 6.2.

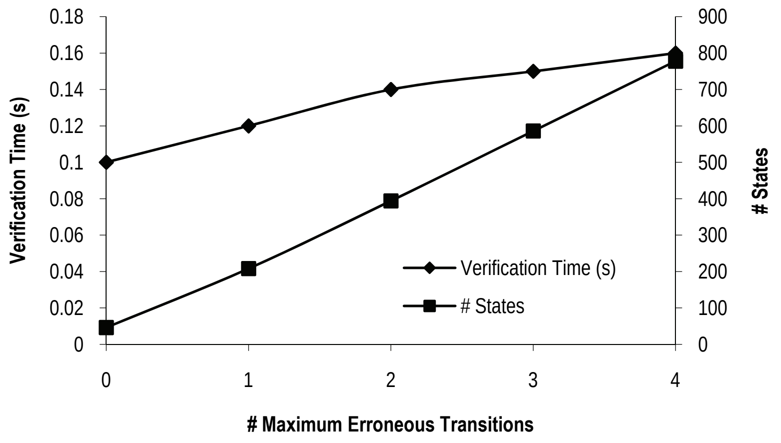


Figure 6.2: Plot of the maximum number of erroneous transitions vs. the number of system model states and transition time.

These results indicate that both the size of the statespace and the verification time increase linearly with the number of erroneous transitions.

6.3 Application

To demonstrate how this type of error generation can be used, we revisit the simplified Patient Controlled Analgesia (PCA) Pump example produced in Phase 2 of the modeling effort discussed in [31] and Chapter 3.

6.3.1 Formal Modeling

All of the formal models were constructed using the Symbolic Analysis Laboratory (SAL) language [65]. Formal models of the mission were represented as a set of viable prescription options (realistic PCA dosages and delays). The mission (prescription), human task, human-device interface, and device automation were independently modeled. Because the PCA pump generally operates in a controlled environment, no environmental model was included. Because of the limited available pump documentation, the system automation model was restricted to pump programming procedures. For more information about this modeling process, model granularity, and the rationale behind the modeling decisions see [27, 31] and/or Chapter 3. Note that because this particular application was not concerned with how a practitioner programs a specific prescription into the pump, but the circumstances under which he may make an error, this version of the model was modified slightly to decrease its complexity with only a subset of prescription options placeholding for more realistic ones. PCA doses were restricted to between 1 and 10 ml (in 1 ml increments) and delays were restricted to be within 1 and 20 minutes (in 1 minute increments). The human mission was also restricted to allowable PCA doses of 5 and 10 ml and prescribed delays of 10 and 20 minutes.

6.3.2 Task Modeling

An instantiated EOFM was created encompassing the following high-level goal directed behaviors for performing a variety of pump activities:

- Turning on the pump,
- Stopping the infusion of medication,
- Turning off the pump,
- Entering a prescribed value for PCA dosage volumes (in ml)
- Entering a prescribed value for the delay between PCA doses (in minutes), and
- Selecting whether to start or review an entered prescription.

A description of each of these can be found in [31] and/or Chapter 3. The tasks most relevant to this discussion are those related to the programming of PCA dosages and delays, both of which have the form shown in 6.3. For a given value *X*, the corresponding EOFM becomes relevant when the interface for setting that value is displayed. A practitioner first changes the displayed value to that from the prescription. The value could be changed by selecting different digits with presses to the Left and Right buttons (*PressLeft* and *PressRight*), clearing the display by pressing the Clear button (*PressClear*), or changing a digit by pressing the Up button (*PressUp*). The practitioner can continue to execute the change activity (a repeat condition) as long as the displayed value does not match the prescription value. The displayed value is accepted by pressing the enter key.

6.3.3 EOFM to SAL Translation

The EOFM instance was translated twice into SAL code and incorporated into the larger formal system model: once for normative behavior and once for erroneous human behavior

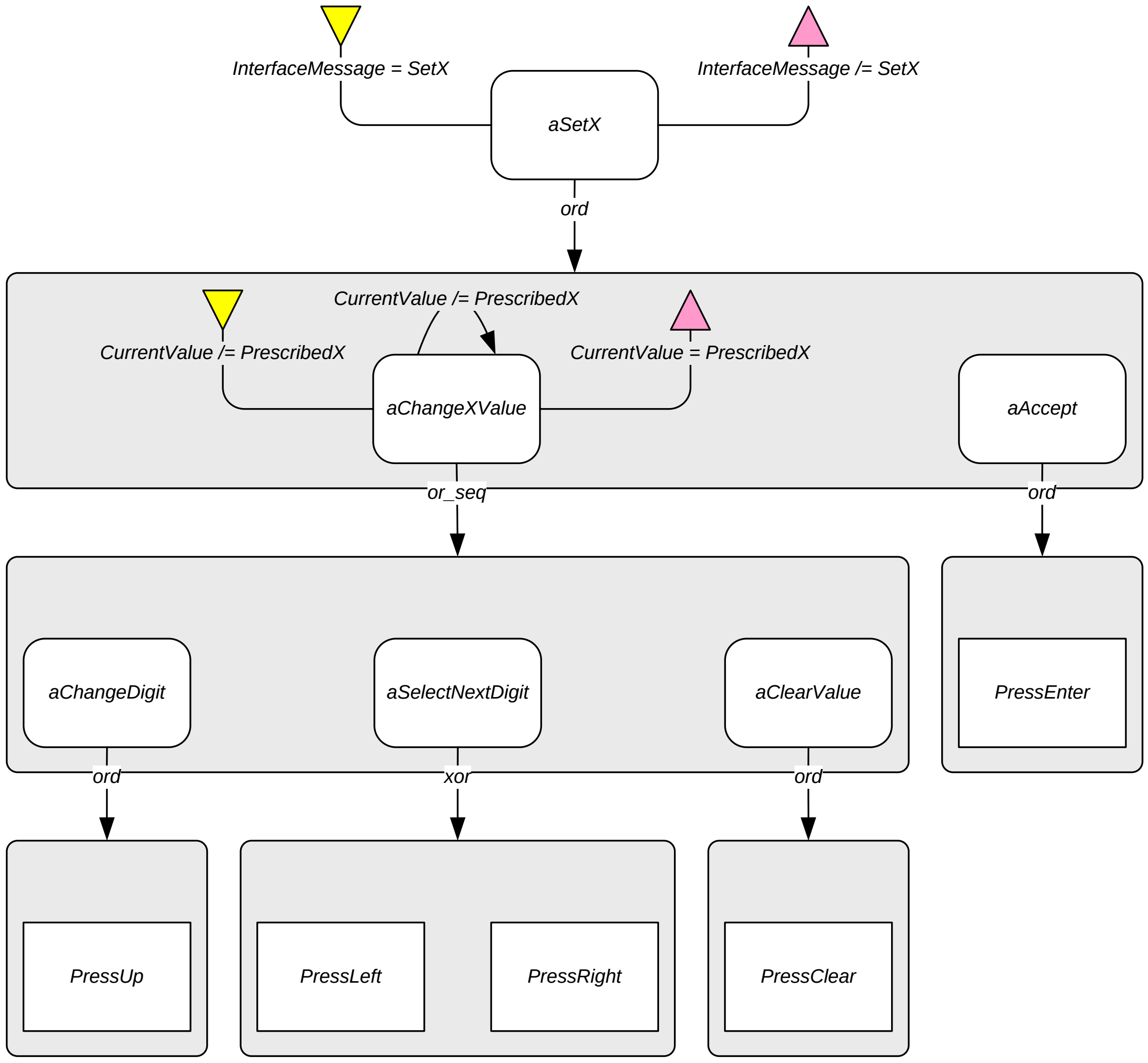


Figure 6.3: State transition representation of the formal device automation model.

with a maximum of one erroneous transition. The normative behavior model's EOFM representation was 132 lines of code. Its corresponding formal, normative representation was 392 lines of SAL code. Its corresponding formal, erroneous representation was 570 lines of SAL code.

6.3.4 Specification and Verification

We specify that, when treatment is administering, this should always mean that the entered prescription should match that specified by the mission.

$$\mathsf{G}\left(\begin{array}{l}(\mathit{InterfaceMessage} = \mathit{TreatmentAdministering}) \\ \Rightarrow \left(\begin{array}{l}\mathit{PCADose} = \mathit{PrescribedPCADose} \\ \wedge\ \mathit{Delay} = \mathit{PrescribedDelay}\end{array}\right)\end{array}\right) \tag{6.1}$$

When checked against the formal system model with the translated normative task behavior model, it verified to true in 9 minutes having visited 4,897,845 states.

The formal system model containing the erroneous human behavior model (which had a total statespace of 27,637,526) produced a counterexample after 86 seconds illustrating the following failure sequence:

1. The pump starts in the off state and the practitioner has to program in a prescription specifying a PCA dose of 10 ml with a 20 minute delay.

2. The practitioner turns the pump on by pressing the on/off button, putting the pump's interface in the state for programming PCA dosage with a displayed value of 0 (00) with the cursor under the tens digit.

3. The practitioner press the up button to set the displayed PCA dosage value to 10.

4. The practitioner accepts the PCA dosage by pressing the enter button, causing the pump's interface to transition to the state for programming the delay, with a displayed value of 0 (00) with the cursor under the tens digit.

5. The practitioner changes the displayed value to 10 minutes by pressing the up button.

6. The practitioner erroneously completed the activity for changing the displayed value (the erroneous *Executing* to *Done* transition) and presses enter to accept a delay value of 10 minutes. The pump transitions to the interface state for starting or review treatment.

7. The practitioner starts treatment by pressing the start button, causing treatment to administer with the pump interface in the *TreatmentAdministering* state. Thus, the specification has been violated with the pump administering treatment with an unprescribed delay value.

6.3.5 Redesign

We can use our method to investigate potential design changes that correct the discovered problem. One possible way of preventing this problem from occurring is to force the practitioner to review the entered prescription every time it changes. This can be accomplished by having the pump keep track of whether or not the practitioner has reviewed the entered prescription or not, and only letting him start the administration of treatment after an entered or changed prescription has been reviewed. This change was made to the PCA pump model, and the resulting model was verified against 6.1 with the erroneous human behavior model from above. This time, the specification verified to true in 51 minutes having visited 210,249,809 states.

6.4 Discussion

The erroneous behavior generation process presented here provides an additional means of allowing practitioners to automatically determine when potentially unexpected erroneous behavior can result in a violation of a systems safety properties. Further, the generation process meets all of its requirements, allowing it to be integrated into our method for the formal verification of human-automation interaction:

1. By adding erroneous transitions to the formal semantics of an EOFM's activity execution state representing erroneous applications of strategic knowledge (pre, repeat, and completion conditions), we are capable of replicating the observable manifestation of attentional failures associated with Reason's [159] slips: omission, repetition, or commission (due to capture).
2. The number of possible erroneous transitions is constrained by a maximum and a counter preventing generated erroneous behaviors from making the task behavior model unbounded.
3. The erroneous behavior generation does not alter the structure of the EOFM and is thus compatible with the EOFM to SAL translator and counterexample visualizer.

6.4.1 Tradeoff Between Erroneous Behavior Generation Techniques

In terms of complexity, the error generation process presented here represents an alternative to the method presented in Chapter 5, where model complexity increases linearly with the number of allowable erroneous behaviors rather than exponentially. This is further reinforced by the fact that, for the presented application, the system model with an erroneous human behavior model with a maximum of one erroneous transition had a smaller statespace than a system model with an unconstrained human operator (27,637,526 vs 126,617,856 states), a condition not achieved using the techniques from Chapter 5.

The two generation techniques produce different erroneous behaviors. The techniques discussed here can generate higher level erroneous behaviors based on the incorrect execution of activities where as the method discussed in Chapter 5 can be used to generate lower level erroneous acts, and can allow for the modeling of many more extraneous behaviors as it is capable of generating erroneous actions that are not associated with the currently executing activity. Because of this, analysts may wish to evaluate a system using both techniques either in separation or together in order to obtain the most complete system evaluation.

6.4.2 Excluding Specific Erroneous Behaviors

As with the other erroneous human behavior generation method, it is conceivable that an analyst using this method will receive a counterexample illustrating a system problem involving an erroneous human behavior that he is not interested in or that cannot be corrected through a cost effective design intervention. In this situation, the analyst may wish to rerun the analysis without considering a specific erroneous behavior.

The analyst can accomplish this by manually editing the erroneous human behavior model to remove the undesired erroneous transition. Given the way EOFM formal semantics are implemented in SAL, each erroneous transition is represented by a single guard (the condition on the transition) and a set of assignments under the guard. Thus, to remove any given erroneous transition, an analyst need only delete or comment out the associated guard and assignments. This procedure is used as part of an evaluation documented in Chapter 8.

Future work should investigate other means of allowing analysts to exclude specific or groups of erroneous transitions from formal verifications without the need to modify the formal model's code.

6.4.3 Error Generation

The erroneous behavior generation process discussed here is only capable of replicating capture slips for activities in a particular peer group: either within a given decomposition, or all parent level activities. However, capture slips can also manifest as a human operator perform all or part of a completely unrelated activity, especially if the activities occur under similar circumstances or are are composed of similar sequences of behavior [159]. Future work should investigate how such slips could be incorporated into our erroneous behavior generation process.

Reason's GEMS [159] classifies erroneous behaviors beyond the slip designations that have been discussed here. Specifically, slips only relate to erroneous behaviors that occur as a result of attentional failures which result in operators incorrectly performing tasks that they know how to perform correctly. A different class of erroneous behaviors, mistakes, occur when the human operator intentionally performs an erroneous behavior because he does not know how to perform a task correctly. This can occur either because of rule-based or knowledge-based failures. Rule based mistakes occur when the human performs a valid rule or schema for achieving a goal in an incorrect place or performs an invalid rule. Failures at the knowledge level occur when the operator has incorrect knowledge about the domain or environment. Future work should investigate how cognitive modeling could be paired with our method in order to generate mistakes.

The work of Blandford, Curzon, and Rukšė et al. [61, 62, 160, 161] have used cognitive modeling to produce erroneous human behaviors in verifications of models containing human-automation interaction. Doing this, they can generate erroneous behaviors related to the repetition of actions, the omission of actions, the commission of correct actions in the wrong context, the replacement of one action with another, the performance one or more actions out of order, and the performance of unrelated actions; all of which can occur for a variety cognitive reasons. Even though we only model human task behavior, our two error generation techniques are capable of generating all of these erroneous behaviors without the need for detailed cognitive modeling. Thus, the use of human task behavior modeling with formal verification is similarly powerful to the cognitive modeling work in in terms of its ability to evaluate the impact of erroneous human behavior on system safety properties.

Chapter 7

Counterexample Visualization*

Using our method, instantiated EOFM task models are translated into the language of the Symbolic Analysis Laboratory (SAL) [65] using the language's formal semantics [33]. Formal verifications are performed on the complete system model. Each step in a SAL produced counterexample is presented as a list of variable values sorted by variable name, with no indication of the relationships between variables. Further, the translation process divorces the formal representation of the human task behavior from its original EOFM instantiation. This chapter reviews the literature on counterexample visualization and synthesizes concepts from existing techniques to show how the human-automation interaction architectural framework and the visual notation supported by the EOFM can be used to create a counterexample visualization to help analysts evaluate the role of human-automation interaction in specification violations.

7.1 Counterexample Visualization Techniques

A variety of tools and techniques have attempted to display counterexamples in ways that are more useful than the standard output. These include variable tables; state diagrams;

*This chapter is derived from [30]

process and sequence diagrams; and domain or application dependent representations.

7.1.1 Variable Tables

Tables are typically used to depict variable values in each step in the counterexample, allowing variable values to be easily compared between steps. Table representations are supported by some model checkers such as the Cadence SMV [137]. These tables can also be enhanced to make it easier to compare variable values between steps by highlighting changes [49, 133]. They can also allow analysts to hide variables and steps from the display [120].

7.1.2 State Diagrams

A number of counterexample visualization concepts have focused on displaying the execution path through a state diagram of the model. Tools such as UPPAAL2k [8] and STATEMATE [92] represent models using the statecharts visual formalism [91] and allow counterexamples to be visually inspected by highlighting states and/or transitions active at each step.

Some tools [6, 52, 75] allow representations of a model's state space to be interactively explored to find witnesses or counterexamples. In these representations, a subset of the systems states are depicted as nodes in a directed graph with model specified transitions between them. The presented state space subset is calculated from user specifiable proof strategies [52, 75] or statistical measures [6]. Nodes can be interactively examined in order to get a complete view of their variable values, and the tools provide feedback about whether temporal logic properties evaluate to true. Human analysts can expand their search of the state space by interactively selecting paths or applying new proof strategies. The tools facilitate this task by highlighting paths statistically likely to produce a counterexample [6] or label each graph edge with the proof steps used to reach the target states [52].

7.1.3 Process and Sequence Diagrams

Process and sequence diagrams have also been used to visualize counterexamples, where variables are either grouped together in domain relevant designations (such as processes or threads for software) or represented by themselves [7, 8, 10, 49, 75, 104, 119, 175]. These designations are listed along an axis with a line extending out below them along a time or counterexample step axis. A mark (such as a dot or box) on one of these lines indicates a change in the state of the designation's variables at the given time or step, and can usually be interactively inspected to access full state variable value listings. Marks connected at a given step or time by a line or arrow can either show synchronized changes between the designations [119] or that one designation is passing information to another [10]. The lines extending from designations can be highlighted with different colors to convey the truth value of temporal logic properties [119, 175].

7.1.4 Domain and Application Dependent Representations

Several visualization techniques translate counterexample data into representations specific to a particular domain or application such as timing plots for models of computer hardware [109, 177]. Models animating human interaction with visual prototypes of human-device interfaces for counterexamples and formal model simulation traces have also been explored [3, 49].

7.1.5 Common Features

These visualization share common features that support evaluation including:

1. **Encapsulation of variables or states:** The sequence diagrams and application dependent representations allow model state variables to be encapsulated in higher level designations that are familiar to the analyst. These also sort model variables and remove visual clutter.

2. **Interactive detail refinement:** By allowing analysts to interactively query for information not currently displayed, visualizations support encapsulation without removing access to detailed information.

3. **Highlighting analysis relevant changes:** The discussed representations visually emphasize changes in model variables at several levels: individual variables; designations; and system properties specified in temporal logic. Tables, sequence diagrams, and state diagram animations highlight changes in individual variables. Sequence diagrams and tables show coordination between changes in state between different variables or designations. Some sequence diagram and state diagrams provide visual feedback about the value of analysis-relevant temporal logic properties.

7.2 Operational Concept and Design

An analyst performing formal verifications of human-automation interaction is interested in determining how human behavior contributes to a violation of a system specification. The analyst wants to examine the conditions under which the human operator performs actions and what the impact of those actions are on the other elements of the system. To support analysts perform such a verification using SAL, our architectural framework, and our EOFM task modeling language; we have developed a counterexample visualization that draws from the common features of other visualization techniques and EOFM's visual notation. This allows an analyst to visualize the execution state of the human task behavior at each counterexample step and compare it to information from other architectural components while highlighting changes in model state at the individual variable and architectural levels.

7.2.1 Encapsulation of Variables or States

The visualization encapsulates variable states based on the elements of the architectural framework (mission, task behavior, human-device interface, device automation, environment, and other[1]) and EOFM's visual notation. High level designations of these are organized in a table with designations as the rows and counterexample steps as the columns.

7.2.2 Interactive Detail Refinement

The visualization allows an analyst to interactively inspect the values of encapsulated variables. An analyst can traverse the table by either using navigation buttons (previous: ◀ and next: ▶) or by scrolling through the table cells and selecting a specific step. Selecting a cell moves a cursor (↓) that points to the associated step's column and presents a detailed view of the model variable's values in a separate, detailed view. This view presents the individual variable values from the system model elements for the given step in separate labeled columns. It also displays the execution state of the human task task behavior model using EOFM's visual notation.

The formal semantics of the EOFM language [33] specify that each activity and action in an instantiated EOFM has three possible execution states: *Ready* (waiting to execute), *Executing*, and *Done* (finished executing). When the visualizer presents the execution state of the human operator's task behavior model, it renders the entire graph for the goal level (root) activity that is executing. It color codes each of the activities and actions in this

[1]A designation used for any variables that do not fit in the architectural designations, such as erroneous behavior counters or handshake protocol variables.

structure to indicate its execution state: white for *Ready*, green for *Executing*, and grey for *Done*.

7.2.3 Highlighting Analysis Relevant Changes

The visualization highlights changes in variable values in both the high level encapsulated designations and the individual variables. At the high level, each table cell's color indicates whether or not there has been a change in one of the associated designation's variables since the previous step: white for no change, and yellow for a change. In our architecture, human task behavior can only produce a change in the other elements of the system architecture if a human action is performed. Thus, a counterexample step with a human action is indicated with an 'X' in its corresponding table cell. In the detailed view, variables whose values changed from the previous step are highlighted in yellow. An activity or action whose execution state has changed since the previous step is presented with a yellow highlight around its border.

7.2.4 Implementation

A counterexample visualization prototype is currently implemented in Microsoft Visio and Visual Basic for Applications. It takes an instantiated EOFM and a text file containing a SAL produced counterexample as input. The software identifies variables within the counterexample that represent the human task behavior model. It then presents the remaining variables to the analyst who indicates under which architectural designation the remaining variables belong: the human operator's mission, the human-device interface, the device automation, or the operational environment. The software then renders each detailed view of the counterexample as a separate page in a Visio document. The high-level encapsulation table (labeled “Navigation Form”) is presented as a dialog box that is presented over each page.

7.3 Example 1: Evaluating a System with a Normative Task Model

The following simple example illustrate the capabilities of this visualization using the formal model of a human operator driving down a street towards a traffic light in a car equipped with a simple cruise control ([33] and Chapter 4). The driver of the car wants to drive safely down the road. His goal is to drive at his desired (mission) speed while safely responding to traffic lights and avoiding merging traffic. This traffic is merging from a ramp intersecting the road before the traffic light. The relative distance between the car and the light is represented in intervals: Very Very Far, Very Far, Far, Merging, Close, Very Close, and At Intersection.

The driver can drive at one of 3 speeds (Slow, Moderate, or Fast) using a gas pedal to increase and decrease the gas. Increasing the gas (pressing the gas pedal) causes the car to accelerate to the next faster speed. Decreasing the gas decelerates the car to the next slower speed. The driver can release the gas pedal (which causes the car to decelerate until it stops) and can press the break. The driver can enable or disable the cruise control using available buttons although there is no visual indication of when the cruise is enabled. Cruise can also be disabled by pressing the break. When enabled, the cruise control will keep the car moving forward at its current constant speed unless the driver increases the gas. In this situation, the driver controls the car’s speed above the cruise speed.

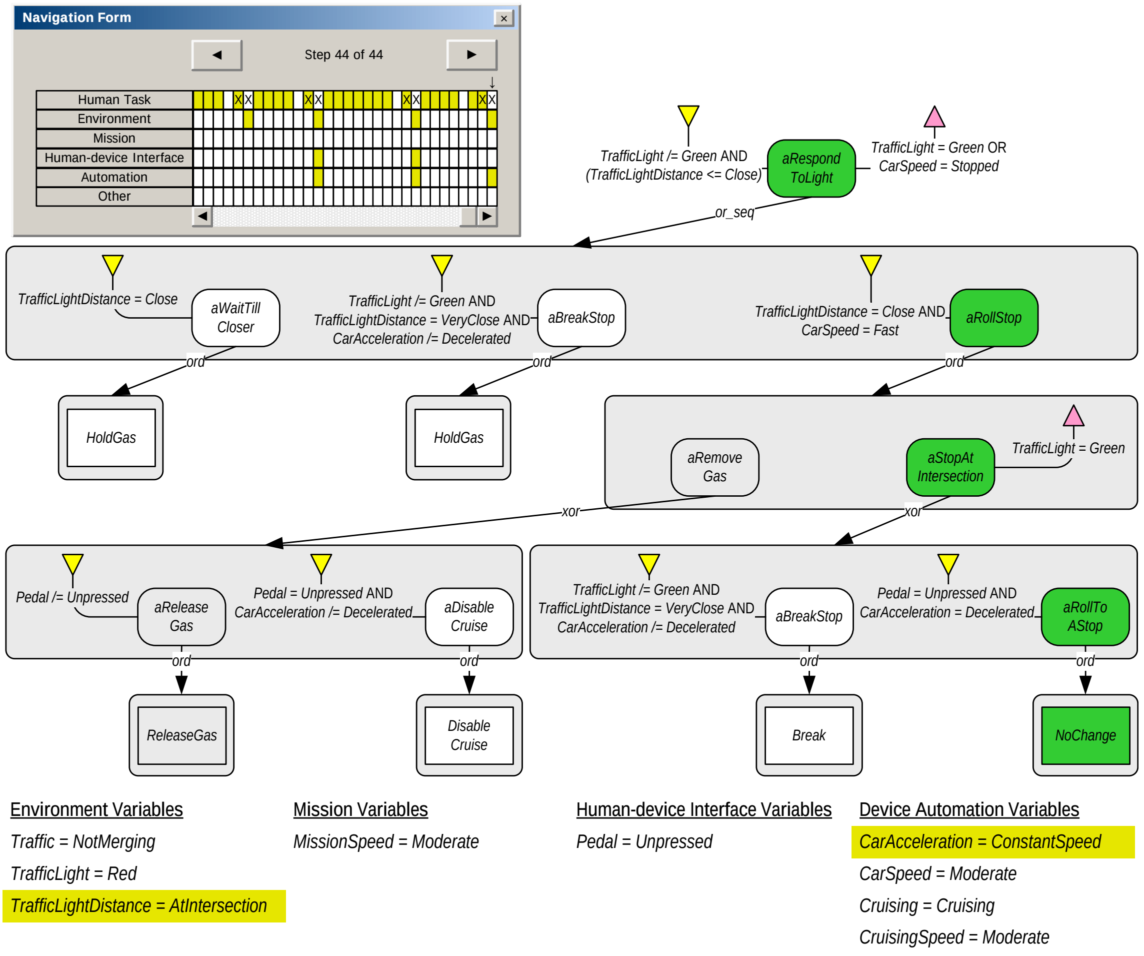
The formal system model architecture [27, 31] includes the human-device interface (the pedal and the indicated car’s speed), device automation (the car’s speed and acceleration), operational environment (the color of the light, its relative position to the car, and whether or not there is merging traffic), and human mission (the driver's desired speed). It also contains the human task behavior which is translated from an instantiated EOFM for the driving tasks: driving at the desired speed (adjusting the car's speed cruise control), avoiding merging traffic (by accelerating or slowing down to avoid the traffic), and responding to the light (waiting until very close to the light and breaking, or rolling to a stop from further away). A full specification of this model can be be found in [33].

Formal verification was performed on this system model using SAL's symbolic model checker (SAL-SMC) to ensure that the driver will never run a red light (reach the intersection when the light is red with the car not being stopped). This is specified in LTL as:

$$\mathbf{G}\neg\left(\begin{array}{l} \mathit{TrafficLightDistance} = \mathit{AtIntersection} \\ \wedge\ \mathit{TrafficLight} = \mathit{Red} \\ \wedge\ \mathit{Car} \neq \mathit{Stopped} \end{array}\right) \tag{7.1}$$

When checked against the formal system model, this specification produced a counterexample. The violation occurs in the last step of the counterexample (step 44; Figure 7.1): where the driver is attempting to roll to a stop at the traffic light. The driver is not pressing the gas pedal, but the car is moving at a moderate, constant speed (not decelerating) with the cruise control enabled. Here the driver has attempted to roll to a stop without disabling the cruise control.

Examining this step (Figure 7.1) reveals that the operator had previously attempted to remove gas to the car by releasing the gas pedal (*ReleaseGas* via *aReleaseGas* and *aRemoveGas*) rather than disabling the cruise control. The analyst can use the navigation form to see why this occurred by stepping back through the counterexample. At step 33 (Figure 7.2) the driver should disable the cruise control in order to successfully cut the

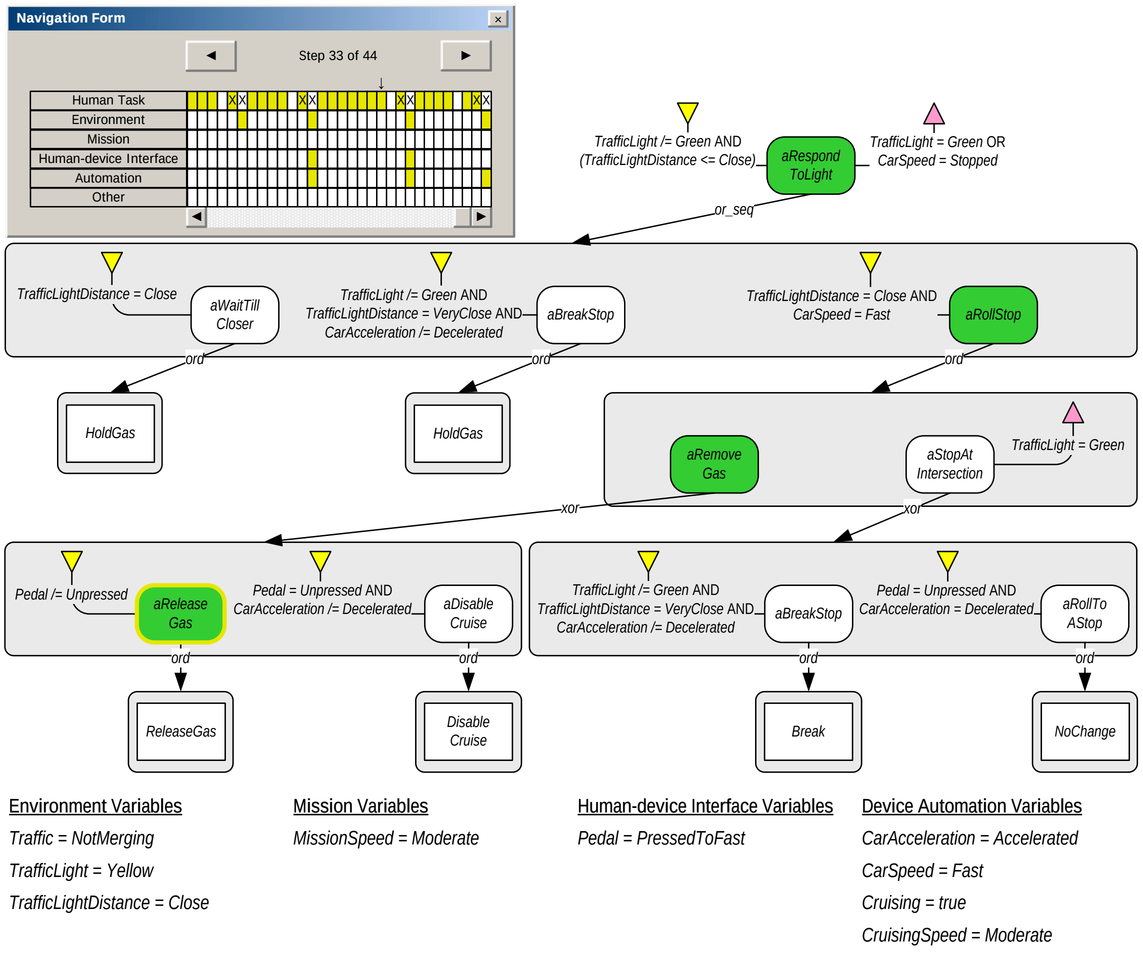

Navigation Form
Step 44 of 44
Human Task
Environment
Mission
Human-device Interface
Automation
Other
TrafficLight /= Green AND (TrafficLightDistance <= Close)
aRespond ToLight
TrafficLight = Green OR CarSpeed = Stopped
or_seq
TrafficLightDistance = Close
aWaitTill Closer
TrafficLight /= Green AND TrafficLightDistance = VeryClose AND CarAcceleration /= Decelerated
aBreakStop
TrafficLightDistance = Close AND CarSpeed = Fast
aRollStop
ord
ord
ord
HoldGas
HoldGas
aRemove Gas
aStopAt Intersection
TrafficLight = Green
xor
xor
Pedal /= Unpressed
aRelease Gas
Pedal = Unpressed AND CarAcceleration /= Decelerated
aDisable Cruise
TrafficLight /= Green AND TrafficLightDistance = VeryClose AND CarAcceleration /= Decelerated
aBreakStop
Pedal = Unpressed AND CarAcceleration = Decelerated
aRollTo AStop
ord
ord
ord
ord
ReleaseGas
Disable Cruise
Break
NoChange

Environment Variables	Mission Variables	Human-device Interface Variables	Device Automation Variables
Traffic = NotMerging	MissionSpeed = Moderate	Pedal = Unpressed	CarAcceleration = ConstantSpeed
TrafficLight = Red			CarSpeed = Moderate
TrafficLightDistance = AtIntersection			Cruising = Cruising
			CruisingSpeed = Moderate

Figure 7.1: Step 44 from the visualization of the counterexample. The car has reached the intersection while moving at a constant, moderate speed while the traffic light is red, a violation of (7.1). The operator has attempted to perform a roll stop by keeping his foot off of the gas pedal. However, this has not impacted the car's speed because the cruise control is enabled and the car is at its cruise speed.

car's gas supply as part of performing a roll stop (*aDisableCruise* via *aRemoveGas* and *aRollStop*). However, even though cruise is enabled (as indicated by *Cruising* = *true* under 'Device Automation Variables'), the driver is pressing the gas pedal. Thus he performs the activity for releasing the gas pedal (*aReleaseGas*) instead.

To determine why the human operator is pressing the gas pedal, the analyst can look

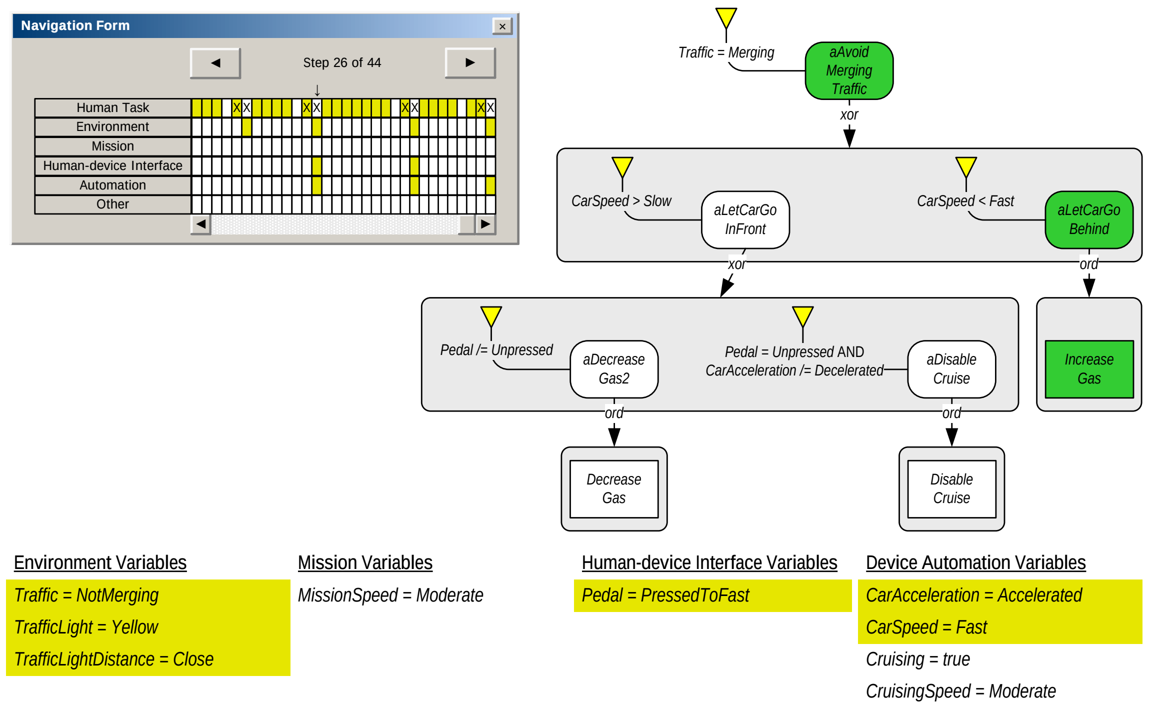

Navigation Form
Step 33 of 44
Human Task
Environment
Mission
Human-device Interface
Automation
Other
TrafficLight /= Green AND (TrafficLightDistance <= Close)
aRespond ToLight
TrafficLight = Green OR CarSpeed = Stopped
or_seq
TrafficLightDistance = Close
aWaitTill Closer
TrafficLight /= Green AND TrafficLightDistance = VeryClose AND CarAcceleration /= Decelerated
aBreakStop
TrafficLightDistance = Close AND CarSpeed = Fast
aRollStop
ord
HoldGas
HoldGas
aRemove Gas
aStopAt Intersection
TrafficLight = Green
xor
Pedal /= Unpressed
aRelease Gas
Pedal = Unpressed AND CarAcceleration /= Decelerated
aDisable Cruise
TrafficLight /= Green AND TrafficLightDistance = VeryClose AND CarAcceleration /= Decelerated
aBreakStop
Pedal = Unpressed AND CarAcceleration = Decelerated
aRollTo AStop
ReleaseGas
Disable Cruise
Break
NoChange

Environment Variables	Mission Variables	Human-device Interface Variables	Device Automation Variables
Traffic = NotMerging	MissionSpeed = Moderate	Pedal = PressedToFast	CarAcceleration = Accelerated
TrafficLight = Yellow			CarSpeed = Fast
TrafficLightDistance = Close			Cruising = true
			CruisingSpeed = Moderate

Figure 7.2: Step 33 from the visualization of the counterexample. The car is close to the light and the light is yellow. Thus the driver is attempting to respond to the light by performing a roll stop. To accomplish this task, he “removes” gas from the car by performing the activity for releasing the gas pedal.

at the navigation form to see when the last human action was performed. This occurs in step 26, where the ‘X’ appears in the navigation form table. When inspected, its associated detailed view reveals that while cruise was enabled, the driver has pressed the gas pedal (*IncreaseGas*) to accelerate the car to let merging traffic in behind him (Figure 7.3).

Thus, the visualization helps to determine that this violation occurs when the human operator accelerates his car after enabling the cruise control in order to let in merging traffic



Environment Variables	Mission Variables	Human-device Interface Variables	Device Automation Variables
Traffic = NotMerging	MissionSpeed = Moderate	Pedal = PressedToFast	CarAcceleration = Accelerated
TrafficLight = Yellow			CarSpeed = Fast
TrafficLightDistance = Close			Cruising = true
			CruisingSpeed = Moderate

Figure 7.3: Step 26 from the visualization of the counterexample. The driver has just performed the action for increasing the gas to avoid merging traffic by letting the merging traffic pass behind. This has caused the gas pedal to be pressed to the "fast" position, with the car accelerating to the fast speed, allowing the traffic to merge, and the car to go to the "Close" interval. The traffic light has also turned yellow.

and then attempts to roll to a stop at a traffic light.

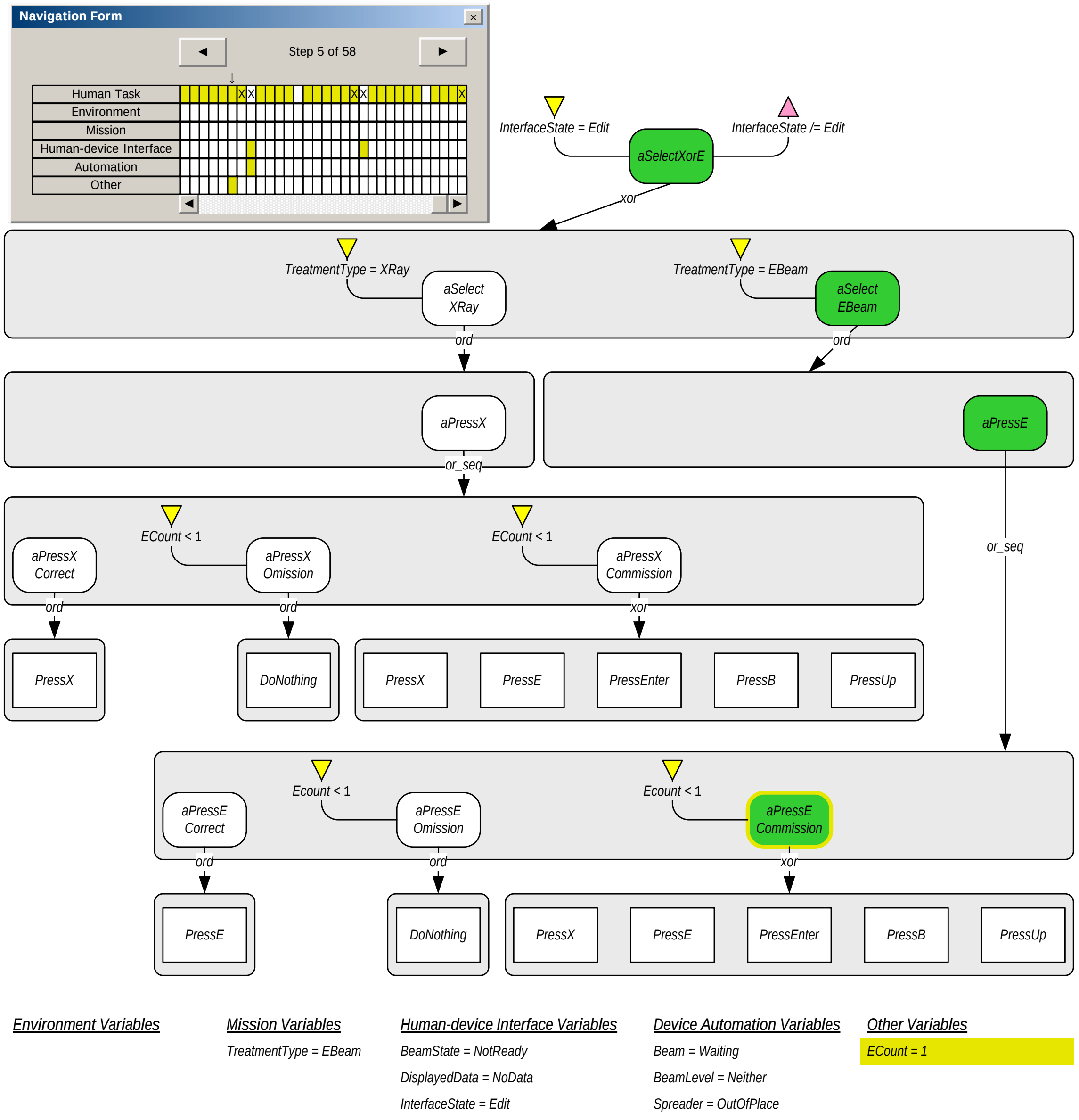
7.4 Example 2: Evaluating a System with a Phenotypical Erroneous Task Model

The visualization can also be used to identify what erroneous behaviors contribute to a discovered system violation. Consider the failure discovered for the radiation therapy machine from Chapter 5, where a failure was discovered in which a single erroneous human act contributed to a situation where the machine administered an unshielded xray treatment, a dangerous operating condition. We can use the visualization of a counterexample illustrating this this failure sequence and use it to identify the erroneous behavior that contributed to this problem.

The navigation form for the visualization of this counterexample shows us that a change has occurred in the "Other" designation of variables at Step 5. Since the only variable in the other designation is the erroneous behavior counter (*ECount*) we know that an erroneous behavior occurs beginning at this step. Examining this step (Figure 7.4) reveals that the practitioner has just started performing the activity for performing an erroneous commission (*aPressECommission*). We can then examine the two following steps (Step 7 is shown in Figure 7.5) to see that the practitioner completes this activity by pressing the 'X' button which puts the interface into the state for displaying xray data, sets the beam to the xray power level, and moves the spreader in place.

7.5 Example 3: Evaluating a System with a Knowledge-based Erroneous Task Model

We can also use the counterexample visualizer to identify strategic knowledge-based erroneous behaviors that contribute a discovered system problems. For example, in the PCA pump application (Chapter 6) a situation was discovered where a misapplication of strategic knowledge resulted in a practitioner incorrectly programming the pump. The examination of the visualization of the counterexample illustrating this shows that a change in the "Other" designation (the erroneous behavior counter *KCount*) occurs at step 32. An examination of this step (Figure 7.6) shows that the activity for changing the displayed value of the delay between dosages (*aChangeDelayValue*) has erroneously transitioned from *Executing* to *Done* without current displayed value (*CurrentValue*) matching the prescription

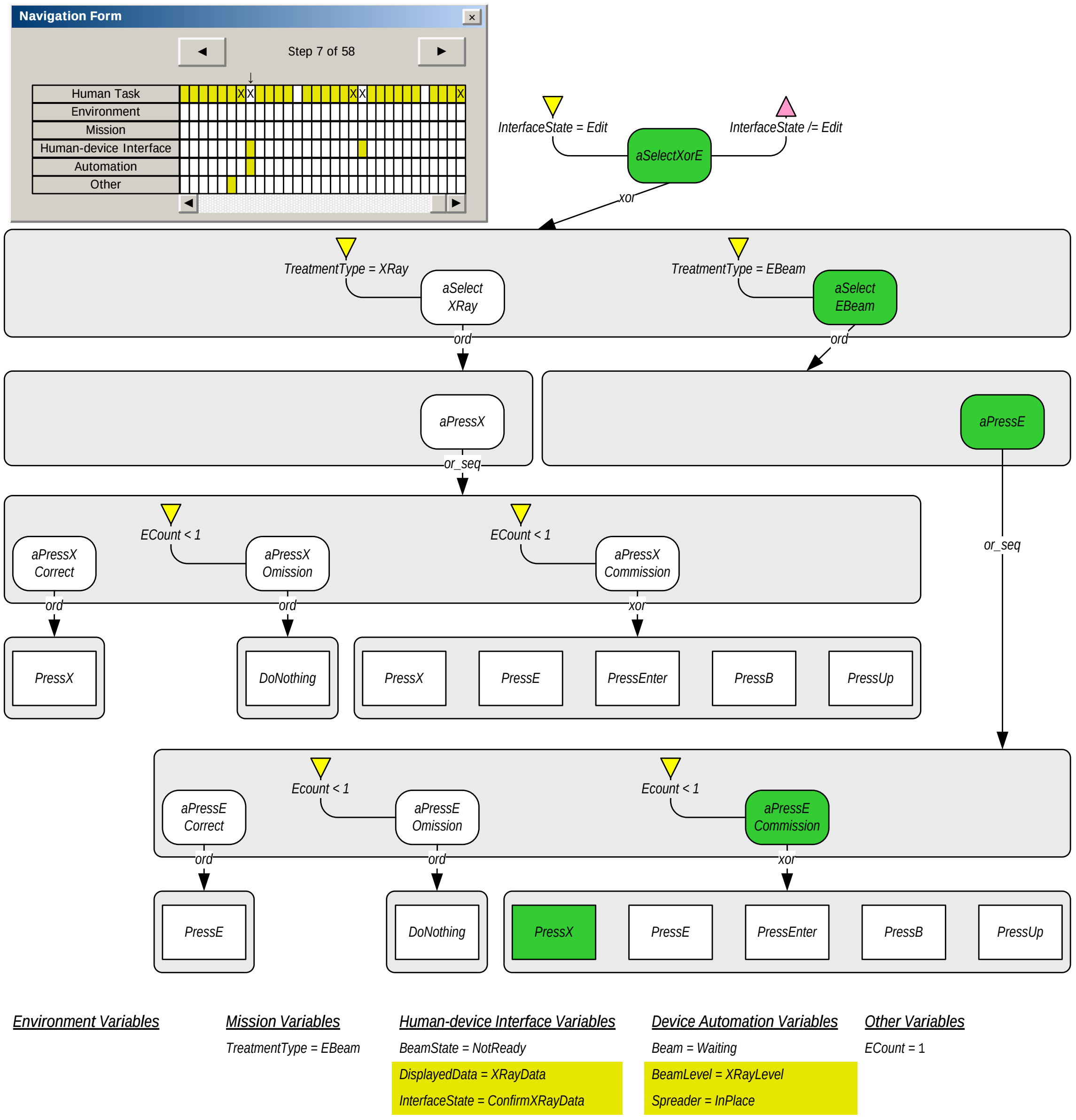


Environment Variables	Mission Variables	Human-device Interface Variables	Device Automation Variables	Other Variables
	TreatmentType = EBeam	BeamState = NotReady	Beam = Waiting	ECount = 1
		DisplayedData = NoData	BeamLevel = Neither	
		InterfaceState = Edit	Spreader = OutOfPlace	

Figure 7.4: Step 5 from the visualization of the radiation therapy counterexample. The practitioner has just started performing an erroneous commission activity which has incremented the erroneous behavior count (*ECount*).

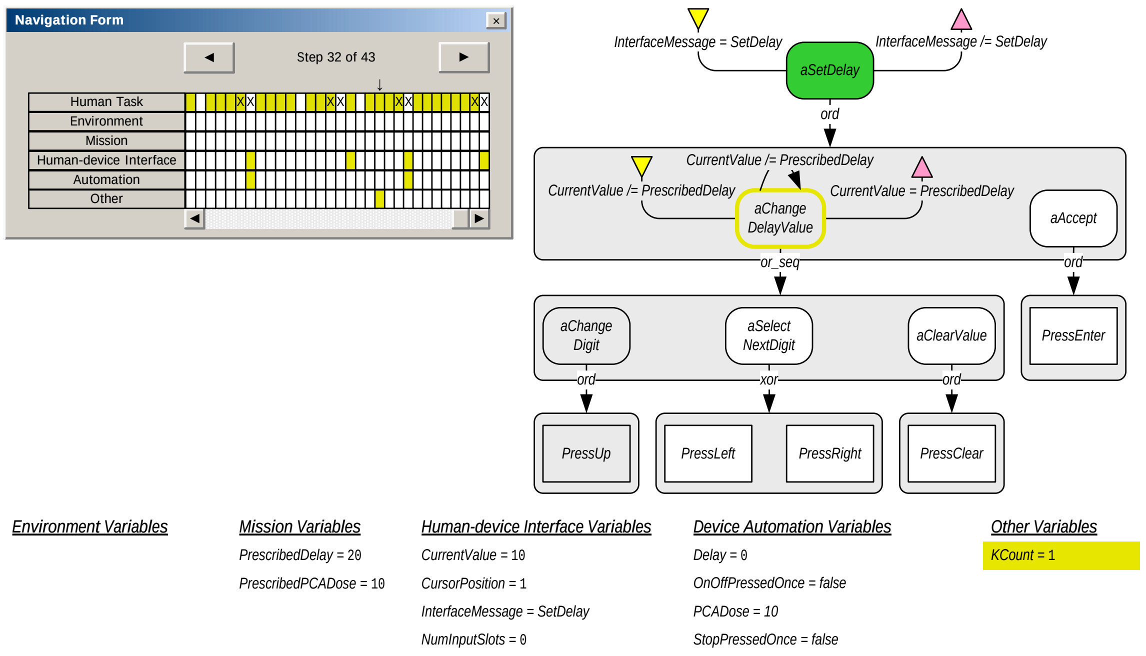
value (*PrescribedDelay*).

At step 35 (Figure 7.7), we can see that as a result of this erroneous behavior, the human operator has confirmed the value: setting the delay to the incorrect value.



Environment Variables	Mission Variables	Human-device Interface Variables	Device Automation Variables	Other Variables
	TreatmentType = EBeam	BeamState = NotReady	Beam = Waiting	ECount = 1
		DisplayedData = XRayData	BeamLevel = XRayLevel	
		InterfaceState = ConfirmXRayData	Spreader = InPlace	

Figure 7.5: Step 7 from the visualization of the radiation therapy counterexample. The practitioner has erroneously pressed the 'X' key which has put the interface into the state for displaying xray data, set the beam to the xray power level, and moved the spreader in place.



Environment Variables	Mission Variables	Human-device Interface Variables	Device Automation Variables	Other Variables
	PrescribedDelay = 20	CurrentValue = 10	Delay = 0	KCount = 1
	PrescribedPCADose = 10	CursorPosition = 1	OnOffPressedOnce = false	
		InterfaceMessage = SetDelay	PCADose = 10	
		NumInputSlots = 0	StopPressedOnce = false	

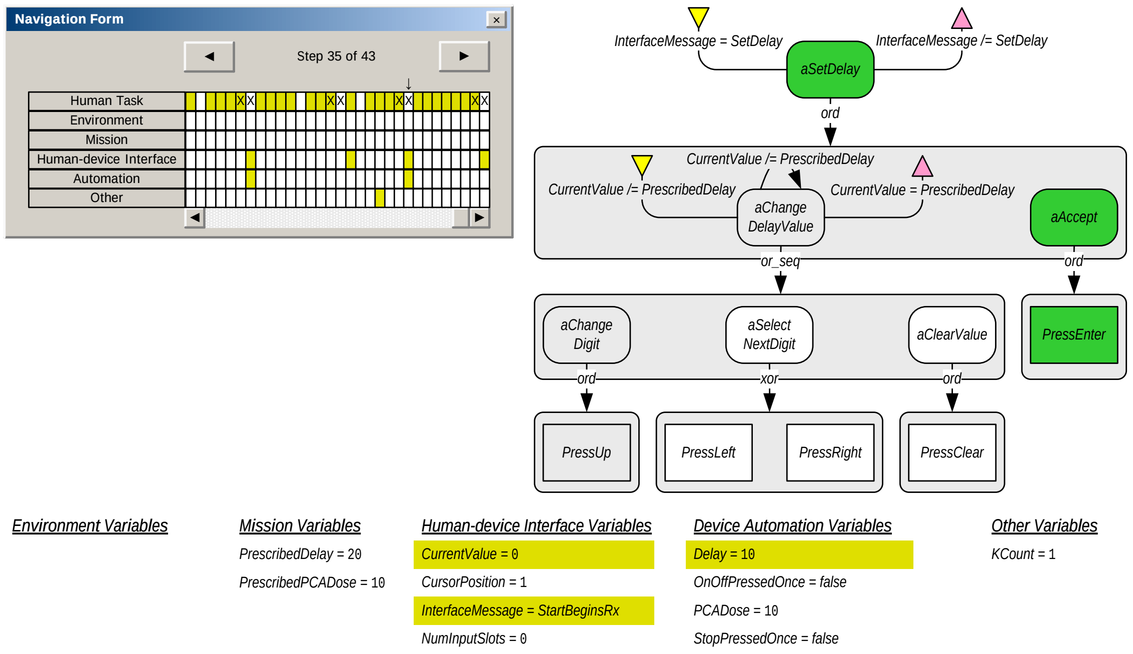
Figure 7.6: Step 32 from the visualization of the PCA pump counterexample. The pump programmer has just erroneously finished changing the displayed value of the delay between dosages: *aChangeDelayValue* has transitioned from *Executing* to *Done* and the erroneous behavior counter (*KCount*) has incremented.

7.6 Discussion

The counterexample visualization presented here supports an analyst attempting to interpret a SAL produced counterexample when using our human-automation interaction architectural framework and our EOFM task modeling language by providing a means to determine how human task behavior impacts other elements of the system architecture, and thus ultimately contribute to a specification violation. It accomplishes this by exploiting the visual notation of the EOFM and useful features of other visualization techniques:

- It encapsulates variables into designations from the architectural framework and presents task model data using the EOFM visual notation;

- It allows the analyst to interactively inspect counterexample steps to get detailed



Environment Variables	Mission Variables	Human-device Interface Variables	Device Automation Variables	Other Variables
	PrescribedDelay = 20	CurrentValue = 0	Delay = 10	KCount = 1
	PrescribedPCADose = 10	CursorPosition = 1	OnOffPressedOnce = false	
		InterfaceMessage = StartBeginsRx	PCADose = 10	
		NumInputSlots = 0	StopPressedOnce = false	

Figure 7.7: Step 35 from the visualization of the PCA pump counterexample. The pump programmer has confirmed the incorrect delay ($Delay \neq PrescribedDelay$) by pressing enter.

information for the execution state of the human task behavior and all other model variables; and

- It highlights changes in the high level encapsulation view, the detailed view of the variables, and the human task behavior execution state.

This visualization has been used successfully to support all of application analyses presented in this document. However, there are additional ways it could be improved and evaluated.

Based on the literature, there are other visualization features that could be incorporated. Several existing visualizations [6, 52, 75, 119, 175] provide feedback about how logically expressed properties evaluate at each step, often with color coding. While our counterexample visualization displays the conditions associated with task behavior activities, it does not provide any visual indication of how they evaluate (*true* or *false*). Additionally, our visualization provides no feedback about the evaluation of temporal logic properties (like that used to produce the counterexample). Future work should investigate how to incorporate visual feedback about property evaluations into our visualization.

Several of the tools we discussed [6, 52, 75] allow analysts to interactively explore the state space of a model. The counterexamples produced by SAL-SMC represent a single execution path through the model, and thus do not support additional model exploration. However, SAL does have a simulator that supports exploration. Future work should investigate how our visualization could be made to work with SAL's simulator.

Our visualization was explicitly designed to help analysts interpret counterexamples. However, such a visualization may be useful for debugging models during development. Future work should determine what the requirements are for debugging and related visualization tools.

Our visualization has only been used to examine single counterexamples in isolation. However, it is conceivable that analysts may wish to compare different counterexamples in order to diagnose potentially related specification violations. Future work should investigate what the requirements are for such a feature and possibly adapt the visualization to support it.

Finally, future work should evaluate our visualization with a human subject experiment; where we would evaluate whether analysts could identify executing human task behavior and its impact on other system variables more efficiently with our visualization than with a typical SAL counterexample. Future work should also investigate how our visualization compares to other visualization techniques such as variable tables and sequence diagrams. This is discussed in greater depth in Chapter 9.

Chapter 8

Design Exploration

All of the examples up to this point have illustrated a particular feature of our method. In this chapter, we show how our method can be used to evaluate the design of a human-automation interactive system in a number of different ways. We describe a human-automation interaction issue associated the deployment of spoilers with an aircraft on approach in which the pilot is performing the before landing checklist (a Douglas DC-8 application inspired by [67]). In these analyses we use a formal system model containing all elements of the human-automation interaction architectural framework. Across the analyses we show how our method can be used to explore the impact of different normative task behaviors, erroneous human behavior generated using the methods discussed in Chapter 5 and Chapter 6, and degraded performance of the device automation. Potential interventions to discovered problems are explored.

8.1 Application: Aircraft on Approach

In most instrument landing systems, an aircraft pilot must position the aircraft so that it will align with the runways glideslope: a diagonal path (3° from horizontal) to help pilots descend onto the runway.

The "before landing" checklist indicates what must be true in order for the aircraft to land:

- The ignition must be set to override;
- The landing gear must be down;
- The spoilers should be armed; and
- The flaps should be extended to 40°.

The vertical position of the aircraft relative to the glideslope is displayed with a moving diamond on the glideslope indicator (right side of Figure 8.1). When the aircraft is within range of the instrument landing system and nearing the glideslope, the diamond will become "alive", moving towards the center of the display. As it moves, it will first pass through the "two dot" and then the "one dot" positions. When the aircraft is on the glideslope, the diamond is at the capture position.

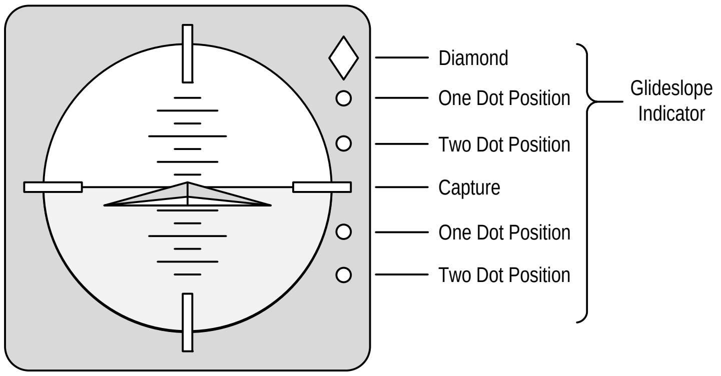


Figure 8.1: A simplified representation of an aircraft artificial horizon display with a glideslope indicator on the right. The diamond is not yet alive.

The pilot usually performs the items on the "before landing" checklist in order to ensure that the aircraft will land safely.

The ignition should be set to override in order to ensure that, should the engine quite, there will be enough ignition power to restart it. The ignition is controlled by a switch, and a light illuminates when the switch is set to override.

Once the glideslope indicator diamond is alive, the pilot can deploy the landing gear. Pulling the landing gear lever opens the landing gear doors and deploys the gear. In a well functioning aircraft the doors can take approximately 10 seconds to completely open. As such, the landing gear will fully deploy before the landing gear doors are completely open. Three lights in the cockpit (one for each of the landing gear) illuminate when the landing gear is fully deployed. Another light illuminates when the landing gear doors begin to open, and remains on until they are completely open.

The pilot progressively extends the flaps in order to reduce the aircraft's stalling speed, thereby allowing the aircraft to fly safely at slower speeds. Extending flaps also increases drag which helps to slow the aircraft. In general, when the aircraft is between the one dot and capture positions, the pilot has slowed to a speed where the flaps should be set to 25°. When the aircraft has reached the capture position he should set the flaps to 40°. Pilots may also set the flaps to progressive intermediate degrees before and/or in between these two settings. The position of the flaps is indicated by a gauge in the cockpit.

Spoilers are retractable plates on the wings of the aircraft which, when deployed, decrease the lift of the aircraft. They are deployed during landing to prevent the aircraft from lifting off of the runway. Spoilers can be deployed manually or automatically. The pilot can arm the spoilers for automatic deployment by pulling a lever. A light in the cockpit indicates when the spoiler are armed. Alternatively, a pilot can manually deploy the spoilers when the aircraft touches the runway.

8.1.1 Problems with Spoilers

Two potential problems have been identified relating to the deployment of spoilers. Firstly, if the spoilers are never deployed (either via automatic or manual deployment) this can result in the aircraft overrunning the runway as occurred with American Airlines Flight 1420 [145]. Secondly, having the spoilers deploy in flight will result in the aircraft losing lift possibly resulting in a hard landing or a crash. This was the case with Air Canada flight 621 [83] and Loftleidir Flight 509 [84], both Douglas DC-8s.

The first condition can occur if the pilot forgets to arm the spoilers (as happened with American Airlines Flight 1420 [145]). The second problem can also result from this, where the pilot attempts to correct the problem but, because he is unfamiliar with manual spoiler deployment, he prematurely deploys the spoilers manually (this was the case for Air Canada flight 621 [83]). However, the second problem can also occur due to the mechanism that automatically deploys the spoilers. If spoilers are armed before the landing gear has deployed or the landing gear doors have fully opened, the armed spoilers may automatically deploy [67].

8.1.2 Objectives

We evaluate issues related to spoiler arming for this application using our method. We exploit the modular nature of our architecture to run a series of verifications to explore the behavior of the system and potential solutions to discovered problems. This analysis occurs across the following phases:

1. We explore different representations of normative human behavior;
2. We explore different representations of erroneous human behavior; and
3. We explore variations in the behavior of the automation.

However, first we discuss the EOFM and formal system models on which these analyses were performed.

8.2 Formal System Model

The formal system model was constructed around our architecture [27, 31] with models of the operational environment, device automation, human-device interface, human (pilot) mission, and human task behavior.

8.2.1 Operational Environment

The operational environment of an actual aircraft includes the weather, air traffic, air traffic control, and the state of the runways (among other things). For our purposes, the environment is modeled as the relative distance of the aircraft from the capture position on the glideslope. It is assumed that the aircraft starts at a position in which the glideslope diamond is not alive, and that the aircraft proceeds up to the capture positions and begins to descend on the glideslope, a process that will take 18 seconds. Thus, the relative position of the aircraft from its modeled initial position is discretized into intervals from 0 to 18 such that the aircraft passes from one interval to the next in one second (Figure 8.2). This means the aircraft speed and altitude are abstracted into the position.

In our model, the glideslope indicator diamond's behavior is directly associated with the aircraft's position. The aircraft starts at position 0 where the glideslope diamond is not alive. At position 1, the glideslope diamond becomes alive. At position 6 the aircraft is "two dots" below the glideslope. It is "one dot" below at position 11. Capture occurs at position 17. At position 18, the aircraft is in the process of landing.

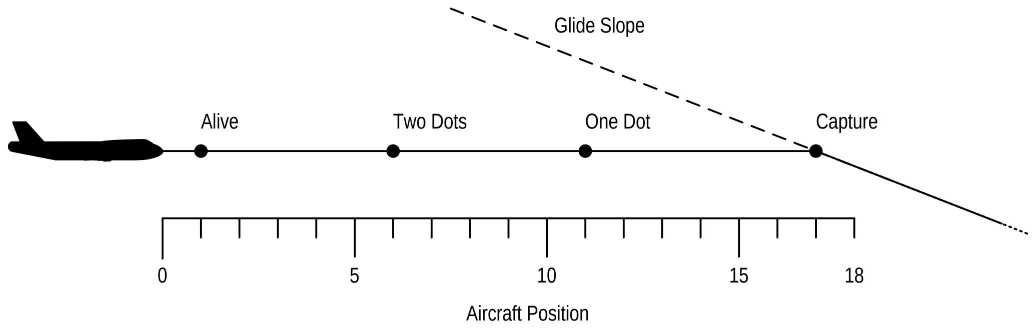


Figure 8.2: The position (*Position*) of the aircraft as it approaches its intersection with the glideslope.

8.2.2 Device Automation

The formal model of the device automation represented the functionality of the aircraft's landing gear, spoilers, and landing gear doors. The ignition was not explicitly modeled in the device automation, though it was modeled as part of the human-device interface (see Section 8.2.3).

The landing gear (Figure 8.3) starts in the up position as it would before the pilot performs the "before landing" checklist. When the pilot pulls the landing gear lever (*PullGearLever*) the landing gear transitions to the down position.

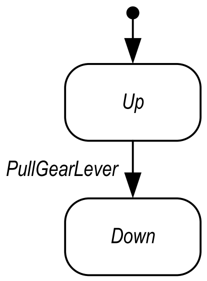


Figure 8.3: State transition representation of the formal model of the landing gear (*LandingGear*).

As would happen in an actual approach, the landing gear doors (Figure 8.4) start in the closed position. When the pilot pulls the landing gear lever, the doors begin to open. In the model it takes a constant amount of time (10 seconds) for the doors to completely open, where the amount of time corresponds to the number of distance positions (Figure 8.2) the aircraft has passed through (one second per interval).

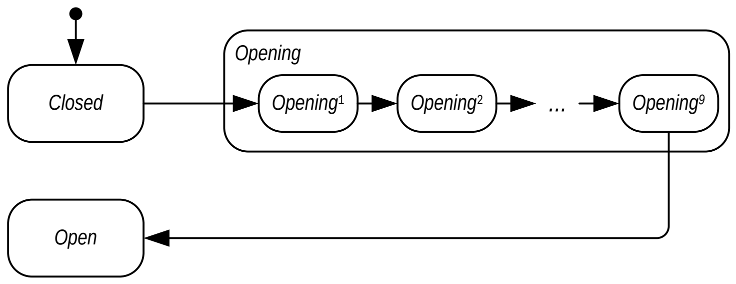


Figure 8.4: State transition representation of the formal model of the landing gear doors (*GearDoors*), where the number of state transition in the *Opening* designation are set to a constant to model the amount of time it takes for the doors to open. Here, there are nine *Opening* states. Thus there are ten transitions required for the doors to completely open, corresponding to a door opening time of 10 seconds.

The flaps (Figure 8.5) start in the clean configuration (0°), as it actually would be before the pilot performs the "before landing" checklist. The flaps can be set to 25° and 40° when the pilot performs the action for setting either.

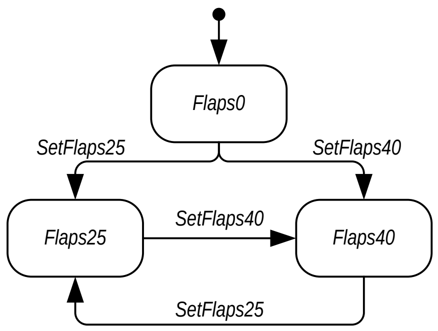


Figure 8.5: State transition representation of the formal model of the flaps (*GearDoors*).

The spoilers (Figure 8.6) are unarmed, as they would be at the beginning of an approach. They are armed when the pilot pulls the lever to arm the spoilers (*ArmSpoilers*).

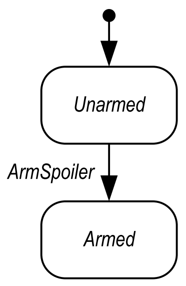


Figure 8.6: State transition representation of the formal model of the spoilers (*Spoilers*).

8.2.3 Human-device Interface

The formal model of the human-device interface represents the state of the cockpit controls and indicator lights associated with arming the spoilers, the landing gear doors, the landing gear, the flaps, the glideslope indicator, and the ignition; all of which change state in response to changes in the automation or environment as well as human actions.

The state of the glideslope indicator (Figure 8.7) is dependent on the position of the aircraft (Figure 8.2). At position 0 the glideslope indicator's diamond is inactive. At position 1 it becomes alive. It indicates "two dots" at position 6 and "one dot" at position 11. At position 17, it indicates capture.

The state of the ignition is indicated by the ignition switch and an indicator light. The ignition switch (Figure 8.8(a)) starts in the un-flipped state. It transitions between the flipped and un-flipped states when the pilot flips the switch. The ignition light (Figure 8.8(b)) is on when the switch is flipped and off when it is un-flipped.

The state of the landing gear and landing gear doors are indicated by the human-device interface's gear lever (Figure 8.9(a)), three landing gear lights (Figure 8.9(b)), and the gear doors light (8.9(c)). The gear lever starts in the un-pulled position. It becomes pulled when the pilot pulls the gear lever. The three landing gear lights are off whenever the landing gear is up and on when it is down. The gear doors light is dependent on the state of the

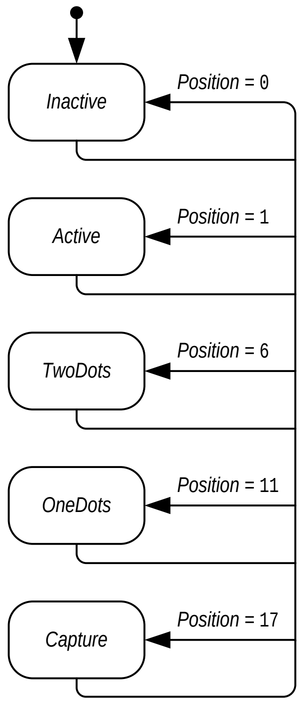


Figure 8.7: State transition representation of the formal model of the glideslope indicator (*GSIndicator*).

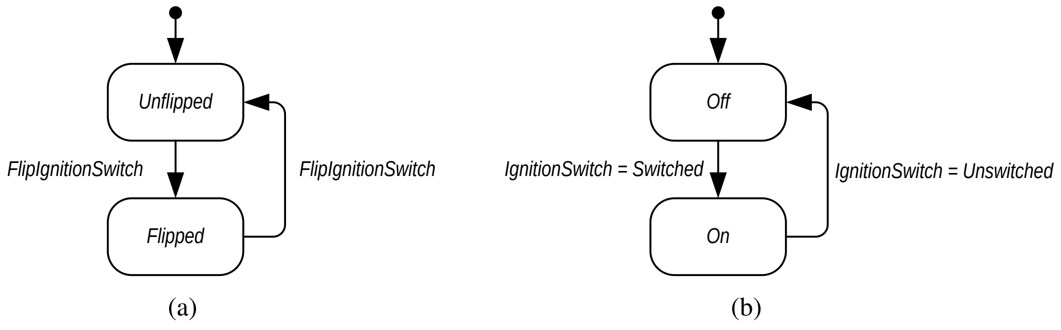
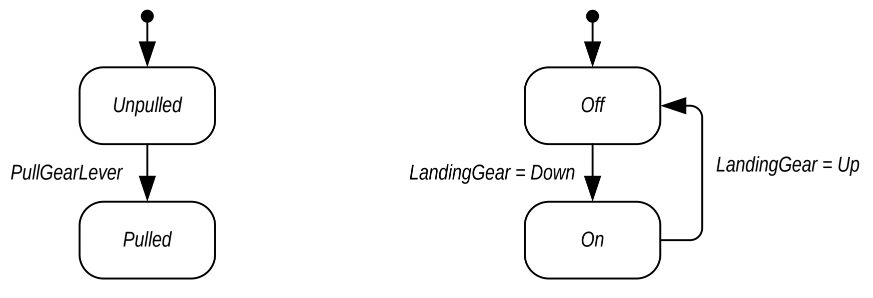


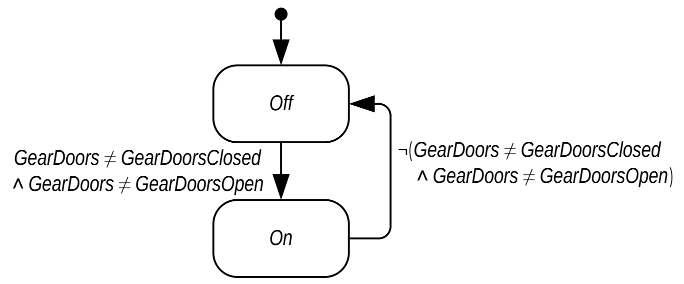
Figure 8.8: State transition representation of the formal model of the (a) ignition switch (*IgnitionSwitch*) and the (b) ignition light (*IgnitionLight*).

landing gear doors. When the doors are either open or closed, the light is off. Otherwise the light is on.

The state of the flaps is indicated by the gauge the pilot uses to set the angle of the flaps



(a) (b)


Off
GearDoors ≠ GearDoorsClosed
∧ GearDoors ≠ GearDoorsOpen
On
¬(GearDoors ≠ GearDoorsClosed
∧ GearDoors ≠ GearDoorsOpen)

(c)

Figure 8.9: State transition representation of the formal model of (a) the landing gear lever (*GearLever*), (b) the three landing gear lights (*ThreeGearLights*), and (c) the gear doors light (*GearDoorsLight*).

(Figure 8.10). It reflects the state of the flaps as determined by the automation.

The state of the spoilers (armed or unarmed) is indicated by the lever used to arm the spoilers (8.11(a)) and the spoiler indicator light (8.11(b)). The lever starts out in the un-

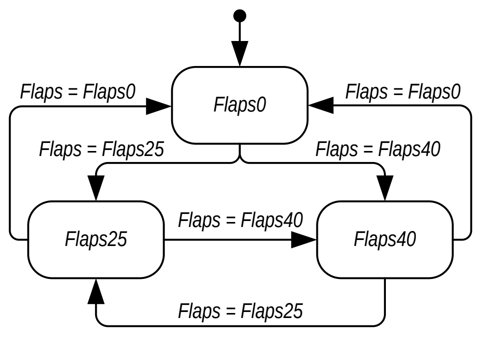


Figure 8.10: State transition representation of the formal model of the flaps gauge (*Flaps-Gauge*).

pulled position and transitions to pulled when the pilot performs the action for arming the spoilers. The indicator light is dependent on the state of the spoilers from the automation. If the spoilers are armed then the light is on. Otherwise the light is off.

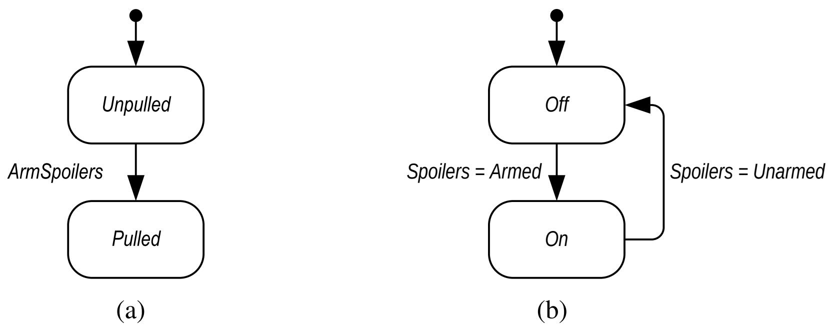


Figure 8.11: State transition representation of the formal model of the (a) lever used to arm the spoilers (*SpoilerLever*) and the (b) spoiler indicator light (*SpoilerIndicator*).

8.2.4 Human Mission

Airline policy will typically dictate whether or not pilots should arm the spoilers or manually deploy them during landing. Further, pilots have been known to hold preferences related to which spoiler option they use (see [84]). Thus, the pilot may or may not wish to arm the spoilers, where it is presumed that a pilot who prefers to manually deploy the spoilers will do so once the aircraft touches down. This preference constitutes the mission model as a Boolean variable *PreferToArmSpoilers* which can be either *true* or *false* respectively.

8.3 Human Task Behavior Modeling

An instantiated EOFM describes the human pilot task behavior for performing the “before landing” checklist using a single *humanoperator*. This human operator pilot has access to input variables from the human-device interface (the glideslope indicator, the ignition light, the ignition switch, the gear level, the gear doors light, the three landing gear lights, the flaps gauge, the spoiler lever, and the spoiler indicator) and the human mission (the preferences for arming or not arming spoilers).

The pilot model generates *humanaction* outputs representing actions performed through the human-device interface: flipping the ignition switch (*FlipIgnitionSwitch*), pulling the landing gear lever (*PullGearLever*), setting the flaps to either 25° or 40° (*Set-Flaps25* and *SetFlap40* respectively), and pulling the lever to arm the spoilers (*ArmSpoil-ers*).

A goal directed task model was constructed representing the procedure the pilot follows when preparing to land the aircraft using the "before landing" checklist (Figure 8.12). The pilot can override the ignition (*aOverrideIgnition*) before the glideslope indicator diamond is alive if the ignition light is off, thus fulfilling the first item on the "before landing" checklist. For the second item on the "before landing" checklist, the pilot can deploy the landing gear (*aDeployLandingGear*) if the glideslope indicator is alive and the three landing gear lights are off. When the glideslope indicator reads one dot, the pilot can set the flaps to the intermediate 25°. The pilot can arm the spoilers, the third item on the "before landing" checklist, through the *aSetSpoilers* activity if he prefers to arm the spoilers, and both the spoiler indicator and landing gear doors lights are off. If he does not prefer to arm the spoilers or the spoiler indicator is on, the activity will complete without the pilot pulling the lever to arm the spoilers (*ArmSpoiler*). Once the glideslope indicator reaches the capture position, the pilot can set the flaps to 40° (*sSetFlaps40*), the fourth item on the "before landing" checklist.

Pilots use the "before landing" checklist to guide them through the procedure [67]. While pilots generally follow checklist items in order, they may complete them out of sequence. In order to model both of these conditions, two version of this task model were created: one where the pilot will always perform the task in order (enforced by an *ord* decomposition for *aPrepareForLanding*) and one where he can perform them in any order (an *and_par* decomposition for *aPrepareForLanding*).

8.4 EOFM to SAL Translation

The EOFM task model instances were translated into SAL code and incorporated into the larger formal system model. In its original XML form, the human task behavior models were represented in 86 lines of code. The translated SAL versions were represented in 155 lines of code.

8.5 Specification

To ensure safety, we wanted to check two conditions related to the spoilers. In the first we wanted to ensure that if the aircraft was landing (at position 18), the spoilers would be armed if that was the pilot's preference. This was represented in LTL as follows:

$$\mathbf{G}\left(\begin{array}{l}(Position = 18)\\ \Rightarrow\left(\begin{array}{l}(PreferToArmSpoilers \wedge Spoilers = Armed)\\ \vee(\neg PreferToArmSpoilers \wedge Spoilers = \neg Armed)\end{array}\right)\end{array}\right) \tag{8.1}$$

In the second specification we wanted to ensure that the system would never reach the condition where the spoilers could prematurely deploy: a condition which occurs when the spoilers are armed and the landing gear doors are opening. This was represented in LTL as

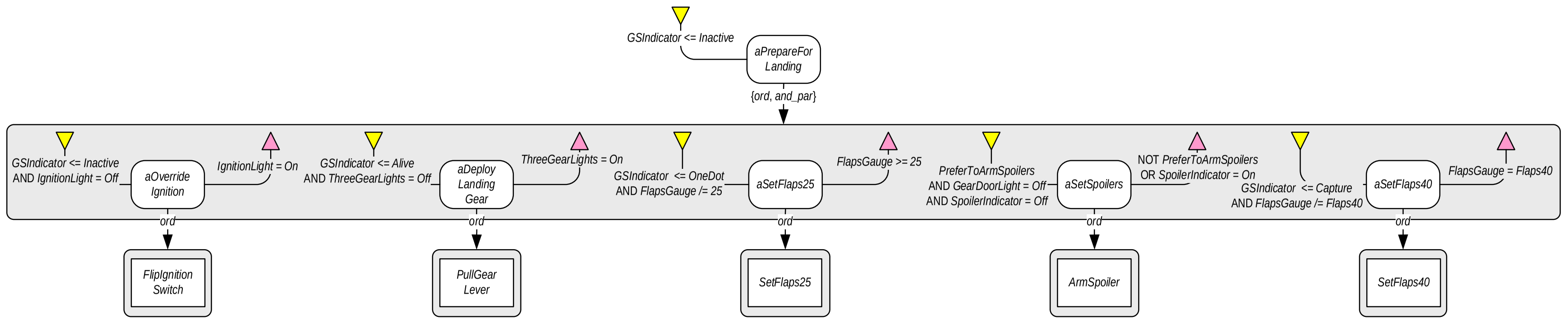

GSIndicator <= Inactive
aPrepareFor Landing
{ord, and_par}
GSIndicator <= Inactive AND IgnitionLight = Off
aOverride Ignition
IgnitionLight = On
GSIndicator <= Alive AND ThreeGearLights = Off
aDeploy Landing Gear
ThreeGearLights = On
GSIndicator <= OneDot AND FlapsGauge /= 25
aSetFlaps25
FlapsGauge >= 25
PreferToArmSpoilers AND GearDoorLight = Off AND SpoilerIndicator = Off
aSetSpoilers
NOT PreferToArmSpoilers OR SpoilerIndicator = On
GSIndicator <= Capture AND FlapsGauge /= Flaps40
aSetFlaps40
FlapsGauge = Flaps40
ord
FlipIgnition Switch
PullGear Lever
SetFlaps25
ArmSpoiler
SetFlaps40

Figure 8.12: Visualization of the EOFM task model for preparing to land the aircraft. Note that the decomposition of *aPrepare-ForLanding* can have either the *ord* or *and_par* decomposition

follows:

$$\mathbf{G}\neg\left(\begin{array}{l} Spoilers = Armed \\ \wedge GearDoors \neq Closed \\ \wedge GearDoors \neq Open \end{array}\right) \tag{8.2}$$

8.6 Apparatus

All verifications were completed using SAL-SMC 3.0, the SAL symbolic model checker. Verifications were conducted on a 3.0 gigahertz dual-core Intel Xeon processor with 16 gigabytes of RAM running the Ubuntu 9.04 desktop.

8.7 Phase 1 Analyses: Exploring Different Representations of Normative Human Behavior

8.7.1 Modeling

In the first set of analyses, formal verifications were run for (8.1) and (8.2) on two versions of the formal system model: one in which the human task behavior model used the *ord* decomposition operator to ensure all activities are performed in order and one in which the *and_par* decomposition operator is used to allow activities to be performed in any order.

8.7.2 Verification Results

For the model employing the human task behavior with the *ord* decomposition operator, both (8.1) and (8.2) verified to true (239 visited states in 1.14 seconds and 239 visited states in 1.12 seconds respectively).

For the system model using the human task behavior with the *and_par* decomposition operator, (8.1) verified to true (725 visited states in 1.18 seconds). However, the verification of (8.2) returned a counterexample after 0.58 seconds.

When this counterexample was examined using the visualizer, it revealed that the pilot's first action was to arm the spoilers (Figure 8.13). He followed this by deploying the aircraft landing gear, an action that resulted in the landing gear doors opening (Figure 8.14). Thus a violation of (8.2) occurred with the landing gear doors opening while the spoilers were armed.

8.7.3 Discussion

There are a number of different ways in which this problem could be addressed. Resolution could come through changes to the automation. For example, the spoiler system could be redesigned so that the spoilers could be armed while the landing gear doors are opening without risk of premature deployment. In such a situation it would be unnecessary to even check (8.2). However, such a solution may require an expensive retrofit if the aircraft is already in operation. Another possible solution would be to implement a forcing function [142] to prevent the pilot from being able to arm the spoilers before the landing gear doors are open. However, this solution would also have associated expense and could artificially limit the procedures pilots could use to mitigate emergencies.

Another solution could change the pilot's mission: where pilots are not allowed to have a preference about arming spoilers and would only be allowed to deploy them manually. This modification eliminates the violation without introducing a new one: (8.1) and (8.2) verified to true in just over a second having visited 118 states for the *ord* model and in 204 states for the *and_par* model. However, this may also not be a desirable solution as it could lead to an increase in pilots manually deploying spoilers prematurely, a problem that has

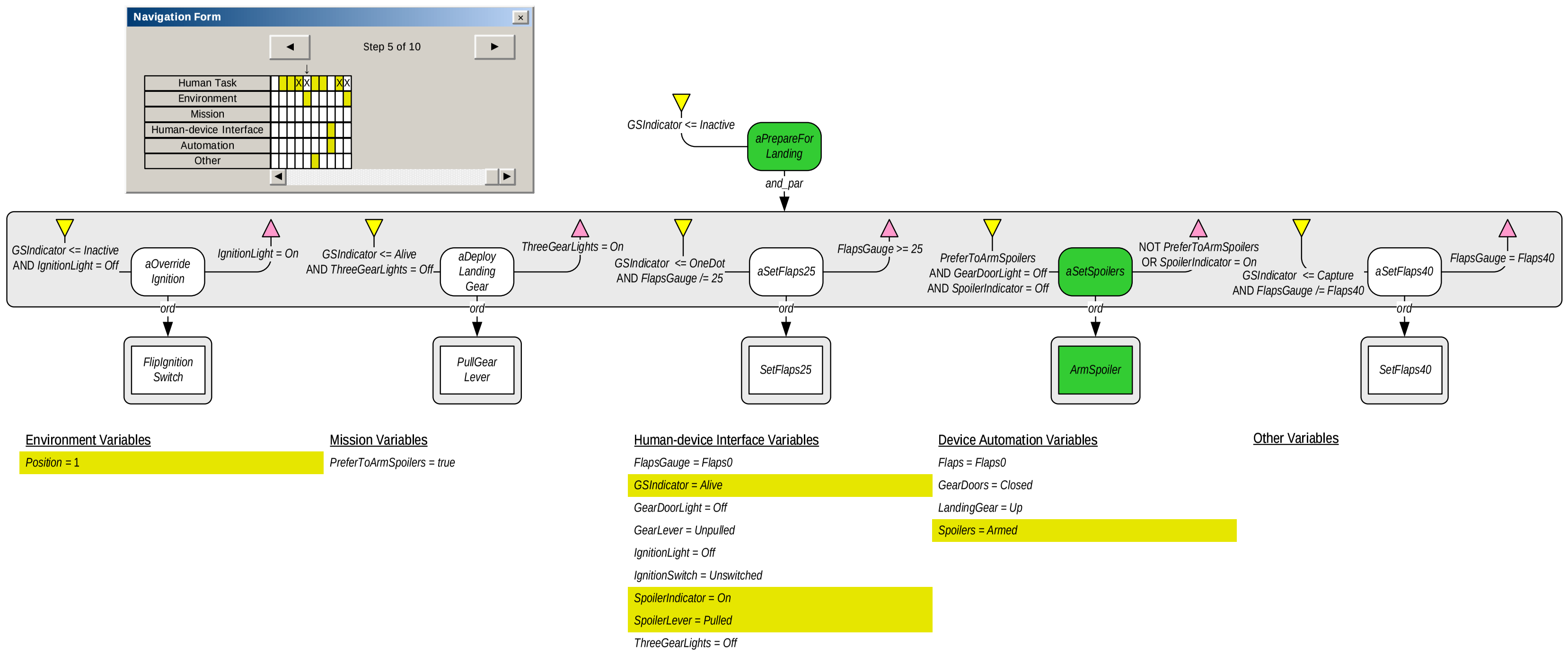


Figure 8.13: Step 5 from the visualization of the counterexample for (8.2) and the task model with the *and_par* decomposition. The pilot has just performed the action for arming the spoilers which has resulted in the spoiler lever being pulled and the spoiler indicator light turning on. The aircraft has also progressed to a new position resulting in the glideslope indicator becoming alive.

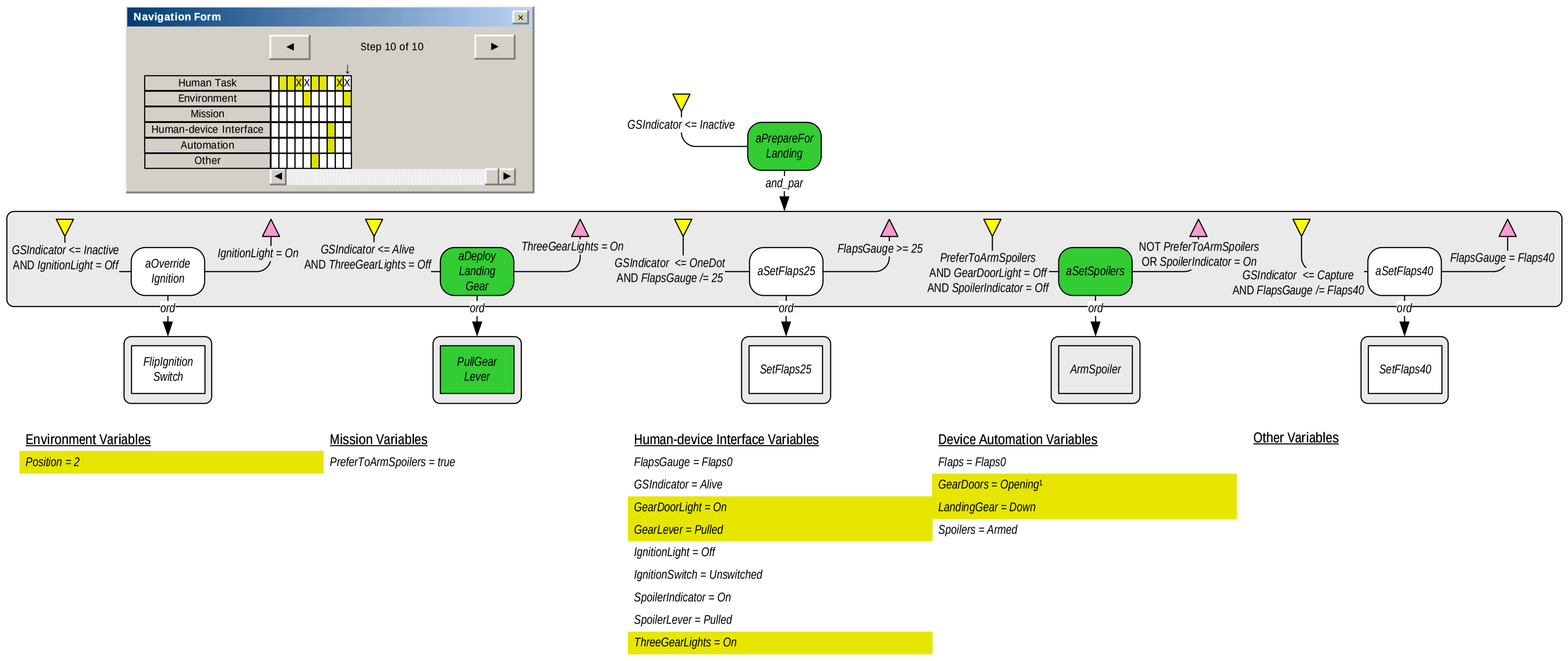


Figure 8.14: Step 10 from the visualization of the counterexample for (8.2) and the task model with the *and_par* decomposition. The pilot has followed his action of arming the spoilers by deploying the landing gear. This has resulted in the landing gear descending, with the landing gear lever in the pulled position, and the three gear lights coming on. This has also resulted in the landing gear doors opening causing the landing gear doors light to come. Thus we have a violation of (8.2): the spoilers are armed while the landing gear doors are opening.

been known to occur [67, 83, 84].

Another option is to alter the pilot's task through additional policy and/or training [15]. In this situation, the *and_par* task model could be made irrelevant if pilots always performed the "before landing" checklist activities in order. Training could also address the criteria pilots use for arming the spoilers. For example, if the precondition has the additional constraint that the three landing gear lights must be on before a pilot arms the spoilers, the discovered violation is eliminated without adding any additional violations: (8.1) and (8.2) both verified to true in just over one second having visited 239 states for the *ord* model and 431 states for the *and_par* model.

8.8 Phase 2 Analyses: Exploring Different Representations of Erroneous Human Behavior

8.8.1 Modeling

In the second phase of analyses we explore how our two different erroneous behavior generation methods might provide insights into potential human-automation interaction issues related to the spoilers. To accomplish this we use the two task behavior models from above (one with *ord* decomposition and one with the *and_par* decomposition) with the precondition modified to include the condition that the three gear lights be on. Each task model was used in the creation of two separate formal system models: one with a phenotypical erroneous human behavior model (with a maximum of one erroneous act), and one with a strategic knowledge-based erroneous human behavior model (with a maximum of one erroneous transition).

8.8.2 The Phenotypical Erroneous Human Behavior Model

Chapter 5 introduced the phenotypical erroneous human behavior generation method in which instantiated EOFMs could have each of their actions replaced with additional EOFM structure designed to allow them to perform the correct action or erroneously perform an omission (no action) or a commission (which could replace the correct action with another one or intrude an additional action). The number of generated erroneous human behaviors was limited by a maximum. Here, we use this methodology to explore the impact of at most one phenotypical erroneous act on the aircraft approach system.

8.8.2.1 Verification Results

Verifications of (8.1) and (8.2) were run against all four models.

When (8.1) was checked against the model with the *and_par* decomposition (where tasks could be performed in any order) it returned the following counterexample after 30.85 seconds:

1. While the aircraft was at position 0, the pilot (who preferred to arm the spoilers) correctly flipped the ignition switch to override the ignition.
2. At position 1, the pilot erroneously set the flaps to 25° instead of pulling the landing gear lever to deploy the landing gear (Figure 8.15).
3. Because the completion condition for deploying the landing gear (the three gear lights being on) was not satisfied while the completion condition for setting the flaps to 25° was (flaps set to 25°), *aDeployLandingGear* remained executing while *aSet-Flaps25* transitioned from ready to done.
4. With nothing to do, the pilot let the aircraft proceed incrementally to position 17.
5. Having reached the capture position, the pilot correctly set the flaps to 40°.

6. Thus the aircraft then reached position 18 without arming the spoilers because the precondition for arming the spoilers never became true due to the erroneously performed attempt to deploy the landing gear.

When (8.2) was checked against the model with the *and_par* decomposition the following counterexample was returned after 11.95 seconds:

1. While the aircraft was at position 0, the pilot attempted to override the ignition but erroneously performed the action for arming the spoilers (Figure 8.16).

2. At position 1, the pilot then correctly pulled the gear lever to deploy the landing gear. This resulted in the spoilers being armed while the landing gear doors were opening.

When (8.1) was checked against the model with the *ord* decomposition (where the task were performed in order) the following counterexample was returned after 23.25 seconds:

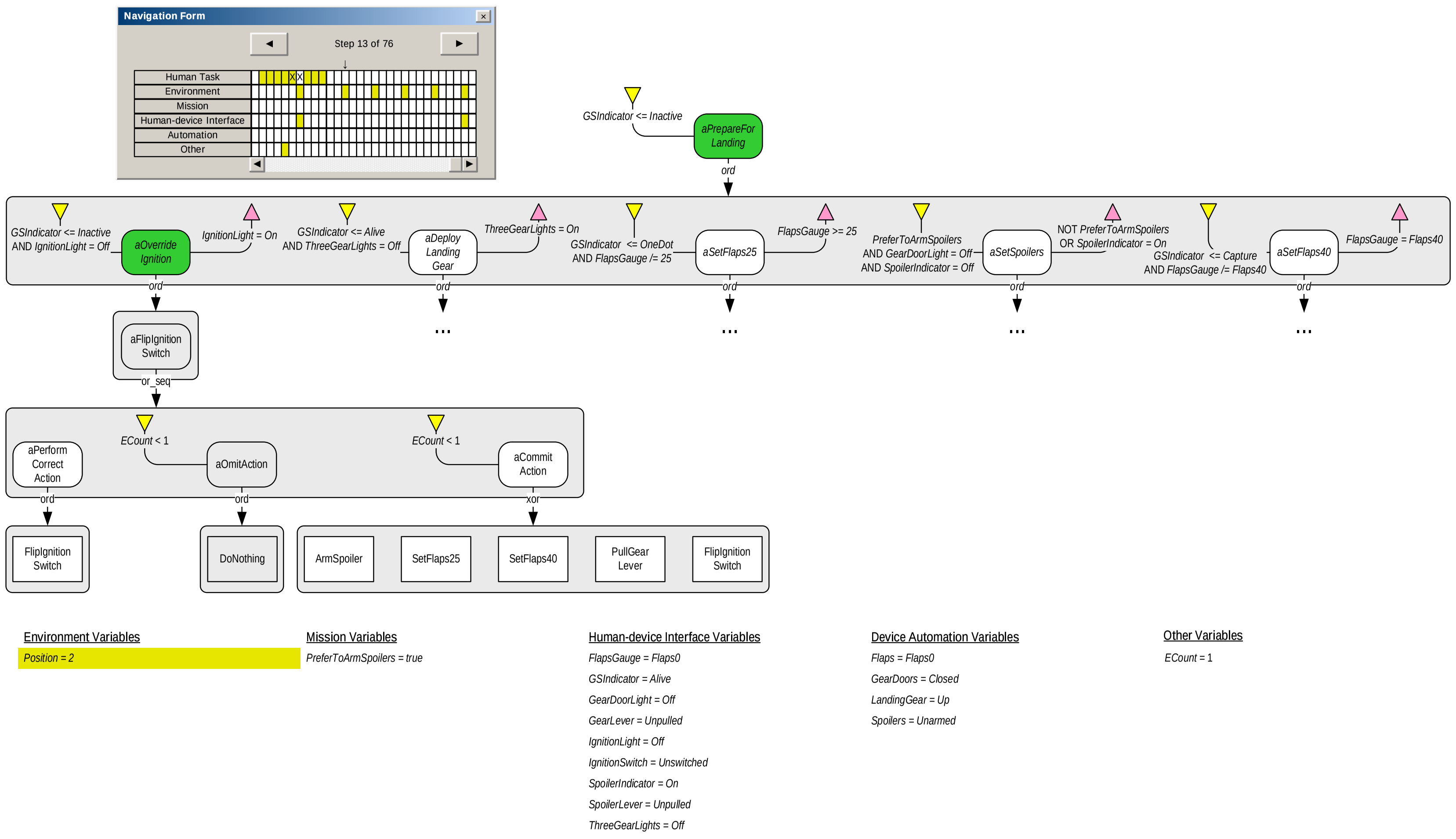
1. While the aircraft was at position 0, the pilot (who preferred to arm the spoilers) attempted to override the ignition but erroneously did nothing.

2. This resulted in the completion condition (the ignition light being on) failing to be satisfied. As such, this task never completed which prevented the remaining activities (like deploying the landing gear, arming the spoilers, and setting the flaps) from being performed (Figure 8.17).

3. Thus the aircraft progressed to position 18 without the spoilers being armed.

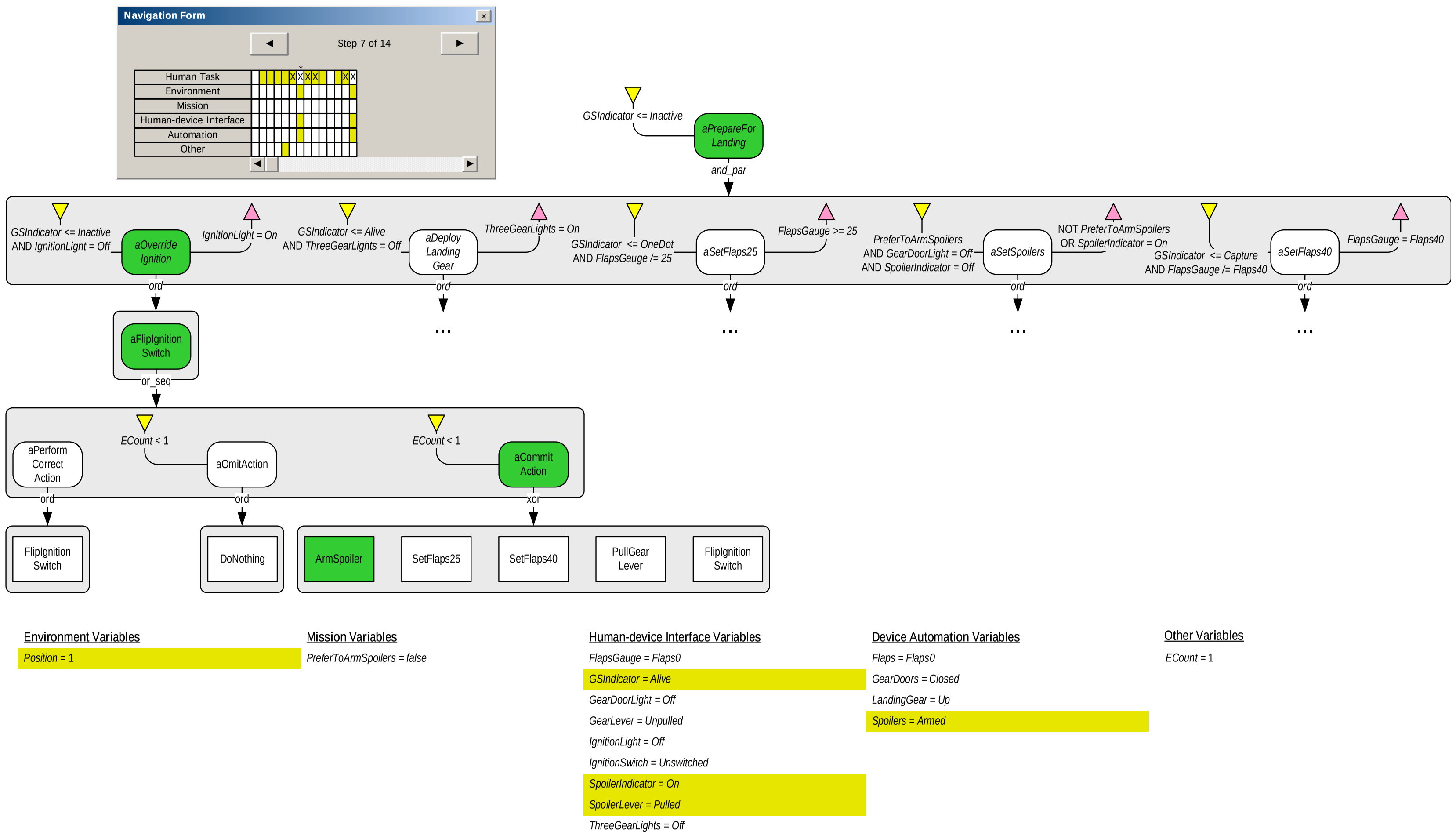
When (8.2) was checked against the model with the *ord* decomposition, the following counterexample was returned in 12.46 seconds:

1. While the aircraft was at position 0, the pilot correctly flipped the ignition switch to override the ignition.



Environment Variables	Mission Variables	Human-device Interface Variables	Device Automation Variables	Other Variables
Position = 2	PreferToArmSpoilers = true	FlapsGauge = Flaps0	Flaps = Flaps0	ECount = 1
		GSIndicator = Alive	GearDoors = Closed	
		GearDoorLight = Off	LandingGear = Up	
		GearLever = Unpulled	Spoilers = Unarmed	
		IgnitionLight = Off		
		IgnitionSwitch = Unswitched		
		SpoilerIndicator = On		
		SpoilerLever = Unpulled		
		ThreeGearLights = Off		

Figure 8.15: Step 14 from the visualization of the counterexample for (8.1), the task model with the *and_par* decomposition, and phenotypical erroneous behavior generation with a maximum of one erroneous act. The pilot has erroneously set the flaps to 25° instead of pulling the landing gear lever. Note that the . . . indicate the error generation structure for each of the original actions in the normative task behavior model (Figure 8.15).



Environment Variables
Position = 1

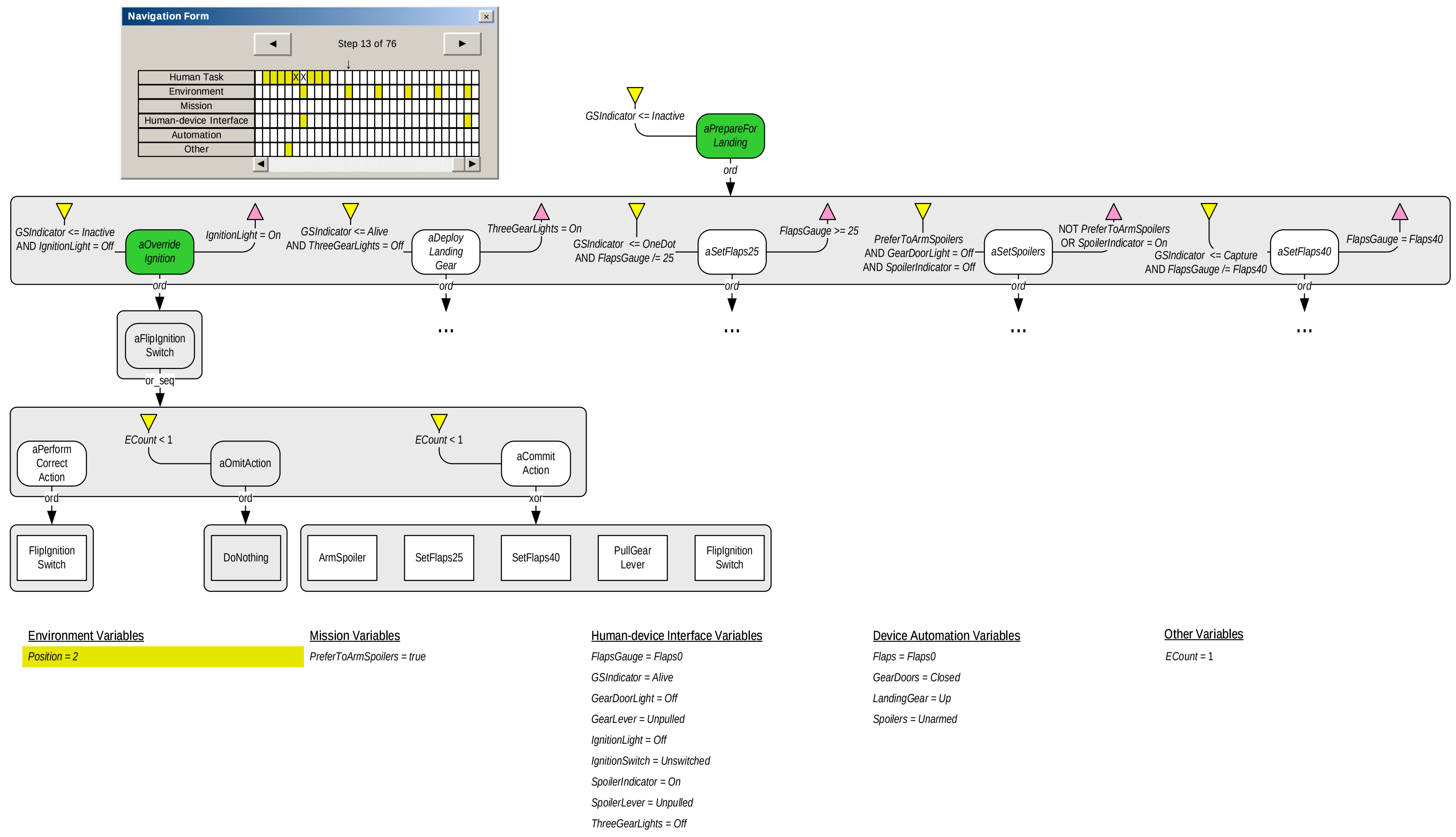
Mission Variables
PreferToArmSpoilers = false

Human-device Interface Variables
FlapsGauge = Flaps0
GSIndicator = Alive
GearDoorLight = Off
GearLever = Unpulled
IgnitionLight = Off
IgnitionSwitch = Unswitched
SpoilerIndicator = On
SpoilerLever = Pulled
ThreeGearLights = Off

Device Automation Variables
Flaps = Flaps0
GearDoors = Closed
LandingGear = Up
Spoilers = Armed

Other Variables
ECount = 1

Figure 8.16: Step 7 from the visualization of the counterexample for(8.2), the task model with the *and_par* decomposition, and phenotypical erroneous behavior generation with a maximum of one erroneous act. The pilot has erroneously armed the spoilers instead of flipping the ignition switch.



Environment Variables	Mission Variables	Human-device Interface Variables	Device Automation Variables	Other Variables
Position = 2	PreferToArmSpoilers = true	FlapsGauge = Flaps0	Flaps = Flaps0	ECount = 1
		GSIndicator = Alive	GearDoors = Closed	
		GearDoorLight = Off	LandingGear = Up	
		GearLever = Unpulled	Spoilers = Unarmed	
		IgnitionLight = Off		
		IgnitionSwitch = Unswitched		
		SpoilerIndicator = On		
		SpoilerLever = Unpulled		
		ThreeGearLights = Off		

Figure 8.17: Step 17 from the visualization of the counterexample for (8.1), the task model with the *ord* decomposition, and phenotypical erroneous behavior generation with a maximum of one erroneous act. The pilot has previously erroneously done nothing instead of flipping the switch to arm the spoilers. Because the completion condition for *aOverrideIgnition* has not been satisfied, no further human actions can be performed. Note that the . . . indicate the error generation structure for each of the original actions in the normative task behavior model (Figure 8.12).

2. At position 1, the pilot correctly pulled the gear lever to deploy the landing gear.

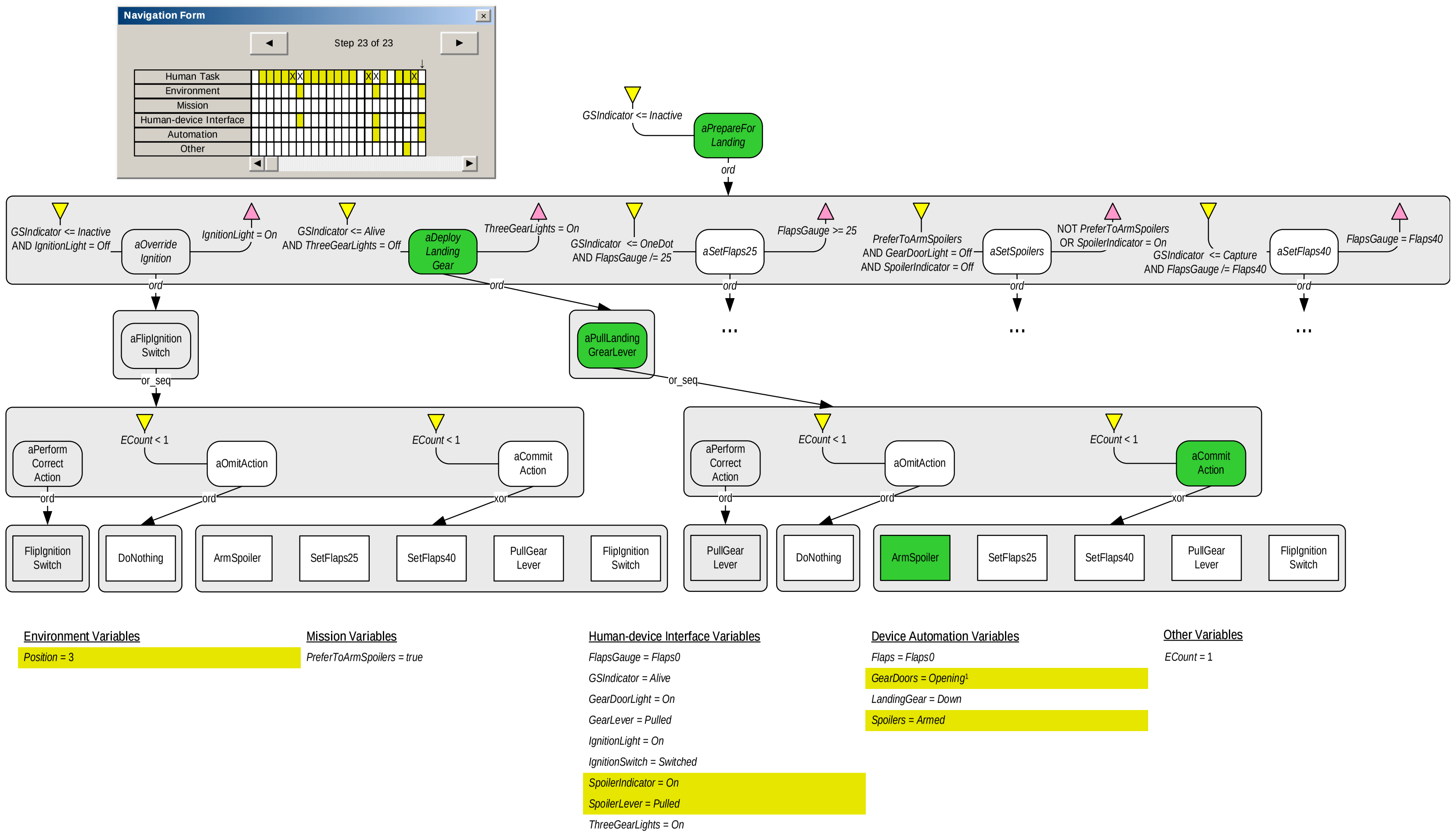
3. At position 2, before completing the activity for deploying the landing gear (*aDeployLandingGear*), the pilot erroneously intruded the action for arming the spoilers while the landing gear doors were opening. Thus the spoilers armed while the landing gear doors were opening.

8.8.2.2 Discussion

These results are somewhat problematic in that they do not reflect realistic pilot behavior. For example, while it is possible for a pilot to replace pulling the landing gear lever with setting the flaps, it represents an unlikely action and is thus not particularly useful for analysis.

Another problem is seen in the way that the error generation can break the execution of the task model. For example, the counterexample for (8.1) observed for the model employing the *ord* decomposition occurred because an erroneous behavior was performed in the activity for overriding the ignition (*aOverrideIgnition*) which prevented its completion condition from being satisfied and thus preventing the execution of any additional activities (see Figure 8.17).

The fact that the phenotypical erroneous behavior generation was compatible with the Therac-25 application (Chapter 5) suggests that there are some applications in which phenotypical erroneous human behavior is more suited than others. This is likely because the task models used in the Therac-25 did not employ completion conditions which were dependent on the correct execution of a single action. Future work should attempt to identify when an application is suited for analysis with phenotypical erroneous behavior generation and how task models can be structured to accommodate such analyses.



Environment Variables
Position = 3

Mission Variables
PreferToArmSpoilers = true

Human-device Interface Variables
FlapsGauge = Flaps0
GSIndicator = Alive
GearDoorLight = On
GearLever = Pulled
IgnitionLight = On
IgnitionSwitch = Switched
SpoilerIndicator = On
SpoilerLever = Pulled
ThreeGearLights = On

Device Automation Variables
Flaps = Flaps0
GearDoors = Opening[1]
LandingGear = Down
Spoilers = Armed

Other Variables
ECount = 1

Figure 8.18: Step 25 from the visualization of the counterexample for (8.2), the task model with the *ord* decomposition, and phenotypical erroneous behavior generation with a maximum of one erroneous act. The pilot has erroneously intruded the action for arming the spoilers after previously correctly pulling the landing gear lever. Note that the . . . indicate the error generation structure for each of the original actions in the normative task behavior model (Figure 8.12).

8.8.3 The Strategic Knowledge-based Erroneous Behavior Model

Chapter 6 introduced an erroneous behavior generation method in which activities could erroneously transition between execution states due to the misapplication of strategic knowledge contained in pre, repeat, and completion conditions. This could allow activities to be erroneously omitted, repeated, or committed. The number of erroneous transitions was limited by a maximum. Here, we use this methodology to explore the impact of at most one erroneous transition on the aircraft approach system.

8.8.3.1 Verification Results

When (8.1) was checked against the model with the *and_par* decomposition, the following counterexample was returned after 2.01 seconds:

1. While the aircraft was at position 0, the pilot (who preferred to arm the spoilers) correctly flipped the ignition switch to override the ignition.

2. At position 1, the pilot erroneously omitted the activity for deploying the landing gear (*aDeployLandingGear*) due to an erroneous executing to done transition (Figure 8.19), thus preventing the landing gear from being deployed.

3. The pilot then let the aircraft fly to position 11 where, because the glideslope indicator was at the one dot position, he correctly performed the action for setting the flaps to 25°.

4. Because the landing gear was never deployed, the precondition for arming the spoilers never became true, thus the pilot let the aircraft proceed to position 17 without performing any additional actions.

5. At position 17, the aircraft reached capture, thus the pilot correctly set the flaps to 40°. The aircraft then proceeded to position 18.

6. Thus the aircraft reached position 18 without the spoilers being armed.

When (8.2) was checked against the model with the *and_par* decomposition, the following counterexample was returned after 0.86 seconds:

1. While the aircraft was at position 0, the pilot erroneously performed the activity for arming the spoilers (Figure 8.20): an erroneous ready to executing transition.

2. At position 1, he pulled the landing gear lever to correctly deploy the landing gear. This resulted in the spoilers being armed while the landing gear doors were opening.

When (8.1) was checked against the model with the *ord* decomposition, a counterexample was returned in 1.79 seconds:

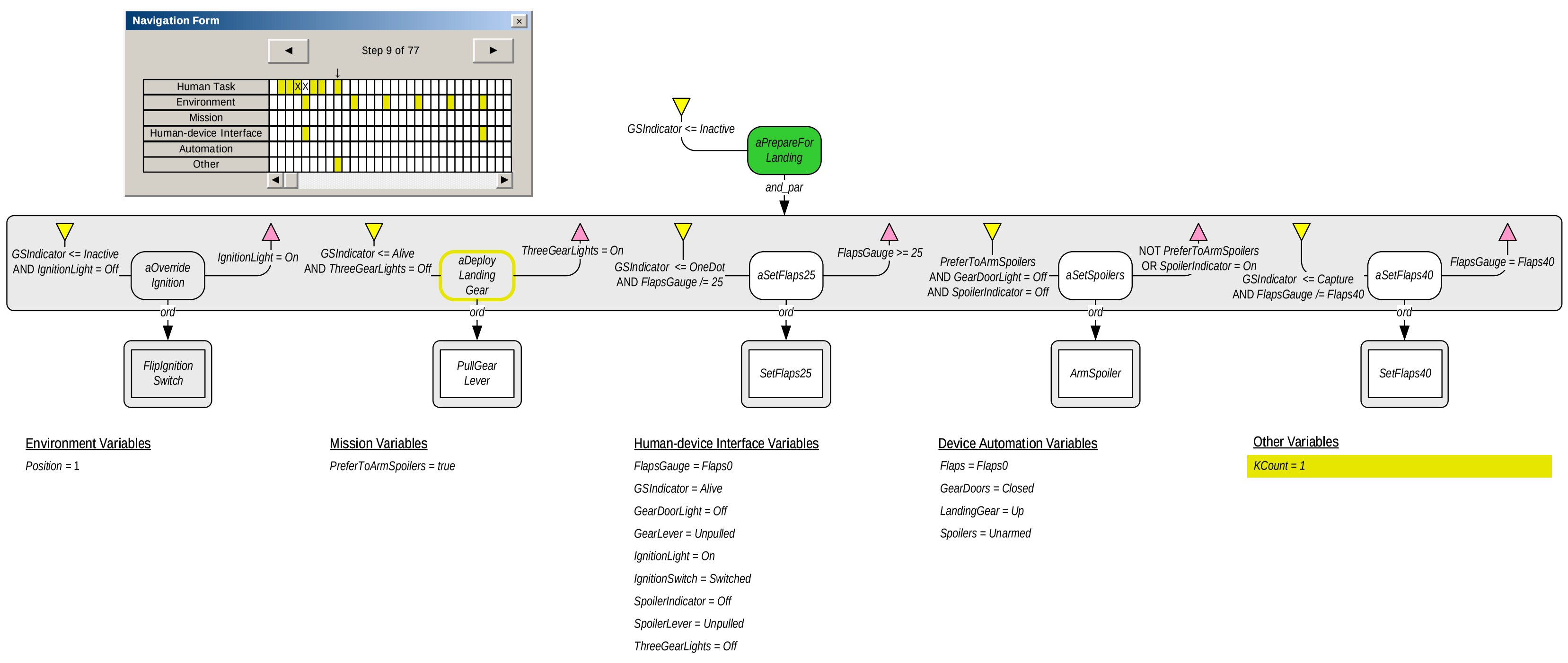
1. While the aircraft was at position 0, the pilot (who preferred to arm the spoilers) correctly flipped the ignition switch to override the ignition.

2. At position 1, the pilot omitted the activity for deploying the landing gear (the result of *aDeployLandingGear* erroneously transitioning from executing to done), thus preventing the landing gear from deploying (the same erroneous behavior shown in Figure 8.19).

3. The pilot then lets the aircraft fly to position 11 where, because the glideslope indicator was at the one dot position, he correctly performed the action for setting the flaps to 25°.

4. Because the landing gear was never deployed, the precondition for arming the spoilers never became true, thus the pilot let the aircraft proceed to position 18 without performing any additional actions.

5. Thus the aircraft reached position 18 without the spoilers being armed.



Environment Variables
Position = 1

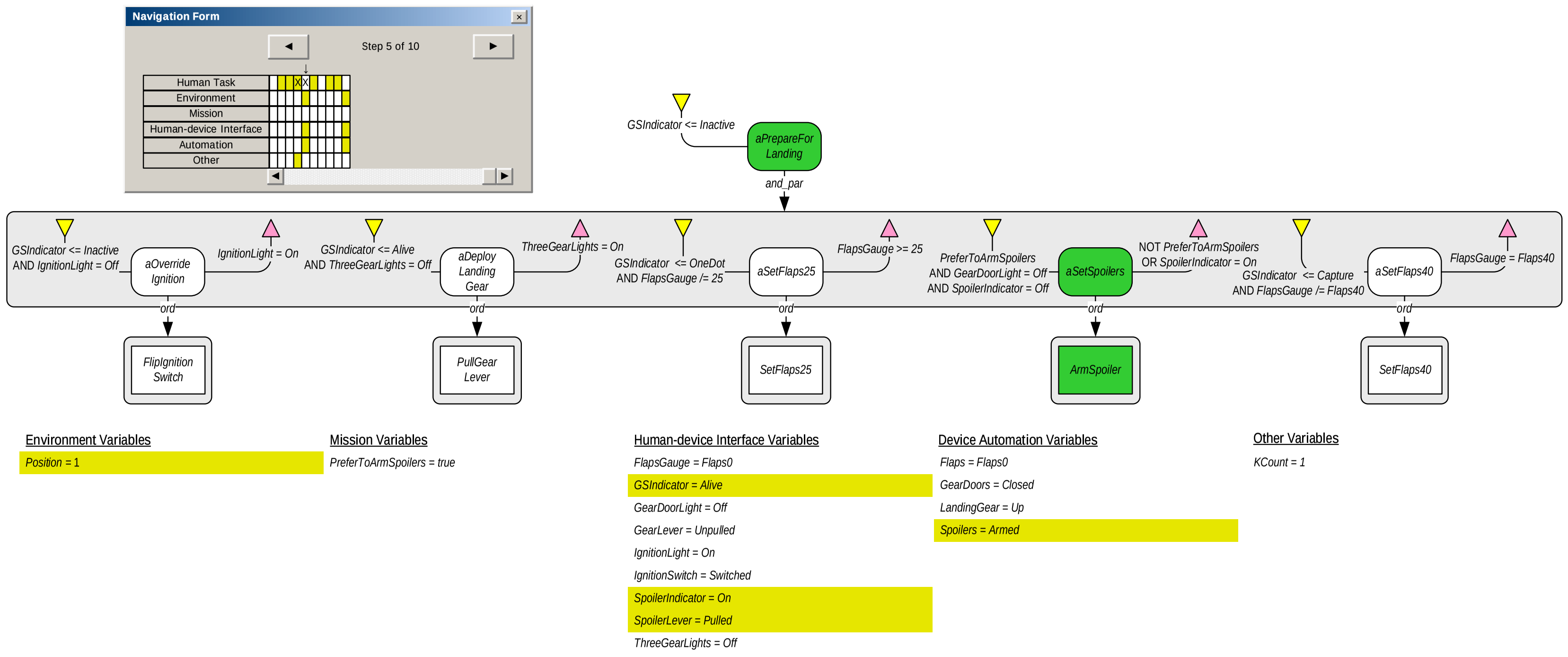
Mission Variables
PreferToArmSpoilers = true

Human-device Interface Variables
FlapsGauge = Flaps0
GSIndicator = Alive
GearDoorLight = Off
GearLever = Unpulled
IgnitionLight = On
IgnitionSwitch = Switched
SpoilerIndicator = Off
SpoilerLever = Unpulled
ThreeGearLights = Off

Device Automation Variables
Flaps = Flaps0
GearDoors = Closed
LandingGear = Up
Spoilers = Unarmed

Other Variables
KCount = 1

Figure 8.19: Step 9 from the visualization of the counterexample for (8.1), the task model with the *and_par* decomposition, and knowledge-based erroneous behavior generation with a maximum of one erroneous transition. *aDeployLandingGear* has erroneously transitioned from ready to done and the erroneous behavior counter (*KCount*) has incremented.



Environment Variables
Position = 1

Mission Variables
PreferToArmSpoilers = true

Human-device Interface Variables
FlapsGauge = Flaps0
GSIndicator = Alive
GearDoorLight = Off
GearLever = Unpulled
IgnitionLight = On
IgnitionSwitch = Switched
SpoilerIndicator = On
SpoilerLever = Pulled
ThreeGearLights = Off

Device Automation Variables
Flaps = Flaps0
GearDoors = Closed
LandingGear = Up
Spoilers = Armed

Other Variables
KCount = 1

Figure 8.20: Step 5 from the visualization of the counterexample for (8.2), the task model with the *and_par* decomposition and knowledge-based erroneous behavior generation with a maximum of one erroneous transition. *aSetSpoilers* has just previously erroneously transitioned from ready to executing (incrementing *KCount*) which has resulted in the spoilers being armed before any other activities occur.

When (8.2) was checked against the model with the *ord* decomposition, it verified to true in 1.51 seconds having visited 926 states.

8.8.3.2 Additional Verification Results

It is unlikely that pilots will not deploy the landing gear, the source of the problems found when the models were checked against (8.1). As such, the counterexamples associated with these verifications could be considered artifacts of our formal system models. To allow for the possibility of discovering more realistic system failures, these artifacts were eliminated by removing the erroneous executing to done transition of *aDeployLandingGear* (the transition associated with the failure to deploy the landing gear) from the models using the method discussed in Chapter 6. The following are the results of (8.1) being checked against these modified models.

When (8.1) was checked against the modified model with the *and_par* decomposition, the following counterexample was returned after 2.01 seconds:

1. While the aircraft was at position 0, the pilot (who prefers to arm the spoilers) correctly flipped the ignition switch to override the ignition.

2. At position 1, the pilot correctly performed the action for deploying the landing gear, deploying the landing gear and initiating the opening of the landing gear doors.

3. The aircraft proceeded along its path until position 11 where the landing gear doors become completely open.

4. At position 11, because the glideslope indicator was at the one dot position, the pilot correctly performed the action for setting the flaps to 25°.

5. At position 12, the activity for setting the spoilers was omitted (*aSetSpoilers* erroneously transitioned from ready to done).

6. At position 17, the aircraft reached the capture position and thus the pilot set the flaps to 40°.

7. The aircraft then proceeded to position 18 without the spoilers being armed.

When (8.1) was checked against the model with the *ord* decomposition it verified to true in 1.49 seconds having visited 752 states.

8.8.4 Discussion

The analyses show that the task model with the *ord* decomposition is more resistant to failures than the model with the *and_par* decomposition. These results suggest that, if airlines can enforce a strict adherence to the behavior represented by the model with the *ord* decomposition, they may be less likely to experience problems related to premature spoiler deployment and failure to arm spoilers. This work could be followed up with additional studies, possibly with real pilots in actual operating conditions, to determine if this is true.

Should analysts or designers wish to address the problems discovered with the *and_par* task behavior model, they could pursue some of the options addressed in the discussion of Phase 1: eliminating spoiler arming as an option (in the mission) and preventing spoiler arming before the landing gear doors are completely open. Future work should explore these potential solutions.

While the phenotypical erroneous human behavior generation method did not facilitate many insights into human-automation interaction for this application, strategic knowledge-based erroneous human behavior generation has. This suggests that there may be some applications better suited to each erroneous behavior generation method. Future work should attempt to identify properties of applications that suggest analysis with the different erroneous behavior generation methods.

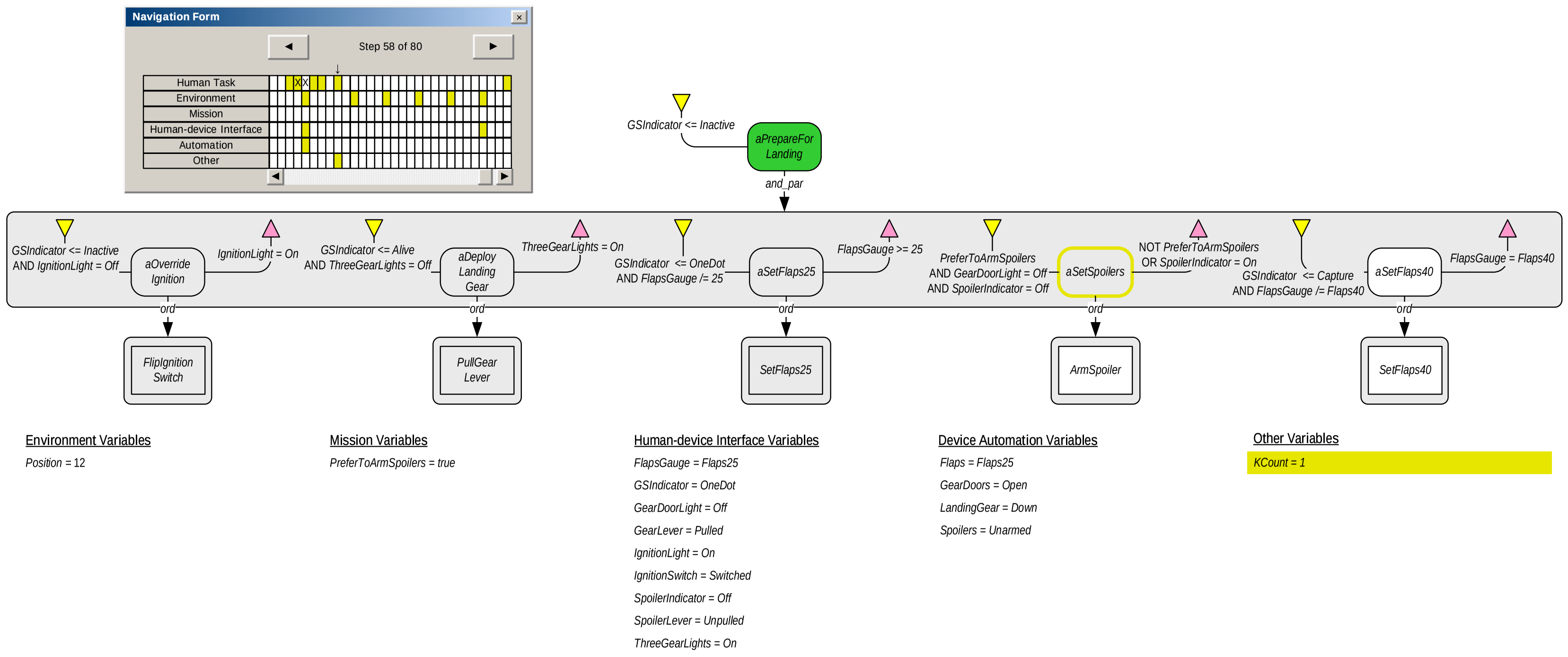


Figure 8.21: Step 58 from the visualization of the counterexample for (8.1), the task model with the *and_par* decomposition, and knowledge-based erroneous behavior generation with a maximum of one erroneous transition. *aSetspoilers* has erroneously transitioned from ready to done and the erroneous behavior counter (*KCount*) has incremented.

8.9 Phase 3 Analyses: Exploring Variations in the Behavior of the Automation

8.9.1 Modeling

In the third phase of modeling we show how our architecture can be used to explore how variations in the behavior of automated systems can impact system safety properties.

Aside from the human operator, there can be anomalous conditions in device automation and/or the environment that can impact system performance. For example, aging mechanics in aircraft automation can impact overall system performance. For our purposes, we are concerned with how the time delays associated with aging hydraulic systems may influence human-automation interaction issues related to the deployment of spoilers.

For this phase of analysis, we assume that the aging hydraulic systems in the landing gear doors openers can delay the door opening process by up to 7 seconds beyond the 10 seconds the doors took to open normatively (Figure 8.4). We can exploit the modularization of our architecture to replace the previous device automation model with one in which the landing gear opening can take between 0 and 7 additional seconds (in 1 second increments) to open making the range of potential landing gear opening time between 10 and 17. All other device automation models were kept the same, as were the mission and environment model. These were used to create formal system models using the normative task behavior model with the *ord* decomposition and one with the normative task behavior model with the *and_par* decomposition (both using the corrected precondition discussed at the end of Phase 1).

8.9.2 Verification Results

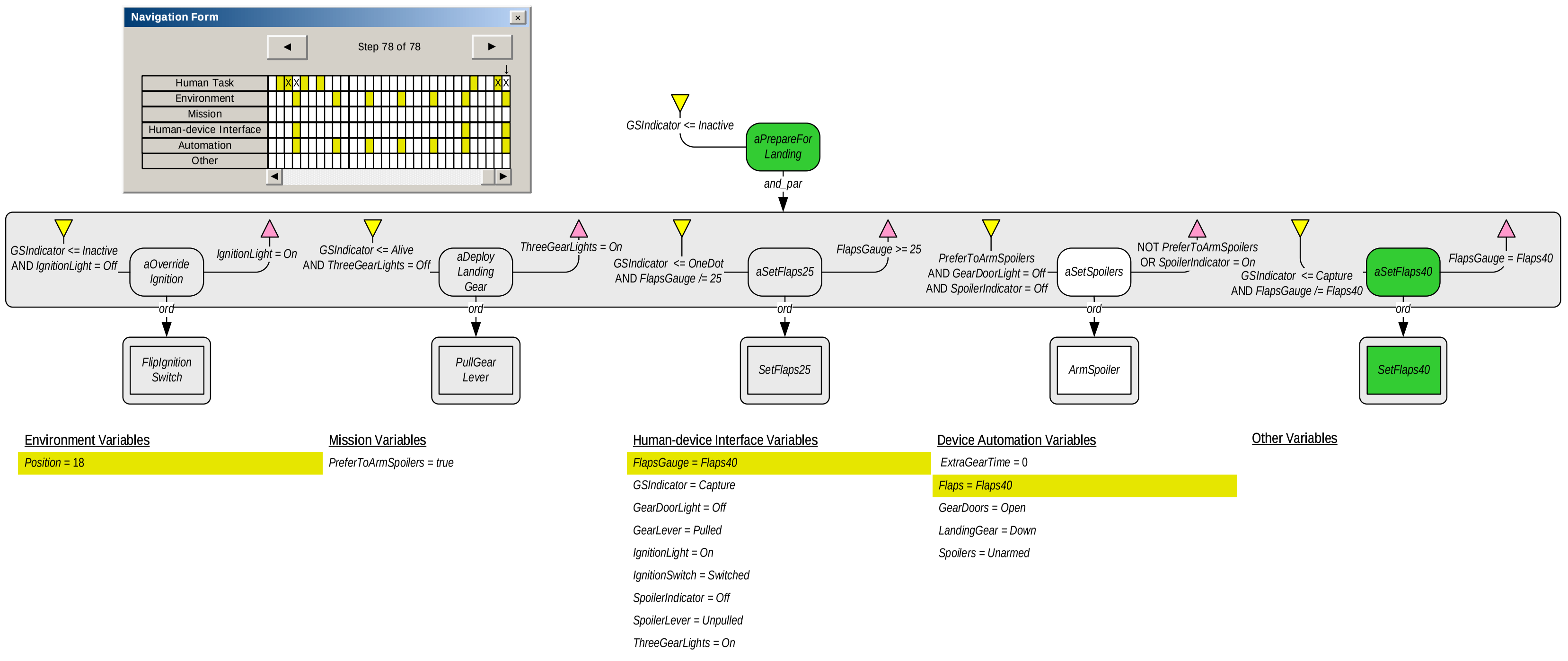
When (8.1) was checked against the model using the *and_par* decomposition operator, the following counterexample was returned after 1.43 seconds:

1. While the aircraft was at position 0, the pilot (who preferred to arm the spoilers) correctly flipped the ignition switch to override the ignition.
2. At position 1, the pilot correctly performed the action for deploying the landing gear, deploying the landing gear and initiating the opening of the gear doors. Due to the aging nature of the gear door hydraulics, the gear doors would take 16 seconds to open rather than the normative 10.
3. At position 11, because the glideslope indicator was at the one dot position, the pilot correctly performed the action for setting the flaps to 25°.
4. At position 17, the landing gear doors light turned off because the doors finished opening and, because the glideslope indicator was at the one dot position, the pilot correctly performed the action for setting the flaps to 40°.
5. The aircraft then proceeded to position 18 where the landing gear doors light turned off, thus the aircraft had reached position 18 without the spoilers being armed (Figure 8.22).

When (8.2) was checked against the model using the *and_par* decomposition it verified to true in 1.23 seconds having visited 1931 states.

When (8.1) was checked against the model using the *ord* decomposition operator, the following counterexample was returned after 1.45 seconds:

1. While the aircraft was at position 0, the pilot (who preferred to arm the spoilers) correctly flipped the ignition switch to override the ignition.



Environment Variables
Position = 18

Mission Variables
PreferToArmSpoilers = true

Human-device Interface Variables
FlapsGauge = Flaps40
GSIndicator = Capture
GearDoorLight = Off
GearLever = Pulled
IgnitionLight = On
IgnitionSwitch = Switched
SpoilerIndicator = Off
SpoilerLever = Unpulled
ThreeGearLights = On

Device Automation Variables
ExtraGearTime = 0
Flaps = Flaps40
GearDoors = Open
LandingGear = Down
Spoilers = Unarmed

Other Variables

Figure 8.22: Step 78 from the visualization of the counterexample for the task model with the *and_par* decomposition and an automation model with a variably degraded landing gear door hydraulic system. The aircraft has reached position 18 without the pilot arming the spoilers due to the landing gear doors not completely opening until position 17.

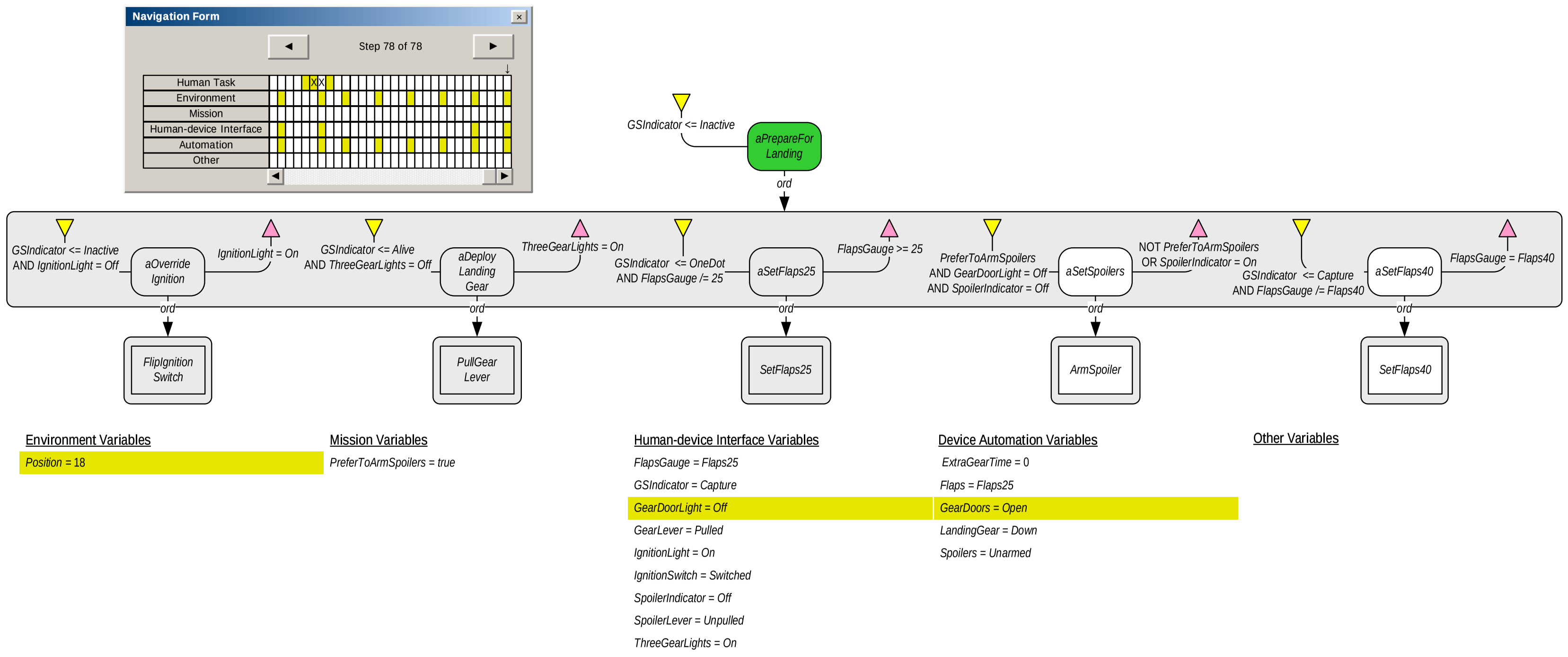
2. At position 1, the pilot correctly performed the action for deploying the landing gear, deploying the landing gear and setting the landing gear doors begin opening. Due to the aging nature of the gear door hydraulics, the gear doors would take 17 seconds to open rather than the normative 10.
3. At position 11, because the glideslope indicator was at the one dot position, the pilot correctly performed the action for setting the flaps to 25°.
4. The pilot then waited to arm the spoilers because the landing gear doors were still opening and thus the landing gear doors light was on.
5. The aircraft proceeded to position 18 when the landing gear doors light finally turned off. However, the aircraft had reached position 18 without the spoilers being armed (Figure 8.23).

When (8.2) was checked against the model using the *ord* decomposition, it verified to true in 1.18 seconds having visited 1403 states.

8.9.3 Discussion

This example illustrates how anomalous or degraded behavior in device automation can impact human-automation interaction: as delays in the hydraulic systems prevented the pilot from performing the tasks necessary for preparing the aircraft for landing.

There are a number of ways engineers could address this. As has been previously discussed, the aircraft could be modified to allow spoilers to be armed while the aircraft landing gear doors were opening without the risk of premature deployment. This would allow spoilers to be armed much earlier in the process, and thus there would be less risk of this process being usurped by time delays.



Environment Variables
Position = 18

Mission Variables
PreferToArmSpoilers = true

Human-device Interface Variables
FlapsGauge = Flaps25
GSIndicator = Capture
GearDoorLight = Off
GearLever = Pulled
IgnitionLight = On
IgnitionSwitch = Switched
SpoilerIndicator = Off
SpoilerLever = Unpulled
ThreeGearLights = On

Device Automation Variables
ExtraGearTime = 0
Flaps = Flaps25
GearDoors = Open
LandingGear = Down
Spoilers = Unarmed

Other Variables

Figure 8.23: Step 78 from the visualization of the counterexample for the task model with the *ord* decomposition and an automation model with a variably degraded landing gear door hydraulic system. The aircraft has reached position 18 without the pilot arming the spoilers due to the landing gear doors did not completely opening until position 18.

Alternatively, airlines could simply require that pilots manually deploy the spoilers. When the mission model was updated to reflect this change, 8.1) verified to true for both the *and_par* (1002 visited states in 0.82 seconds) and *ord* (676 visited states in 0.81 seconds) formal system models. However, as was previously noted, this may increase the risk of premature manual spoiler deployment during actual landing.

Another solution could be to establish a maintenance policy on the aircraft to ensure that the landing gear door hydraulics open within a given time. For example, if maintenance can ensure that landing gear doors can open in under 15 seconds, (8.1) verifies to true for both the *and_par* (1439 visited states in 1.39 seconds) and *ord* (1021 visited states in 1.35 seconds) formal system models.

In general, the analyses from this phase demonstrate how our method can be used to find human-automation interaction related system problems that arise due to failures or degraded performance in system components. Further, the ability to replace the previous device automation model with one exhibiting variable degraded performance, and the ability to explore potential interventions that address the discovered problems, illustrate the flexibility of our formal system modeling architectural framework.

Disciplines such as error injection [180], reliability engineering [72], and resilience engineering [102] offer theories about how errors, degraded performance, and uncertainty can be modeled as part of automation and environment behavior in complex systems. Future work should investigate how theories and practices from these fields could potentially be used to extend our method so that it could systematically incorporate degraded or erroneous automation and environmental behavior.

8.10 General Discussion

Although the example presented here is simplistic, our method was able to facilitate a number of analyses which allowed the design of the aircraft approach system to be explored in a variety of different capacities. The phase 1 analyses showed how different human task behaviors could be used to explore a system design. The phase 2 analyses showed how the different erroneous behavior generation processes could be used to find potential failures associated with erroneous human behavior and how erroneous behaviors not pertinent to the analyses could be removed. Phase 3 analyses showed how alternative models of the device automation could be employed in analyses. Further, in all phases, the flexibility of our formal modeling architecture was demonstrated in the way different normative human task behaviors, erroneous human task behaviors, device automations, and human missions were modified and incorporated into the formal system model in order to explore different designs and interventions that addressed some of the discovered problems.

In a more realistic example, the application would likely be more complicated, and the analyst may have many more specifications he would want to check against each design variation. In such a circumstance, it is likely that the analyst may want to compare the results of different analyses in order to diagnose similar problems that exist between designs, and to compare and contrast the performance of the designs. Future work should investigate how additional tools and analyses might be incorporated into our method in order to facilitate these sorts of comparative evaluations.

Chapter 9

Contributions and Future Work

This work has shown that it is possible to automatically incorporate erroneous human behavior into task analytic models for the purpose of formally verifying system safety properties in light of both normative and erroneous human behavior. This was done by using our novel method to discover and evaluate problems with human-automation interactive systems. Each of the different applications that were employed in the verification illustrated the different ways the method could be used, and the insights it could provide (Table 9.1).

Firstly, the applications demonstrate the flexibility of the formal modeling architecture in that not all formal system models need to have every element of the architecture. While the aircraft and and cruise control examples have models of every element of the architecture, the PCA pump and radiation therapy machine applications did not have environment models.

Alternatively, the nature of the human task is different between the modeled applications. For the PCA pump, the primary task was data driven in that it was primarily fulfilling mission goals related to entering data into the automated system. In the other models, the human tasks were procedural.

Thirdly, the erroneous human behavior prediction was exploited differently in order to show how problems with human-automation interaction could be discovered with our method. In all of our applications, normative task models were used in formal verifications. For the aircraft and cruise control examples these verifications initially produced counterexamples. However, changes to the formal system model resulted in models that verified to true. The other application models verified to true with normative task behavior models without modification.

Erroneous human behavior models were tested with all but the cruise control application. Phenotypical erroneous behavior models were generated for the radiation therapy machine and aircraft applications and used in formal verifications which found specification violations. Knowledge-based erroneous behavior models were generated for the PCA pump and aircraft applications and also produced specification violations when evaluated as part of a formal system model. In all applications employing erroneous task behavior models, changes were made to the formal system model and formal verification was performed to ensure that the erroneous behavior would no longer contribute to specification violations.

All of the counterexamples produced in the verifications of the different application's models were evaluated with the counterexample visualizer.

9.0.1 Specific Contributions

9.0.1.1 The EOFM Language

The EOFM language developed as part of this work is itself a contribution as it provides a generic, platform independent means of modeling human task behavior. This language supports a superset of the features supported by similar modeling paradigms such as OFM [139], CTT [156], GOMS [110], and UAN [94] (see [28, 33] for a complete discussion of

Table 9.1: Different applications have exhibited different capabilities of our method. These relate to the elements of the architectural framework utilized, whether or not normative or erroneous human task behavior was modeled, verification outcomes with normative and/or erroneous human behavior and/or degraded automation performance, what elements of the architectural framework were changed and verified to fix discovered violations, and whether or not the visualizer was used to evaluate counterexamples.

		Application			
	Capability	PCA Pump	Cruise Control	Radiation Therapy Machine	Aircraft On Approach
Framework	Mission	●	●	●	●
	Human task	●	●	●	●
	Human-device interface	●	●	●	●
	Device automation	●	●	●	●
	Environment	–	●	–	●
Human task	Normative	●	●	●	●
	Erroneous	●	–	●	●
Verification outcome	Violation with normative behavior	–	●	–	●
	Valid with normative behavior	●	●	●	●
	Violation with phenotypical erroneous behavior	–	–	●	●
	Violation with knowledge-based erroneous behavior	●	–	–	●
	Valid with erroneous behavior	●	–	●	●
	Violation with degraded automation	–	–	–	●
	Valid with degraded automation	–	–	–	●
Redesign change	Mission	–	–	–	●
	Human task	–	●	–	●
	Human-device interface	●	●	–	–
	Device automation	–	–	●	●
Illustrate counterexample visualization		●	●	●	●

Note. A ● indicates that the associated application supported the associated capability. A – indicates that the associated application implementation did not.

this subject):

- The language allows for the direct modeling of observable, atomic human actions.
- The language allows models to be constructed as a hierarchy of activities and actions.

- The language supports a superset of the cardinalities and temporal orderings supported by OFM, CTT , GOMS, and UAN.
- The language allows for the conditional executions of activities for specifying when they can start, repeat, and complete execution.
- The language is capable of allowing models to receive information from external sources through the use of custom types, constants, and input variables.
- The language allows activities to be reused between and within task models.
- The language supports an extended OFM graphical notation for visually describing model activity and action hierarchies as well as the cardinal, temporal, and conditional execution restrictions on their execution.

The language is specified in RELAX NG and implemented in XML making the language platform independent and easy to parse with existing code libraries. It is this technology that has been used in both the EOFM to SAL translation (see [33] and Chapter 4) and the counterexample visualizer (see [30] and Chapter 7).

9.0.1.2 Erroneous Behavior Prediction

The ability to automatically predict and incorporate erroneous human behavior into task analytic models is a significant contribution. In all previous work in which task analytic models were used in formal verification, erroneous behavior was either not included in the analyses [3, 4, 14, 15, 70, 150, 155, 157] or had to be manually incorporated [82]. Thus, the capacity to automatically predict erroneous behaviors marks a significant step forward, allowing analysts to determine how erroneous behavior might contribute to unsafe system conditions in unexpected ways.

9.0.1.3 Enhanced Operator Function Model Semantics and Translation

The EOFM to SAL translation process is a contribution for two reasons. Firstly, the documentation for many of the task analytic modeling paradigms such as OFM and CTT is scant, making the formal interpretation of their semantics ambiguous. The documentation of the EOFM's formal semantics are explicitly defined [28], avoiding such ambiguity. Secondly, it allows human factors and systems engineers to code task analytic models in notation that mimics the structure of task models and represents models more compactly than its equivalent formal representation. This is seen in the applications, where the SAL representation of the task model was always between 80% and 161% bigger than its EOFM counterpart (Figure 9.1).

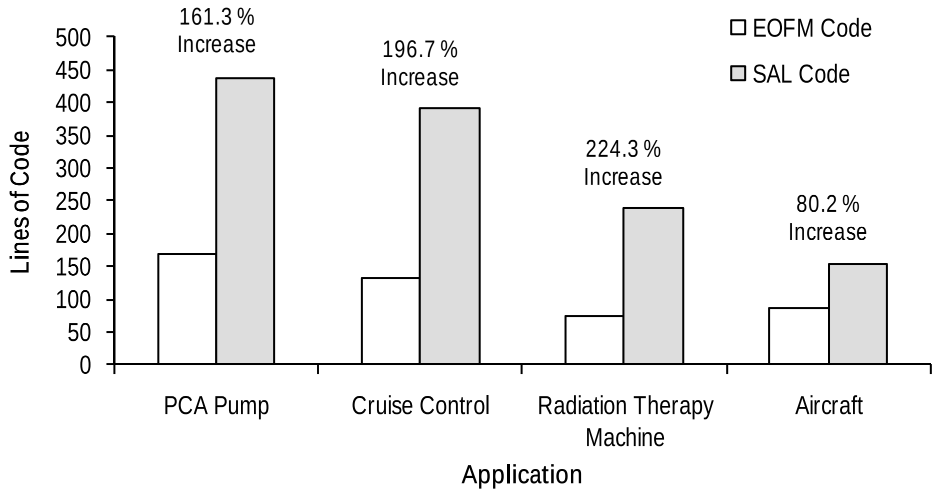


Figure 9.1: Comparison of code sizes between EOFM and SAL representations of the human task behavior models for different applications. The label above each pair of bars indicates the percent increase in code size from the EOFM to SAL representation.

9.0.1.4 Formal System Model Architectural Framework

The formal system model architectural framework (Figure 3.1) is a contribution in that its use demonstrates that it is possible to verify human-automation interaction as part of a system model based around concepts important to human-automation interaction: human mission, human task behavior, human-device interface, automated device, and operation environment. A secondary contribution of this framework was illustrated with the Baxter Ipump model ([31] and Chapter 1) where it was shown that the inclusion of a realistic human task behavior model resulted in a state space reduction of 98% from a model that had previously utilized a completely unconstrained human operator (one that could perform any action at any given time). Thus, the use of this framework, when appropriate, could help combat issues associated with model space complexity: where the model is too big to fit in the memory of the machine, making it incapable of being formally verified. Finally, the ability of different human mission, human task behavior, and device automation models to be swapped in and out has been demonstrated in several examples, but most prominently in the aircraft on approach application.

9.0.1.5 Counterexample Visualization

The use of the EOFM's visual notation to illustrate how human behavior contributes to problems reported in counterexamples was useful for allowing us to interpret model checking results. Further, the feature of grouping model variables based on their location in a model architecture, and highlighting when these variables change was also very useful in addition to being well supported in the counterexample visualization literature [7, 8, 10, 49, 49, 75, 104, 119, 133, 175].

9.1 Future Development of the Method

While each chapter has focussed on how different individual pieces of the method could be improved, there are several ways in which the method in general could be enhanced.

9.1.1 Scalability and Complexity Optimization

The scalability of our method is illustrated through our testing and benchmark results as well as the applications themselves. The benchmarks give analysts an estimate of how complexity increases with the number of actions and decomposition operators (Chapter 4) as well as how it increases for the number of generated erroneous behaviors. For the applications, the PCA pump provided an upper bound on the complexity a model can have when being used with our method using the computational resources we have available.

Given these results there are significant limits to what analyses can be evaluated using our method. Thus future work should investigate how complexity improvements could be made to the formal representation of the task models and how system features relevant to human-automation interaction can be abstracted or simplified in the formal system model representation.

9.1.2 Extension to Multi-operator Systems

All of the applications discussed have been single operator systems. However, it is likely that this method could be easily adapted to accommodate systems with multiple operators. Aside from the extensions to the EOFM language that may help facilitate this (see Chapter 4), this may also require extensions to the modeling architecture. Multi-operator systems can be configured in a number of different ways. Operators can be closely or disparately located both spatially or temporally; they may be interacting with centralized or distributed automation; they may share or have disparate human-device interfaces; they may or may not have access to means of inter-human communication with or without latency; they may have compatible or conflicting goals; and there may different or disparate environmental conditions that may influence any element of the system. Future work should investigate how our architecture could be adapted or redesigned to accommodate these variable features of multi-operator systems.

Additionally, multiple operator systems will inevitably result in additional scalability concerns as the modeling of multiple operators and interfaces will certainly add complexity, especially if human erroneous behavior prediction is utilized.

Multiple operators also open the opportunity for generating erroneous human behavior related the multi-operator systems, such coordination or communication problems. Future work should investigate this as well.

9.1.3 Human Subject Testing

The discussion of the EOFM language (Chapter 4) and the counterexample visualizer (Chapter 7) both addressed how each could be evaluated in a human subject test in order to assess their usability compared to the options currently offered by SAL. Such tests could provide experimental validity to the hypothesis that these tools are more usable to human factors engineers than those currently offered by SAL. Human subject tests could also be used to improve the method as a whole. Such experiments could train practitioners with all elements of the method and have them use the method to perform several analyses so that they could provide feedback on how the tools that support the method may be changed or enhanced in order to make them easier to use.

9.1.4 Comparison with Other Methods

In the presented work we illustrate how our method can be used to find a number of human-automation interaction related system failures in realistic applications. However, we do not compare our method with other methods that may provide similar insights.

Our method supports the generation of erroneous human behavior that is comparable to the behavior generated using cognitive models with formal verification [19, 62, 63, 160, 161]. Future work could compare these two methods in order to see if there are any discrepancies between the erroneous behaviors they generate and determine if there are applications better suited to analyses with either method. Future work could also compare how the two methods scale with respect to statespace complexity for different applications.

Human Reliability Analysis (HRA) [101] is a completely different type of analysis that is more commonly used in human-automation interaction. It is concerned with determining what the probability is that a human operator will normatively perform required activities in order to allow analysts to assess the probability of failures in safety critical systems. Future work should determine what the advantages and disadvantage of HRA are compared to our technique.

9.2 Future Development of Formal Verification of Human-automation Interaction

The work presented here is an incremental development in the state of knowledge in the intersection of human-automation interaction and formal methods. As such, this work may help contribute to or benefit from future developments in these fields.

9.2.1 Advances in Formal Methods

As formal modeling and verification technology improves, the complexity of the systems they can accommodate will increase. Additionally, future developments in lightweight formal methods [35, 107] may prove useful as they allow parts or a system to be formally modeled and verified using compact modeling languages that can be quickly verified. A formal system architectural frameworks like that used in this work may be useful in such lightweight analyses as they may allow certain system sub-models to be eliminated for certain analyses. Light weight modeling techniques like those offered by ADEPT [81, 172] allow human operators to quickly prototype human-device interface behavior and immediately check a number of properties which might suggest problems with human-automation interaction. Work related to formally modeling and reasoning about the role of human behavior's contribution to system failures in accident reports [13, 15, 112–114] may also suggest lightweight analyses that only consider the safety critical elements of systems.

9.2.2 Model Validity and Design Integration

In order to be useful to provide insights about actual systems, all of the models used in the formal verification need to be valid. If they are not, the verification process has the potential to find problems that may not exist in the actual system, or miss problems that exist in the actual system but not the models. One of the ways of dealing with this is to incorporate formal model analyses into the design and development process: where formal modeling and verification techniques are directly associated with design documents and system specifications.

In the formal methods community, languages like LUSTRE [90] and the associated Safety Critical Application Development Environment (SCADE) [1] allow designers to formally specify models of embedded, reactive, synchronous systems; formally verify them; and generate C and Ada code guaranteed to exhibit the verified properties.

Within the formal human-automation interaction literature, Aït-Ameur and Baron, Campos and Harrison, Dwyer et al. [3, 49, 77] have adapted their modeling frameworks to work with human-device interfaces built in Java and Visual Basic, thus allowing the actual software implementations to be used in the formal analyses. While this is useful if one is developing systems in these environments, these processes are limited to software systems.

When working with models of human task behavior and cognition, analysts have the added task of validating their models against actual human behavior or cognition. Aït-Ameur and Baron, Bastide et al., Campos and Harrison [3, 18, 49] have shown that it is possible to execute formal models as if they were computer programs while allowing human operators to interact with them. They have used this ability to experimentally validate human task behavior models against actual human behavior. Future developments may extend such techniques to other human behavior and cognitive models.

9.2.3 Integrated Development Environments

Many of the issues associated with design integration could be addressed through the development of a formal human-automation interaction, integrated development environment. Such an environment could allow a variety of different verifications and validations to be performed without the analyst having to work directly with the underlying formalisms. It could allow human factors engineers to perform their modeling in familiar notations. It could also allow models to be interacted with or visually animated for debugging and validation purposes.

Environments such as SUIDT [3], Petshop [18], ADEPT [81, 172], IFADIS [133], IVY [49], and CogTool [111] have made some progress towards such an environment, but are still in their infancy. Future IDE's could build on the feature sets encompassed by these environments. Such an IDE would ideally support all of the features discussed below.

9.2.3.1 System Modeling Architecture

The IDE should support a system modeling architecture that allows system elements relevant to human-automation interaction to be modeled independently of each other, and that would allow any element irrelevant to a given analysis to be excluded. Our architecture could be extended to encompass human cognition and human mental models of automation.

9.2.3.2 Human Cognitive and Behavioral Modeling Architecture

The IDE should include an integrated framework for allowing different elements of human cognitive and behavior to be modeled as is appropriate for the desired analysis. Kieras and Polson [121] discuss how to formally model human operator knowledge about interacting with an automated device and evaluate its impact on system performance using simulation. This knowledge was categorized as follows:

1. Task-relevant knowledge describes the human operator goals that the device could be used to achieve and the procedures or tasks the human operator thinks he can use to accomplish them;

2. Device layout knowledge encompasses the human operator's understanding of the physical layout of the device's information displays and control widgets;

3. Device behavior knowledge describes how the human operator thinks his actions will affect the device's observable behavior; and

4. How-it works knowledge describes how the operator thinks the internals of the device work.

This architecture could be adapted into an IDE in order to allow analysts to run verification analyses using different human operator knowledge. For example, device behavior and how-it works task-relevant knowledge could be used to support mode confusion analyses; task-relevant knowledge could be used to support formal verifications with task analytic models; and combinations of the different categories could be used to support different cognitive modeling analyses.

9.2.3.3 Verification Environment Independence

To avoid the problems associated with the heterogeneity of formal modeling and verification techniques, the IDE should support modeling techniques that are independent of any given verification environment. This would allow all modeled constructs to be created using notations and paradigms familiar to the human factors community. For example human-device interfaces and automation behavior could be graphically specified using techniques like those employed in SUIDT [3], IVY [49], Petshop [18], or ADEPT [81, 172]. Human task behaviors could be represented in their own notations as they are in SUIDT [3], and EOFM [26, 28, 31, 33]; or through point-and-click and drag-and-drop functionality as it is done in CogTool [111]. Other model architectural elements could be handled similarly. All models could then be translated into a desired verification environment, where different formalisms and verification tools could be supported through plug-ins.

9.2.3.4 Assisted Specification Property Creation

In order to help analysts express properties they wish to check against their formal model, an IDE could provide a number of properties that could be automatically checked (as is done in ADEPT [81]) as a well as a number of temporal logic patterns they could use to build custom properties (as is done in IVY and IFADIS [49, 133]).

9.2.3.5 Counterexample Visualization

With the use of abstract representations, it will be necessary to translate counterexamples into a presentation compatible with those representations so that analysts will be able to interpret them. Bolton and Bass [26, 30] have shown how visualizations of task analytic models can be used to illustrate how human behavior contributed to problems found in counterexamples. Several researchers have explored the animation of task models [3] and interface prototypes [49, 133] as part of counterexample visualization. A formal human-automation interaction IDE should support and extend these features.

9.2.3.6 Interactive Model Execution

SUIDT [3], Petshop [18], CogTool [111] and ADEPT [172] allow models to be executed as interactive applications. Thus models can be debugged and evaluated experimentally. Additionally, SUIDT allows task behaviors modeled using CTT to be validated against behavior of human operators interacting with the model. A formal human-automation interaction IDE should support these features.

9.3 Conclusion

The work presented here has contributed to the efforts to evaluate human-automation interaction analyses with formal verification by showing that it is possible to predict erroneous human behavior's contribution to system failure using human task behavior without the need for detailed cognitive modeling. In doing this we have created a number of tools to support our effort. Future effort will explore the usefulness of these tools to the human factors and formal methods communities, and hopefully lead to the development of environments that facilitate better design integration with formal verification of human-automation interactive systems.

Appendix A

EOFM Code Listing for the Driver Task Behavior Model

Below is the EOFM code listing for the task behavior model of the driver discussed in Chapter 4. Note that prefixes not used in the text are used in the code to identify modeling constructs: constants (c), userdefinedtypes (t), humanoperator (p), inputvariable (i), humanaction (h), and activity (a).

```
<?xml version="1.0" encoding="UTF-8"?>
<?oxygen RNGSchema="OFMr7.rng" type="xml"?>
<eofms>
  <constant name="cStart" basictype="INTEGER">5</constant>
  <constant name="cClose" basictype="INTEGER">2</constant>
  <constant name="cVeryClose" basictype="INTEGER">1</constant>
  <constant name="cAtIntersection" basictype="INTEGER">0</constant>

  <userdefinedtype name="tMissionState">{Hurry, NoHurry}</userdefinedtype>
  <userdefinedtype name="tPedalState">{Pressed, Unpressed}</userdefinedtype>
  <userdefinedtype name="tCarMovementState">{Accelerating, Decelerating, ConstantSpeed,
    Stopped}</userdefinedtype>
  <userdefinedtype name="tLightDistance">[cAtIntersection..cStart]</userdefinedtype>
  <userdefinedtype name="tLightColor">{Red, Yellow, Green}</userdefinedtype>

  <humanoperator name="pDriver">

    <inputvariable name="iTrafficLight" userdefinedtype="tLightColor"/>
    <inputvariable name="iTrafficLightDistance" userdefinedtype="tLightDistance"/>
    <inputvariable name="iCar" userdefinedtype="tCarMovementState"/>
    <inputvariable name="iPedal" userdefinedtype="tPedalState"/>
    <inputvariable name="iMission" userdefinedtype="tMissionState"/>

    <humanaction name="hEnableCruiseControl" behavior="autoreset"/>
    <humanaction name="hDisableCruiseControl" behavior="autoreset"/>
    <humanaction name="hIncreaseGas" behavior="autoreset"/>
```

```
<humanaction name="hHoldGas" behavior="autoreset"/>
<humanaction name="hDecreaseGas" behavior="autoreset"/>
<humanaction name="hReleaseGas" behavior="autoreset"/>
<humanaction name="hBreak" behavior="toggle"/>

<eofm>
  <activity name="aDriveDownTheStreet">
    <precondition>iTrafficLightDistance /= cAtIntersection AND
      (iTrafficLight = Green OR iTrafficLightDistance &gt; cClose)</precondition>
    <decomposition operator="xor">
      <activity name="aGoFaster">
        <decomposition operator="ord">
          <action humanaction="hIncreaseGas"></action>
        </decomposition>
      </activity>
      <activity name="aSlowDown">
        <decomposition operator="ord">
          <action humanaction="hDecreaseGas"></action>
        </decomposition>
      </activity>
      <activity name="aMaintainSpeed">
        <decomposition operator="xor">
          <activity name="aCrews">
            <precondition>iPedal = Pressed</precondition>
            <decomposition operator="sync">
              <action humanaction="hEnableCruiseControl"></action>
              <action humanaction="hReleaseGas"></action>
            </decomposition>
          </activity>
          <activity name="aHoldSpeed">
            <decomposition operator="ord">
              <action humanaction="hHoldGas"></action>
            </decomposition>
          </activity>
        </decomposition>
      </activity>
      <activity name="aStopCruisingAndMaintainSpeed">
        <precondition>iCar = ConstantSpeed AND iPedal = Unpressed</precondition>
        <decomposition operator="sync">
          <action humanaction="hDisableCruiseControl"></action>
          <action humanaction="hIncreaseGas"></action>
        </decomposition>
      </activity>
    </decomposition>
  </activity>
</eofm>


<eofm>
  <activity name="aRespondToLight">
    <precondition>iTrafficLight /= Green AND (iTrafficLightDistance &lt;= cClose)
      </precondition>
    <decomposition operator="xor">
      <activity name="aRollStop">
        <precondition>(iTrafficLightDistance = cClose AND iMission = NoHurry)
          </precondition>
        <decomposition operator="xor">
          <activity name="aReleaseGas">
            <precondition>iPedal = Pressed</precondition>
            <decomposition operator="ord">
              <action humanaction="hReleaseGas"></action>
            </decomposition>
          </activity>
          <activity name="aStopCruisingAndReleaseGas">
```

```
                <precondition>iPedal /= Pressed</precondition>
                <decomposition operator="sync">
                  <action humanaction="hDisableCruiseControl"></action>
                  <action humanaction="hReleaseGas"></action>
                </decomposition>
              </activity>
            </decomposition>
          </activity>
          <activity name="aBreakStop">
            <precondition>iTrafficLightDistance = cVeryClose AND iCar /= Decelerating
              </precondition>
            <decomposition operator="ord">
              <action humanaction="hBreak"></action>
            </decomposition>
          </activity>
          <activity name="aContinueWithNoChange">
            <precondition>(iTrafficLightDistance = cClose AND iMission = Hurry)
              OR (iPedal = Unpressed and iCar = Decelerating)</precondition>
            <decomposition operator="ord">
              <action humanaction="hHoldGas"></action>
            </decomposition>
          </activity>
        </decomposition>
      </activity>
    </eofm>

  </humanoperator>
</eofms>
```

Appendix B

EOFM to SAL Translator Validation

SAL was used to validate that translated instantiated EOFMs conformed to the formal semantics. This was done by developing a number of temporal logic specification patterns designed to verify that activities or actions within an EOFM instance conformed to the transitions from Figure 2.3 and that the specified parallelism of activities and actions was maintained for the different decomposition operators. These patterns were instantiated for several examples designed to allow for the validation of the different execution state conditions supported by the EOFM: activities decomposing into actions with the different decomposition operators; activities decomposing into other activities with the different decomposition operators; and multiple root activities in the same model. We first discuss the specification pattern before discussing the applications for which they were applied.

B.1 Activity Execution State Transition Specification Patterns

LTL specification patterns are described below for each of the of the transitions in Figure 2.3(a). In all, the *activity* variable represents the execution state variable for the activity against which the specification will be checked. Based on the formal semantics (Section 2.2.3), this can be either *ready*, *executing*, or *done*. The *precondition*, *repeatcondition*, and *completioncondition* variables refer to the activity's pre, repeat, and completion conditions from its XML markup. The *startcondition*, *endcondition*, and *reset* variables refer to the activity's start, end, and reset condition as they are defined in the formal semantics.

The *ready* to *executing* transition is validated using an LTL formula which asserts that whenever the activity transitions from *ready* to *executing*, the activity's *startcondition* and *precondition* will always be *true* and the *completioncondition* will always be *false*:

$$\mathbf{G}\left(\begin{array}{l}(activity = ready \wedge \mathbf{X}\,(activity = executing)) \\ \quad \Rightarrow (startcondition \wedge precondition \wedge \neg completioncondition)\end{array}\right) \tag{B.1}$$

The *executing* to *executing* transition is validated using an LTL formula which asserts that whenever the activity is *executing* and its *endcondition*, *repeatcondition*, and not its *completioncondition* are *true*, the activity will always be *exectuing* in the next state:

$$\mathbf{G}\left(\begin{array}{l}(activity = executing \wedge endcondition \wedge repeatcondition \wedge \neg completioncondition) \\ \quad \Rightarrow \mathbf{X}\,(activity = executing)\end{array}\right) \tag{B.2}$$

The *executing* to *done* transition is validated using an LTL formula which asserts that whenever the activity transitions from *executing* to *done*, the activity's *endcondition* and *completioncondition* will always be *true*:

$$\mathbf{G}\left(\begin{array}{l}(activity = executing \wedge \mathbf{X}\,(activity = done)) \\ \quad \Rightarrow (endcondition \wedge completioncondition)\end{array}\right) \tag{B.3}$$

The *ready* to *done* transition is validated using an LTL formula which asserts that whenever the activity transitions from *ready* to *done*, the activity's *startcondition* and *completioncondition* will always be *true*:

$$\mathbf{G}\left(\begin{array}{l}(activity = ready \wedge \mathbf{X}\,(activity = done)) \\ \quad \Rightarrow (startcondition \wedge completioncondition)\end{array}\right) \tag{B.4}$$

The *done* to *ready* transition is validated using an LTL formula which asserts that whenever the activity transitions from *done* to *ready*, the activity's *reset* will always be *true*:

$$\mathbf{G}\left(\left(activity = done \wedge \mathbf{X}\left(activity = ready\right)\right) \Rightarrow reset\right) \tag{B.5}$$

B.2 Action Execution State Transition Specification Patterns

LTL specification patterns are described below for each of the transitions in Figure 2.3(b). In all, the *action* variable represents the execution state variable for the action against which the specification will be checked. The *startcondition* and *parentreset* variables refer to the action's start and parent reset conditions as they are defined in the formal semantics. The *endcondition* is not explicitly used because, as defined in the formal semantics, it is assumed to be *true*.

The *ready* to *executing* transition is validated using an LTL formula which asserts that whenever the action transitions from *ready* to *executing*, the activity's *startcondition* will always be *true*:

$$\mathbf{G}\left(\left(action = ready \wedge \mathbf{X}\left(action = executing\right)\right) \Rightarrow startcondition\right) \tag{B.6}$$

The *executing* to *done* transition is validated using an LTL formula which asserts that whenever the action transitions from *executing*, it will always transition to *done*:

$$\mathbf{G}\left(\left(action = executing \wedge \mathbf{X}\left(action \neq executing\right)\right) \Rightarrow \mathbf{X}(action = done)\right) \tag{B.7}$$

The *done* to *ready* transition is validated using an LTL formula which asserts that whenever the action transitions from *done* to *ready*, the activity's *parentreset* will always be *true*:

$$\mathbf{G}\left(\left(action = done \wedge \mathbf{X}\left(action = ready\right)\right) \Rightarrow parentreset\right) \tag{B.8}$$

B.3 Restrictions on Activity and Action Execution Parallelism

While the specifications above check that the execution orders stipulated by the EOFM's formal semantics are adhered to, they do not overtly check the restrictions on execution parallelism specified by the decomposition operators. However, we can also perform formal verifications to validate that these are adhered to.

Each of the specifications used to check these properties assumes that the decomposition has two sub acts (*subact1* or *subact2* corresponding to either the execution state of either actions or activities).

For sequential decomposition operators (*ord* and those ending in *_seq*), we can verify that only one sub act will ever be executing:

$$\mathbf{G}\left(\begin{array}{c}(\mathit{subact1} = \mathit{executing} \Rightarrow \mathit{subact2} \neq \mathit{executing}) \\ \wedge\,(\mathit{subact2} = \mathit{executing} \Rightarrow \mathit{subact1} \neq \mathit{executing})\end{array}\right) \tag{B.9}$$

For parallel decomposition operators (those ending in *_par*), we want to verify that it is possible for there to be any combination of one or more sub acts*executing*. This is achieved by generating witnesses, counterexamples that illustrate the desired property. Thus we can generate a witness showing that both activities can be *executing* at the same time:

$$\mathbf{G}\neg(\mathit{subact1} = \mathit{executing} \wedge \mathit{subact2} = \mathit{executing}) \tag{B.10}$$

Or we can generate witnesses showing that either activity can be *executing* while the other is not:

$$\mathbf{G}\neg(\mathit{subact1} = \mathit{executing} \wedge \mathit{subact2} \neq \mathit{executing}) \tag{B.11}$$

$$\mathbf{G}\neg(\mathit{subact1} \neq \mathit{executing} \wedge \mathit{subact2} = \mathit{executing}) \tag{B.12}$$

For the *sync* decomposition operator, we can verify that the each sub act is *executing* if and only if the other is *executing*:

$$\mathbf{G}(subact1 = executing \Leftrightarrow subact2 = executing) \tag{B.13}$$

For the *xor* decomposition operator, we can verify that the each sub act is *executing* only if the other is *ready*:

$$\mathbf{G}\left(\begin{array}{c} (subact1 = executing \Rightarrow subact2 = ready) \\ \wedge\,(subact2 = executing \Rightarrow subact1 = ready) \end{array}\right) \tag{B.14}$$

B.4 Validation Applications

The validation applications were defined to cover a number of the structural conditions that can arise in EOFM instances: activities decomposing into actions with the different decomposition operators; activities decomposing into other activities; and multiple root activities in the same model. In all cases the human task behavior model interacts with a simple human-device interface model which can receive all human operator actions. The operator also receives Boolean inputs (*precondition*, *repeatcondition*, and *completioncondition*) from the human-device interface model which give it access to simulated pre, repeat, and completion conditions which can change between *true* and *false* (or remain unchanged) at each step in a system model's execution.

B.4.1 A Single Top Level Activity Decomposing Into Actions

The first set of validated applications used a human task behavior model of the form shown in Figure D.1. Using this template, nine models were developed, one for each decomposition operator, where a given decomposition operator would replace *decomposition* in Figure D.1.

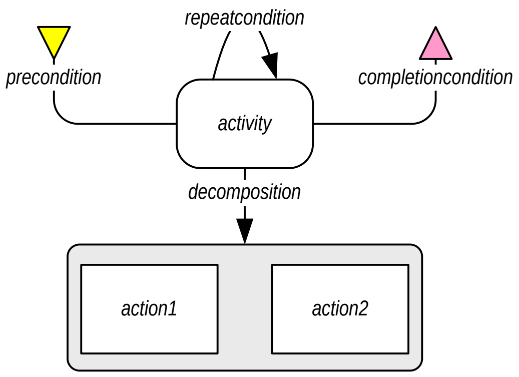


Figure B.1: A visualization of an EOFM instance with a single top level activity decomposing into two actions.

System models using these as their human task behavior models were checked against specification patterns. (B.1) - (B.5) were applied to *activity* (from D.1) for each decomposition operator. (B.6)-(B.8) were applied for both *action1* and *action2* (each replacing *action* in the LTL specifications). (B.9)-(B.14) were applied with *action1* and *action2* (as *subact1* and *subact2* respectively in the LTL specifications) for the appropriate decomposition operator. The following definition of start, end, and reset conditions were utilized (where appropriate) in these verifications for the given decomposition operator:

and_par

activity

$startcondition = (activity = ready)$

$endcondition = (activity = executing \wedge action1 = done \wedge action2 = done)$

$reset = (activity = done)$

action1

$startcondition = (action1 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

action2

$startcondition = (action2 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

and_seq

activity

$startcondition = (activity = ready)$

$endcondition = (activity = executing \wedge action1 = done \wedge action2 = done)$

$reset = (activity = done)$

action1

$startcondition = (action1 = ready \wedge activity = executing \wedge action2 \neq executing)$

$parentreset = repeatcondition \vee (activity = done)$

action2

$startcondition = (action2 = ready \wedge activity = executing \wedge action1 \neq executing)$

$parentreset = repeatcondition \vee (activity = done)$

optor_par

activity

$startcondition = (activity = ready)$

$endcondition = (activity = executing \wedge action1 \neq executing \wedge action2 \neq executing)$

$reset = (activity = done)$

action1

$startcondition = (action1 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

action2

$startcondition = (action2 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

optor_seq – zero or more actions must be performed in any order where actions need not be performed one at a time *activity*

$startcondition = (activity = ready)$

$endcondition = (activity = executing \wedge action1 \neq executing \wedge action2 \neq executing)$

$reset = (activity = done)$

action1

$startcondition = (action1 = ready \wedge activity = executing \wedge action2 \neq executing)$

$parentreset = repeatcondition \vee (activity = done)$

action2

$startcondition = (action2 = ready \wedge activity = executing \wedge action1 \neq executing)$

$parentreset = repeatcondition \vee (activity = done)$

or_par

activity

$startcondition = (activity = ready)$

$$endcondition = \left(\begin{array}{l} activity = executing \wedge action1 \neq executing \wedge action2 \neq executing \\ \wedge (action1 = done \vee action2 = done) \end{array} \right)$$

$reset = (activity = done)$

action1

$startcondition = (action1 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

action2

$startcondition = (action2 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

or_seq

activity

$startcondition = (activity = ready)$

$$endcondition = \left(\begin{array}{l} activity = executing \wedge action1 \neq executing \wedge action2 \neq executing \\ \wedge (action1 = done \vee action2 = done) \end{array} \right)$$

$reset = (activity = done)$

action1

$startcondition = (action1 = ready \wedge activity = executing \wedge action2 \neq executing)$

$parentreset = repeatcondition \vee (activity = done)$

action2

$startcondition = (action2 = ready \wedge activity = executing \wedge action1 \neq executing)$

$parentreset = repeatcondition \vee (activity = done)$

ord

activity

$startcondition = (activity = ready)$

$endcondition = (activity = executing \wedge action2 = done)$

$reset = (activity = done)$

action1

$startcondition = (action1 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

action2

$startcondition = (action2 = ready \wedge activity = executing \wedge action1 = done)$

$parentreset = repeatcondition \vee (activity = done)$

sync

activity

$startcondition = (activity = ready)$

$endcondition = (activity = executing \wedge action1 = done \wedge action2 = done)$

$reset = (activity = done)$

action1

$startcondition = (action1 = ready \wedge action2 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

action2

$startcondition = (action2 = ready \wedge action1 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

xor

activity

$startcondition = (activity = ready)$

$$endcondition = \left(\begin{array}{c} activity = executing \wedge action1 \neq executing \wedge action2 \neq executing \\ \wedge (action1 = done \vee action2 = done) \end{array} \right)$$

$reset = (activity = done)$

action1

$startcondition = (action1 = ready \wedge action2 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

action2

$startcondition = (action2 = ready \wedge action1 = ready \wedge activity = executing)$

$parentreset = repeatcondition \vee (activity = done)$

B.5 A Single Top Level Activity Decomposing Into Activities

The second set of applications used in the validation test utilized a human task behavior model of the form shown in Figure B.2. Using this template, eight models were developed, one for each decomposition operator besides *sync*, where a given decomposition operator would replace *decomposition* in Figure B.2.

System models using these as their human task behavior models were checked against specification patterns. (B.1) - (B.5) were applied for both *activity1* and *activity2* (each

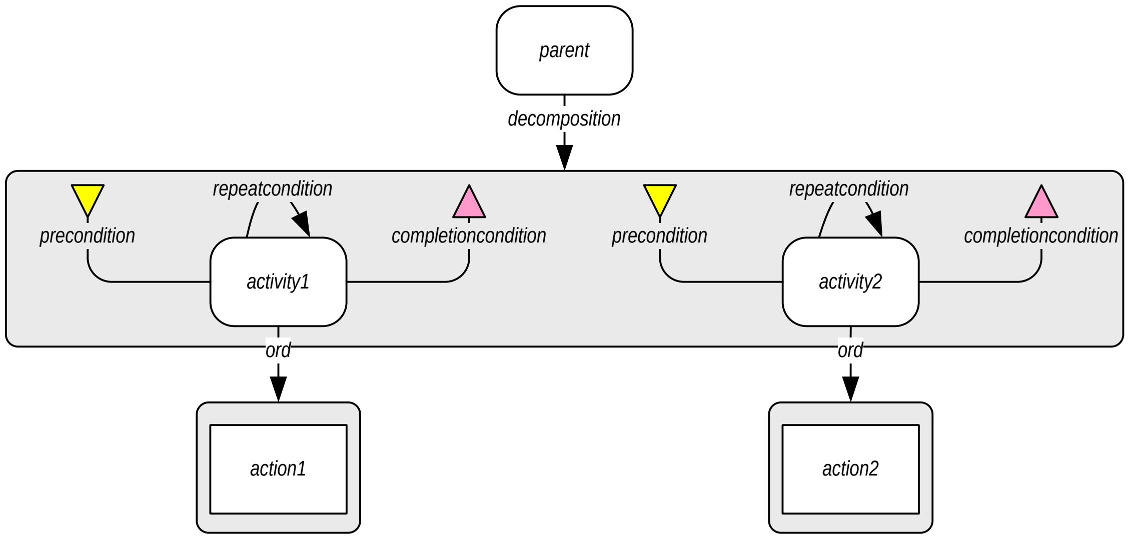


Figure B.2: A visualization of an EOFM instance with a single top level activity decomposing into two activities.

substituting for *activity* in the LTL specifications) for each decomposition operator. (B.9)-(B.14) were applied with *activity1* and *activity2* (as *subact1* and *subact2* respectively in the LTL specification) for the appropriate decomposition operator. The following definition of start, end, and reset conditions were utilized (where appropriate) in these verifications for the given decomposition operator:

and_par

activity1

$startcondition = (activity1 = ready \wedge parent = executing)$

$endcondition = (activity1 = executing \wedge action1 = done)$

$reset = (parent = done)$

activity2

$startcondition = (activity2 = ready \wedge parent = executing)$

$endcondition = (activity2 = executing \wedge action2 = done)$

$reset = (parent = done)$

and_seq

activity1

$startcondition = (activity1 = ready \wedge parent = executing \wedge activity2 \neq executing)$

$endcondition = (activity1 = executing \wedge action1 = done)$

$reset = (parent = done)$

activity2

$startcondition = (activity2 = ready \wedge parent = executing \wedge activity1 \neq executing)$

$endcondition = (activity2 = executing \wedge action2 = done)$

$reset = (parent = done)$

optor_par

activity1

$startcondition = (activity1 = ready \wedge parent = executing)$

$endcondition = (activity1 = executing \wedge action1 = done)$

$reset = (parent = done)$

activity2

$startcondition = (activity2 = ready \wedge parent = executing)$

$endcondition = (activity2 = executing \wedge action2 = done)$

$reset = (parent = done)$

optor_seq

activity1

$startcondition = (activity1 = ready \wedge parent = executing \wedge activity2 \neq executing)$

$endcondition = (activity1 = executing \wedge action1 = done)$

$reset = (parent = done)$

activity2

$startcondition = (activity2 = ready \wedge parent = executing \wedge activity1 \neq executing)$

$endcondition = (activity2 = executing \wedge action2 = done)$

$reset = (parent = done)$

or_par

activity1

$startcondition = (activity1 = ready \wedge parent = executing)$

$endcondition = (activity1 = executing \wedge action1 = done)$

$reset = (parent = done)$

activity2

$startcondition = (activity2 = ready \wedge parent = executing)$

$endcondition = (activity2 = executing \wedge action2 = done)$

$reset = (parent = done)$

or_seq

activity1

$startcondition = (activity1 = ready \wedge parent = executing \wedge activity2 \neq executing)$

$endcondition = (activity1 = executing \wedge action1 = done)$

$reset = (parent = done)$

activity2

$startcondition = (activity2 = ready \wedge parent = executing \wedge activity1 \neq executing)$

$endcondition = (activity2 = executing \wedge action2 = done)$

$reset = (parent = done)$

ord

activity1

$startcondition = (activity1 = ready \wedge parent = executing)$

$endcondition = (activity1 = executing \wedge action1 = done)$

$reset = (parent = done)$

activity2

$startcondition = (activity2 = ready \wedge parent = executing \wedge activity1 = done)$

$endcondition = (activity2 = executing \wedge action2 = done)$

$reset = (parent = done)$

xor

activity1

$startcondition = (activity1 = ready \wedge parent = executing \wedge activity2 = ready)$

$endcondition = (activity1 = executing \wedge action1 = done)$

$reset = (parent = done)$

activity2

$startcondition = (activity2 = ready \wedge parent = executing \wedge activity1 = ready)$

$endcondition = (activity2 = executing \wedge action2 = done)$

$reset = (parent = done)$

B.5.1 Two Top Level Activities

The last application used in the validation test utilized a human task behavior model in Figure B.3.

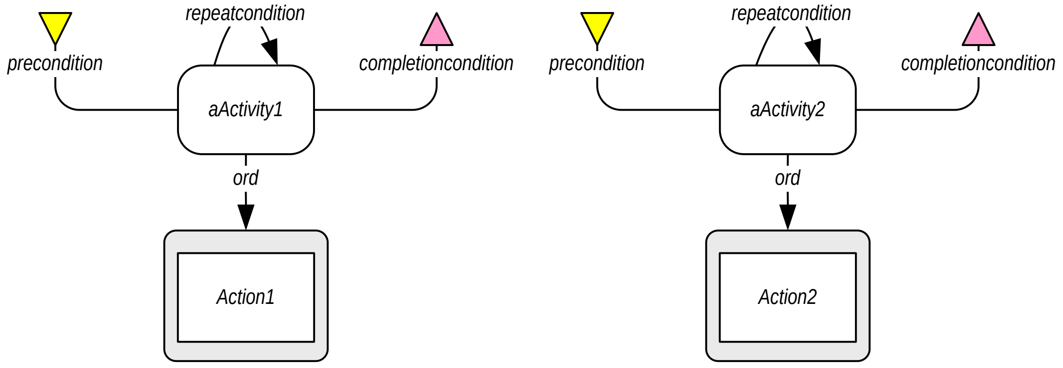


Figure B.3: A visualization of an EOFM instance with two top level activities.

A system model using this as its human task behavior models were checked against specification patterns (B.1) - (B.5) for both *activity1* and *activity2* (each substituting for *activity*). The following definition of start, end, and reset conditions were utilized (where appropriate) in these verifications for the given decomposition operator:

activity1

$startcondition = (\mathit{activity1} = ready \wedge \mathit{activity2} \neq executing)$

$endcondition = (\mathit{activity1} = executing \wedge \mathit{action1} = done)$

$reset = (\mathit{activity1} = done)$

activity2

$startcondition = (\mathit{activity2} = ready \wedge \mathit{activity1} \neq executing)$

$endcondition = (\mathit{activity2} = executing \wedge \mathit{action2} = done)$

$reset = (\mathit{activity2} = done)$

B.6 Results

All specifications verified to *true* with the exception of those derived from (B.10)-(B.12) which produced the expected witnesses.

B.7 Conclusions

While these applications do not exhaustively test every possible task behavior, they provide reasonable confidence that the EOFM to SAL translation process is adhering to the formal semantics, particularly for two activities and actions. They are correct for: an activity decomposing into multiple actions with all possible decomposition operators; an activity decomposing into multiple activities with all possible decomposition operators; and multiple top level activities. Additionally, all activities utilized in the applications discussed in the document were visually inspected to ensure that all observed counterexample conformed to the formal semantics.

Appendix C

Phenotypical Erroneous Human Behavior Validation

SAL was used to validate that translated instantiated EOFMs with phenotypical erroneous behavior generation were exhibiting the expected behavior. This was done by constructing a simple instantiated EOFM in which a single activity (*aParent*) with no conditions decomposes into a single action (*a*) with an ordered (*ord*) decomposition operator. A formal interface model was also created that could receive three different human actions (*a*, *b*, and *c* all defined as *humanaction* nodes in the instantiated EOFM's markup) and was capable of recording up to four human actions in the sequence that they were submitted (*action1*, *action2*, *action3*, and *action4* which could assume values *a*, *b*, *c*, ε [1] depending on the action that was performed).

Three formal models were built using these constructs where the interface model was paired with translated versions of the instantiated EOFM[2]: one with no generated erroneous behavior, one with a maximum of one erroneous act, and one with a maximum of two erroneous acts.

[1]No Action

[2]The translated EOFMs were modified so that *aParent* would not transition from *done* to *ready*, allowing the interface model to record the sequence actions performed for a single execution of *aParent*.

LTL specification properties were checked against each model to ensure that expected properties of erroneous behavior generation were maintained. The fist set of such properties were designed to ensure that all three models could only generate the action execution sequence expected for the maximum number of erroneous acts. This was done using specification properties expected to generate witnesses for specific sequences of recorded actions (counterexamples illustrating that a specific sequence could be achieved) or would verify to *true* if the sequence was unachievable. This was done for all of the possible valid action sequences that could be executed for the given instantiated EOFM with up to two erroneous acts. The temporal logic pattern for for each of these specifications is shown in (C.1) where *a1*, *a2*, *a3*, and *a4* can be any value the associated action variable could assume.

$$\mathbf{G}\neg\left(\begin{array}{l} aParent = done \\ \wedge action1 = a1 \\ \wedge action2 = a2 \\ \wedge action3 = a3 \\ \wedge action4 = a4 \end{array}\right) \tag{C.1}$$

Table C.1 indicates all of the action sequences that were verified using (C.1) along with the expected result of the verification. When these were checked against the actual model, all of the expected results were observed.

As a direct extension of these verifications, two additional ones were also conducted to ensure that there would never be a circumstance in any of the models in which four actions were performed (C.2) and that there was never a circumstance in which three actions were performed in which the correct action *a* was not one of the actions (C.3). Both *verified* to true in all models. These verifications coupled with those associated with (C.1) and Table C.1 prove that the erroneous behavior generation structure is producing the expected action

Table C.1: Expected Verification Results for (C.1)

Action Sequences				Expected Verification Result		
				Max. ♯ Erroneous Acts		
a1	a2	a3	a4	0	1	2
ε	ε	ε	ε	×	✓	✓
a	ε	ε	ε	✓	✓	✓
b	ε	ε	ε	×	✓	✓
c	ε	ε	ε	×	✓	✓
a	a	ε	ε	×	✓	✓
a	b	ε	ε	×	✓	✓
b	a	ε	ε	×	✓	✓
a	c	ε	ε	×	✓	✓
c	a	ε	ε	×	✓	✓
b	b	ε	ε	×	×	✓
b	c	ε	ε	×	×	✓
c	b	ε	ε	×	×	✓
c	c	ε	ε	×	×	✓
a	a	a	ε	×	×	✓
a	a	b	ε	×	×	✓
a	b	a	ε	×	×	✓
b	a	a	ε	×	×	✓
a	a	c	ε	×	×	✓
a	c	a	ε	×	×	✓
c	a	a	ε	×	×	✓
a	b	c	ε	×	×	✓
a	c	b	ε	×	×	✓
b	a	c	ε	×	×	✓
b	c	a	ε	×	×	✓
c	a	b	ε	×	×	✓
c	b	a	ε	×	×	✓

Note. In the above a ✓ indicates that when the associated action sequence is checked against the indicated model with (C.1), that it was expected to return a counterexample. A × indicates that (C.1) was expected to verify to true, indicating the infeasibility of the action sequence.

sequences without producing any that weren't for up to two erroneous behaviors.

$$\mathbf{G}\,(a4 \neq \varepsilon) \tag{C.2}$$

$$\mathbf{G}\left(\left(\begin{array}{l} aParent = done \\ \wedge action1 \neq \varepsilon \\ \wedge action2 \neq \varepsilon \\ \wedge action3 \neq \varepsilon \\ \wedge action4 = \varepsilon \end{array}\right) \Rightarrow \left(\begin{array}{l} action1 = a \\ \vee action2 = a \\ \vee action3 = a \end{array}\right)\right) \tag{C.3}$$

Verifications were also run for the models supporting both one and two erroneous acts to ensure that the erroneous act counter would never exceeded the maximum (C.4) and that they would still allow for the correct action to be performed without any erroneous acts occurring (C.5). Both verified to true for the two models.

$$\mathbf{G}\left(ECount \leq ErrorMax\right) \tag{C.4}$$

$$\mathbf{G}\left(\left(\begin{array}{l} aParent = done \\ ECount = 0 \end{array}\right) \Rightarrow \left(\begin{array}{l} action1 = a \\ \wedge action2 = \varepsilon \\ \wedge action3 = \varepsilon \\ \wedge action4 = \varepsilon \end{array}\right)\right) \tag{C.5}$$

These tests provide reasonable confidence that the phenotypical erroneous behavior generation process is behaving as intended. This conclusion is also supported by the application discussed in Chapter 5 in which the erroneous human behavior generation process produced results consistent with what was expected.

Appendix D

Strategic Knowledge-based Erroneous Behavior Validation

SAL was used to validate that translated instantiated EOFMs with strategic knowledge-based erroneous behaviors were exhibiting the expected behavior. This was done by developing a number of temporal logic specification patterns designed to verify that models were conforming to the activity execution state transitions from Figure 6.1, both normative and erroneous. All validations were performed for the execution of *activity* (Figure D.1) whose formal representation was created by translating its associated instantiated EOFM into SAL with a maximum of one erroneous transition (*KMax* = 1). This translated EOFM interacts with a simple human-device interface model which can receive all human operator actions. The operator also receives Boolean inputs (*precondition*, *repeatcondition*, and *completioncondition*) from the human-device interface model which provide it with simulated pre, repeat, and completion conditions which can change between *true* and *false* (or remain unchanged) at each step in a system model's execution.

activity has the following start and end conditions:

$$startcondition = (activity = ready)$$

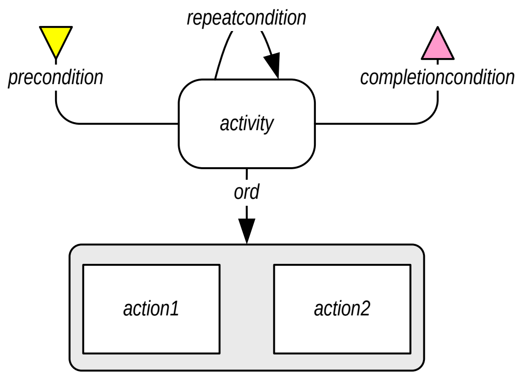


Figure D.1: A visualization of an EOFM instance with a single top level activity decomposing into two actions with an *ord* decomposition operator.

$$endcondition = (acivity = executing \wedge action2 = done)$$

These were used to construct LTL properties to test that the execution state of *activity* was adhering to the transition specified in Figure 6.1, one specification for each transition.

To check that *activity* could properly erroneously transition from ready to executing, we created a specification which asserted that, if the activity is going to make this transition erroneously (as indicated by the instrumentation of *KCount*), this always implies that its *startcondition* is *true* and either its *precondition* is *false* or its *completioncondition* is *true*:

$$\mathbf{G}\left(\left(\begin{array}{l} activity = ready \\ \wedge\mathbf{X}(activity = executing) \\ \wedge KCount = 0 \\ \wedge\mathbf{X}(KCount = 1) \end{array}\right) \Rightarrow \left(\begin{array}{l} startcondition \\ \wedge\neg(precondition \wedge \neg completioncondition) \end{array}\right)\right) \quad \text{(D.1)}$$

To check that *activity* could properly normatively transition from ready to executing, we created a specification which asserted that, if the activity was making this transition normatively (without an instrumentation of *KCount*), that this always implies that its *start-*

condition is *true*, its *precondition* is *true*, and its *completioncondition false*:

$$\mathbf{G}\left(\left(\begin{array}{l} activity = ready \\ \wedge \mathbf{X}(activity = executing) \\ \wedge \left(\begin{array}{l} KCount = 0 \wedge \mathbf{X}(KCount = 0) \\ \vee KCount = 1 \wedge \mathbf{X}(KCount = 1) \end{array}\right) \end{array}\right) \Rightarrow \left(\begin{array}{l} startcondition \\ \wedge precondition \\ \wedge \neg completioncondition \end{array}\right)\right) \tag{D.2}$$

To check that *activity* could properly erroneously repeat, we created a specification which asserted that, if the activity remained executing with an erroneous transition, this would always imply that its *endcondition* is true and that either the *repeatcondition* is *false* or that the *completioncondition* is *true*:

$$\mathbf{G}\left(\left(\begin{array}{l} activity = executing \\ \wedge \mathbf{X}(activity = executing) \\ \wedge KCount = 0 \\ \wedge \mathbf{X}(KCount = 1) \end{array}\right) \Rightarrow endcondition \wedge \neg \left(\begin{array}{l} repeatcondition \\ \wedge \neg completioncondition \end{array}\right)\right) \tag{D.3}$$

To check that *activity* could properly normatively repeat, we created a specification which asserted that, if the activity is executing with its *endcondition true*, its *repeatcondition true*, its *completioncondition false*, and no change in the number of erroneous transition; that this will always imply that the activity is executing in the next state:

$$\mathbf{G}\left(\left(\begin{array}{l} activity = executing \\ \wedge endcondition \\ \wedge repeatcondition \\ \wedge \neg completioncondition \\ \wedge \left(\begin{array}{l} (KCount = 0 \wedge \mathbf{X}(KCount = 0)) \\ \vee (KCount = 1 \wedge \mathbf{X}(KCount = 1)) \end{array}\right) \end{array}\right) \Rightarrow \mathbf{X}(activity = executing)\right) \tag{D.4}$$

To check that *activity* could properly erroneously transition from executing to done, we created a specification which asserted that, if it makes this transition erroneously, this always implies that its *endcondition* is *true* and its *completioncondition* is *false*:

$$\mathbf{G}\left(\begin{pmatrix} activity = executing \\ \wedge \mathbf{X}(activity = done) \\ \wedge KCount = 0 \\ \wedge \mathbf{X}(KCount = 1) \end{pmatrix} \Rightarrow \begin{pmatrix} endcondition \\ \wedge \neg completioncondition \end{pmatrix}\right) \tag{D.5}$$

To check that *activity* could properly normatively transition from executing to done, we created a specification which asserted that, if the activity was making this transition normatively, that this always implies that its *endcondition* is *true* and its *completioncondition* is *true*:

$$\mathbf{G}\left(\begin{pmatrix} activity = executing \\ \wedge \mathbf{X}(activity = done) \\ \wedge \begin{pmatrix} (KCount = 0 \wedge \mathbf{X}(KCount = 0)) \\ \vee(KCount = 1 \wedge \mathbf{X}(KCount = 1)) \end{pmatrix} \end{pmatrix} \Rightarrow \begin{pmatrix} endcondition \\ \wedge completioncondition \end{pmatrix}\right) \tag{D.6}$$

To check that *activity* could properly erroneously transition from ready to done, we created a specification which asserted that, if it makes this transition erroneously, this always implies that its *startcondition* is *true* and its *completioncondition* is *false*:

$$\mathbf{G}\left(\begin{pmatrix} activity = ready \\ \wedge \mathbf{X}(activity = done) \\ \wedge KCount = 0 \\ \wedge \mathbf{X}(KCount = 1) \end{pmatrix} \Rightarrow \begin{pmatrix} startcondition \\ \wedge \neg completioncondition \end{pmatrix}\right) \tag{D.7}$$

To check that *activity* could properly normatively transition from ready to done, we created a specification which asserted that, if the activity was making this transition normatively, that this always implies that its *startcondition* is *true* and its *completioncondition* is *true*:

$$\mathbf{G}\left(\begin{pmatrix} activity = ready \\ \wedge \mathbf{X}(activity = done) \\ \wedge \begin{pmatrix} (KCount = 0 \wedge \mathbf{X}(KCount = 0)) \\ \vee(KCount = 1 \wedge \mathbf{X}(KCount = 1)) \end{pmatrix} \end{pmatrix} \Rightarrow \begin{pmatrix} startcondition \\ \wedge completioncondition \end{pmatrix}\right) \tag{D.8}$$

Finally, we checked that the number of erroneous transitions would never exceed the maximum:

$$\mathsf{\textbf{G}}\,(KCount \geq 0 \wedge KCount \leq EMax) \tag{D.9}$$

All of these specifications verified to *true* or generated the expected witnesses giving us reasonable confidence that the strategic knowledge-based erroneous human behavior generation process was working as intended. This conclusion is also supported by the application discussed in Chapter 6 in which the erroneous human behavior generation process produced results consistent with what was expected.

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