NON-MONOTONIC REASONING FOR REQUIREMENTS ENGINEERING
State Diagrams Driven by Plausible Logic

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Abstract: We extend the state diagrams used for dynamic modelling in object-oriented analysis and design. We suggest that the events which label the state transitions be replaced with plausible logic expressions. The result is a very effective descriptive and declarative mechanism for specifying requirements that can be applied to requirements engineering of robotic and embedded systems. The declarative model can automatically be translated and requirements are traceable to implementation and validation, minimising faults from the perspective of software engineering. We compare our approach with Petri Nets and Behavior Trees using the well-known example of the one-minute microwave oven.

1 INTRODUCTION

We extend state transition diagrams in that we allow transitions to be labelled by statements of a non-monotonic logic, in particular Plausible Logic. We show that this has several benefits. First, it facilitates requirements engineering. Namely, we show this approach can be more transparent, clear, and succinct than other alternatives. Therefore, it enables better capture of requirements and this leads to much more effective system development. Furthermore, we show that such diagrams can be directly, and automatically translated into executable code, i.e. no introduction of failures in the software development process.

Finite automata have a long history of modelling dynamic systems and consequently have been a strong influence in the modelling of the behaviour of computer systems (Rumbaugh et al., 1991, Bibliographical notes, p. 113-114). System analysis and design uses diagrams that represent behaviour of components or classes. State diagrams (or state machines) constitute the core behavior modeling tool of object-oriented methodologies. In the early 90s state machines became the instrument of choice to model the behaviour of all the objects of a class. The Object-Modeling Methodology (OMT) of Rumbaugh et al. (1991, chapter 5) established state diagrams as the primary dynamic model. The Shlaer-Mellor approach established state models to capture the life cycle of objects of a given class (Shlaer and Mellor, 1992).

Class diagrams capture the static information of all objects of the same class (what they know, what they store), but behaviour is essentially described in models using states and transitions. The prominence of OMT and Shlaer-Mellor has permeated into the most popular modelling language for object-orientation, the Unified Modeling Language (UML). “A state diagram describes the behavior of a single class of objects” (Rumbaugh et al., 1991, p. 90). Although the state diagrams for each class do not describe the interactions and behaviour of several objects of diverse classes in action (for this, UML has collaboration diagrams and sequence diagrams), they constitute a central modelling tool for software engineering.

Although UML and its variants have different levels of formality, in the sense of having a very clear syntax and semantics, they aim for the highest formality possible. This is because their aim is to remove ambiguity and be the communication vehicle between requesters, stakeholders, designers, implementors, testers, and users of a software system. Thus, they offer constraints very similar to the formal finite state machine models. For example, in a deterministic finite state machine, no two transitions out of the same state can be labelled with the same symbol. This is because formally, a deterministic finite state machine consists of a finite set of states, an input language (for events), and a transition function. The transition function indicates what the new state will be, given an input and the current state. Other
Table 1: The Transition Function as a Table.

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adornments include signalling some states as initial and some as final. However, a fundamental aspect of finite state machines is that the transition function is just that, a function (mathematically, a function provides only one value of the codomain for each value in the domain).

Granted that the model can be extended to a non-deterministic machine, where given an input and a state, a set of possible states is the outcome of the transition. In this case, the semantics of the behaviour has several interpretations. For example, in the theory of computation, the so-called power set construction shows that non-deterministic and deterministic finite state machines are equivalent. However, other semantics are possible, such as multi-threaded behaviour. Therefore, as a modelling instrument in software engineering, it is typically expected that the conditions emanating from a state are mutually exclusive and exhaustive. “All the transitions leaving a state must correspond to different events” (Rumbaugh et al., 1991, p. 89). Namely, if the symbol $c_i$ is a Boolean expression representing the guard of the transition, then $\bigvee_{i=1}^{n} c_i = \text{true}$ (the exhaustive condition), and $c_i \land c_j = \text{false}$, $\forall i \neq j$ (the exclusivity condition).

In fact, Shlaer-Mellor also suggest the analysis should make use of the State Transition Table (STT) (Shlaer and Mellor, 1992). Table 1 is the tabular representation of the transition function “to prevent one from making inconsistent statements” (Shlaer and Mellor, 1992, p. 52) and they provide an illustration where two transitions out of the same state and labelled by the same event are corrected using the table.

Recently, the software engineering community has been pushing for Requirements Engineering (RE) (Hull et al., 2005), concerned with identifying and communicating the objectives of a software system, and the context in which it will be used (Nuseibeh and Easterbrook, 2000). Hence, RE identifies and elicits the needs of users, customers, and other stakeholders in the domain of a software system. RE demands a careful systematic approach. Significant effort is to be placed on rigorous analysis and documented specification, especially for security or safety critical systems. RE is important because a requirement not captured early may result in a very large effort to re-engineer a deployed system.

## 2 NON-MONOTONIC LOGIC IN STATE DIAGRAMS

An ambition of both artificial intelligence (AI) and software engineering is to be able to only specify what we want, without having to detail how to achieve this. The motivation for our approach has a similar origin. We aim at producing a vehicle of communication that would enable the specification of behaviour without the need for imperative programming tools. Therefore, we want to use a declarative formalism (a similar ambition has lead to the introduction of logic programming and functional programming). Non-monotonic logic is regarded as quite compatible with the way humans reason and express the conditions and circumstances that lead to outcomes, as well as a way to express the refinements and even exceptions that polish a definition for a given concept. In fact, non-monotonic reasoning is regarded as one of the approaches to emulate common-sense reasoning (Russell and Norvig, 2002). We illustrate that the addition of this declarative capability to state transition diagrams for capturing requirements is beneficial because the models obtained are much simpler (a fact necessary to ensure that the natural language description has indeed been captured). This way, we only need to specify the what and can have all of the how within an embedded system generated automatically.

With our approach, modelling with state-diagrams is sufficient to develop and code behaviours. The semantics of a state is that it is lasting in time, while a transition is assumed to be instantaneous. The state-diagram corresponds closely to the formalism of finite state machines (defined by a set $S$ of states, a transition function $t : S \times \Upsilon \rightarrow S$, where $\Upsilon$ denotes a possible alphabet of input symbols). In our case, we can specify the behaviour by the table that specifies the transition function $t$ (Table 1).

We still use the notion of an initial state $s_0$, because, in our infrastructure that implements these ideas (Billington et al., 2009), in some external-state transition, behaviours must be able to reset themselves to the initial state. A final state is not required, but behaviours should be able to indicate completion of a task to other modules. Now, current practice for modelling with finite state machines assumes that transitions are labelled by events. In both the Shlaer-Mellor approach and OMT (Rumbaugh et al., 1991), transitions are labelled by events only. For example, in Fig. 1, a transition is labelled by the event ball_visible (e.g. a sensor has detected a ball). A slight extension is to allow labels to be a decidable Boolean condition (or expression) in a logic with values true or false (that is, it will always be possi-
In the agent model, reactive systems are seen as an alternative to logic-based systems that perform planning and reasoning (Wooldridge, 2002), which has no implication, and no negation (only OR and AND). Thus our use of a non-monotonic logic is a significant variation.

3 PLASIBLE LOGIC

Non-monotonic reasoning (Antoniou, 1997) is the capacity to make inferences from a database of beliefs and to correct those as new information arrives that makes previous conclusions invalid. Although several non-monotonic formalisms have been proposed (Antoniou, 1997), The β algorithm for PL uses the closed world assumption while the π algorithm uses the open world assumption. The family of non-monotonic logics called Defeasible Logics has the advantage of being designed to be implementable. The main members of this family, including Plausible Logic (PL), are compared in (Billington, 2008), listing their uses and desirable properties. Although the most recent member of this family, CDL (Billington, 2008), has some advantages over PL (Billington and Rock, 2001), the differences are not significant for the purposes this paper. We shall therefore use PL as its corresponding programming language, DPL, is more advanced. If only factual information is used, PL essentially becomes classical propositional logic. But when determining the provability\(^2\) of a formula, the proving algorithms in PL can deliver three values (that is, it is a three-valued logic), +1 for a formula that has been proved, −1 for a formula that has been disproved, and 0 when the formula cannot be proved and attempting so would cause an infinite loop. Another very important aspect of PL is that it distinguishes between formulas proved using only factual information and those using plausible information. PL allows formulas to be proved using a variety of algorithms, each providing a certain degree of trust in the conclusion. Because PL uses different algorithms, it can handle a closed world assumption (where not telling a fact implies the fact is false) as well as the open world assumption in which not being told a fact means that nothing is known about that fact.

In PL, all information is represented by three kinds of rules and a priority relation between those rules. The first type of rules are strict rules, denoted by the strict arrow → and used to model facts that are certain. For a rule A → l we should understand that if all literals in A are proved then we can deduce l (this is simply ordinary implication). A situation such as Humans are mammals will be encoded as human(x) → mammal(x). Plausible rules A ⇒ l use

\[\begin{align*}
\text{BALL_CHASER} & \\
\text{follow} & \text{ Do:walk} & \text{search} & \text{ Do:spin} & \\
\text{ball_not_visible} & & & & \\
\end{align*}\]

Figure 1: Simple Finite State Diagram.
the plausible arrow $\Rightarrow$ to represent a plausible situation. If we have no evidence against $l$, then $A$ is sufficient evidence for concluding $l$. For example, we write \textit{Birds usually fly} as $\text{bird}(x) \Rightarrow \text{fly}(x)$. This records that when we find a bird we may conclude that it flies unless there is evidence that it may not fly (e.g. if it is a penguin). Defeater rules $A \Rightarrow \neg l$ say if $A$ is not disproved, then it is risky to conclude $l$. An example is \textit{Sick birds might not fly} which is encoded as $\{\text{sick}(x), \text{bird}(x)\} \Rightarrow \neg \text{fly}(x)$. Defeater rules prevent conclusions that would otherwise be risky (e.g. from a chain of plausible conclusions).

Finally, a priority relation $>_{\text{pb}}$ between plausible rules $R_1 >_{\text{pb}} R_2$ indicates that $R_1$ should be used instead of $R_2$. The following example demonstrates the expressive power of this particular aspect of the formalism:

$$\{\} \Rightarrow \text{quail}(\text{Quin}) \quad \text{Quin is a quail}$$

$$\text{quail}(x) \Rightarrow \text{bird}(x) \quad \text{Quails are birds}$$

$$R_1 : \text{bird}(x) \Rightarrow \text{fly}(x) \quad \text{Birds usually fly}$$

From the rule $R_1$ above, one would logically accept that \textit{Quin flies} (since \textit{Quin is a bird}).

$$\{\} \Rightarrow \text{quail}(\text{Quin}) \quad \text{Quin is a quail}$$

$$\text{quail}(x) \Rightarrow \text{bird}(x) \quad \text{Quails are birds}$$

$$R_2 : \text{bird}(x) \Rightarrow \neg \text{fly}(x) \quad \text{Quails usually do not fly}$$

However, from $R_2$, we would reach the (correct) conclusion that Quin usually does not fly. But what if both knowledge bases are correct (both $R_1$ and $R_2$ are valid)? We perhaps can say that $R_2$ is more informative as it is more specific and so we add $R_2 >_{\text{pb}} R_1$ to a knowledge base unifying both. Then PL allows the agent to reach the proper conclusion that Quin usually does not fly, while if it finds another bird that is not a quail, the agent would accept that it flies. What is important to note here is that if the rule set is consistent, all proofs withing PL will also be consistent. I.e. as long as any conflicts between plausible rules are properly resolved using priority relations, it will never be possible to prove both a literal $l$ and its negation $\neg l$ at the same time.

Note that Asimov’s famous Three Laws of Robotics are a good example of how humans describe a model. They define a general rule, and the next rule is a refinement. Further rules down the list continue to polish the description. This style of development is not only natural, but allows incremental refinement. Indeed, the knowledge elicitation mechanism known as Ripple Down Rules (Compton and Jansen, 1990) extracts knowledge from human experts by refining a previous model by identifying the rule that needs to be expanded by detailing it more.

4 A CLASSICAL EXAMPLE

We proceed here to illustrate our approach with an example that has been repeatedly used by the software engineering community, e.g. (Dromey and Powell, 2005; Myers and Dromey, 2009; Shlaer and Mellor, 1992; Wen and Dromey, 2004; Mellor, 2007). This is the so-called one-minute microwave oven (Shlaer and Mellor, 1992). Table 2 shows the requirements as presented by Myers and Dromey (Myers and Dromey, 2009, p. 27, Table 1). Although this is in fact not exactly the same as the original by Shlaer and Mellor (Shlaer and Mellor, 1992, p. 36), we have chosen the former rather than the latter because we will later compare with Behavior Trees regarding model size and direct code generation.

### 4.1 Microwave in Plausible Logic

Because we have a software architecture that handles communication between modules through a decoupling mechanism named the whiteboard (Billington et al., 2009), we can proceed at a very high level. We assume that sensors, such as the microwave button, are hardware instruments that deposit a message on the whiteboard with the signature of the depositing module and a time stamp. Thus, events like a button press or actions such as energising the microwave tube are communicated by simply placing a message on the whiteboard. Thus, knowledge of an event like a button push simply exists because a corresponding message has appeared on the whiteboard. Similarly, an action like energising the microwave tube is trig-

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Table 2: One-Minute Microwave Oven Requirements.

<table>
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<tr>
<th>Req.</th>
<th>Description</th>
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<tbody>
<tr>
<td>R1</td>
<td>If the oven is closed and you push the button, the oven will start cooking (that is, energise the power-tube) for one minute.</td>
</tr>
<tr>
<td>R2</td>
<td>If the button is pushed while the oven is cooking, it will cause the oven to cook for an extra minute.</td>
</tr>
<tr>
<td>R3</td>
<td>Pushing the button when the door is open has no effect.</td>
</tr>
<tr>
<td>R4</td>
<td>Whenever the oven is cooking or the door is open, the light in the oven will be on.</td>
</tr>
<tr>
<td>R5</td>
<td>Opening the door stops the cooking.</td>
</tr>
<tr>
<td>R6</td>
<td>Closing the door turns off the light. This is the normal idle state, prior to cooking when the user has placed food in the oven.</td>
</tr>
<tr>
<td>R7</td>
<td>If the oven times out, the light and the power-tube are turned off and then a beeper emits a warning beep to indicate that the cooking has finished.</td>
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3Matters are a bit more complex, as messages on the whiteboard expire or are consumed, and for actuators, they could have a priority and thus actuators can be organised with “subsumption” (Brooks, 1991).
Figure 2: Simple theories for 2-state machines.

(a) DPL for 2-state machine controlling tube, fan, and plate.

(b) DPL for 2-state machine controlling the light.

Figure 3: Simple 2-state machines control most of the microwave.

The light in the microwave is on when the door is open as well as when the microwave is cooking. So, the cues for the light are not the same as those for energising the tube. However, the light is in only one of two states LIGHT OFF or LIGHT ON. The default state is that the light is off. This is Rule L0 in the theory for the light (see Fig. 2b). However, when cooking the light is on. So Rule L1 has priority over L0. There is a further condition that overwrites the state of the light being off, and that is when the door is open (Rule L2).

Note that in this model, the two rules L1 and L2 override the default Rule L0, while in the model for cooking the priorities caused each new rule to refine the previous rule. The control button (Fig. 4) also has two states. In one state, CB ADD, the time left can be incremented, while in the other state, pushing the button has no effect. Again, between these two states we place transitions labelled by an expression of PL (in all cases, simple outputs of a theory). The control button does not add time unless the button is pushed. This is reflected by Rule CB0 and Rule CB1 below and the priority that CB1 has over CB0. When the door is open, pushing the button has no effect; this is Requirement R3 and expressed by Rule CB2 and its preference over CB1. Because we already have defined that a push of a button adds time to the timer (except for the conditions already captured), if the button is not pushed, then we do not add time. This is a strict rule that in DPL is expressed by a disjunction.

The final requirement to model is the bell, which is armed while cooking, and rings when there is no time left. This is the transition noTimeLeft from
4.2 Translation into Code

Once the high level model has been established in DPL, translation into code is straightforward. A Haskell proof engine implementation of DPL allows the interpretation and formal verification of the developed rule sets (Billington and Rock, 2001). This implementation was extended to include a translator that generates code that can be used in C, C++, Objective-C, C# and Java. The Haskell translator creates optimised Boolean expressions through the truth tables generated from the DPL rules. These Boolean expressions are then written out as C code that can directly be compiled and linked with libraries and application code. Incidentally, the C syntax for Boolean expressions is not only the same in supersets of C (such as C++ and Objective-C), but also in modern, related programming languages such as Java\(^4\).

Figure 6 shows the DPL theories for the state diagram transitions translated into C by the Haskell proof engine. This code can then directly be used as a header file for a generic embedded system state machine to test the transition conditions. Subsequent refinements of the rules do not require any changes to the generic state machine code. A simple recompilation against the updated, generated header files is sufficient to update the behaviour of the state machine.

5 Evaluation

The original approaches to modelling behaviour with finite state diagrams (Rumbaugh et al., 1991; Shlaer...
and Mellor, 1992) had little expectation that the models would directly translate to implementations without the involvement of programmers using imperative object-oriented programming languages. However, the software development V-model (Wiegers, 2003) has moved the focus to requirements modelling, and then directly obtaining a working implementation, because this collapses the requirements analysis phase with the verification phase. There are typically two approaches. First, emulating or simulating the model, which has the advantage that software analysts can validate the model and implementation by running as many scenarios as possible. The disadvantage is the overhead incurred through the interpretation of the model, rather than its compilation. The second approach consists of generating code directly from the model (Wagner and Wolstenholme, 2003; Wagner et al., 2006). This removes the overhead of interpreting at run-time the modelling constructs. Approaches to the automatic execution or translation of models for the behaviour of software have included the use of UML state diagrams for generating code (Mellor, 2007), the automatic emulation or code generation from Petri nets (Girault and Valk, 2001), and the automatic emulation or code generation from Behavior Trees (Wen and Dromey, 2004; Wen et al., 2007b; Wen et al., 2007a). A more recent trend is models@run.time, where “there is a clear pressure arising for mirroring the problem space for more declarative models” (Blair et al., 2009).

5.1 Contrast with State Diagrams

Simulation and direct generation of code from a state diagram is clearly possible, since one only needs to produce generic code that reads the transition table (encoded in some standard form), then deploy and interpret that repeatedly by analysing the events received as well as the current state, and moving to the proper subsequent state. This has been suggested for UML (Mellor, 2007) and is the basis of the design pattern state (Larman, 1995, p. 406). However, while Finite State Machines continue to enjoy tremendous success (Wagner and Wolstenholme, 2003), “there is no authoritative source for the formal semantics of dynamic behavior in UML” (Winter et al., 2009). The best example for the success of Finite State Machines is stateWorks (www.stateworks.com) and its methodology (Wagner et al., 2006). We have downloaded the 60-day free license of stateWorks Studio and the SWLab simulator (Fig. ??). Note that this finite state machine has only 5 states (the documentation of this example with stateWorks admits the model has issues, e.g. “to reset the system for the next start, we have to open and then close the door” and “the control system always starts even when the timeout value is 0”). These issues can be fixed but additional infrastructure is necessary, including ‘counters’ and ‘switch points’ as well as usage of the ‘real time database (RTDN)’. The stateWorks example describes generic of microwave behaviour and needs some more polishing to capture more detailed requirements e.g. those outlined in Table 2. Since we argue in favour of using finite state machines for modelling behaviour, this tool concurs with that approach. However, our evaluation confirms that using PL is more powerful and closer to the original specification than the “positive-logic” transitions in stateWorks.

5.2 Contrast with Petri Nets

Petri Nets (Peterson, 1977; Holloway et al., 1997) provide a formal model for concurrency and synchronisation that is not readily available in state diagrams. Thus, they offer the possibility of modelling multi-threaded systems that support requirements for concurrency. Early in the modelling effort Petri Nets were dismissed: “Although they succeed well as an abstract conceptual model, they are too low level and inexpressive to be useful to specify large systems” (Rumbaugh et al., 1991, p. 144). However, because it is quite possible to simulate or interpret a Petri Net (or to generate code directly from it), they continue to be suggested as an approach to directly obtain implementations from the coding of the requirements (Gold, 2004; Lian et al., 2008; Lakos, 2001; Saldhana and Shatz, 2000).

We have used PIPE 2.5 (pipe2.sf.net) to construct a model of the microwave as per the requirements in Table 2 (see Fig. 8). It becomes rapidly apparent that the synchronisation of states between com-
Figure 8: Capturing the requirements in Table 2 as a Petri Net, grouped by the various components of the microwave.

Components of the system forces to display connectors among many parts in the layout, making the model hard to grasp. Even if we consider incremental development, each new requirement adds at least one place and several transitions from/to existing places. Therefore, we tend to agree that even for this small case of the one-minute microwave, the Petri Net approach seems too low level and models are not providing a level of abstraction to assist in the behaviour engineering of the system. One advantage of Petri Net models is that there are many tools and algorithms for different aspects of their validation. For example, once a network is built with PIPE, this software has algorithms to perform GSPN Analysis, FSM analysis, and Invariant Analysis. However, even for this example, considered simple and illustrative in many circles, the model is not a suitable input for any of the verification analysis in PIPE. On a positive note, some first-order logics have been included in transitions to create Predicate/Transition Nets (Genrich and Lautenbach, 1979; Genrich, 1991). Consequently, we see no reason why our approach to use a non-monotonic logic cannot be applied to Petri Nets.

5.3 Contrast with Behavior Trees

Behavior Trees (Wen et al., 2007a) is another powerful visual approach for Behaviour Engineering (the systematic progression from requirements to the software of embedded systems). The approach provides a modelling tool that constructs acyclic graphs (usually displayed as rooted tree diagrams) as well as a Behavior Modelling Process (Dromey and Powell, 2005; Myers and Dromey, 2009) to transform natural language requirements into a formal set of requirements. The Embedded Behavior Runtime Environment (eBRE) (Myers and Dromey, 2009) executes Behavior Tree models by applying transformations and generating C source code. The tool Behavior Engineering Component Integration Environment (BECIE) allows Behavior Trees to be drawn and simulated. Proponents of Behavior Trees argue that these diagrams enable requirements to be developed incrementally and that specifications of requirements can be captured incrementally (Wen et al., 2007b; Wen and Dromey, 2004). The classic example of the one-minute microwave has also been extensively used by the Behavior Tree community (Wen and Dromey, 2004; Dromey and Powell, 2005; Myers and Dromey, 2009). Unfortunately, for this example, Behavior Trees by comparison are disappointing. In the initial phase of the method, requirements R1, R2, R5, R6 in Table 2 use five boxes (Wen and Dromey, 2004; Dromey and Powell, 2005), while R3 and R4 demand four. Six boxes are needed for requirement R7 (Wen and Dromey, 2004; Dromey and Powell, 2005). Then, the Integration Design Behavior Tree (DBT) demands 30 nodes (see (Dromey and Powell, 2005, p. 9) and (Wen and Dromey, 2004, Fig. 5)). By the time it becomes a model for eBRE the microwave has 60 nodes and 59 links! (Myers and Dromey, 2009, Fig. 6) and the Design Behavior Tree (Myers and Dromey, 2009, Fig. 8) does not fit legibly on an A4 page. Sadly, the approach seems to defeat its purpose, because on consideration of the system boundaries (Myers and Dromey, 2009, Fig. 7), outputs to the alarm are overlooked. Moreover, the language for logic tests in the tools for Behavior Trees is far more limited than even the ‘positive-logic’ of stateWORKS. The equivalence between finite state machines and Behavior Trees (Billington et al., 2010) is based on the observation that Behavior Trees correspond to the depth-first search through the treads of the states of the system behaviour control. It is not surprising that the notion needs far more nodes and connections than the corresponding finite state machine.

6 FINAL REMARKS

We stress two more aspects of the comparison. First, the approaches above attempt, in one way or another, to construct the control unit of the embedded system, and from it the behaviour of all of its components. This implies that the control unit has a state space that is a subset of the Cartesian product of the states of the components. Our approach is more succinct not only because of a more powerful logic to describe state transition, but because our software architecture decouples control into descriptions for the behaviour of components. Second, our experience with this approach and the development of non-monotonic mod-
els show that capturing requirements is structured and incremental, enabling iterative refinement. That is, one can proceed from the most general case, and produce rules and conditions for more special cases. We ensured that our method delivers executable embedded systems directly from the modelling by implementing an oven where the hardware is constructed from LEGO Mindstorm pieces, sensors, and actuators (see Fig. 9). As with eBRE, we output Java source code but execute a finite state machine. The execution then is verified because of the clear connection between the model and the source code (as well as testing it on the hardware).

5

ENDASH

REFERENCES


