Arrangements of Finite-state Machines
Semantics, Simulation, and Model Checking

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Keywords: Applications and Software Development, Model-based Testing and Validation, Model Execution and Simulation, Executable UML.

Abstract: We propose a contrasting approach to the main stream direction that UML and `STATEMATE` have recently taken when using finite-state machines (FSMs) to model behaviour. That is, rather than the event-driven model that is currently dominant, we suggest to adopt a model of time, a synchronous model. We do support concurrency in our arrangements of FSMs but eliminate the sources of unpredictable threads of execution. Currently, such capacity of the dominant semantics actually results in the need to create many language constructs to regulate threads that, in many cases, even result in imprecise semantics, hampering their use for model-driven development (MDD). By allowing transitions to only be labeled by statements of logic and by executing the machines with an offline schedule, we obtain a simpler language, with less burden for the developer. This creates far reaching potential for accompanying tools, such as integrated development environments, simulators, and even formal verification through model-checking. Model-checking is of particular importance as MDD becomes ubiquitous. Model-checking is possible for our FSMs as we do not need to consider all possible combinations of progress of each of the many threads that the event-driven alternative requires.

1 INTRODUCTION

We present a language of arrangements of finite-state machines (FSMs) that aims at offering simplicity of constructs and high versatility. Thus, this paper introduces a minimal subset of UML 2 and Harel's state charts with two significant characterisations. The first characterisation is that we adopt the synchronous model of FSMs as opposed to the asynchronous model (Harel and Naamad, 1996, Section 9, "Two models of time"). That is, our FSMs are not waiting in a state to be woken up by the occurrence of an event. In fact, once an arrangement of FSMs is present, one step of one of the FSMs is executed in each time-slot. The other significant characterisation is that transitions are labeled by queries (and not by events) to an inference engine. The idea of transitions labeled by queries (and not by events) can probably be traced to the `XABSL` modelling language (Lötzsch et al., 2004; Risler and von Stryk, 2008) for robots and agents where transitions are labeled by decision trees. This combines a declarative model (a model that describes what the software knows about, what concepts to use, what things mean), with the action model of FSMs. Minimality is sought to reduce implementation complexity, maximise ease of adoption and use, remove implicit assumptions and provide a clear semantics (several authors (von der Beeck, 1994; Eshuis, 2009; Breen, 2004; Simons, 2000) discuss the problems with state charts and as a result, there have been several revisions even to UML state-charts). In particular our modelling notation seeks agreement with UML, SXML (W3C, 2012) and Harel's state charts to maximise adoption.

2 FINITE-STATE MACHINES

Our state machines are in close proximity with the mathematical model of behaviour, the so called finite-state automata (Hopcroft et al., 1979) that produce output, also known as transducers. That is, our FSMs consist of a set S of states, and a transition function $T : S \times E \rightarrow S$. There is a distinguished state $s_0 \in S$, named the initial state. In our case, E is a set of Boolean expressions (in their most general form, our FSMs use a decidable logic and allow expressions from such a logic to label the transitions; for example, in many case studies we have used a common sense non-monotonic logic, Defeasible Logic (DPL)). This is an aspect that characterises our FSMs, and is very

Estivill-Castro V. and Hexel R..
Arrangements of Finite-state Machines - Semantics, Simulation, and Model Checking.
DOI: 10.5220/0004317101820189
In *Proceedings of the 1st International Conference on Model-Driven Engineering and Software Development* (MODELSWARD-2013), pages 182-189
ISBN: 978-989-8565-42-6

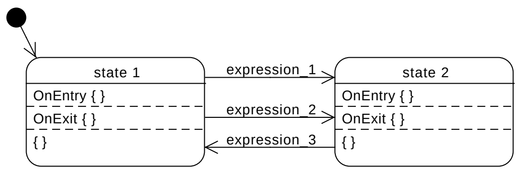


Figure 1: Basic elements of the notation.

useful for declarative modelling.

Our FSMs will be of a synchronous type. The set E are expressions. T is usually a *partial function*, that is, there are pairs (s_i, e_t) for which T is not defined; so, T is usually called the transition table. The standard general description of the semantics for $T(s_i, e_t) = s_j$ is that when the machine is in state $s_i \in S$ and if the expression e_t evaluates to true, the machine will move to the state s_j. However, this requires that, (for any $t \neq s$), if $T(s_i, e_t)$ and $T(s_i, e_s)$ are defined and $T(s_i, e_t) \neq T(s_i, e_s)$, then e_t and e_s never be true simultaneously (unless one is modelling completely non-deterministic behaviour).

We simplify the burden for the behaviour designer by making the projection of T on each state a sequence instead. That is, $T(s_i, e_t) = s_j$ will cause a transition to state s_j if e_t evaluates to true and no previous expression e_s evaluates to true ($\forall s < t$ in the sequence $T(s_i, \cdot)$). Note that while this is simply syntactic sugar, it does make the task of the behaviour designer a lot simpler.

In a FSM, each state models a period in time where an action[1] takes place. However, there are three sections where actions are grouped. An **OnEntry** section is executed upon arrival to the state, while actions in the **OnExit** section are executed as the machine departs that state. Thus, the actions in these two sections are executed once and only once. The third section is a section for internal actions[2] that are executed only if none of the transitions fires. When the internal actions are completed, execution returns to evaluate the sequence of expressions that label transitions out of the state and the cycle is repeated. We refer to one pass over the cycle as a *ringlet*.

Because our models consist of arrangements of FSMs, variables used in each of the sections above are of 3 types. The first type, **local variables**, are exclusive to one and only one FSM (that is their scope is only the states of one FSM). **Internal variables** are shared by all the FSMs in the arrangement (that is, their scope is all the states of the FSMs in the arrangement). Finally, **external variables** are variables whose scope goes even beyond the arrangement of the FSMs and in embedded systems, are variables that are set by external sensors or are set to activate effectors and actuators. The environment that holds the variables is named the *whiteboard* (Hayes-Roth, 1988), but it also correspond to the software architecture pattern of a repository (Sommerville, 2010).

By design, in one ringlet execution there is only one **read** operation by which a local copy of external and internal variables in the scope of the current FSMs is made before the execution of any section or the evaluation of any expression labelling any transition. That is, all execution in a ringlet is in the same context that is not modified by any other concurrent FSM or any external event (a new sensor reading, for example). If no transition fires and the internal actions complete, when a new ringlet commences, a new read of the external scope will take place. All writes of external or internal variables by a FSM take place immediately in the shared context.

The arrangement of FSMs is executed by a round-robin switch from one ringlet of one FSMs to the next one in the arrangement. Thus, the arrangement of FSMs is a single sequential execution, executed by one thread that interprets the semantics described above. It is possible also to indicate a relative frequency for each FSMs enabling different rates of progress which are implemented by each FSMs having a certain number of ringlets performed before passing the execution token to the next FSM in the arrangement. Note that this style of execution is very much in line with the time-triggered architecture (Kopetz and Bauer, 2003) (as opposed, as we mentioned earlier, to an event-driven architecture).

We make a first contrast with other approaches. Historically, the de-facto standard for FSMs is derived from the `STATEMATE` model (Harel and Naamad, 1996; Harel et al., 1990) but there have been many alternative proposals (von der Beeck, 1994). There are several commercial products including *QP*™ (Samek, 2008), *BotStudio* (Michel, 2004) *StateWORKS* (Wagner et al., 2006) and *MathWorks*® *StateFlow*. The UML form of FSMs derives from OMT (Rumbaugh et al., 1991, Chapter 5), and the MDD initiatives of Executable UML (Mellor and Balcer, 2002). In all of these, the set E is a set of events, or a set of input symbols. But, in UML 2 and other FSM languages that enable guard conditions, a need appears to recommend best practices (Klotzbuecher, 2012), where the exclusive disjunction of all guard conditions out of a state shall always be true. Also, in UML 2 and `STATEMATE`, two transitions from a single state that evaluate to true represents a conflict and an invalid configuration. This is not a concern in our modelling language. Expressions out of a state

[1]We make no distinction between actions and activities, and more on this will be discussed later.

[2]In UML known as the `do` section.

form a list (in Fig. 1 we have indicated this by a sequence numeral) and thus, the second expressions can be seen as the conjunction with the negation of the first. *MathWorks*®, *StateFlow* with *Symlink* concurs with our approach and specifies a sequential evaluation of only one event at a time and a mechanism to specify priorities in transitions but its larger set of primitives and its semantics requires complex translations for performing model-checking (Agrawal et al., 2004).

Our use of a single-thread execution for the several FSMs in the arrangement, *as opposed to parallelisation* by a semantics that just specifies concurrency (that is arbitrary rate of progress for each, as each is executed within an independent thread) brings several advantages. It has been argued that from the design point of view, open concurrency (where the management of switches between threads is left to the system) represents an unnecessary cognitive load in the model designer (Breen, 2004) as it opens all sorts of needs for communication, synchronisation and consideration of communication delays. There is added complexity in ensuring properties like fairness, management of critical sections, no deadlock, and extermination of starvation. It is also the case that the execution (that is implementation) is usually less efficient, as concurrency control mechanisms consume CPU cycles and may need to manage context switches and communication primitives with native support from the operating system or the hardware. Perhaps more important is actual formal verification that models are correct. Model-checking of systems that enable concurrent threads must consider a universe of all possible states of the system, represented by the Cartesian product of all possible states of each thread. This combinatorial explosion significantly complicates the formal verification of such a system. For robotic systems and embedded systems where there may be several timing requirements, sequential execution has been proposed as superior to the multiplication of threads (Merz et al., 2006).

By using sequential scheduling we maintain concurrency, and the models produced with the logic-labelled FSMs can be verified using model-checking technology (`NuSMV`) within a matter of seconds (Estivill-Castro et al., 2012c; Coleman et al., 2012), while for the same case studies, but using Behavior Trees – which have explicit notation for spawning parallel threads – require several days of CPU to verify equivalent properties (Grunske et al., 2011).

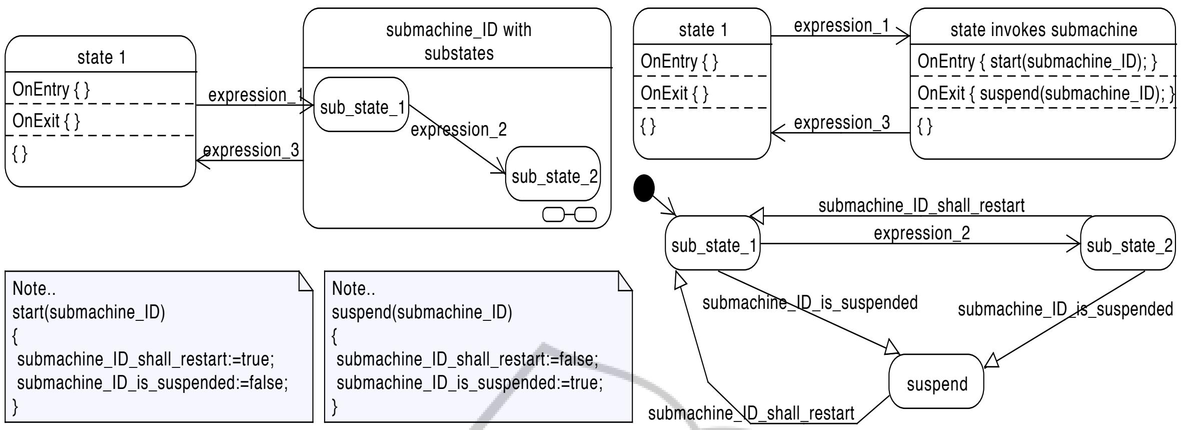
It is important to note that the approach presented here is not a departure from the event model of traditional FSMs. In fact, the ability of our FSMs to use statements in a decidable common-sense logic allows for a more complex event definition with clear value and temporal semantics (Billington et al., 2010). Sensors that trigger events in an embedded system are mapped to external variables of which a snapshot is taken at the **read** pre-determined point at the start of the ringlet (Estivill-Castro et al., 2012a). Our choice to place only one **read** instance of the variables per ringlet may seem to contradict the `STATEMATE` "execution time" requirement that suggest changes in any point in time should be reflected in the next. However, `STATEMATE`'s approach creates serious problems in robotics applications where there is an *open environment* (Klotzbuecher, 2012), and languages like `rFSM` also take an approach to evaluate the set of transitions out of a state in the same context.

3 MODULARISATION

Harel's state charts (Harel and Politi, 1998) introduced a hierarchy of states, i.e., states that themselves contain other states; providing abstraction and modularisation for the construction of larger models. Modularity is a very powerful design tool (Baldwin and Clark, 2000) and such sub-machines can be re-used, facilitating the design of behaviours as components.

With our approach, modularity is achieved through a model of suspension. Each FSM has a `SUSPENDED` state. In its `SUSPENDED` state, a machine simply passes the execution token to the next FSM in the arrangement. Our language offers specialised expressions to control suspension. The expression `suspend(machine_id)` triggers an implicit transition in the FSM identified by `machine_id` from its current state to its `SUSPENDED` state, recording what the current state was. The expression `resume(machine_id)` triggers an implicit transition of the corresponding machine (from its `SUSPENDED` state) back to the recorded, previous state. The expression `restart(machine_id)` triggers an implicit transition of the machine from its `SUSPENDED` state to the machine's initial state (effectively restarting the machine from the beginning).

Because modularity is an important design tool, and although a hierarchy of FSMs machines is not enforced, our flexibility enables the construction of a very powerful notion of submachine. To do this, the parent machine places the corresponding `restart(sub_machine_id)` in its **OnEntry** section, and the corresponding `suspend(sub_machine_id)` in its **OnExit** section. If the corresponding sub-machine, creates itself a further level of sub-machines, then the sub-machine puts `suspend` instructions for its sub-machines in the **OnEntry** sec-



```
Note..
start(submachine_ID)
{
 submachine_ID_shall_restart:=true;
 submachine_ID_is_suspended:=false;
}
```

```
Note..
suspend(submachine_ID)
{
 submachine_ID_shall_restart:=false;
 submachine_ID_is_suspended:=true;
}
```

Figure 2: Semantics of the submachines in terms of the basic structures. The code in the notes and the arrows with a triangle head (which have highest priority for each state) are implicit (they are never drawn; they are embedded in the interpreter).

tion of its own `SUSPEND` state. This pattern is illustrated in Fig. 2. Moreover, the `restart`, `suspend` and `resume` instructions can create more flexible launch and suspend patterns in an arrangement of FSMs.

In contrast, the Harel's sub-machine model suggests a certain level of concurrency (two threads, one for the submachine and one for the parent machine). Breen (2004) identifies two issues with this, (1) broadcasting of events, and (2) a need for structural priority to resolve which transitions in the stack of nested states is to be evaluated. We point out to a third fundamental problem due to nested states implying concurrency or parallel execution. Namely, the modelling tool, while powerful, leaves open the scheduling of the threads of control that prescribes the CPU cycles for each state. As a result, any model-checking of the hierarchical state-charts must consider all possible combinations of progress of each thread (at instruction level, i.e. at a much lower level than even a Kripke structure for the given FSMs). This results in a combinatorial explosion that complicates (and in most cases makes infeasible) the practice of formal model-checking.

We do have concurrency in our modelling language. But we specify the semantics of the schedule. First, we have a single thread of control. Second, we have structured, as a sequence, the transitions leading out of each state. Thus, we can have machines in an arrangement that are not required to be submachines, resolving the three fundamental problems mentioned in the previous paragraph. Note that others (Merz et al., 2006) – in particular, the `rFSM` language (Klotzbuecher, 2012) – have also chosen to remove the parallelism of state-charts because of these issues. Also note that while `STATEMATE` and UML 2 both use structural priority, the order of priorities is reversed. UML 2 assigns higher priority to transitions in deeper nested states.

We stress the importance of the semantics of our submachine model in comparison with UML and `STATEMATE`. The hierarchical machines of UML, with independent threads for the machine and submachines, implies that the evaluation of a transaction in a submachine overlaps with the transition of higher states in the hierarchy and examples show that this can lead to stuck execution. UML 2.1 circumvents this problem by prohibiting the initial transition from defining guard conditions, but introduces a semantic point variation that leaves open the semantics of transitions to composite states without initial conditions. `STATEMATE` semantics can also lead to code that gets stuck (there are semantical differences between simulated and generated code (Harel and Naamad, 1996, page 303)). Our deterministic semantics completely avoids this issue and maintains concurrency. In robotic systems, and embedded systems with only one (single-core) processor, parallel execution is just conceptual, as the system would always execute a sequential schedule (albeit with the concurrency issues pointed out above). We do not lose the conceptual modularity of several FSMs but add much clearer modelling capabilities (and reliability due to execution determinism).

4 TRANSITIONS

Our transitions do not have events, as we indicated, but an event causes (in our reference implementation) a change of a Boolean variable `event_hasHappened` in a whiteboard. Thus, the UML form `event [ guard ] / effect` of a transition is in fact the conjunction of the Boolean variable `event_hasHappened` and the `guard`. So, the expressivity is the same but we handle the above structure by `event_hasHappened && guard / effect`. Consider robotic soccer; the vision module sets the variable `ballIsVisible` in the whiteboard and this is the expression that switches from a state of searching for the ball to a behaviour that seeks the ball.

We only have effects with a very clear semantics. We take the view that the **OnEntry** for *S* is executed once and exactly once. And naturally, the **OnExit** for *S* is part of the transition leaving *S*. We allow effects only thus as an intermediate virtual state. That is, effects are just syntactic sugar for a model with an intermediate state (Fig. 3). This now explains why we do not distinguish between atomicity and non-atomicity of the `do` section of a state as all the executable code corresponding to the arrangement of FSMs is scheduled sequentially and execution of any code in the arrangement cannot be preempted by another section of code in the model. That is, there is no distinction in our language between activities and actions.

This makes very clear that in our semantics, transitions belong to the source state, and finish in a target state. We note that other FSM modelling languages (for example `rFSM`) require transitions actually to depart a set of *active* states (this is mainly due to the hierarchical nesting of states discussed earlier).

In contrast, UML's event-labeled transitions present challenges. Note that transitions labeled with the conjunction of events

`event_1` && `event_2`[`guard`]/`effect`.

have inspired the debate of "event history" as the transition would not "fire" unless both events happen "at the same time". Thus, even event-based FSMs use some event-history mechanism, but in our case, the concerns regarding event-history are removed from the behaviour designer and are simply handled in the sensor-rate update of the whiteboard.

The *effects* component (and also **OnEntry** and **OnExit** sections) usually cause variation points or undefined semantics. In UML, and its variants, effects are actions (and thus atomic, the **OnEntry** and **OnExit** sections of states are also atomic), and cannot be interrupted, to avoid these semantic issues. The problem of being interrupted is the result of the possible existence of another thread in the hierarchy of nested states which can raise an event for which we have a transition now. The UML, and its variants, declare **OnEntry** and **OnExit** sections, like effects, as parts of the transition. However, even in this case, it is not always clear that the **OnEntry** section of a state *S* is part of the previous transition that moved control to the state *S*. This is extremely important as the current state *S* may have a transition simply labeled `true` and with the highest priority.

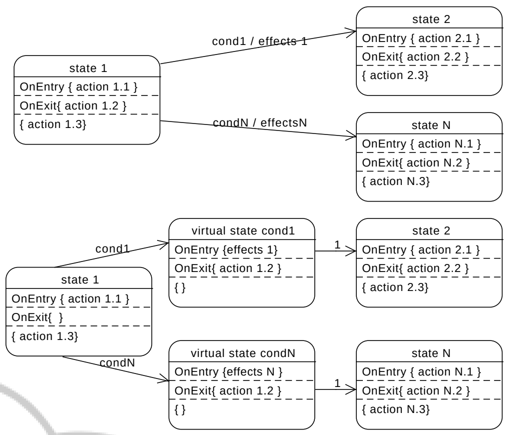


Figure 3: Transition `effect` part is an **OnExit** section for a separate, virtual state.

This also raises the issue of *boundary-crossing* transitions. Simons (2000) has already argued the redundancy of these types of transitions as well as the conceptual challenges caused to behaviour designers by allowing these. Note also that this use caused revision from UML 2 to UML 2.1 (in particular the introduction of multiple *exit* points) and that further issues were addressed in UML 2.3 making the owner of a transition the *least-common ancestor* (LCA). Note that our language keeps things simple, and avoids all these issues completely, siding with Simon's argument. That is, boundary-crossing transitions are impossible to be drawn. The implicit transitions of the `restart` and `resume` mechanism described before are just syntactic sugar that avoid requiring a separate, explicit suspend state replicated for every state in an FSM and corresponding transitions back to the previous state and the initial state.

The issue of a hierarchy of states and the LCA is a result of state hierarchies. UML allows *internal transitions* (although UML leaves open their priority with respect to self-transitions), because in a state-hierarchy these are not redundant; but otherwise they are (Simons, 2000). Thus, we also do not include internal transitions in our language. Recall that an internal transition is a self-transition (that is a transition with the same source and target state) but where neither the **OnEntry** nor the **OnExit** sections execute (while a self-transition is an ordinary transition that executes the **OnEntry** and the **OnExit** sections). If the behaviour designer wishes to express an internal transition, we suggest the pattern of Fig. 4.

4.1 Pseudo-states

This discussion takes us to the UML concept of pseudo-states. We do have *initial* pseudo-states, in-

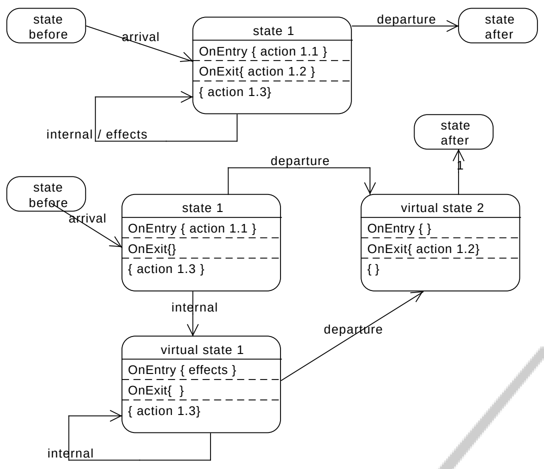


Figure 4: Internal transitions are relevant only for their **effect** and can be constructed with this pattern.

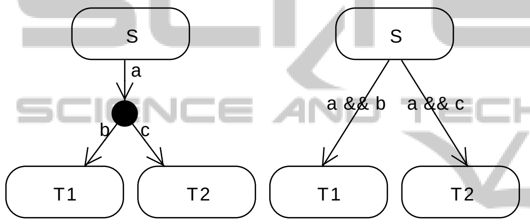


Figure 5: A junction (left) modelled through a common clause *a* (right).

dicated by the full-circle. The semantics is clearly the corresponding point in the ringlet of the state *S* pointed by the arrow from the initial pseudo-state (namely, just before the **OnEntry** of *S*). But, we do not have UML's *choice* pseudo-states in our transitions at all. Note that UML recommends the use of an *else* transition with the use of choice as execution becoming stuck is otherwise a possibility. Without loss of generality, we simply remove this. Correspondingly, we treat UML's *junction* simply as syntactic sugar to factor out a common clause in a conjunction (as illustrated in Fig. 5).

Naturally, the issues with the open thread leads to *exit* and *entry* pseudo-states in UML, but with a very delicate semantics that varies whether the pseudo-state is drawn inside the sub-state or in the boundary. This danger has been noticed by `rFSM` and we follow their approach by simply eliminating them.

UML then offers a *Completion Event* as a synchronisation event for the possibility of the `do` section being interrupted and other sub-states waiting for such completion as well. UML also assumes unrealisticly that the departure of a state implies the arrival to an *exit* pseudo-state of all its sub-machines (and the termination of their activities). This is unrealistic even in the multi-threaded realisation unless a native operating-system call can abort those threads. Any other realisation where the sub-thread are actually waiting for a signal so themselves send a signal to halt a device (say a thread is in control of the motor) depends on the priorities given by the thread management to deliver the signal to the thread, and for this one to have a sufficient CPU slice in order for itself to send the halting signal to the motor controller. We claim that our synchronised scheduling is thus more effective. We can predict how many steps will be needed for the thread controlling the motor to become live and perform its **read** of the signal in the whiteboard and then shut down the motor. Such predictability has been demonstrated by our model-checking of several case studies.

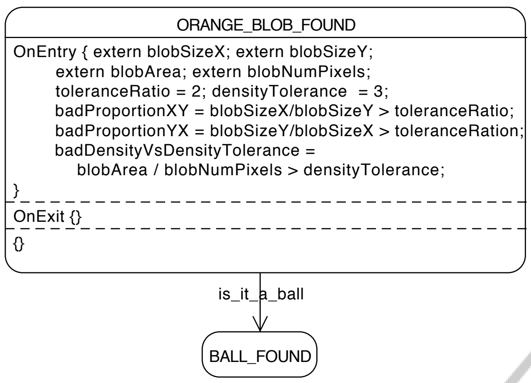
We do not have any explicit representation of *final* or *terminate* pseudo-states (similarly to `rFSM`). Our arrangement of machines maintains variables of the form `machine_ID_isRunning` that enables the discovery that some machine in the arrangement is in its suspended state or has reached a final state. Such completion happens when a FSM reaches a state without any transition departing. This effectively removes the machine form the scheduling.

The UML *history* pseudo-state is covered by our `resume` primitive, but without the need that occurs in UML of enabling deep and shallow history pseudo-states (that again are a result of the parallel threads of hierarchical states). Finally, the synchronous model proposed here also makes superfluous the UML *join* and *fork* pseudo-states, and UML *deferred* events. An aspect that UML allows is inheritance between FSMs; our language currently does not support this, but to the best of our knowledge, to date, nobody else has chosen to to include such a facility.

5 EXAMPLES

We have successfully used our approach to model and implement numerous case studies. Perhaps most importantly, we have been able to uncover hidden complexities and errors in prior modelling of software engineering problems (Winter and Yatapanage, ; Grunske et al., 2011). To this end, we have both performed formal model checking (Estivill-Castro et al., 2012c) as well as simulation of system behaviour (Coleman et al., 2012).

The **first example** where we used an arrangement of FSMs is a widely studied case of a micro-wave oven. The model can be fully verified by formal model-checking (even with integer variables in the timer) and it can be executed as a `Java` program on an NXT robot or a `C++` program on a Nao robot. This il-



```
OnEntry { extern blobSizeX; extern blobSizeY;
        extern blobArea; extern blobNumPixels;
        toleranceRatio = 2; densityTolerance  = 3;
        badProportionXY = blobSizeX/blobSizeY > toleranceRatio;
        badProportionYX = blobSizeY/blobSizeX > toleranceRation;
        badDensityVsDensityTolerance =
            blobArea / blobNumPixels > densityTolerance;
}
OnExit {}
{}
```

Figure 6: Section of the vision pipeline to recognise a blob of orange as a ball.

```
% BallConditions.d

name{BALLCONDITIONS}.

input{badProportionXY}.
input{badProportionYX}.
input{badDensityVsDensityTolerance}.

BC0: {}            => is_it_a_ball.
BC1: badProportionXY  =>  ~is_it_a_ball. BC1 > BC0.
BC2: badProportionYX  =>  ~is_it_a_ball. BC2 > BC0.
BC3: badDensityVsDensityTolerance  =>  ~is_it_a_ball. BC3 > BC0.

output{b is_it_a_ball, "is_it_a_ball"}.
```

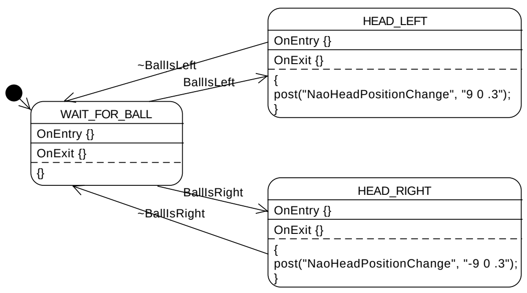
Figure 7: Theory that defines when a blob is a ball.

lustrates the language independence and platform independence of this MDD approach. The model can also be simulated (Coleman et al., 2012) and has been subjected to fault injection to produce FMEA tables for the analysis of failure-robustness (Estivill-Castro et al., 2012c; Estivill-Castro et al., 2012a).

Two examples where this approach has been successful in performing simulation, model-checking, and execution across platforms, are a Mine Pump and an Industrial Press (Coleman et al., 2012; Estivill-Castro et al., 2012c; Estivill-Castro et al., 2012a). A **fourth case study** where simulation and model-checking has been very effective has been the Ambulatory Infusion Pump (Estivill-Castro et al., 2012b). That case study utilises multiple submachines.

In a **fifth example**, these FSMs have also been used to include a planner, with re-planning (in the sense of artificial intelligence) into the capabilities of a robot while maintaining platform independence (Ferrer Mestres, 2012).

Our FSMs are used by the MiPal team at RoboCup. We now show here a **sixth example** of combining a non-monotonic logic with a vision pipeline to illustrate how powerful the combination of a declarative language with the arithmetics facilitated of an imperative language can be. To illustrate the power of combining the arithmetic provided by



```
{
post("NaoHeadPositionChange", "9 0 .3");
}
```

```
{
post("NaoHeadPositionChange", "-9 0 .3");
}
```

Figure 8: A simple ball tracker.

`simpleC` with the declarative nature of DPL we show a simple example of filtering for image recognition of objects in robotics. In particular, in robotic soccer (RoboCup), images are processed at a frame rate of 30 frames per second by a vision pipeline that, after segmentation, builds blobs of colours. We illustrate the filtering of blobs by the declarative language (this is basically a description of when a blob is considered a ball, and, for simplicity, we ignore many other aspects). Suffice it to say that usually, a blob of orange should be recognised as a ball (this is rule `BC0` in the DPL file; see Fig. 7).

However, if the blob's size on the *X* axis is much larger than the blob's size in the *Y* direction, it is considered a rectangular blob, far from the more square-shaped blob that corresponds to a ball (the blob is the smallest bounding rectangle that contains the orange pixels); thus, this is not a ball (rule `BC1`). Similarly, if the blob's size for *Y* with respect to the *X* size (this is rule `BC2`) and both of these rules defeat rule `BC0`; thus we have the relations `BC1 > BC0` and `BC2 > BC0`. Finally, if the number orange of pixels is much smaller than the area of the blob in pixels, there are many gaps of non-orange and it should not be considered a ball (rule `BC3` which also defeats `BC0`). Incrementally, more sophisticated and refined revisions on the conditions can be made by adding rules to the theory of Fig. 7, while the arithmetic is kept in Fig. 6.

Also, in robotics, a traditional topic is the tracking of an object by a feedback control (and can also be illustrated by Robotic soccer) as the robot tracks the ball. Such tracker can be coded in our modelling language and it appears in Fig. 8.

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