**Complete Code Generation from UML State Machines**

Keywords: UML State Machine, code generation, semantics-conformance, efficiency, events, C++

Abstract: An event-driven architecture is a useful way to design and solve the complexity of today’s systems. The UML State Machine and its visualizations are a powerful means to the modeling of the logical behavior of such an architecture. Model Driven Engineering generates executable code from state machines. However, exist- ing generation approaches tools from UML State Machines are still limited to simple cases, especially when considering concurrency and pseudo states such as history, junction, and event types. This paper provides a pattern and tool for complete and efficient code generation approach from UML State Machine. It extends the IF-ELSE-SWITCH constructions of programming languages with our concurrency support. The code gener- ated with our approach has been executed with a set of state-machine examples that are part of a test-suite described in the recent OMG standard Precise Semantics Of State Machine. The traced execution results com- ply with the standard and are a good hint that the execution is semantically correct. The generated code is also efficient: it supports multi-thread-based concurrency, and the (static and dynamic) efficiency of generated code is improved compared to considered approaches.

# 1INTRODUCTION

The UML State Machine (USM) (Specification and Bars, 2007) and its visualizations are efficient to model the behavior of event-driven architectures. Tools and approaches [XX] are proposed to auto- matically translate USMs into executable code in the context of Model-Driven Engineering (MDE) (Muss- bacher et al., 2014).

However, despite many advantages of MDE and USM, they are not really widely adopted as a recent survey revealed (Whittle et al., 2014). This is partially due to poor support for code generation (Forward, ).

On one hand, the usefulness and semantics of USM are being empowered by OMG by providing more concepts and their precise semantics such as pseudo states and composite state machines. On the other hand, existing code generation tools and ap- proaches have some issues regarding completeness, semantics and efficiency of generated code. Existing approaches either support a subset of USM modeling concepts or handle composite state machines by flat- tening into simple ones with a combinatorial explo- sion of states, and excessive generated code (Badred- din et al., 2014a). Specifically, the following lists some of the current issues:

**Completeness:** Existing tools and approaches mainly focus on the sequential aspect while the concurrency of state machines is not much taken into account. Pseudo states are not rigorously supported by exist- ing tools such as Rhapsody (IBM, 2016). Designers are then restricted to a subset of USM concepts during

design.

**Efficiency:** Code generated from tools such as Rhap- sody (IBM, ) and FXU (Pilitowski and Derezin˜ska, 2007) depends on the libraries provided by the tool vendor, which makes the generated code non portable. Event processing speed and executable file size of generated code are not optimized (Charfi et al., 2012).

**Semantics: the** semantics of UML State Machine is defined by a recent OMG-standardized: Pre- cise Semantics of State Machine (PSSM) (OMG, 2015). This standard is not (yet) taken into account for validating the runtime execution semantics of generated code.

Given the above issues, the objective of this paper is to present a novel code generation pattern and its tooling support. The latter offers efficient code gen- erated from USMs with full concepts to reduce the modeling-implementation gap.

The proposed pattern extends IF-ELSE construc- tions with our support for concurrency. Runtime execution of generated code experimented with the PSSM test suite.

To sum up, the contributions of this paper are:

1. an approach and tooling support for code gener- ation from USMs with full features; (2) an empirical study on the semantic-conformance and efficiency of gen- erated code; and (3) application of the tool to a case study.

We assume that readers of this paper have knowl- edge about UML State Machine and its basic execution se- mantics.

The remaining of this paper is organized as fol-

lows: Section 2 describes the modeling of applica- tions using UML State Machines. Section 3 mentions the unique features of our tool. Thread-based con- currency is designed in Section 4. Based on this de- sign, a code generation approach is proposed Section

5. The implementation and empirical evaluation are reported in Section 6. The application of our tool to a case study is presented in Section 7. Section 8 discusses related work. The conclusion and future work are presented in Section 9.

# 2STATE MACHINES AND UML EVENTS

This section presents overview of using UML State Machines for modeling and designing reactive software applications. A state machine is used for describing the behavior of either a class in object- oriented design or a component in component-based design. In the following, we commonly use the term *class* since a component is usually transformed into an object-oriented class.

The state machine processes external and inter- nal events. UML defines four event types: *CallEvent, SignalEvent, TimeEvent, ChangeEvent*. A call event is associated with an oper- ation/method and emitted if the operation is invoked. The processing of call events is synchronous meaning that it runs within the thread of the operation caller. The processing of other events is asynchronous mean- ing that these events received by the class are stored in an event queue which is maintained by the class at runtime for later processing. A signal event is as- sociated with a UML signal type containing data. It is emitted if the class receives an instance of the sig- nal type. From a programming perspective, we pro- vide an API *sendSignal* to send the signal instance from environment code or other classes to the class and store the event in the queue.

A time event specifies the time of occurrence rel- ative to a starting time. The latter is defined as the time when a state with an outgoing transition triggered by a time event is entered. The time event is emitted if this accepting state remains active longer that the relative time of occurrence. Once emitted, it triggers the transition. In other words, the state, which is the source vertex of a transition triggered by a time event, will remain active for a maximal amount of time specified by the time event. A change event has a boolean expression and is fired if the expression’s value changes from false to true. Note that unlike call and signal events, time and change events are au- tomatically fired inside the class.

**Deferred events**: A state can spec- ify to defer some events. It means that an event in front of the event queue which is in the list of de- ferred events of an active state will be not processed immediately but pulled from the queue to a deferred queue for keeping de- ferred events. In other words, the deferred events will not be processed while the state remains active. The deferred event will be pushed back to the event queue if another event in the event queue is processed.

We support all of these events to model event- driven reactive applications.

# FEATURES

Our pattern and tool has some unique features compared to other tools as followings:

**Completeness:** Our tool supports all state machine vertexes and transitions including all pseudo states and transition kinds such as external, local, and in- ternal. Hence, the tool improves flexibility of using UML State Machines to express architecture behav- ior. For the moment, the only issue with the tool is that it cannot deal with transitions from an entry point to an exit point.

**Event support:** Our tool promotes four UML event types and event deference mechanism, which are able to express synchronous and asynchronous behaviors and exchange data between components/classes.

**UML-conformance:** A recent specification formal- izing the Precise Semantics of UML State Machine (PSSM) is under standardization by the OMG. It defines a test suite with 66 test cases for certifying the confor- mance of runtime execution of code generated from UML State Machines. We have experimented our tool with the test suite. Traced execution results of 62/66 test cases comply with the standard and are, therefore, a good hint that the execution is semantically correct.

**State machine configuration:** Asynchronous events are stored in an event queue. Change expressions of change events are monitored and periodically evalu- ated1 to track their values. Our tool allows to config- ure the event queue size and periodic time for evalua- tion of change events. The configuration is not speci- fied by UML because the specification wants to be ab- stract. We allow to determine these values through a specific profile. Fig. 1 shows the configuration stereo- type annotated on the state machine example.

**Efficiency:** We conducted experiments on some benchmarks to show that code generated by our tool

1Currently, this discrete evaluation mechanism is not recommended for critical systems since the monitor might miss change event occurrences between two evaluations.

is efficient and can be used to develop resource- constrained embedded software. Specifically, event processing is fast and the size of executable files com- piled from generated code is small.

**Event API:** Generated code in our tool provides APIs for environment code to invoke operations or send data signals to reactive classes. The invocations and sending will automatically fire events for state ma- chines to process.

**Concurrency:** Concurrency aspects in state ma- chines including doActivity of states, orthogonal re- gions, event detection, and event queue manage- ment are handled by the execution of multiple threads. Currently, we use POSIX threads for concur- rency.

# 4CONCURRENCY

This section describes our design of concurrency aspects of state machines in generated code at run- time.

## Thread-based design

The concurrency of USMs is based on multiple thread, including permanent and spontaneous threads. While permanent threads (PTs) are created once and live as long as the state machine is alive, spontaneous threads (STs) are spawned and active for a while. Each PT is initialized at the state machine initialization. The design of threads is based on the thread pool pattern, which initializes all threads at once, and the paradigm ”wait-execute-wait”. In the latter, a thread **waits** for a signal to **execute** its asso- ciated method and goes back to the **wait** point if it receives a stop signal or its associated method com- pletes. Each PT is associated with one of the follow- ing actions:

* + - *doActivity* of each state if has any.
    - Sleep function associated with a time event which

counts ticks and emits the event once it completes.

* + - Change detect function associated with a change

event which observes a variable or a boolean ex-

pression and pushes an event to the queue if a change occurs.

* + - State machine main thread, which reads events

from the event queue, and sends start and stop sig-

nals to other PTs.

STs which are spawned by a parent thread, joined until and destroyed once the associated methods com- plete. The STs follow a paradigm in which the spawning parent must wait until its children complete their associated methods. These threads are used for the following cases:

* + - A thread is created for each effect of transitions

outgoing from a *fork* or incoming to a *join*.

* + - Entering a concurrent state, after the entry action

of the state, a thread is created for each orthogonal

region.

* + - Exiting a concurrent state, before the exit action

of the state, a thread is created for each region to

exit the corresponding active sub-state.

## Thread communication

Each PT is associated with a mutex for synchro- nization in the multi-thread-based generated code. The mutex must be locked before the method associated with the thread is executed.

**Run-to-completion:** The event process must follow the run-to-completion semantics of UML State Ma- chines. The semantics means that the state machine completes processing of each event before starting processing the next event. If all events are asyn- chronous, the main thread processes events by read- ing one-by-one from the event queue. However, be- cause we allow call events to be synchronous, the pro- cessing of synchronous and asynchronous events can violate the run-to-completion semantics. To avoid it, a main mutex is associated with the main thread to protect the run-to-completion semantics. Each event processing must lock the main mutex before execut- ing the actual processing. In generated code, lock and unlock are implemented using signals and conditions in POSIX (POSIX, ).

**Multi-threaded problems checking:** We use POSIX threads to realize concurrency in UML State Ma- chines. We use the Valgrind DRD tool (DRD, ) to check multi-thread problems such as data races, dead- lock, and misuse of POSIX threads API in generated code. The latter is derived from the PSSM test suite. The generated code is free of multi-thread errors. The result show that code generated by our tool potentially avoids multi-thread problems.

# 5CODE GENERATION PATTERN

This section describes our code generation pattern for states,

## State

A common state type *IState* is created. The type has two attributes called *actives*, to preserve the hierarchy of composite states, and *previousActives* referring to current and previous active sub-states in case of the presence of history states. Each UML state is transformed into an instance of **IState** and a state ID (which is a child element of an enumeration). During

Listing 1: IState interface and function pointers in C++

1 **t y p e d e f s t r u c t** I S t a t e *{*

**i n t** p r e v i o u s A c t i v e s [ 2 ] ; **i n t** a c t i v e s [ 2 ] ;

3 *}* I S t a t e ;

**c l a s s** C *{*

5 **p r i v a t e** :

I S t a t e s t a t e s [ STATE MAX ] ;

7 **p u b l i c** :

**void** e n t r y ( S t a t e I d i d ) *{*

9 **s w i t c h** *{* i d *} {*

**c as e** S0 ID :

11 / /a c t i o ncodef o reachs t a t e

**break** ;

13 / /codef o ro t h e rs t a t ea c t i o n s

*}*

15 *}*

*}*

Listing 2: Example code generated for doActivity

**while** ( **t ru e** ) *{*

2 mutex [ s t a t e I d ] . l o c k ( ) ;

**while** ( ! i s S t a r t s [ s t a t e I d ] ) *{*

4 / /a w a i ts t a r ts i g n a l

mutex [ s t a t e I d ] . w a i t ( ) ; *}*

6 d o A c t i v i t y ( s t a t e I d ) ;

i s S t a r t s [ s t a t e I d ] = **f a l s e** ;/ /r e s e tw a i tf l a g

8 mutex [ s t a t e I d ] . u n l o c k ( ) ;

**i f** ( ! i s S t o p s [ s t a t e I d ] ) *{*

10 **i f** ( s t a t e I d == S0 ID *| |* . . . ) *{* / /a t o m i cs t a t e s

push Completion Event ( s t a t e I d ) ;

12 *}*

*}*

14 *}*

initialization, each instance initializes its attributes to a default value meaning inactive state.

In the following sections, we only consider C++ as a specific generated language. The discussion of other object-oriented languages are much similar since these share the same concepts.

Listing 1 shows the state type and its instances. *STATE MAX* is the number of states. The state actions such as entry/exit/doActivity are generated to corre- sponding common methods containing action codes. For example, *entry* in the listing implements all of the state action codes.

State *doActivity*s, as specified by UML, are run concurrently. Each *doActivity* is then run within a permanent thread and a mutex is created for control- ling it. Listing 2 shows a code segment for *doActivity* threads. The method *doActivityThread* takes as input a state id to use and call the appropriate mutex and *doActivity*, respectively. The method does nothing and stays in a waiting point if the state correspond- ing to the input parameter state identifier is inactive. If the state active, a start signal is sent to this thread method to start the execution of doActivity.

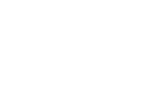
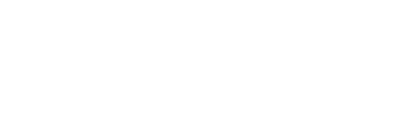
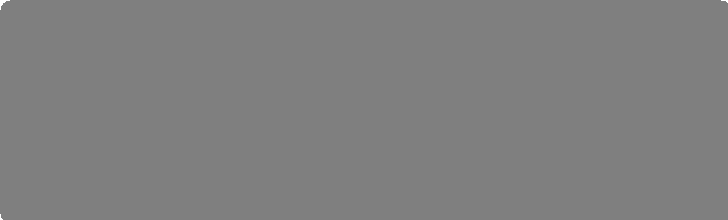


Figure 1: Example illustrating different ways entering a composite state

## Region

Our approach considers regions as elements to be transformed. Specifically, each region is transformed into an entering and exiting method. The entering method controls how a region *r* is entered from an outside transition and the exiting method exits com- pletely a region by executing exit actions of sub-states from innermost to outermost.

A region can be entered two different ways: (1) **entering by default**: the transition ends at the border of composite states; and (2) **cross transition**: enter- ing at a direct or an indirect sub-vertex of composite states. The two entering ways execute the entry ac- tion of the containing composite state after the tran- sition effect. The executions afterwards are different for each way. To illustrate, we use an example as in Fig. 1 with *S1* as a target composite state. *t1* is in the way (1) while *t2, t5, t6* in the way 2.

The entering method associated with the region of *S1* has a parameter *enter mode* telling how the en- tering should be executed. *enter mode* takes values depending the number of transitions coming to the composite state. The detail of how these modes are implemented in specific languages are not discussed here. Listing 3 shows the C++-like example code gen- erated.

By default, the region’s active sub-state is set after the execution of any effect associated with the initial transition, *S*3 is set as active sub-state of *S*1. Entering at (*S2*) sets the active sub-state of *S1* directly to *S2*. In case of an indirect sub-state (*S*4), the entry action of *S*3 is executed before *S*4 is set as the active-sub state of *S*3 and the entry execution of *S*4. It is worth noting that after the execution of each entry action, a start signal is sent to activate the waiting thread associated with *doActivity* of the corresponding state.

Transitioning from a vertex to a sub-vertex of the composite state (transition from *S*0 to *SH* is a partic- ular case) is not as simple as that of two states. This is detailed in the next section.

The method generated for exiting a region is sim- pler than that of entering. It basically executes the exit actions of all the active sub-states from innermost to outermost.

Listing 3: Example code generated for the region of S1

vo i d S 1 Region 1 Enter ( i n t e n t e r m o d e ) *{*

2 **i f** ( e n t e r m o d e == DEFAULT) *{*

s t a t e s [ S1 ID ] . a c t i v e s [ 0 ] = S3 ID ;

4 e n t r y ( S3 ID ) ; s e n d S t a r t S i g n a l ( S3 ID ) ; S 3 Region 1 Enter ( DEFAULT) ;

6 *}* **e l s e i f** ( e n t e r m o d e == S2 MODE) *{*

/ / . .

8 *}* **i f** ( e n t e r m o d e == SH MODE) *{*

State IDEnum h i s ;

10 **i f** ( s t a t e s [ S1 ID ] . p r e v i o u s A c t i v e s [ 0 ] ! = STATE MAX) *{*

h i s = s t a t e s [ S1 ID ] . p r e v i o u s A c t i v e s [ 0 ] ;

12 *}* **e l s e** *{*

h i s = S2 ID ;

14 *}*

s t a t e s [ S1 ID ] . a c t i v e s [ 0 ] = h i s ;

16 e n t r y ( h i s ) ; s e n d S t a r t S i g n a l ( h i s ) ;

**i f** ( S3 ID == h i s ) *{*

18 S 3 Region 1 Enter ( S3 REGION1 DEFAULT ) ;

*}*

20 *}* **e l s e i f** ( e n t e r m o d e == S4 MODE) *{*

s t a t e s [ S1 ID ] . a c t i v e s [ 0 ] = S3 ID ;

22 e n t r y ( S3 ID ) ; s e n d S t a r t S i g n a l ( S3 ID ) ; S 3 Region 1 Enter ( S4 MODE) ;

24 *}* **e l s e i f** ( e n t e r m o d e == ENP MODE) *{* . . . *}*

## Event

Similar to the approach in (Niaz et al., 2004), one method is generated for each event. An event enumeration *EventId* is created whose children are event identifiers associated with events. The event list of a state machine contains explicitly defined events and a special event called completion event, which is implicitly implemented. A completion event is fired when either the execution of the *doActivity* of sim- ple/atomic state completes or all regions of a compos- ite state have reached final states. For each event type, the pattern is realized as followings:

**CallEvent**: When its associated operation is called, the event processing waits and locks the main mutex protecting the run-to-completion semantics as previ- ously mentioned, and executes the event processing (see 4.2).

**SignalEvent**: An API *sendSignal* is created for en- vironment code to interact and send an instance of the signal associated with the event is written into the event queue. When the API is called, an event is emit- ted and written into the event queue.

**TimeEvent**: A thread associated with the event is cre- ated and initialized at the initialization. Within the thread execution, its associated method waits for a signal, which is sent after the execution of the entry of an accepting state, to start sleeping for a duration specified by the event. When the relative time expires, the event is emitted and written to the event queue if the state is still active.

**ChangeEvent**: A thread is initialized but its associ- ated method does not wait for a signal to start. The

method periodically checks whether the value of the boolean expression of the event is updated from false to true. If so, the event is committed to the event queue.

As above presented, all asynchronous incoming events are stored in a runtime priority queue, in which each event type has a configurable priority. A comple- tion event always has the highest priority. Others are equal by default. Event type, priority, identifier, asso- ciated state *stateId* of completion events, and signal data are specified in an internal structure. The associ- ated state is used to specify which state completes its doActivity execution.

## Transitions

Each event triggers a list of transitions. We sup- pose *Ttrig*(*e*) is the transition list triggered by the event *e*, and *Strig*(*e*) is a depth-ordered (from innermost to outermost) set of the source states of the transitions in *Ttrig*(*e*). To present how the body of event methods is generated, we define functions as followings:

Algorithm 1 describes how the generation pro- cess works with an event. It first finds the inner- most active states which are able to react to *e* by or- derly looping over *Strig*(*e*). This ensures that, in case of multiple transitions activated by the event, the generated code for the transitions outgoing from innermost states will be executed. For each transi- tion from an innermost state, code for active states and deferred events, guard checking, and transi- tion code segments are generated by *GEN CHECK*, *GEN GUARD*(*t*) and *GEN TRANS*, respectively. If the identifier of *e* is equal to one of the deferred event list of the corresponding state (not shown in this pa- per), *GEN CHECK* generates code, which checks whether the event to be deferred and pushes the event to a deferred event queue managed by the runtime main thread. The latter also pushes the deferred events back to the main queue once one of the pending events is processed and the active state is changed.

**Algorithm 1** Code generation for transition

**Require:** Event *e*

**Ensure:** Code generation process for event method

1: **procedure** EVENTGENPROCESS(*e*)

2: **for** *∀* s *∈ Strig* (*e*) **do**

3: *Ts* = *{t ∈ Ttrig* (*e*)*|src*(*t*) = *s}*

4: **for** *∀t ∈ Ts* **do**

5: *GEN CHECK*(*s, t, e*)

6: *GEN GUARD*(*t*)

7: *GEN TRANS*(*s, t, tgt*(*t*))

For a transition *t*, *GEN CHECK* can generate sin- gle or multiple active state checking code. The latter occurs if the target of the transition is a pseudo state join because the transitions incoming to a *join* are

Listing 4: Example code generated for completion events triggering transitions t14 and t15

**i f** ( e v e n t . s t a t e I d == S6 ID *| |* e v e n t . s t a t e I d == S7 ID ) *{*

2 **i f** ( s t a t e s [ S6 ID ] . a c t i v e s [ 0 ] == S7 ID && s t a t e s [ S6 ID ] . a c t i v e s [ 1 ] == S8 ID ) *{*

4 t h r e a d r 1 =FORK( S 6 Region 1 Exit ) ; t h r e a d r 2 =FORK( S 6 Region 2 Exit ) ;

6 JOIN ( t h r e a d r 1 ) ; JOIN ( t h r e a d r 2 ) ; s e n d S t o p S i g n a l ( S6 ID ) ; **e x i t** S 6 ( ) ;

8 t h r e a d t 1 4 =FORK( e f f e c t ( t 1 4 ) ) ; t h r e a d t 1 5 =FORK( e f f e c t ( t 1 5 ) ) ;

10 JOIN ( t h r e a d t 1 4 ) ; JOIN ( t h r e a d t 1 5 ) ; e f f e c t t 1 6 ( ) ;

12 a c t i v e S t a t e I D = STATE MAX;/ /i n a c t i v es t a t e

*}*

Listing 5: Example code generated for *Fork*1 and *junc*

**i f** ( a c t i v e R o o t S t a t e == S1 ID ) *{*

2 j u n c = 0 ;/ /o u t g o i n g **t r a n s i t i o n** t 9ofj u n c

**i f** ( guard ) *{* j u n c = 1 ; *}*

4 / /E x i ts u b s t a t e sofS1andS1 e f f e c t ( t 9 ) ;

6 **i f** ( j u n c == 0) *{*

e f f e c t ( t 1 1 ) ;

8 *}* **e l s e** *{*

e f f e c t ( t 1 0 )

10 *}*

FORK( e f f e c t ( t 1 2 ) ) ; FORK( e f f e c t ( t 3 ) ) ;

12 / /JOIN. . .== *>* c o n c u r r e n te x e c u t i o n

/ /E n t e rs t a t eS6,S7andS8

14 *}*

14 *}*

fired if and only if all of their source states are active. The detailed discussion on these is not presented due to space limitation. Listing 4, lines 2-3 show a por- tion of the code with multiple checking generated for the completion event processing method. The transitions *t14* and *t15* incoming to *Join*1 are executed if *S6* and *S7* are active. In addition, the code portion checks the state associated with the current comple- tion event emitted upon the completion of either *S6*’s or *S7*’s *doActivity*. Lines 4-6 concurrently exits the sub-states of *S6* by using *FORK* and *JOIN*, which are respectively used to spawn and wait for a thread, for the region methods associated with *S6*’s orthogonal regions, which actually exit *S7* and *S8*. Then, *exit(S6)* is executed before the concurrency of transition ef- fects *t14* and *t15* is taken into account.

**Algorithm 2** Code generation for transition

**Require:** A source *vs* , a target vertex *vt* and a transition *t*

**Ensure:** Code generation for transition

1: **procedure** GEN TRANS(*vs* , *vt* , *t*)

2: Find *sex* and *sen* as vertexes in the same region and directly or indi- rectly containing/being *vs* and *vt* , respectively.

3: Generate IF-ELSE statements for junctions

4: **if** *sex* is a state **then**

5: **for** *r ∈* regions of *sex* **do**

6: *FORK*(*RegionExit*(*r*)) //create thread for exiting region

7: Generate JOIN for threads created above

8: Generate sendStopSignal to *sex*

9: *exit*(*sex* ) //exit the state

10: **if** *vt* is a pseudo state join **then**

11: **for** *in ∈* incoming transitions of *vt* **do**

12: *FORK*(*e f f ect*(*in*)) //create thread for transition effect

13: Generate JOIN for threads created above

14: **else**

15: *e f f ect*(*t*) //execute transition effect

16: **if** *sen* is a state **then**

17: *entry*(*sen* ) //state entry

18: Generate sendStartSignal to *sen*

19: **if** *sen* is a composite state **then**

20: **for** *r ∈* regions of *sen* **do**

21: *FORK*(*RegionEnter*(*r*)) //create thread for entering region

22: Generate JOIN for threads created above

23: **else**

24: Generate for pseudo states by patterns

*GEN TRANS* is able to generate code for transi-

tions between two vertexes. Algorithm 2 shows how it works. The generated code is bound by the defer- ral events, active states, and guard checking.

Firstly, Algorithm 2 looks for the *sex* and *sen* ver- texes contained in the same region and respectively containing the source and target vertexes of the tran- sition *t*. For example, *sex* and *sen* in case of the *t*3 tran- sition are *S*0 and *S*1 contained by the top region. If the transition *t* is part of a compound transition (we use the algorithm presented in (Balser et al., 2004; Knapp, 2004) to compute compound transitions), which in- volves some *junction*s, IF-ELSE statements for junc- tions are generated first (as PSSM says *junction* is evaluated before any action). The composite state is exited by calling the associated exiting region meth- ods (FORK and JOIN for orthogonal regions) in Step 3 and followed by the generated code of transition ef- fects (Step 4 and 5), respectively. If the parent state *sen* of the target vertex *vt* is a state (composite state), the associated entry is executed (Step 6). Entering region methods are then called once the above code completes its execution (Step 7). If the target *vt* of the transition *t* is a pseudo state, the generation pat- tern corresponding to the pseudo-state types is called. These patterns are shown in Table 1.

Note that the procedure in 2 only applies for ex- ternal transitions. Due to space limitation, the detail of generating local and internal transitions is not dis- cussed here but the only difference is that the composite state containing the transitions is not exited.

# 6EMPIRICAL STUDY

The pattern is implemented in the Papyrus Designer tool (pap, ), , an extension of the an extension of the UML modeling tool Papyrus (CEA-LIST). Papyrus designer supports component-based modeling and code generation. The behavior of a component in Papyrus Designer is described by us- ing UML State Machines. The tool allows to use some time notions from the MARTE profile to specify

Table 1: Pseudo state code generation pattern

State machine

|  |  |
| --- | --- |
| Pseudo state | Code generation pattern |
| join | Use *GEN TRANS* for *v*’s outgoing transition (Listing 4, lines 4-6). |
| fork | Use *FORK* and *JOIN* for each of outgoing transitions of *v* (see Listing 5, lines 11-12). |
| choice | For each outgoing, an *IF − ELSE* is generated for the guard of the  outgoing together with code generated by *GEN TRANS*. |
| junctio | n As a static version *choice*, a *junction* is transformed into an attribute *juncattr* and evaluated before any action executed in compound tran- sitions (see Listing 5, lines 2-3 and 6-10). The value of *juncattr* is then used to choose the appropriate transition at the place of *junction*. |
| shallow history | The identifiers of states to be exited are kept in *previousActives* of *IState*. Restoring the active states using the history is exampled as in Listing 3. The entering method is executed as default mode at the first time the composite state is entered (lines 9-19). *previousActives* is updated with the active state identifier before exiting the region containing the history. |
| deep history | Saving and restoring active states are done at all state hierarchy levels from the composite state containing the deep history down to atomic states. Updating *previousActives* is committed before exiting the re- gion, which is directly or indirectly contained by a parent state, in which a deep history is present. |
| entry point | If *enpoint* has no outgoing transition, the composite state is entered by default. Otherwise said, *GEN TRANS* is called to generate code for each outgoing transition. |
| exit point | The code for each transition outgoing from *expoint* is generated by using *GEN TRANS*. If *expoint* has multiple incoming transitions from orthogonal regions, it is generated as a *join* to multiple-check the source states of these incomings. |
| termina | teThe code executes the exit action of the innermost active state, the effect of the transition and destroys the state machine object. |

1 Code generation

Code

1. Simulation
2. Execution



MOKA

Traces 1 Runtime execution

Traces 2

1. Trace comparison

Figure 2: Semantic conformance evaluation methodology

set, we use our code generation tool to generate code.

**Step 2** We simulate the execution of the **State machine** by using Moka to extract a sequence **Trace 1** of ob- served traces including executed actions.

**Step 3** The sequence (**Traces 2**) is obtained through the runtime execution of the code generated in Step 1.

**Step 5** *Trace 1* and *Trace 2* are compared. The code is semantic-conformant if **Traces 1** and **Traces 2** are the same (Blech and Glesner, 2005).

time events. C++ code is generated from these implementa- tions and runs within POSIX systems such as Ubuntu, in which Pthreads are used for implementing threads for concurrency. This section reports our experiments with the standalone on the semantic-conformance and efficiency of generated code.

## Semantic conformance of runtime execution

This section presents our results found during ex- periments with our tool to answer the following re- search question.

***Research question 1:*** *Is the runtime execution of code generated from USMs by our tool semantic- conformant to PSSM?*

To evaluate the semantic conformance of runtime execution of generated code, we use a set of examples provided by Moka (mok, ), which is a model execu- tion engine offering PSSM (and also part of the Papyrus modeler). Fig. 2 shows our method. The latter consists of the following steps:

**Step 1** For a **State machine** from the Moka example

The PSSM test suite consists of 66 test cases for different state macchine element types. The results are promising: our tool passes 62/66 tests including behavior (5/6), choice (3/3), deferred events (6/6), entering (5/5), exiting (4/5), entry(5/5), exit (3/3), event (9/9), final state (1/1), fork (2/2), join (2/2), transition (11/14), terminate (3/3), others (2/2). In fact, our tool fails with some tests such as transi- tions from an *entry point* to an *exit point*. This is, as our observation, never used in practice. Furthermore, as the UML specification says that transitions outgo- ing from an *entry point* of a composite state should end on one of the sub-vertexes.

The results of this evaluation are not enough to proove that our pattern and tooling support preserves the UML State Machine execution properties but are a good hint that runtime execution of generated code is semantically correct (for all but the case identified above)

This evaluation methodology has the limitation that it is dependent on PSSM. Currently, for event support, PSSM only specifies signal evenst. For pseudo-states, histories are not supported. Thus, our evaluation re- sult is limited to the current specification of PSSM.

**Threats to validity: An i**nternal threat is that, all test cases of the PSSM test suite are contained in a sin- gle model file. However, the input to our experiments requires a test case per model file. Furthermore, op- eration behaviors, in PSSM, are defined by activities while our prototype requires fine-grained behavior as blocks of code embedded into models. We manually re-create these tests and convert activities into pro- gramming language code.

## Benchmarks

In this section, we present the results obtained through the experiments on some efficiency aspects of generated code to answer the following question.

***RQ2:*** *Runtime performance and memory usage are undoubtedly critical in real-time and embedded sys- tems. Particularly, in event-driven systems, the per- formance is measured by event processing speed. Is the performance and memory usage of code generated by our tool com- parable to existing approaches?*

700

600

execution time (ms)

|  |  |  |
| --- | --- | --- |
| Left to right: MSM\_O, MLite\_O, EUML\_O, Sine\_N, Sine\_O, QM\_O, OurTool\_N, OurTool\_O | | Left to right: MSM\_O, MLite\_O, EUML\_O,  Sine\_N, Sine\_O, QM\_N, QM\_O, OurTool\_N, OurTool\_O |
|  |  |
|  |
|  |
|  | |

500

400

300

200

100

0

Simple benchmark Composite benchmark



Min Outlier Max Outlier

Two state machine examples are obtained by the pre- ferred benchmark used by the Boost C++ libraries (boost, 2016) in (ben, ). One simple example only

% 400

Figure 3: Event processing speed for the benchmarks

53,3

Processing time comparison in optimization mode

Left to right: MSM,MSMLite,EUML,Sinelabore,QM, and our tool

350,8

consists of atomic states and the other both atomic and composite states.

We compared our tool with tools such as Sinela- bore (which generates efficient code for Magic Draw (Magic, 2016), Enterprise Architect (SparxSystems, 2016)), QM (QM, 2016) , Boost Statechart (Library,

300

200

100

0

208,3

137,9 1

195

100

177,4

75,8

Simple benchmark

Composite benchmark

177,4 190

132,1

100

2016), Meta State Machine (MSM) (MSM, 2016), C++ 14 MSM-Lite (ben, ), and functional program- ming like-EUML(EUM, ).

We used a Ubuntu virtual machine 64 bit hosted by a Windows 7 machine. For each tool, we created two applications corresponding to the two examples, generated C++ code and compiled it in two modes: normal (N), by default GCC compiler; and optimal

(O) with GCC optimization options -O2 -s. 11 mil- lions of events are generated and processed by the simple example and more than 4 millions for the com- posite example. Processing time is measured for each case.

### 6.2.1Speed

Fig. 3 shows the event processing performance of the approaches for the two benchmarks. In the nor- mal compilation mode ( postfix N), Boost Statechart, MSM, MSMLite, EUML are quite slow and not dis- played in the box-plot.

In both of the simple and composite benchmarks, in optimization mode (postfix O) MSMLite and our tool run faster than the others in the scope of the ex- periment. The figure also shows that the optimization of GCC is significant. In normal mode only the per- formance of Sinelabore, QM, and our tool is accept- able. The event processing speed of MSM, MSM Lite and EUML is too slow without GCC optimizations. **6.2.2Binary size and runtime memory**

### consumption

Table 2 shows the executable size for the ex- amples compiled in two modes. Without optimiza- tion, Sinelabore generates the smallest executable size while our approach takes the second place. In GCC optimization mode, MSMLite, Sinelabore and our ap- proach require less static memory than the others.

Figure 4: Event processing performance in optimization

mode

Let’s look closer at the event processing perfor- mance in optimization mode in terms of time medi- ans. Fig. 4 shows the figures of the two benchmarks, relative to the performance of our approach (normalized to 100%). For both of the benchmarks, MSMLite (137.9%) and our ap- proach are more efficient. It also showed that with the support of C++14, the processing in MSMLite is very fast in case of the composite benchmark.

For runtime memory consumption, we use the Valgrind Massif profiler (Mas, ; Nethercote and Se- ward, 2007) to measure memory usage. Table 3 shows the memory consumption measurements in- cluding stack and heap usage for the composite exam- ple. Compared to others, code generated by our ap- proach requires a slight overhead wrt. runtime memory us- age (0.35KB). This is predictable since the major part of the overhead is used for C++ multi-threading using POSIX Threads and resource control using POSIX Mutex and Conditions. However, the overhead is small and acceptable (0.35KB).

# 7TRAFFIC LIGHT CONTROLLER SIMULATION

In order to assess the usability and practicality of using UML State Machines and events, we applied our tool to a simplified Traffic Light Controller (TLC) system as a case study, which is extracted from (**?**).

TLC controls an intersection of a busy highway and a little-used farm-way as in Fig. 5. Detectors are placed along a farmroad to raise the signal *C* as long as a vehicle is waiting to cross the highway. As long

Table 2: Executable size in KB

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Test | MSM | | MSM-Lite | | EUML | | Sinelabore | | QM | | Our tool | |
| N | O | N | O | N | O | N | O | N | O | N | O |
| Simple | 414,6 | 22,9 | 107,3 | 10,6 | 2339 | 67,9 | 16,5 | 10,6 | 22,6 | 16,6 | 21,5 | 10,6 |
| Composite | 837,4 | 31,1 | 159,2 | 10,9 | 4304,8 | 92,5 | 16,6 | 10,6 | 23,4 | 21,5 | 21,6 | 10,6 |

Table 3: Runtime memory consumption in KB. Columns from left to right are SC, MSM, MSM-Lite, EUML, Sinela- bore, QM, and Our tool, respectively.



DetectorOn

f1

a



DetectorOn

f1

b

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| 76.03 | 75.5 | 75.8 | 75.5 | 75.8 | 75.7 | 76.38 |

Farmway C



Intersection

TrafficLight

1

1

+ highway

+ farmroad

Highway

Highway

C

Farmway

Figure 5: Traffic Light Controller (left) and its class dia- gram (right).

as no vehicle is detected on the farmroad, the highway lights should remain green. Otherwise, the highway lights should change from yellow to red, allowing the farmroad lights to become green. The farmroad lights stay green only as long as a vehicle is detected on the farmroad and never longer than a set interval to allow the traffic to flow along the highway. If these conditions are no longer met, the farmroad lights change from green to yellow to red, allowing the highway lights to return to green. Even if vehicles are waiting to cross the highway, the highway should remain green for a set interval.

The object-oriented class diagram follows the de- sign shown in Fig. 5 (right). The behavior of each class is described by a state machine. The design of behaviors of *Inter- section* and *TrafficLight* is shown in Fig. 6 (left and right, respectively). All of the states of *Intersection- StateMachine*, except *FarmwayOpen*, are compos- ite. The details of *SwitchingHighwayToFarmroad* and *SwitchingFarmroadToHighway* are actually shown on the yasmine site (Yasmine, ).

The conditions for switching from the state *High- wayOpen* to *SwitchingHighwayToFarmroad* are: (1) a minimum time for the highway open is elapsed; and

1. the sensors emit a signal.

To show the usability and practicality of UML events, two alternative designs can be specified by us-

IntersectionStateMachine

Initial1 HighwayOpen

SwitchingHighwayToFarmroad

SwitchingFarmroadToHighway

FarmwayOpen



TrafficLightStateMachine

Red OnRed Yellow

Initial1 OnRed\_Yellow

Red\_Yellow OnGreen

OnYellow

Green

Figure 6: State machines for describing the behavior of In- tersection (left) and TrafficLight (right)

Figure 7: Alternative state machine designs for the *High-*

*wayOpen* state

ing time events and change events. Fig. 7 (a) and

1. show the alternatives, respectively. The first design in 7 (a) uses a time event, which triggers the transi- tion from *WaitingForHighwayMinimum* to *Minimum- TimeElapsed*, and a signal event deferred by the *Wait- ingForHighwayMinimum* state. When *HighwayOpen* becomes active, its active sub-state remains *Waiting- ForHighwayMinimum* as long as the minimum time. If a signal C is fired from the detector, a signal event *DetectorOn* is sent to the state machine. The event is, however, not immediately processed but delayed until the active sub-state becomes *MinimumTimeE- lapsed* in case the time event is fired. The signal event is then processed to finish the execution of *Highway- Open* and activate the farmway.

The other design utilizes a change event instead of deferred events for switching from *WaitForPrecondi- tions* to a final state. Two flags *timeFlag* and *detect- Flag* are used. The *WaitForPreconditions* state has two internal transitions. One is triggered by a signal event associated with the signal C and calls a transi- tion effect to update *detectFlag* to true. The other one triggered by a time event sets *timeFlag* to true. The expression associated with the change event updates from false to true once two flags *timeFlag* and *detect- Flag* are set to true. The periodic evaluation time is configured as 10ms.

For simulation of TLC, we reuse the detector class developed in (Yasmine, ) to automatically generate *DetectorOn/DetectorOff* signals.

[To be continued]

# 8RELATED WORK

Code generation from state machines has re- ceived a lot of attention in automated software develop- ment. This section mentions existing code generation patterns and

Table 4: My caption

|  |  |  |  |
| --- | --- | --- | --- |
| Criteria | Yasmine | Our tool | |
| Normal GCC | GCC with  optimization |
| LoC |  |  |  |
| Binary size |  |  |  |

how our approach differs. A systematic review of several pro- posals is presented in (Dom´ınguez et al., 2012).

Switch/if is the most intuitive technique for imple- menting a ”flat” state machine. It either uses a scalar variable (Booch et al., 1998) and a method for each event, or using two variables as the active state and the incoming event used as the discriminators of an outer switch statement to select between states and an inner one/if statement, respectively. The state ta- ble approach (Douglass, 1999) uses one dimension for representing states and the other one for all possi- ble events. These approaches require a transformation from hierarchical to flat state machines. However, these approaches are hardly applied to state machines containing pseudo states such as histories or join/fork.

The object-oriented state pattern (Shalyto and Shamgunov, 2006; Douglass, 1999) transforms a state into a class and an event into a method. Events are processed by delegating from the class containing the state machine to its sub-state classes. Separation of states in classes makes the code more readable and maintainable. Unfortunately, this technique only sup- ports flat state machines. This pattern is extended in (Niaz et al., 2004) to support hierarchical state ma- chines. Recently, a double-dispatch (DD) pattern pre- sented in (Spinke, 2013) extends (Niaz et al., 2004) to support maintainability by representing states and events as classes, and transitions as methods. How- ever, as the results shown in (Spinke, 2013), these pat- terns require much memory because of an explosion of the number of classes and use dynamic memory allocation, which is not preferred in embedded systems. It is worthy noting that none of these approaches provides imple- mentation for all of state machine pseudo states as well as events.

Tools such as (SparxSystems, 2016; IBM, ) apply different patterns to generate code. However, as men- tioned in Section 1, true concurrency, some pseudo- states, and UML events are not supported. FXU (Pil- itowski and Derezin˜ska, 2007) is the most complete tool but generated code is heavily dependent on their own library and C# is generated.

Umple (Badreddin et al., 2014b) is a textual UML programming language, which supports code gener- ation for different languages such as C++ and Java from state machines. However, Umple does not sup- port pseudo states such as fork, join, junction, and

deep history, and local transitions. Furthermore, only call events and time events are specified in Umple.

Our approach combines the classical switch/if pat- tern, to produce small footprint, and the pattern in (Niaz et al., 2004), to preserve state hierarchy. Fur- thermore, we define pattern to transform all of USM concepts including states, pseudo states, transitions, and events. Therefore, users are flexible to create there USM conforming to UML without restrictions.

# 9CONCLUSION

We presented an approach whose objective is to provide a complete, efficient, and UML-compliant code generation from UML State Machines with full features. The design for concurrency of generated code is based on multi-thread of POSIX. The code generation pattern extends the IF-ELSE/SWITCH patterns and uses a hierarchical structure to preserve the state machine hierarchy.

We implemented our pattern as part of the Papyrus Designer tool. We evaluated our tool by conducting experiments on the semantic- conformance and efficiency of generated code. The conformance is tested under PSSM: 62 out of 66 tests passed. These results are a good hint that our tool preserves the UML State Machine semantics during code generation. For efficiency, we used the bench- mark defined by Boost to compare code generated by our tool to other approaches. The results showed that our tool produces efficient code that runs fast in even processing and is small in executable size.

Code produced by our tool, however, consumes slightly more memory than that of the others at run- time. In future work, we will fix this issue by mak- ing multi-thread part of generated code more concise. Furthermore, we will use the pattern to support Java code generation from UML State Machines.

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