An Approach for the Specification and the Verification of Multi-agent Systems Interaction Protocols using AUML and Event B

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Abstract. This paper suggests an approach for the specification and the verification of interaction protocols in multi-agent systems. This approach is based on Agent Unified Modelling Language (AUML) and the Event B method. The interaction protocol, are initially modelled using the AUML protocol diagram which gives graphical and comprehensive models. The resulting model is then translated into Event B and enriched which required interaction protocols properties. We obtain a complete requirement specification in Event B which can be verified using the B powerful support tool like the B4free. In this paper, we focus on the translation process of AUML protocol diagrams into Event B and by an example of multi-agent systems interaction protocol, we illustrate our approach.

1 Introduction

Multi-Agent Systems (MAS) is an area of distributed artificial intelligence that emphasizes the joint behaviors of agents with some degree of autonomy and the complexity arising from their interactions. It is therefore necessary to follow a strict process of modelling, and formal verification. This allows one to model interaction protocols and to rigorously verify required properties before the implementation. In this paper, we propose an approach for the specification and the verification of MAS interaction protocols combining AUML [9] protocol diagrams and Event B [2]. Agent UML extends different diagrams of UML in particular state transitions and sequence diagrams in various ways to model the non-determinism in MAS. AUML with its new diagrams provides many advantages to Agent systems design, such as simplified training and unified communication between development teams. However, the fact that AUML lacks a precise semantics is a serious drawback because it does not allow proofs and in consequence, with AUML, we can not verify required properties of interaction protocols in MAS like safety, deadlock-inexistence, liveness and fairness properties. On the other hand, formal methods are the mathematical foundation for software. They increase the quality of applications development and perform the reliability of the applications. Generally, these techniques are divided into two categories: automatic proving (model checking) [4] and proof systems.

Several solutions have been proposed for the specification of MAS using formal methods. Regayeg and al. [11] proposed the use of the Z method [8] and the LTL notations

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but the problem in this solution is related to the combinatorial explosion of the state number in the modelled system. Mazouzi [1] proposed to model protocol interactions in MAS with colored petri networks but the proposed patterns do not deal with dynamics of the environment. A recent studies [12] [6] [3], which compared the use of formal and semi formal methods concluded that formal methods led to better precision than semi formal ones and that semi formal methods produce more intuitive and readable documents. An appropriate combination of semi-formal techniques and formal methods can give rise to a practical and rigorous multi-agent interaction protocol development method. Our goal, in this context, is to provide a specification and a verification technique for multi-agent systems interaction protocols using AUML protocol diagram which give readable models and an appropriate formal method which allows verification of required properties. This is why we propose in our approach a combination of AUML protocol diagram and Event B. Hence, a semi-formal specification in AUML could be verified. In the proposed approach, the MAS interaction protocols are initially modeled graphically with AUML protocol diagrams. After that, the resulting graphical readable model is translated into Event B in incremental development. This resulting model is enriched by relevant properties (safety, deadlock-inexistence, liveness, strong fairness, etc) which will be proved using the B4free tool [5]. The verification of these properties ensures the correctness and the validation of the described MAS. The interest of such transformation is to allow the possibility to perform proof of this model using the B4free tool. The proposed translation gives a formal semantic for the AUML protocol diagrams using the Event B semantic.

Other works proposed the use of semi-formal and formal method for the design of interaction protocols in MAS. Fadil and al [6] proposed a solution combining AUML with B AMN (Abstract Machine Notation). Our work, which combines AUML and Event B, is near to the one of [6]. However, we propose translation rules for the concepts of AUML into the notation of the Event B which is more adapted than the B AMN to the specification of MAS which are reactive systems. Also, there is a semantic equivalence between messages and interactions in AUML protocol diagram and events in Event B which does not exists with operations in B AMN because operations may be called by the environment.

In this paper, we present the proposed approach which combines AUML and Event B. We focus on the translation process and we define a list of generic rules translating AUML protocol diagrams into Event B. By an example of a Contract-Net protocol [10], we illustrate our approach.

2 The Proposed Approach

In this section, we present a specification and a verification approach combining the semi-formal language AUML and the formal method Event B. The combination consists on transforming semi-formal AUML specifications into Event B which is verifiable by using the B4free tool [5].

As it is shown with the activity diagram of UML (figure 1), our approach is composed mainly on three steps. In the first step, the system is modeled graphically with AUML protocol diagram and the properties expected to be checked by the system are

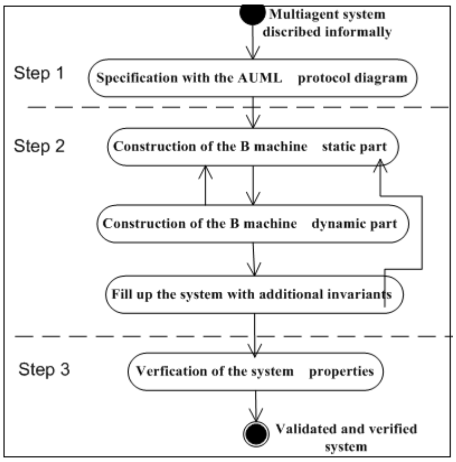


Fig. 1. The proposed specification and verification approach.

described informally. In the second step, the obtained AUML model is translated into Event B specification using translation rules which will be presented in this section 2. Finally, in the third step, the properties are checked from the obtained global system specification using the Event B tool, the B4free. Due to space limitation, we will present only some of the proposed rules which will be illustrated through an example of a contract Net protocol [10]. In the following, we detail the different steps and we illustrate them over the contract-Net protocol as an example [10].

2.1 Step 1: Specification with AUML Protocol Diagram

This step presents the specification of the MAS protocols using AUML [9]. The figure 2.a shows the Contract Net protocol diagram.

2.2 Step 2: Translation of AUML Protocol Diagram into Event B

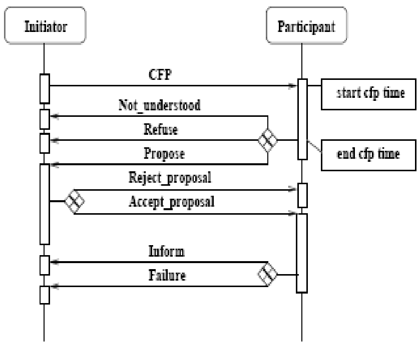
Our main contribution concerns this step which is divided into three sub-steps (figure 1): The construction of the B machine static part, the construction of the B machine dynamic part and the enrichment of the the system with additional properties (liveliness and safety invariants) that will be verified in the third step. In the following we present rules and apply them to the example. We will enumerate the proposed translation rules to simplify the presentation.

Rule 1. This rule is applied to generate the B machine static part:

1. We add three sets: AGENTS, MESSAGES and STATES_E to the SETS clause. The meaning of each set is defined in the table 1.
2. We add three types of variables: $exchanged\_msg$, $hand\_name\_event$ and ett to the VARIABLES clause. The $exchanged\_msg$ variable describes the exchanged

Table 1. The meaning of each set.

Sets	Meaning
AGENTS	Corresponds to all names of agents roles.
MESSAGES	Corresponds to all messages used by the protocol.
STATES_E	Corresponds to different states (events) of the system.



(a)

```
MODEL
   MCnetProtocol
SETS
AGENTS = {initiat0r,participant};
MESSAGES={cfp,propose,refuse,n_understood,
reject,accept,infrm,failure} ;
STATES_E={evt_cfp,evt_d_prn,evt_prn,evt_p,
evt_r,evt_n,evt_d_ra,evt_ra,evt_d_if,evt_if,
evt_i,evt_f,evt_d_evt,evt_a,evt_b,evt_c,
evt_t,evt_fin,evt_begin};
VARIABLES
exchanged_msg,hand_cfp,hand_d_prn,hand_prn,
hand_p,hand_d_ra,hand_ra,hand_d_if,hand_if,
hand_i,hand_d_e,hand_a,hand_b,hand_c,hand_t,ett
INVARIANT
exchanged_msg ∈ AGENTS↔(MESSAGES↔AGENTS)
∧ hand_cfp∈ℕ ∧ hand_d_prn ∈ ℕ ∧ hand_prn ∈  ℕ
∧ hand_p ∈ ℕ ∧ hand_d_ra ∈ ℕ ∧ hand_ra ∈ ℕ
∧ hand_d_if ∈ ℕ ∧ hand_if ∈  ℕ ∧ hand_i ∈ ℕ ∧
hand_d_e ∈  ℕ ∧  hand_a ∈  ℕ ∧ hand_b ∈ ℕ ∧
hand_c ∈  ℕ ∧ hand_t ∈  ℕ ∧ ett ∈ STATES_E
INITIALISATION
exchanged_msg:=∅ ‖
hand_cfp:=0‖hand_d_prn:=0‖hand_prn:=0
‖hand_p:=0‖ hand_d_ra:=0‖ hand_ra:=0‖
hand_d_if:=0‖ hand_if:=0‖ hand_i:=0‖
hand_d_e:=0‖ hand_a:=0‖ hand_b:=0‖
hand_c:=0‖ hand_t:=0‖ett:=evt_begin
```

(b)

Fig. 2. The translation of the static part.

messages between agents. This variable takes the form of a tuple (sender, message, receiver), where the sender and the receiver correspond to the names of the agents roles. For each system state, identified by the event name, we generate a new variable $hand\_name\_event$. This variable takes the value 0 when the event does not happen and the value 1 in the other case. It is specified in the guard of the event. The system states involved throughout the set STATES_E represented by the variable ett.

3. We define the variables types in the INVARIANT clause.
4. We Initialize the variable $exchanged\_msg$ to an empty set, each variable $hand\_name\_event$ to 0 and the variable ett to $evet\_begin$ in the INITIALISATION clause.

For the example in the figure 2.a, we obtain by applying the rule 1, a specification as shown in figure 2.b.

The following rules concern the construction of the B machine dynamic part by translating the simple messages, the complex messages, states of the protocol and of the time. All these will be written in the EVENTS clause.

– **Rule 2.** Simple message translation: Each message in the set MESSAGES is added as an event. The guard of this event is the system state (represented by the variable ett) and its action adds to the variable $exchanged\_msg$, the new message and

Specification 2	Specification 3
event_cfp= SELECT ett=evt_begin THEN exchanged_msg:=exchanged_msg ∪ {initiator↦{cfp↦participant}} ‖ ett:= evt_cfp END	Detec_propose_r_n = SELECT hand_cfp=1 ∧ hand_d_prn=0∧ ett=evt_cfp THEN ANY ee WHERE ee∈ {propose, refuse, n_understood} THEN msg3:=ee END ‖ hand_d_prn:=1 ‖ ett:= evt_d_prn ‖ hand:=3 END ; event_propose_refuse_nunderstood = SELECT hand_d_prn=1 ∧ hand_prn=0∧ett=evt_d_prn THEN exchanged_msg:=exchanged_msg ∪ {participant↦{msg3↦initiator}} ‖ hand_prn:=1 ‖ ett:=evt_prn END ;

Fig. 3. A simple and a complex messages translation.

changes the value of the system state. By applying the rule 2, we obtain the specification 2 (figure 3).

– **Rule 3.** An event just necessarily following another event: For each event which must follow another event, we add in its guard the condition which verifies that the precedent event had happened. For example, the participant response to the initiator with the messages not_understood, refuse or propose only if the initiator send the message CFP to the participant. So, we add to the event $event\_cfp$ the guard ($hand\_cfp = 1$).
– **Rule 4.** Complex message translation: This rule models XOR messages type. If XOR message is applied to a set of messages M1,..., Mn, we have to add in the resulting Event B model, two events. The first event is used for the detection of one of these messages by using a new variable ee and another variable $msg3$ takes its value. In the second event, the variable $msg3$ is added to the variable $exchanged\_msg$. By applying the rule 4, we obtain the specification 3 (figure 3).
– **The protocol Translation:** In this section we focus on the events related to the protocol states that are changing depending on the receiving or sending messages [7] or on the light of the deadline for replies related to the transition. In the first case,when a reply is without a deadline, we assume that the protocol passes through four states: $end, active, error$ and $wait$.
  Rule 5. We add a new set in the B machine (STATES_P), which Corresponds to all states protocol during the communication ($STATES\_P = \{end, active, error, wait\}$). The protocol states are represented by a variable $protocol$. This variable takes different values depending of the messages types. If it is an initiation or negotiation message, we add the specification $protocol := active$. If it is an information, refuse, cancel or agree message, we add the specification $protocol := end$. If it is an error or not_understood message, we add the specification $protocol := error$. If it is a complex message, we add the specification 4 as shown in the figure 4. The first event takes the variable $protocol$ to the state wait and after that for each

Rule 5e

```
event_1 =
SELECT
hand_1=0 ∧ ett=evt_begin
    THEN
exchanged_msg:=exchanged_msg ∪
 {agent1↦{message1↦agent2}}‖
hand_1:=1‖ protocol:=wait ‖
ett:=evt_1‖
    END ;
event_2 =
 SELECT
hand_1=1∧ hand_2=0∧ ett=evt_1∧
exchanged_msg(agent2)={message2↦agent1}
 THEN
protocol:=active‖hand_p:=1‖ett:= evt_2
    END;
event_3 =
 SELECT
hand_1=1∧ hand_3=0∧ ett=evt_prn
∧msg_echanges(agent2)={message3↦agent1}
 THEN
protocol:=end‖ hand_3:=1‖ ett:= evt_3
    END
```

Specification 4

```
event_propose_refuse_nunderstood =
SELECT
hand_d_prn=1 ∧ hand_prn=0∧ett=evt_d_prn
THEN
exchanged_msg:=exchanged_msg ∪
 {participant↦{msg3↦initiator}}‖
hand_prn:=1‖protocol:=wait‖ett:=evt_prn
    END ;
event_propose =
 SELECT
  hand_prn=1 ∧ hand_p=0 ∧ ett=evt_prn∧
 exchanged_msg(participant)={propose↦initiator}
 THEN
  protocol:=active ‖ hand_p:=1‖
  ett:= evt_p
 END;
 event_refuse =
  SELECT
   hand_prn=1 ∧ hand_p=0 ∧ ett=evt_prn ∧
   ∧exchanged_msg(participant)={refuse↦initiator}
  THEN
  protocol:=end ‖ hand_p:=1‖ett:= evt_r
  END;
event_n_understood =
 SELECT
  hand_prn=1 ∧ hand_p=0 ∧ ett=evt_prn∧
 exchanged_msg(participant)={n_understood↦initiator}
 THEN
  protocol:=error‖ett:=evt_n‖hand_p:=1
 END ;
```

Fig. 4. Translation of the protocol state supporting a complex message.

Specification 5

```
OFF=
 SELECT
  protocol=active ∧ (time≥ out_time)
 THEN
  protocol:=end‖
  ett:=evt_fin
 END
```

Specification 6

```
ON=
 SELECT
  protocol=end ∧ time< out_time
 THEN
  protocol:=active‖
  ett:=evt_begin
 END
```

Fig. 5. Events associated to the protocol states with a deadline.

message, we create a new event which makes the variable *protocol* in a different state and the variable *ett* in a new state (evt_name_event).
Rule 6. In the second case, when we have a message with a response delay, two events are added: OFF and ON. When no event can be triggered, the system is blocked. That is the **deadlock** problem. Specially, that situation holds when the protocol is active and $(time >= out\_time)$. To solve this problem, we have added a new event OFF, which puts the protocol to *end* under these conditions as illustrated in specifications 5 (figure 5). To ensure the resumption of protocol, we add the event ON as illustrated in specifications 6 (figure 5).

– **The Time Translation:**
The B machine models are sequential systems and it is not possible to dispose of the time along with another activity. In the Contract-Net protocol, the message CFP waits a response with a deadline. The rule 7 is introduced to model the time in Event B.

Rule 7. If we have a message with a response delay, we introduce the time in Event B by adding a $clock$ defined by an event $tick$ and whose role is to advance the time represented by a variable $time$. The solution is to interleave operations update clocks with system events occurrence by using a new variable $system$.

– **The Timeout Translation:**
  For each message Mi with a response delay, we add to the resulting model three states $stateAi$, $stateBi$ and $stateCi$ (figure 6) where i= 1..n. The system is initially in the state $stateAi$ and passes to the state $stateBi$ when the response (event) holds using the event AtoB. It passes to the state $stateCi$ when the event does not happen and the delay is elapsed using the event AtoC. AtoA holds when the system remains in the state $stateAi$ (no receipt of the following response and the time value has not reached the delay).
  Three states are added in a set STATES_T *(STATES_T =stateAi, stateBi, stateCi)* represented by a variable $state\_i$. This rule add also an event to detect one of events by using a boolean variable v_e which takes a random value of a boolean tf (ie if the event occurs or not).
  Modelling of Parallelism: To model parallelism between time evolution and event occurrence (system behavior) in Event B, we propose to use interleaving. A variable $system$ is used. Once the hand is given to the clock (if $system = 2$) and once is given to the system (if $system = 1$).
  The Livelock: We also propose a solution to avoid the livelock. If there is several events that are true at the same time, i.e that their guards are true, then one of them will be selected on a non-deterministic way. To avoid this problem, we introduce a new variable $hand$ initialized to zero and increases with each occurrence of a new event. Indeed, no guard will be infinitely true since that the hand will be changed.

– **Fill Up the System with Additional Properties (Liveliness and Safety Invariants)**

```
Tick =
  SELECT
  system=2∧ ett=evt_cfp
  THEN
  time:=time+1‖ system:=1
   END;

detec_evt =
  SELECT
system=1
  THEN
    ANY tf WHERE tf∈BOO
  THEN
   v_e:=tf
  END ‖
system:=0
  END;

AtoA =
   SELECT
state=stateA∧ system=0∧
ett=evt_cfp∧ time<out_time
 ∧ v_e=FALSE
   THEN
 system:=2
    END;

AtoB =
   SELECT
 state=stateA∧ system=0∧
 ett=evt_cfp∧ time<out_time∧
 v_e=TRUE∧ hand_cfp=1
   THEN
  hand_cfp:=2‖state:=stateB‖
  system:=4
   END;

AtoC =
   SELECT
 state=stateA∧ system=0∧
 ett=evt_cfp ∧ time=out_time
 ∧ v_e=FALSE
   THEN
 system:=3‖ state :=stateC
   END;
```

Fig. 6. Modelling message with delay in Event B.

In this step, we enrich the model with invariants describing required properties (safety and liveliness). The P1, P2 and P3 invariants are related to a response delay.

The **P1 invariant** expresses that if $(system = 2)$, then necessarily the system remains in the same state $(stateA)$: $((system = 2) \Rightarrow (state = stateA))$.

The **P2 invariant** expresses that if the system is in the state $stateB$, then necessarily the delay has not yet failed: $((system = 2) \Rightarrow (time < out\_time))$.

The **P3 invariant** expresses that if the system is in the state $stateC$, then necessarily the deadline has arrived: $((system = 2) \Rightarrow (time = out\_time))$.

The **P4 invariant** concerns the invariant associated to the complex message type XOR as shown in specification 15 (figure 7).

Invariant P4	Specification 15
(∀ (msg1,msg2).(ett=evt_1) ∧ (hand_1=1) ∧ msg1 ∈ MESSAGES ∧ msg2 ∈ MESSAGES ∧ (agent2↦{msg1↦agent1}) ∈ msg_echanges ∧(agent2↦{msg2↦agent1}) ∈ msg_echanges ∧msg1∈{message1,message2}) ⇒(msg2∉{message1,message2})))	(∀(msg1,msg2). ((((ett=evt_p)∨(ett=evt_r)∨(ett=evt_n)) ∧ (hand=4) ∧ (hand_prn=1) ∧ msg1 ∈ MESSAGES ∧ msg2 ∈ MESSAGES ∧ (agent2↦{msg1↦agent1}) ∈ msg_echanges ∧(agent2↦{msg2↦agent1}) ∈ msg_echanges ∧ msg1∈{propose,refuse,n_understood}) ⇒(msg2∉{propose,refuse,n_understood})))

Fig. 7. The XOR message translation.

The **P5 invariant** concerns the consistency of all events. As an example, if $event\_detec\_propose\_r\_n$ happens implies that $event\_cfp$ had happened: $((hand\_d\_prn = 1) \Rightarrow (hand\_cfp = 2))$. Where the variable $hand\_d\_prn$ is associated to the event $event\_d\_prn$ that is used for the detection of one of the three messages (propose, refuse, not_understood).

The **P6 invariant** concerns the states of the protocol without a response delay associated to the figure 4 and expresses that whenever the system is in a considered state, the protocol takes a certain value. For example, if the system is in CFP state then the protocol is active: $((ett = evt\_cfp) \Rightarrow (protocol = active))$.

2.3 Step 3: The Verification of System Properties

This step ensures that the specification B is correct and check the desired properties by verifying that the invariants are preserved by events [2]. These are what we call proof obligations and are automatically generated by the prover of the B4free tool. We have used the B4free to verify our final Event B model of the Contract-Net protocol resulting from the translation process. All proof obligations have been totally proved automatically.

3 Conclusions and Perspectives

In this paper, we have proposed a specification and a verification approach using AUML and Event B. The system is at first modeled with AUML protocol diagrams which is understandable; the resulting model is translated into the Event B notation to verify required properties. This allows one to verify AUML model by analyzing derived Event B specifications and to prove that the modeled protocol respects all safety and liveliness constraints. We have proposed translation rules for AUML protocol diagrams into Event B and we have shown these rules by an example: the Contract-Net protocol. Our future work will focus of the automatization of this approach. We will develop a tool which allows us to model graphically the protocols and to verify their properties.

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