Multi-Robot System Architecture Design in SysML and BPMN

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1. Introduction

This paper extends the work presented at the 2019 International Conference on Mechatronics, Robotics, and System Engineering (MoRSE) [1]. Related work can be also seen in [2].

Multi-Robot System (MRS) is a cyber-physical system that contains more than one robot, each of them owns a unique set of capabilities. The idea of an MRS is to solve a complex problem by collectively using the current capabilities of existing robots [3]. Therefore, the MRS must match the given problem with the existing robots’ capabilities, to plan the solution steps. Many MRS applications can be seen in swarm robotics, cooperative automated transportation, unmanned aerial vehicles, and cooperative manufacturing [4]. The advantages of an MRS is increasing the performance by saving the time and the effort to solve the problem. Moreover, distributing the solution among different robots provides more computational processing power, this means faster and higher capacity to solve many problems simultaneously [5].

Implementing an MRS without a proper system architecture design is a crucial mistake that is often done by the system developers. Because the system requirements and functionalities are lost in a non-human readable machine code. Therefore, in this article we propose a model driven development approach that uses the system model as the main software artifacts [6]. The proposed design approach in this article is based on the V-Model, which is a de facto solution for complex systems such as MRS.

Figure 1: The V-Model simplified version – adapted from [6]

The V-Model shown in Figure 1 describes the required stages to build an MRS. In the first stage of the V-Model, the system is decomposed. In this stage, the system components and architecture are designed based on the system requirements. In the second stage, the implementation of the MRS is carried out. The implementation of an MRS often involves the coding the individual components. In the final stage, the MRS individual components are tested through unit tests, then integration tests are carried out over sub-systems and eventually the overall integrated system. This article focuses on the first stage of the V-Model to build an MRS. As the design stage is the most curtail stage of an
MRS system building, because all the following stages are depending on this design.

Section 2 of the article describes the problem and the use case of concern. Section 3 introduces the background that is needed to model and simulate the use case. Section 4 discusses the system requirements that are used to build and evaluate the system performance. Modeling the use case is explained in detail in section 5, while its simulation is shown in section 6. Therefore, the performance analysis is explained in section 7. Ultimately, the last section concludes the work and the future research.

2. Problem and use case

The main article objective is to design an MRS architecture model that can be simulated and evaluated due to a predefined evaluation criterion. An MRS architecture is an overall system description that abstracts its functionalities, logic, and constrains [7]. Accordingly, it provides an analysis tool to grasp and improve system characteristics, and a conceptual model that can be used as the system blueprints [8]. In this work, SysML block definition diagram is used to describe the proposed MRS architecture and components as shown in Figure 2 and Figure 3. SysML diagrams will be explained in the next section as many of them are used in constructing the proposed MRS design.

First is the Pb variation, by adding, editing, or omitting a Pb. Second is variation in the number of the available robots. The maximum number of robots that can exist is constrained to three. The robots are constrained to register or deregister through the RbM. Third is the variation in the robots’ capabilities, by updating or editing the capabilities of a robot, the robot is constrained to deregister to be able to update its capabilities, then register again through the RbM, which automatically updates the robot new capabilities in the KB.

3. Solution preliminaries

3.1. Systems Modeling Language

SysML is a general-purpose modeling language that is derived from Unified Modeling Language (UML) [9]. SysML and UML belong are both developed by Object Management Group (OMG). UML is a visual modeling language that is particularly used to construct, design, and document the software systems in fields such as web-development, telecommunication, banking, and enterprise services [10]. While SysML is extending and modifying UML diagrams to fit complex industrial systems that involve variety of hardware, software, information, and processes (e.g., Aviation, Space, Automotive) [11].

Figure 2: SysML block definition diagram for the proposed MRS architecture

Figure 3: SysML internal block diagram for the proposed MRS architecture

Figure 4: UML/SysML use case diagram for the proposed architecture

Figure 5: SysML Taxonomy and comparison to UML
Figure 5 shows the relation between SysML and UML graphs [12]. Requirement and parametric diagram are two new diagrams that distinguish SysML [13]. Section 4 of this article used the requirement diagram to define the system performance criteria requirements and their relations. Block definition diagram and internal block diagram are used to describe the main components of the system architecture and the connection among the components as illustrated in section 2, while the use case diagrams describe the interaction of the system as a black box with the external world or actors. The activity diagram is used in section 5 to represent the MRS components logic. The more detailed logic is represented in the activity model, the easier to automatically generate a low-level code from this activity model. For this reason, BPMN is used to build the MRS logic, as it extends the notations, semantics, and syntax of SysML and UML activity diagram. The state machine diagram is used in section 4 to model the internal states of the robot. While the sequence diagram is used in section 6 to represent the interaction and communication among the components during a simulation scenario.

3.2. Business Process Model and Notation

Since UML activity diagram provides an abstract high-level process description, BPMN extends the UML activity diagram to fulfill the following two drawbacks. First, UML activity diagram lacks the syntax and the logical execution among the actions. Second, the poverty in UML notations and semantics in comparison with BPMN [14].

Table 1: BPMN control gateways

<table>
<thead>
<tr>
<th>Rule</th>
<th>Exclusive OR (EXOR)</th>
<th>Inclusive OR</th>
<th>Parallel AND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split</td>
<td>Inclusive OR (IOR)</td>
<td>Decision</td>
<td>Inclusive OR (IOR)</td>
</tr>
<tr>
<td>Merge</td>
<td>Inclusive OR (IOR)</td>
<td>Inclusive OR (IOR)</td>
<td>All outputs</td>
</tr>
</tbody>
</table>

Flow control gateways is the best example to demonstrate how BPMN is improving UML activity diagram. Flow control gateways are all equivalent to only one notation in UML, which is the decision notation. Table 1 shows the notations, semantics, and syntax of the basic gateways of BPMN. Three different notations are demonstrated in Table 1, which are exclusive-OR, inclusive-OR, and parallel-AND. The three mentioned gates operate either as split or merge context. In split context, exclusive-OR splits one input to only one output based on the conditions on the output branches. Inclusive-OR splits one input to more than one output simultaneously based on the conditions on the output branches. Parallel-AND splits one input to all the output simultaneously when the input branch is triggered. In merge context, exclusive-OR merges any of the input branches to only one output, when any of the input branches is triggered. Inclusive-OR merges more than one input branches to only one output, when these inputs are simultaneously triggered. Parallel-AND merges all the input branches to only one output, when all the inputs are simultaneously triggered [15].

3.3. Java Agent Development

JADE is a Multi-Agent System (MAS) middleware [16] that has been used in this research to deploy the proposed solution as shown in Figure 6-a. Each entity in the proposed SysML internal block diagram is implemented as a JADE agent. JADE Agent Management System (AMS) address each agent with a unique Identifier (AID) to facilitate the communication among the agents. While JADE directory Facilitator (DF) announces the services that every agent afford. JADE applies the Foundation for Intelligent Physical Agent (FIPA) specifications, to enable agent communication through FIPA-Agent Communication Language (FIPA-ACL) [17].

Figure 6 (a) JADE framework – (b) JADE sequence diagram example

Each JADE agent has a complex individual behaviour that can be seen as a composite of two simple behaviours. First is one-shot behaviour that is executed only once when it is triggered. Second is a cyclic behaviour that continuously executed when it is triggered. An example of JADE agent communication and decision making based on their behaviours can be seen in Figure 6-b. JADE is a suitable tool to build an agent simulation based on the MRS SysML/BPMN model. As the MRS logic and architecture can be easily translated to JADE implementation concepts [18].

4. Performance requirements

To evaluate the MRS design, it is necessary to measure the system performance during the simulation. Qualitative criteria such as reusability, scalability, extensibility, and interoperability have been proposed in [19]. However, these criteria are often relatively vague without quantitative performance measurements. Therefore, this research defines the quantitative indicators that are shown in Figure 7. The research assumes that the MRS is a black box that receives different Rq, that can either succeed or fail during the execution. The following measurements can be used to express the system performance:

- Throughput: the number of requests that are processed.
- Latency: the time needed from the request arrival till the request execution.
- Success rate: the number of request that success to be executed per the overall received requests number.
- Failure rate: the number of request that fail to be executed per the overall received requests number.
- Efficiency: the ration between the success rate and the failure rate.

**Multi-Robot System Performance Evaluation**

A group of quantitative criteria that can be measured during the MRS run time to evaluate its overall performance.

**Control System Performance**

A group of quantitative criteria that focuses on evaluating the control system performance with out the external actors (i.e., requestors, and robots).

**Robot Entity Performance**

A group of quantitative criteria that focuses on evaluating the robots performance.

**Throughput**

the number of processed (successful and fail) requests per time unit.

**Success rate**

the number of successful requests divided by the number of received requests per time unit.

**Efficiency**

the success rate divided by its failure rate.

**Availability**

the robot registered time ($T_r$) with respect to its overall time ($T_{ov}$).

**Effectiveness**

the robot controlled time ($T_c$) with respect to its uncontrolled time ($T_{unc}$).

**Latency**

the time taken from the arrival of a request to the start of executing this request (shorter latency means better performance).

**Failure rate**

the number of failed requests divided by the number of received requests per time unit.

**Utilization**

the robot controlled time ($T_c$) with respect to its overall time ($T_{ov}$).

Accordingly, the robot performance criteria are calculated as follows:

- **Availability**: the ration between the robot registered time ($T_r$) and the overall time ($T_{ov}$).
- **Utilization**: the ratio between the robot controlled time ($T_c$) and the overall time ($T_{ov}$).
- **Effectiveness**: the ration between the robot controlled time ($T_c$) and the uncontrolled time ($T_{unc}$).

**5. System model**

**5.1. Requests manager**

The RqM receives requests from various requestors, then it looks for an associated Pb within the KB. If the RqM finds the associated Pb, it forwards it to the PLN. The RqM decision making model is shown in Figure 9 via the BPMN activity diagram.

The RqM uses First Come First Serve (FCFS) technique to schedule the received requests. The RqM checks in the associated Pb for every received request. If there is no associated Pb with the request, the RqM directly sends a negative feedback to the requestor. If the RqM finds an associated Pb to the request, it forwards this Pb to the PLN, and waits for the feedback. If this feedback exceeds predefined limits, the RqM considers this request as a failure one. If not, it waits the execution feedback to forward it to the requestor.

**5.2. Planner**

The PLN receives the Pb and makes sure that it is visible to build a Pv instance according to the current system status. The PLN decision making model is shown in Figure 10 via the BPMN activity diagram.
to check if any of the registered robots' feedback arrived within a predefined time limit. If the robot feedback did not arrive, the RbM sends a negative feedback to the RqM. This feedback means that the whole plan is failed to be executed. If the RbM received a positive feedback from the robot within the predefined time limits, it assigns the next task due to the Pv. If all the tasks in the Pv are executed, the RqM sends a positive feedback to the RqM, otherwise it sends a negative feedback.

6. Simulation

The activity diagrams that have been illustrated in the previous section are used as the MRS blueprints. JADE has been used in this research to deploy these blueprints, and hence enables the MRS simulation during the design phase. The Graphical User Interface (GUI) shown in Figure 12 has been created to achieve interact with every entity in the proposed architecture. The RqM GUI in Figure 12-a can be used to add/edit/remove the Pb. The PLN GUI in Figure 12-b is used to monitor the Pv execution, the robots' availability, the robots' status, the robots' capabilities, and the robots' tasks history. The RbM GUI in Figure 12-b is used to show the assigned tasks status.

To illustrate the simulation scenario, an interaction example among the MRS entities is show in Figure 13. In this example, The RqM receives Rq. Therefore, the RqM sends the Pb in a form of the ACL-message shown in Figure 14-a to the PLN. Accordingly, the PLN constructs a Pv by matching the available robots’ capabilities and tasks history with the received Pb. In this case, R1 and R3 were registered into the MRS as shown in Figure 14-b. As

**Figure 10:** Planner BPMN activity diagram

To construct a Pv instance from a Pb, the PLN checks the available registered robots, the robots' capabilities, and the robots' tasks history. In case that there is only one available robot, the PLN directly considers a plan failure, as it is known in advance that a robot that performed less than two robots' tasks. This is to balance the task assignment among the available robots within the MRS. If all the tasks in the Pb could be assigned to robots, the PLN creates a Pv instance and sends it is the RbM to be executed.

5.3. Robots Manager

The RbM receives the Pv, then it assigns the tasks in this Pv to the available robot. Additionally, the RbM is also responsible for registering/unregister the robots from the MRS, this way it monitors the robots’ availability. The RbM decision making model is shown in Figure 11 via the BPMN activity diagram.

When the RbM assigns a task to a robot, it waits the robot feedback within a time limit. If the robot feedback did not arrive within the predefined limits, the RbM sends a negative feedback to the RqM. This feedback means that the whole plan is failed to be executed. If the RbM received a positive feedback from the robot within the predefined time limits, it assigns the next task due to the Pv. If all the tasks in the Pv are executed, the RqM sends a positive feedback to the RqM, otherwise it sends a negative feedback.

**Figure 11:** Robots-manager BPMN activity diagram

The RbM receives the Pv, then it assigns the tasks in this Pv to the available robot. Additionally, the RbM is also responsible for registering/unregister the robots from the MRS, this way it monitors the robots’ availability. The RbM decision making model is shown in Figure 11 via the BPMN activity diagram.

When the RbM assigns a task to a robot, it waits the robot feedback within a time limit. If the robot feedback did not arrive within the predefined limits, the RbM sends a negative feedback to the RqM. This feedback means that the whole plan is failed to be executed. If the RbM received a positive feedback from the robot within the predefined time limits, it assigns the next task due to the Pv. If all the tasks in the Pv are executed, the RqM sends a positive feedback to the RqM, otherwise it sends a negative feedback.

**Figure 12:** (a) Requests Manager GUI – (b) Planner GUI – (c) Robots Manager GUI

To illustrate the simulation scenario, an interaction example among the MRS entities is show in Figure 13. In this example, The RqM receives Rq. Therefore, the RqM sends the Pb in a form of the ACL-message shown in Figure 14-a to the PLN. Accordingly, the PLN constructs a Pv by matching the available robots’ capabilities and tasks history with the received Pb. In this case, R1 and R3 were registered into the MRS as shown in Figure 14-b. As
T₁ needs (C₁, C₃, C₄) to be executed, T₁ was assigned to R₁, because (C₁, C₃, C₄) are unique capabilities of R₁. Similarly, T₃ was assigned to R₃, as T₃ needs (C₂, C₅) which is unique capability of R₃. However, in case of T₂, both R₁ and R₂ own the capability C₂ which is needed to execute this task. Therefore, the PLN checks both robots’ task history to be able to assign T₂. The PLN finds out that R₁ task history is 9 while R₃ task history is 11. Accordingly, the PLN assigns T₂ to R₁, to balance the robots’ tasks distribution.

ultimately, the PLN sends the Pv in form of the ACL-message shown in Figure 14-b to the RbM. The RbM assigns the tasks to the associated robots according to the Pv. The task assignment is sent as an ACL-message as shown in Figure 14-c. The RbM waits the robots’ feedback within a timeframe window. If all the RbM received success feedbacks for all the assigned tasks, it sends a plan success feedback to the RqM.

7. Simulation results analysis
As it has been demonstrated in the previous section, the robots’ availability, the robot’s capabilities, and the the plan blueprints are the variables that can be used to build different simulation scenarios. Accordingly, to measure the system performance, the robots’ availability was randomly altered during the run time. Thus, analyzing the simulation results has been done by running JADE MAS for 30 minutes as shown in Figure 15, then measuring the system performance indicators that are concluded in section 4. Each one minute, a new request is generated, one robot randomly unregister from JADE MAS, and one random robot register to JADE MAS. the robot’s capabilities and the the plan blueprints do not change during the simulation scenario.
One of the RqM responsibilities is to monitor the requests status. The number of processed requests by the RqM is shown in the graph in Figure 15-a. Accordingly, the MRS throughput can be directly calculated from this chart. On the one hand, MRS throughput expresses how fast the system, therefore it is a relative value. Thus, to understand the MRS throughput, Figure 15-c and Figure 15-d should be considered as well. For instance, the number of requests at minute 4 is two requests as can be seen in Figure 15-a. But, if we look closely into Figure 15-c and Figure 15-d, we will find out that one request is success and another fail. This means that, it is not important if the system is so fast, but most of the requests failed to be executed. On the other hand, MRS latency expresses how much delay in the system as it can be seen in Figure 15-e. If the system delay value is equal to zero as can be seen in the 26th minutes of Figure 15-e, this means that the number of unprocessed requests is equal to zero as well, as can be seen in the 26th minutes of Figure 15-b.

The MRS efficiency graph shown in Figure 15-f is derived from dividing the data in Figure 15-c (successful requests) by the data Figure 15-d (fail requests). The MRS efficiency value is absolute. When the MRS efficiency is higher than one, this means that the number of success requests is higher than the number of fail request. Figure 15-f shows that the simulated MRS efficiency is higher than or equal to one during the simulation runtime.

![Figure 16: (a) Robots States – (b) Robots tasks history](image)

Table 2: Robots availability, utilization, and effectiveness

<table>
<thead>
<tr>
<th>Availability $T_{av}$</th>
<th>Robot 1 (R1)</th>
<th>Robot 2 (R2)</th>
<th>Robot 3 (R3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 min</td>
<td>30 min</td>
<td>30 min</td>
<td>30 min</td>
</tr>
<tr>
<td>30 min</td>
<td>0.67</td>
<td>0.57</td>
<td>0.73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Utilization $T_{uc}$</th>
<th>Robot 1 (R1)</th>
<th>Robot 2 (R2)</th>
<th>Robot 3 (R3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 min</td>
<td>8 min</td>
<td>8 min</td>
<td>8 min</td>
</tr>
<tr>
<td>30 min</td>
<td>0.37</td>
<td>0.27</td>
<td>0.4</td>
</tr>
<tr>
<td>12 min</td>
<td>12 min</td>
<td>12 min</td>
<td>12 min</td>
</tr>
<tr>
<td>30 min</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effectiveness $T_{ec}$</th>
<th>Robot 1 (R1)</th>
<th>Robot 2 (R2)</th>
<th>Robot 3 (R3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 min</td>
<td>8 min</td>
<td>8 min</td>
<td>8 min</td>
</tr>
<tr>
<td>10 min</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

One of the PLN responsibilities is to monitor the balance the tasks among the available robots. Figure 16-a shows that the robots’ available is changing over the simulation runtime. Simultaneously, Figure 16-b shows that the PLN compensates this variation by balancing the MRS. For instance, the task distribution among the available robot is converging to be 6 tasks per robot at the 6th minute of the simulation. Then, the robots’ tasks distribution is diverging till it balanced again to be 20 tasks per robot at the 19th minute of the simulation. Table 2 can be also concluded from Figure 16-a. In this table, $R_1$ is the most utilized and available robot during the simulation runtime, and hence $R_1$ is the most effective in comparison to $R_1$ and $R_2$. Accordingly, the PLN compensates this variation by maximizing $R_1$ and $R_2$ task assignment, to balance them with $R_3$.

8. Summary and Discussion

This article has highlighted new dimensions of the MRS design problem, which are the formalization, simulation, and evaluation of the solution architecture. The proposed modeling approach is based on a formal generic ADLs, that can be used to transfer the solution concept over different system case studies, regardless the implementation technology. Furthermore, the illustrated simulation method can be used to verify different architecture design patterns, based on the concluded system performance measurements.

The fundamental SysML diagrams have been implemented to design the proposed MRS system model. Moreover, BPMN language has been used to implement the activity diagram as it extends UML/SysML notations, semantics, and syntax. The collection of these standard models is used as the MRS blueprints. Those blueprints can be easily coded in any programming environment that supports distributed system implementation. For instance, JADE has been used in this research to implement these blueprints, however Robot Operation System (ROS) or Web Service (WS) are very suitable candidates to deploy the system.

A group of MRS performance requirements have been defined during this article, to quantify the system performance during the simulation runtime. Those criteria can are technology agonistic as well, which means that they can be used to compare between the system performance when it is implemented with different technologies. Furthermore, the system simulation is not only used during the design phased, but it can be reused in a form of a real time digital twin during the implementation phase. For instance, to check in advance different planning and scheduling algorithms before executing them on the real system.

Using a formal description language such as SysML or BPMN enables separating the model from the code, which is a common domain specific programming method. Therefore, in the future work, we will write a code generator that can be used to automatically generate the implementation code. Therefore, the model that has been developed in this article will turn to be executable and will be used as the main software artifact of the project. This can dramatically reduce the coding time and effort and improve the system readability and maintainability. Additionally, in the future work, the same performance measurements that have been used in this article can be used in the implementation phase, as a part of the system visualization.

References


