Modelling and Simulation Paradigms to Support Autonomous System Operationalization

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Abstract. Military Autonomous Systems are one of the critical elements in the current and future operations. System with a level of autonomy is known in the military for more than 50 years. However fully autonomous systems have not been yet fully operationalized. Taken as a military capability, autonomous system must be analyzed, designed and implemented to reflect all Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities, Interoperability and Information (DOTMLPFI) aspects. The first part of the paper describes autonomous system current state of the art and challenges following DOTMPLFI classification. Secondly, the modeling and simulation paradigms, Discrete Event Simulation, Agent Based Modelling and System Dynamics are proposed to be the right candidate for each DOTMLPFI aspects of AS capability development. There are two Use Cases, the first one based on Agent Based Modeling paradigm and the second one based on System Dynamics paradigm, both demonstrating advantages and drawbacks of a single modelling and simulation paradigm. The last part of the paper discusses differences, and mutual support of these two paradigms in the context of AS capability development.

Keywords: Autonomous system · Modelling and simulation · Capability development

1 Introduction

Systems with a defined level of autonomy are known in the society for the long time. Even if those are heavily implemented in the civilian domain multiplied by the evidence of a military autonomous system operationalization need [1], there are still opportunities and challenges in this effort [2]. First examples of its implementation date back to the era of remotely controlled torpedo [3]. The system behaviour and its automation were explicitly defined and there was no dispute about the extent of the automation. From that time many examples of autonomous system have been introduced within the given classification where systems vary the level of cooperation between Autonomous System (AS) and human operator when being deployed [4]. From the first category, AS with Human in the Loop (HIL), where the autonomy is limited in the task like local and global

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planning and motion planning and optimization [5–9] the teleoperated mobile robots can be taken [10, 11]. The second category, AS and Human on the Loop (HOL), contains applications where only critical decisions are made by human and other activities are fully autonomous [12]. This category may even be represented by complex SW solutions that serves to better decision-making process [13]. The third category, AS and Human out of the Loop (HOUTL), where there is not human being intervention, is now under heavy critic because of moral, ethical and legal consequences [14, 15]. With the current and future AS deployment, the critical element will be its countering as well [16, 17].

Importance and potential of Modeling and Simulation (M&S) in the process of AS design, implementation and operationalization has been declared by many authors [18–23]. However, the role of M&S in the articles has not been classified using the military capability development approach and classification called DOTMLPFI [24].

In the article, after the introduction chapter, challenges in the AS domain are introduced following the DOTMLPFI classification being covered by the second chapter. The third chapter brings in accordance with the previous classification proposed suitable candidates of modelling and simulation paradigms for each category. The fourth chapter shows Use Cases of M&S paradigms being used in the AS domain. The closing chapter compares M&S paradigms each other to specify its benefits and drawbacks in the AS operationalization context.

2 Autonomous System Operationalization and Capability Development Approach

DOTMLPFI classification approach is used in the military as a mnemonic tool to tackle Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities, Interoperability aspects in the planning process of the future capability development. Generally, any military planning process at the strategic level should be driven by this acronym not to forget any important planning view on the final product. It helps defining requirements and gaps when specifying a new effort in the military context while bringing thinking outside the box. Further part of the chapter describes current state and main challenges in each DOTMLPFII aspects of AS where M&S is applicable.

Doctrine aspect covers tactics, procedures, best practices and laws enabling to conduct a given task. Current best tactics are available for only for HIL and HOL AS. To design and verify these approaches even with HOUTL AS, the virtual environment is needed. Real battlefield is mission oriented and cannot bring verification opportunities in such extent like virtual testing environment. Therefore, design and implementation of M&S experimental frameworks is a need [25].

Organization aspect covers organic structure, relation and grouping that are used by capability being developed. Finding the ideal composition and the structure of cooperating and collaborating ASs and human beings based on the current and mainly future mission objectives is very demanding effort. Even with the current progress in the Artificial Intelligence it is not successfully implemented. Experiments driven by constructive simulations being able to replicate ASs and human operators and human factors bring a new possibility to these types of tasks [26].

Training aspect includes full spectrum of individual education and training up to the collective one. In the paper, exercises are part of T aspect. Simulation environments now support all forms and types of training. Distributed simulation environments following the current simulation best practices and standards like High Level Architecture, Distributed Interactive Simulation or Data Distribution Service are the core of any training framework. Current trend and challenge are to integrate all types of simulation available into these training frameworks. This approach is called Live, Virtual, Constructive (LVC) integration [27]. Models and life AS assets are not yet fully integrated in this framework. However, the integration of individual simulation assets should be done only if technologically required by Training Objectives, otherwise it might be resources demanding activity without added value to the training event. Training is not just about training with AS, it should be open to the idea of training events for HOUTL AS. It would require designing a new training concept for AS and human being cohabitation.

Materiel aspect covers all technology related components, equipment, systems, capacity and performance. It may be further classified based on the conceptual model of AS composed of blocks of sensors, AS communication with AS and human being, external environment, control mechanisms, effectors, movement, sources of energy and internal signal processing. These building blocks are heavily investigated; however, there are still missing or challenging parts:

- no mature common languages for AS design, development and verification and validation of individual components of AS taken as a system of systems;
- no common languages for HMI following the HIL, HOL, and HOUTL classification;
- missing approaches to enhance AS perception to be closer to the human being;
- no M&S standards for the synthetic environment extended by inclusion of information needed for collaboration among human being, AS and ASs;
- no agreed ontology of AS operationalization;
- no simulation platforms available for AS components composition following the HIL, HOL, and HOUTL philosophy.

Leadership aspect covers the way the capability should be used by leaders that are not a part of the capability. It is related to the philosophy how to prepare the leadership not about execution of training. Promising M&S approach is an immersive training environment for individuals putting leaders into the situation that is replicating the current and the future mission environment with AS HIL, HOL a HOUTL capacity. In this way, the leadership is exercised in the use of the future capability. It should not be mistaken with the UAVs operators' training that is in many cases already available [28].

Personnel aspect includes human beings who operates or support a new capability and their qualification. These aspects do not cover only the operators training mentioned in the previous paragraph [28], but it contains design and optimization of the numbers, structure and methods of theses operators' preparation to get expected quality for deployment. As for the operators' training, a challenging part is to introduce human being factors like stress and post trauma syndromes into the mission preparation.

Facilities aspect covers all infrastructure needed to prepare, accommodate, deploy and sustain a new capability. These types of activities are well known and supported by

M&S, namely by operations research approaches typically represented by optimization tasks. Logistic flows and spare parts distribution are examples of these activities.

Interoperability aspect covers all factors needed to work and collaborate in the coalition that must be added to a new capability. Gaps in the interoperability may be identified from the M&S experimental frameworks where national ASs and national doctrinal procedures are implemented. These experimental frameworks need to comply to M&S related standards; therefore, it should be founded in High Level Architecture, Distributed Interactive Simulation or Data Distribution Service for the internal distribution of information among simulation assets, Military Scenario Definition Language and Coalition Battle Management Language for the orders and reports interoperability and finally, Robot Operating System for the implementation of AS and its components.

3 M&S Paradigms for the AS Capability Classification

Modelling and Simulation is a scientific discipline containing two main activities. The first one, modelling, produces a model that is any meaningful representation of a defined part of a modeled system. The model serves to better understand the structure; however, there is not "big" analytical value from the experimental point of view. To make an experiment over the model, the simulation must be carried out to generate raw data sets that are analyzed. Therefore, in the context of the article, only M&S paradigms that can transform, easy per experience, a model into the simulation are taken into the consideration. These are Discrete Event Simulation (DEVS), Agent Based Modeling (ABM) and System Dynamics (SD). This approach is driven by the idea of simulation-based paradigm [29].

DEVS requires a view on the model like a design of a process that is composed of a flow of operations that are consuming resources. Operations form delays, activities, splits and branches. Operations are competing for limited resources and therefore queues belong to the DEVS paradigm. ABM is the newest paradigm comparing to the DEVS and SD. It is founded in the idea of defining local agent characteristics, behavior and the way they communicate each other while overseeing the whole system looking for its patterns of characteristic and behavior. It can help to find unexpected parameter of the modeled system while knowing the system microstructure. Agents that are represented by people, ideas, systems and organizations form the system microstructure. SD models system as a casually closed structure with internal behavior. It allows to define feedback loops that balance of reinforce the modeled flow. Stocks represents an accumulation and describes the system state. Flows are rates in which the stocks are being changed. For further reading on the use of these M&S paradigms refer to Borshchev's paper [30].

DOTMLPFI classification is primary used for a capability development, however to have AS fully operational, the whole AS life cycle must be taken into the consideration. AS life cycle, generally from the system engineering or any system or system of systems point of view, is composed of the following steps: Design, Development, Verification and Validation and Operational Use. For further reading on AS life cycle refer to Hodicky's paper [31].

Therefore, each aspect of DOTMLPFI is confronted with the each steps of the AS life cycle and proper M&S paradigm is recommended. Table 1 demonstrates what M&S paradigm has potential to be used in the defined step of AS capability life cycle.

Table 1. M&S paradigms supporting AS operationalization

AS	Design	Development	Verification and validation	Operational use
D	ABM, DEVS, SD	ABM, DEVS, SD	ABM, DEVS	
O	ABM, DEVS, SD	ABM, DEVS, SD	ABM, DEVS	ABM, DEVS, SD
T	ABM, DEVS, SD	ABM, DEVS	ABM	ABM, DEVS, SD
M	ABM, DEVS			ABM, DEVS, SD
L	ABM, DEVS	ABM, DEVS	ABM	ABM, DEVS
P	ABM, DEVS	ABM, DEVS	ABM	
F	ABM, DEVS		ABM	ABM, DEVS
I	ABM, DEVS		ABM	

4 Use Cases of M&S Paradigm Used in the AS Domain

This section describes two Use Cases of M&S supporting AS operationalization.

The first Use Case uses ABM paradigm. Development of operations concepts is a critical activity belonging to the Doctrinal aspect of AS capability development. The model of simplified ASs lifecycle and their ability to discover Targets was implemented in Anylogic application to reveal details of needed number of ASs with defined capability related to elapsed time to acquire Targets. Two population of agents were created with defined behavior described by state charts. Figure 1 demonstrates the first population of agents called AS with all states that AS goes through, starting from its Availability for mission, through Mission execution up to Maintenance, if needed.

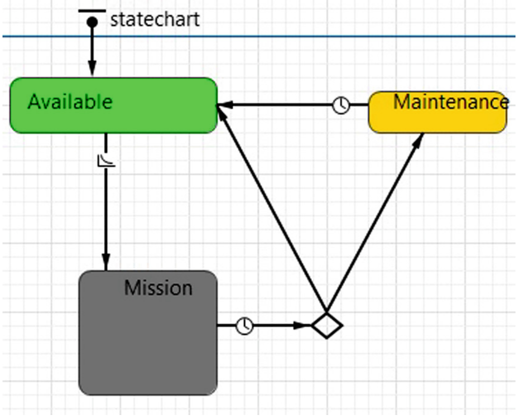

Fig. 1. AS state chart

Figure 2 demonstrates the second population of agents called Targets described by the state chart changing Target status among Detection, Detected and Not Detected states.

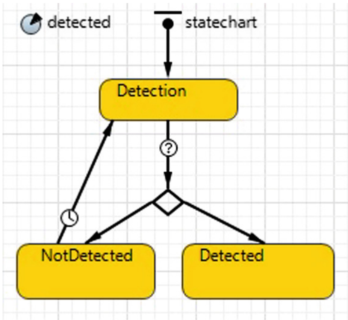

Fig. 2. Target state chart

The two charts in Fig. 3 where populated as the result of simulation runs over the stochastic model.

Fig. 3. Populated charts from the model execution

These two charts demonstrate situation with basic setting of 10 agents for both AS and Targets. It reveals that if at least two AS are needed to confirm acquisition of a Target then in the defined pace of ASs deployment, failure and maintenance, the minimum acquired time for all Targets is around 160 h in defined area of operation. Having detailed ABM brings opportunity to run what-if experiments to get estimates of the architecture of the operation and proposed structure and numbers of ASs.

The second Use Case uses System Dynamics paradigm. "System dynamics is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems. System dynamics is also a rigorous modelling method that enables us to build formal computer simulations of complex systems and use them to design more effective policies and organizations" [32].

To demonstrate System Dynamics approach to AS modelling, we can introduce a qualitative model of an AS capability. In DOTLMPFI qualification, we can define a required capability as:

$$C(t) = \min_i C_i(t),\ \ i \in I = \{D, O, T, L, M, P, F, I\},\ C_i(t) \in \langle 0, 1\rangle. \tag{1}$$

Required capability $C = 1$ if every its component reaches 1. Equation 1 says that the capability quality cannot exceed its limits, i.e. training can be optimized to an optimal level, which means that $C_T\ (t_S) = 1$ at defined time t_S. On the other hand, overall capability quality is determined by its weakest component and cannot be improved by a better performance of other components. This interpretation is simplified but admissible considering the qualitative approach.

For the use case we limit ourselves by selecting Training, Materiel and Personnel components, see Fig. 4. Each component is modelled by a feedback structure, where rectangle boxes represent accumulations, double arrows with valves represent inflows and outflows and single arrows represent information couplings. The model was created in Vensim application.

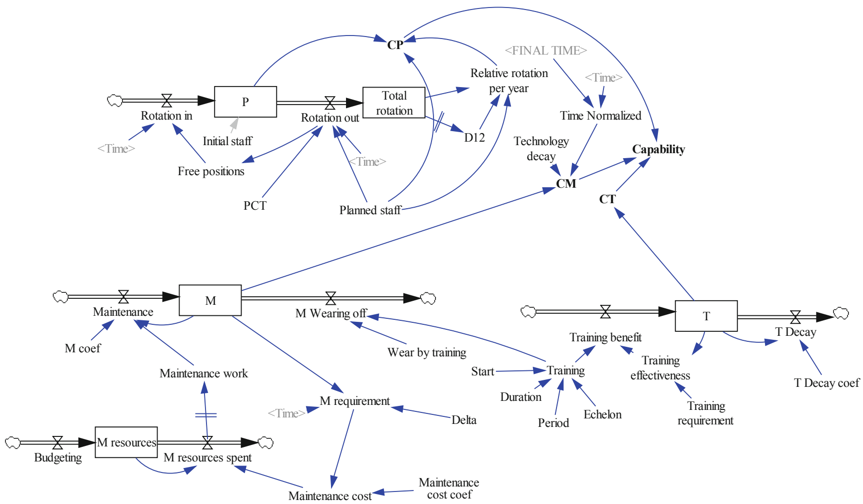

Fig. 4. Capability model with T, M and P component

The personnel model deals with required personnel number and personnel rotation in given period. To be capable of operation, both values must be within limits usually given by doctrines. In this simple case it is supposed that Rotation out takes random values within limits given by PCT ratio (maximum rotation per year in percentage) using uniform distribution.

Training contribution to the overall capability uses periodic training pattern given by a training start, a duration, a period and an echelon.

The Materiel component of the capability is influenced by financial resources available (M resource) which must fulfil requirements (M requirement) to hold the Materiel component at required level. The Maintenance requirement is generated by wearing off caused by utilization in the training process. To incorporate into the model maintenance requirements from an operational engagement would just mean to use a different utilization pattern. The Technology decay is an external factor which can act against the required capability. In case the required capability is detection, it can represent a new technology introduced into opponent equipment preventing or decreasing detection by autonomous systems.

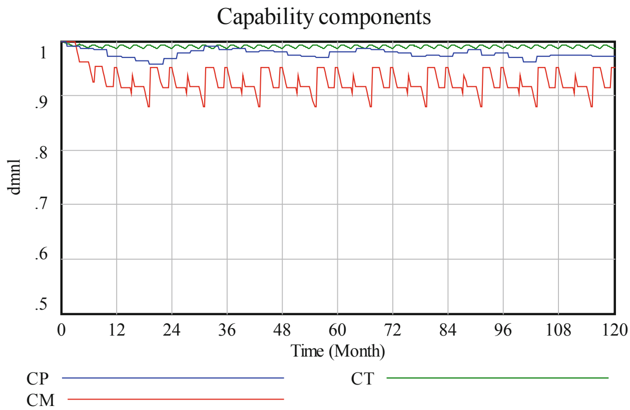

Fig. 5. Capability components function in time

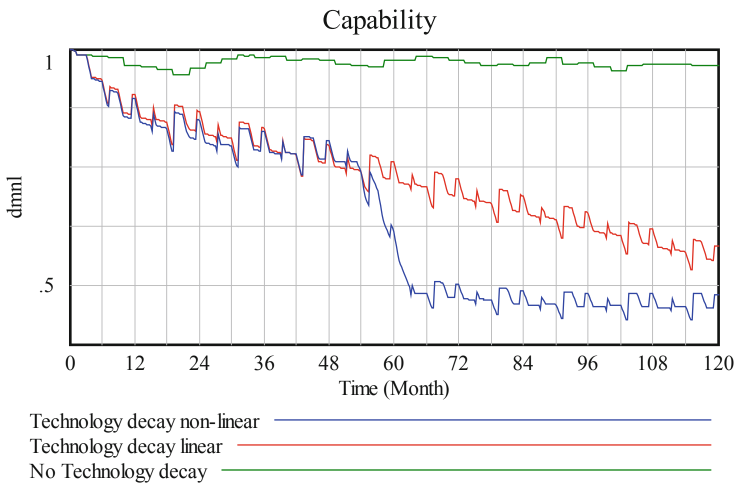

Fig. 6. Influence of Technology decay on Capability

Results of the simulation are given in Figs. 5 and 6. The first figure shows waveforms of Capability components. The second figure demonstrates influence of Technology decay on Capability. All component models can be further decomposed and detailed and dependencies among them can be modelled and analysed.

5 Conclusion

Development of a new capability shouldn't be done in an isolated fashion, using separated DOTMLPFI aspect. This shall be applicable even to the AS operationalization. AS has its own lifecycle and therefore the overall philosophy to the AS capability development should follow the two-dimensional approach. The first dimension covers all DOTMLPFI aspects, their combination and their effects of mutual dependences. The second dimension is bringing system engineering point of view and offers deeper partitioning of DOTMLPFI classification into phases of AS life cycle. This two-dimensional approach to the AS capability development opens a space for the creativity in the process. To evaluate SD approach to AS capabilities, it is necessary to say that this paradigm support high level of abstraction and fits better to strategies evaluation, capability life cycle modelling and seeking from organization structure and composition. It best fits to the Doctrine and Organization aspects of AS capability development. Limitation of the method is given by stocks and flows philosophy, where it is not possible to follow individual entities. AMB can be used to support operationalization of AS through all DOTMLPFI aspects, however not in all phases of AS life cycle. Its main value is seen in the Training and Materiel aspects of DOTMLPFI together with DEVS where SD is not seen as applicable. All in all, using a single modelling and simulation paradigm loses the potential of reveling unexpected features from the simulation that should be the main driver of any experiment. Therefore, if possible, the model should be designed in the open fashion to be extensible by other M&S paradigm. Next phase of the research will be focused on a detailed model of each DOTMLPFI aspect of AS capability development while mixing ABM and DS paradigms.

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