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EXPERIMENTING WITH THE MOSAIC WARFARE CONCEPT

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ABSTRACT

Mosaic warfare is a warfighting theory suggesting that a force made up of a larger number and variety of agile, fluid and scalable weaponry, sensors and platforms is more effective and resilient than a force developed following system of systems approach. Each member of a mosaic force is as distinct as the tiles in a mosaic. They can decide and act based on local situational awareness. This can have an overpowering advantage as compared to going head-to-head against the enemy's similar weapons and platforms. Mosaic warfare increases the speed of decision-making and can enable commanders to mount more simultaneous actions which creates additional complexity to the decision-making of the opposing forces. The enabling technologies for the mosaic warfare concept are investigated, the experimentation environment for testing the concept is created, the preliminary discovery experiments are conducted and the results from these experiments are presented.

1 INTRODUCTION

Mosaic Warfare is a war-fighting concept based on the theory that the accumulation of higher number and variety of smaller effects can make a greater impact compared to lower number and variety of bigger effects (Clark et al. 2020; Magnuson 2018; Sapathy 2019a). The theory also implies that the effectors are smaller in size but more agile both in maneuverability and decision making. They act collaboratively following a decentralized command and control scheme. In other words, every effector is an autonomous system, i.e., an agent that collaborates with all the other agents to meet their common objectives.

The mosaic concept differs fundamentally from the system of systems model where each part is uniquely designed for a specific function. The mosaic concept distributes and disintegrates sensors and weapons. The parts of a mosaic force are insignificant and dispensable but when they are together they are invaluable. It shifts from dominance to lethality and changes today’s centralized monolithic systems with distributed collaborating entities (Sapathy 2019a).

The title of mosaic warfare may be misleading because the concept does not aim a perfect tessellation such as in a mosaic, on the contrary there are lots of overlaps. The essence of the theory is based on hitting the same target multiple times with a variety and higher number of small, agile, fluid and scalable effectors, which also makes it hard for the enemy to figure out a course of action to counter a confusing mixed bag of an opponent.

Mosaic warfare is sometimes called as the delegation concept in military circles, as it is highly involved in decentralized decision making process. At the first glance, the theory is in conflict with one of the main principles of warfare, namely unity of command. Nevertheless, it is not, because political, strategic and operational objectives are still developed by the appropriate levels in the command hierarchy, and even decisive conditions and lines of efforts are designed by the relevant commands. It enables faster decisions by leveraging distributed formations, as a result, it degrades the decision making of the opposing commanders, and improves the adaptability and survivability of own forces (Clark et al. 2020).

One key advantage of the concept is its ability to add highly-effective unexpected elements to a battle engagement mix, such as collaborating autonomous or unmanned platforms in air, ground and at sea. As technology evolves, the integration of autonomous and unmanned platforms can add the asymmetric edge that mosaic warfare promises while also reducing risk to military personnel. Therefore, advanced technology is a key word in the mosaic warfare concept. Electronic and information system technologies offers solutions to complement mosaic warfare capabilities, and to develop its force that include more composable and often autonomous elements (Clark et al. 2020).

Moreover, the mosaic warfare concept targets the power of dynamic systems, as it aims to create adaptability for its own forces and places the complexity in the direction of the enemy. It works through a network that consists of low-cost sensors, multi-domain command and control nodes, and cooperative manned and unmanned systems. In addition to that, it uses technology components such as microelectromechanical systems, artificial intelligence and data analytics, swarm intelligence, swarm prediction, and information fusion. Such technologies greatly enhance and empower the mosaic warfare concept.

In Section 2, we briefly introduce the enabling technologies. Mosaic warfare can leverage existing technology and concepts such as wireless sensor networks and network centric warfare. The other emerging and future technologies, such as swarm intelligence, may pave the way for new opportunities to further amplify the strength of the concept. The dependence on these technologies is an important fact that needs to be analyzed when designing the experimentation environment and testing with the concept. In Section 3, we explain the challenges and ways to model and simulate mosaic warfare. We assume mosaic warfare as a strategic concept. It will lead to and count on many operating and functional concepts, and therefore a multiresolution and all domain simulation framework is required. We propose a methodology and tools for the simulation based experimentation that can address the challenges of the future functional concepts on mosaic warfare in this section. We experiment on various aspects of the concept and present our preliminary results in Section 4. Finally, we conclude our paper in Section 5.

2 TECHNOLOGY COMPONENTS OF THE MOSAIC WARFARE

The technology components of the mosaic warfare concept include but not limited to the list in Table 1. In this section, we briefly introduce each of them, because mosaic warfare is a strategic concept and a number of operating and functional concepts (ACT 2021) will also be required. Those functional concepts will be based on a combination of the technologies listed in Table 1 and more. Therefore, a multiresolution all domain testing environment is needed to experiment with the mosaic warfare concept.

Table 1: Key technology components.

Technology	Description
Wireless Sensor Networks and Internet of Things	power aware ad hoc networking and collaboration technologies
Swarm Intelligence and Prediction	intelligence algorithms inspired by the social beings such as ants, birds and fish
Big Data Analytics and Information Fusion	data in high volume and variety, flowing in high velocity, difficult to verify accuracy and with great commercial value
Network Centric Warfare	linking and networking of sensors, C2 and combat systems
Microelectromechanical & Nanoelectromechanical Systems	electromechanical systems with components in micrometer and nanometer scale respectively
Artificial Intelligence and Augmented Intelligence	simulation of intelligence behavior in computer, integration of human intelligence with artificial intelligence
Democratization of Technology	less regulated technology affordable and accessible by ordinary people all over the world

2.1 Wireless Sensor Networks and Internet of Things

Dependable and adaptable communications linkages and data sensors are vital to implementing mosaic warfare successfully. Wireless sensor and actuator networks (WSAN) and Internet of Things (IoT) technologies can be leveraged for mosaic warfare. WSAN are power aware ad hoc networking technologies that have been extensively studied for almost three decades (Akyildiz et al. 2002; Cayirci et al. 2006; Cayirci and Rong 2009). WSAN are distributed systems that adapt and react the ambient conditions reported through the collaborative effort of sensor and actuator nodes. Actuators in WSAN control several devices attached to them based on the sensed data obtained from sensor nodes. These actuators can be deployed inside the sensor field, and they may be collocated or dispersed. The sensed data can be conveyed from sensor nodes to actuators either by an automated architecture or by a semi-automated architecture. In the automated architecture the sensed data are routed directly to actuators. In the semi automated architecture the sensed data are first routed to a collector which processes the gathered data and relays the fused data to the related actuators.

The Internet of Things (IoT) (Atzori et al. 2010) integrates several technologies and communications solutions, including identification and tracking technologies, wired and wireless sensor and actuator networks, enhanced communication protocols and distributed intelligence for smart objects. The basic idea of IoT is the pervasive presence of a variety of things or objects that are able to interact with each other and cooperate with their neighbors to reach common goals through unique addressing schemes. The IoT is also a mature research field the same as WSAN and can be leveraged in the design and implementation of the mosaic warfare functional concepts.

2.2 Swarm Intelligence and Prediction

Swarm-based systems are inspired by the behavior of some social living beings, such as ants, termites, birds, and fish (Parpinelli and Lopes 2011). Self-organization and decentralized control are remarkable features of swarm-based systems that leads to an emergent behavior. An emergent behavior emerges through local interactions among system components and it is not possible to be achieved by any of the components of the system acting alone. Initially, the swarm intelligence algorithms followed one of two mainstreams: ant colony optimization (ACO) and particle swarm optimization (PSO).

The ACO algorithms are based on the foraging behavior of ants. The ants aim to find the shortest path between the food source and their nest. For this, ants locally communicate with each other through a chemical substance called pheromone. They lay down pheromone on the trail that leads to food. The others reinforce the path with further pheromone, i.e., positive feedback, and they follow the route with the highest pheromone. As less ants follow the same route, the pheromone fades. This indirect communication system is called stigmergy. From the combination of stigmergy, positive feedback and evaporation an emergent behavior takes place in the ant colony, leading them to find the shortest path between a food source and the colony.

The PSO algorithms is motivated by the movement of fish schools and bird flocks. Each individual of a population has its own life experience and is able to evaluate the quality of its experience. As social individuals they also have knowledge about how well their neighbors have behaved. These two kind of information corresponds to the cognitive component (individual learning) and social component (cultural transmission), respectively. Hence, an individual decision is taken considering both the cognitive and the social components, thus, leading the population to an emergent behavior of forage for food or escape from a predator.

For the last decade, in addition to ACO and PSO, new swarm intelligence paradigms, which were inspired from the foraging behavior of other social living beings, have been introduced. Swarm intelligence finds also application in prediction for various purposes. The mosaic warfare and swarm intelligence concepts have many commonalities, and mosaic warfare can largely benefit from swarm intelligence and prediction technologies.

2.3 Big Data Analytics and Information Fusion

Inferring information from big data and fusing the information as knowledge becomes increasingly challenging, because data are available in larger and larger volumes and higher and higher variety (Chen and Zhan 2014). Moreover, data are flowing continuously, and therefore, time is limited to process data into the higher levels in data-information-knowledge-wisdom (DIKW) hierarchy (Snidaroa 2015). The accuracy and reliability of data and information, and therefore trust (Cayirci and Oliveria 2018) to them also becomes a bigger and bigger issue. The need for a new scalable information fusion and knowledgebase management schemes has emerged for various fields, such as, open source, measurement and signature, and signal intelligence fusion. Extensive research both by academia and industry have introduced decentralized big data analytics and information fusion solutions (Cayirci and Rong 2018). These solutions are among the enabling technologies for the mosaic warfare concept.

2.4 Network Centric Warfare

One may argue that the earlier version of the mosaic warfare concept is the network centric warfare although they differ from each other significantly. The network centric warfare concept has revolutionized the warfare from platform centric to network centric thinking. The concept did not aim changing the existing combat systems but creating a more effective command and control (C2) in engagements.

Network centric warfare has emerged from the technological developments of the information age. It focuses on the combat power that can be generated from linking and networking of sensors, C2 and combat systems. The essence of the concept is based on the ability to create a high level of shared awareness. It aims integrating joint warfare components that operate in disparate domains (sea, land, air, space). Another important feature of network centric warfare is that the information conveyed across the communication is not restricted only to sentences, it includes data as live video feeds and imagery which is a real time data (FTD 2005; Gangadharaiah and Hallur 2014).

Obviously the technology and systems created following the network centric warfare concept are the critical enablers of the mosaic warfare concept.

2.5 Microelectromechanical Systems and Nanoelectromechanical Systems

Microelectromechanical systems (MEMS) are the systems made up of microscopic devices with moving parts. They merge at the nanoscale into nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are made up of components between 1 and 100 micrometers in size, and MEMS generally range in size from 20 micrometres to a millimetre, although components arranged in arrays can be more than 1000 mm^2.

A typical MEMS usually consist of a central processing unit and several components that interact with the surroundings, such as microsensors and actuators. MEMS are susceptible to ambient electromagnetism and fluid dynamics. Therefore phenomenon, such as electrostatic charges, magnetic moments, surface tension and viscosity are more important design considerations comparing to the larger scale mechanical devices. MEMS technology is distinguished from molecular nanotechnology or molecular electronics in that the latter two must also consider surface chemistry. NEMS components are in nanometer scale.

MEMS and NEMS are the result of the efforts for the miniaturization of electromechanical systems for the last century. It has not only enabled concepts like mosaic warfare but also impact on their design.

2.6 Artificial Intelligence and Augmented Intelligence

Artificial Intelligence (AI) is a field in computer science, which was established in late 1950s. It attempts to understand, model and design intelligent systems or in other words aims the simulation of intelligent behavior in computer. In simplest term, AI is manufactured thinking and learning. AI can provide solutions to many challenges faced in operational theaters. It helps selecting a course of action among many. Multichannel human machine interactions are made possible through natural language processing and brain wave recognition by AI. Speech Recognition is also an important application of AI where it can understand various accents, background noise, incidents, locations, etc. AI based video analytics understand the visual input on computer. Robotics is another important application of AI where robots are able to perform the tasks given by human. The application areas of AI are limitless.

Two main alternative approaches have been pursued by the AI researchers: symbolic and psychological. The earlier approach is called classical or symbolic AI. In these earliest approaches it is predicted that each and every process with either a person or machine participation can be conveyed by symbols which are adjustable according to the set of predefined rules (Murshida et al. 2019). The symbolic approach is a mathematically oriented way of abstractly describing processes leading to intelligent behavior. On the other hand, the physiologically approach favors the modelling of brain functions in order to reverse-engineer intelligence.

Augmented intelligence (AuI) integrates human intelligence (HI) and artificial intelligence (AI) to harness their strengths and mitigate their weaknesses. The combination of HI and AI has seen to improve both human and machine capabilities, and achieve a better performance compared to separate HI and AI approaches (Yau et al. 2021).

Both AI and AuI have the key places in the definition of mosaic warfare and their replication in a virtual theater stand as one of the major challenges in simulating the mosaic warfare concept.

2.7 Democratization of Technology

The democratization of technology has two meanings: ease in innovation and development, ease in access and usage. Technology is not regulated and owned by few leading nations as it used to be but ubiquitously developed by people and companies of all sizes in all over the World. New generations are born into advanced technology which becomes easier and more natural to be used by ordinary people. The need for technical people with exceptional skills almost completely diminished. The bottom line is that consumers have greater access to use and purchase technologically sophisticated products, as well as to participate meaningfully in the development of these products which are much more affordable comparing to several years before. This fact has a great impact both on the necessity and the design of the mosaic warfare concept.

3 SIMULATION BASED EXPERIMENTATION WITH MOSAIC WARFARE CONCEPT

3.1 The Challenges in Experimenting with the Mosaic Warfare Concept

The mosaic warfare concept implies that a lot of diverse pieces quickly move following a decentralized decision making process. That can introduce a distinct strategic military advantage, nevertheless, those pieces have to act consistently with all the others such that all the actions contribute meeting the operational and ultimately strategic objectives. This requires excellent communications, advanced decentralized decision making, coordination and collaboration algorithms. Partial communications, flaws in decision and collaboration algorithms can lead to missed opportunities or catastrophic outcomes. The bottom line is that the functional concepts, such as a swarm intelligence algorithm for the mosaic platforms, need to be developed and their performance are very important on the success of the mosaic warfare concept. Although they are critical for the overarching concept, we have to isolate the testing of the mosaic warfare concept from this secondary layer of concepts, which is our first challenge in setting the experimentation environment.

A lot of diverse pieces also indicates high number of simulated entities, which create difficulties in preparing and validating the databases and controlling the high number of entities during simulation. Additionally, the simulation of such a high number of entities in a very dynamic and fluid theater necessitate high performance computing.

The objectives of the concept are clear to us, and therefore it is relatively easier to determine the dependent parameters. Still, we set this experimentation as a discovery experiment because this is the first time that we experiment with the mosaic warfare concept. Therefore, we focus on deciding the performance measures, understanding the factors influencing them and discovering the relations between the measures and factors.

3.2 JWTC Experimentation Environment

The main tool in our experimentation environment is Hybrid Multidomain Operations and Tactics Simulator (hymots®). The hymots® software architecture is depicted in Figure 1, and introduces major advantages for simulating mosaic warfare concept. The first group of these advantages apply to testing not only the mosaic warfare concept but any warfighting concept:

- It has an experimentation mode, which generates confidence intervals rather than a single random outcome. That eases the workload on the analysts significantly.
- It can reach 300:1 simulation speeds even when simulating 40,000 agents in an area of 4,000km×4,000km, and therefore the results are obtained in very short time.
- It supports all domains (air, land, maritime, space and cyberspace), disasters and hybrid environments.

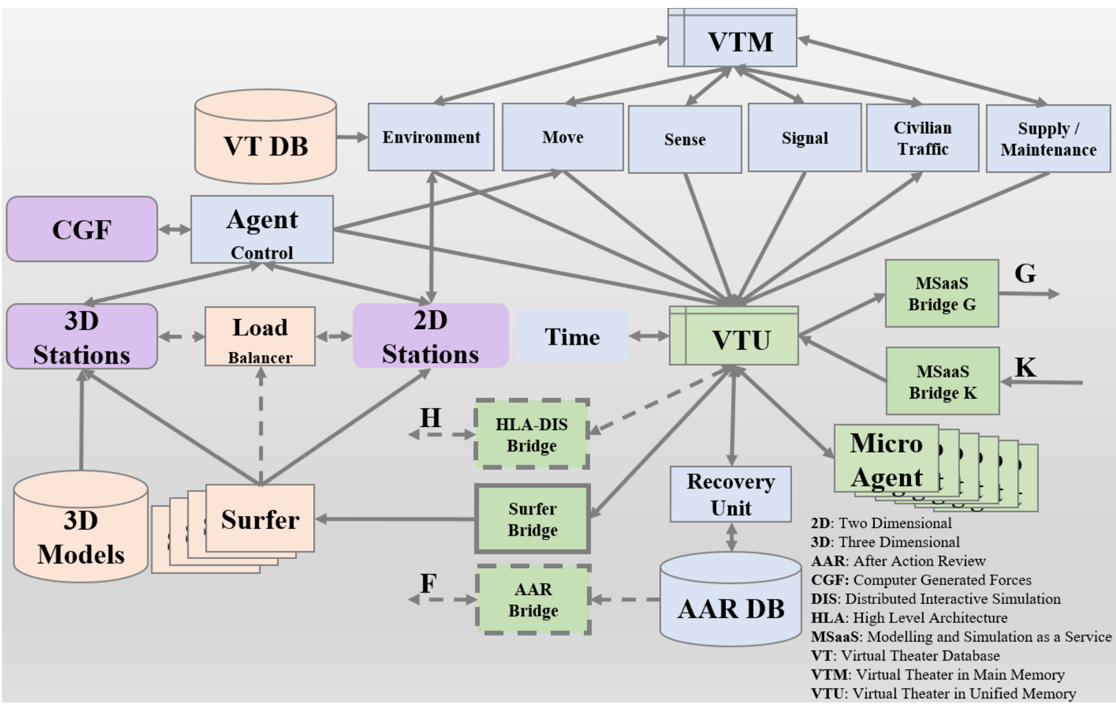

Figure 1: The simulation environment software architecture.

The second group of advantages are specifically helpful when experimenting with the mosaic warfare concept:

- It is an agent based simulation system. Each agent represents a simulated entity (e.g., a military unit, a civilian entity or group). A separate microprocess is run for each agent which behave autonomously to meet the objectives and to comply with the orders given to them. They interact

with the other agents via a common virtual theater. This is almost a perfect replication of the mosaic warfare concept in a simulated environment.
- Agents can be controlled completely by the user commands or the control of a subset of them can be left to artificial intelligence (computer generated forces - CGF). The CGF component can be used for replicating the decentralized dynamic decision making process which is a critical component in the mosaic warfare concept.
- Through modelling and simulation as a service (MSaaS) bridges, the environment can be connected to other simulation services for testing with various detailed aspects related to mosaic warfare that can emerge later.

The algorithms for the decentralized control of the autonomous collaborating entities have an impact on the performance of the mosaic warfare concept. In our study, we isolate the overarching concept from the detailed functional concepts developed for the autonomous behavior of the entities. Therefore, at this stage we do not need CGF component of the architecture. Similarly, our simulation environment is self-sufficient for running our preliminary discovery experiments, and hence we do not need to use MSaaS bridges yet.

3.3 Design of Experiment

The main proposition for our experiments is that the mosaic warfare concept performs better than system of systems approach. We need to state this proposition more formerly in order to design our preliminary set of discovery experiments:

Definition 1 Mosaic Warfare is a war-fighting concept based on high number and variety of small, agile, fluid and scalable capabilities.

Definition 2 System of systems is a model where each part uniquely designed for a specific function such that they are complementing the overarching system to meet its objective.

Proposition 1 The accumulation of higher number and variety of smaller effects can make a greater impact compared to lower number and variety of bigger effects.

Proposition 2 The survivability of the warfare capacity made up of higher number and variety of smaller assets is higher compared to the warfare capacity made up of lower number and variety of bigger assets.

Our experimentation objective is to investigate the independent parameters (i.e., the factors of interest that affect the selected performance measures) and their relations with the dependent parameters (i.e., performance measures) to develop hypotheses following on these two propositions. The dependent parameters are pretty trivial to retrieve from the propositions. For proposition one, the dependent parameter is effectiveness of capabilities, and for Proposition 2 it is the survivability of the capabilities. One can anytime include cost and warfare development time as important measures, however, we will exclude them in order to isolate our propositions from limitless numbers of other factors. Our dependent parameters (i.e., measures) are in Table 2:

Table 2: The list of dependent parameters.

Parameter	Meaning
ε_m	**Effectiveness** of mosaic capabilities against system of systems capabilities
σ_m	**Survivability** of mosaic capabilities against system of systems capabilities
ε_s	**Effectiveness** of system of systems capabilities against mosaic capabilities
σ_s	**Survivability** of system of systems capabilities against mosaic capabilities

The effectiveness $\boldsymbol{\varepsilon_f}$ of side $\boldsymbol{f}$ is measured as the ratio between the number of destroyed entities $\boldsymbol{x_o}$ of the opposing side *o* and the total number of the entities $\boldsymbol{t_o}$ of the opposing side before the combat starts. Therefore, the effectiveness and survivability of the mosaic side *m* and system of system side *s* are given by Equations 1-4.

$$\varepsilon_m = \frac{x_s}{t_s} \quad (1)$$

$$\varepsilon_s = \frac{x_m}{t_m} \quad (2)$$

$$\sigma_m = \frac{t_m - x_m}{t_m} = 1 - \varepsilon_s \quad (3)$$

$$\sigma_s = \frac{t_s - x_s}{t_s} = 1 - \varepsilon_m \quad (4)$$

Our preliminary experiments are for discovery, therefore we have to simplify and isolate the design to a few factoring parameters that we can easily control. Our goal is to gain further insight into the dynamics of the concept before setting up more complex experiments. For our first set of discovery experiments, the independent parameters in Table 3 are selected:

Table 3: The list of independent parameters.

Parameter	Meaning	Range
Density ratio $\boldsymbol{\rho}$	The ratio between the number of mosaic and system of systems capabilities	1-10 (Steps of 1)
Precision ratio $\boldsymbol{\psi}$	The ratio between the probability of hit by mosaic and system of systems capabilities	0.88-2 (Steps of ~0.06)
Resilience ratio α	The ratio between the termination thresholds (i.e., the number of hits to get terminated) of mosaic and system of systems capabilities	0.5-0.09 (Steps of ~0.04)
Duration t	The combat duration, i.e., the consecutive simulation time steps that the simulation continued before being terminated	1-10 (Steps of 1)

The value range for the independent parameters are selected such that they are simple enough and clearly disparate to start building an intuition into the relation between the measures and factors. Please also note that we only test mosaic forces against system of systems forces. Mosaic against mosaic will be tested in the later experiments.

To avoid running 10,000 experiments, we designed experimentation configurations by only partially factoring the independent parameters. For each experimentation configuration, the results for the dependent parameters are given and analyzed in the following section.

4 EXPERIMENTAL RESULTS

The preliminary results from our experiments are depicted in Figures 2-5. Please note that, the processes for decision making, command and control (C2) are not included in this first set of experiments. It is intuitively clear that agility in decision making is a strong feature of the mosaic concept, nevertheless, it is too early to reach a conclusion on that at this stage of our experiments, in which the kinetics are the main focus.

We first experimented with the density ratio, which is the ratio of densities between mosaic (M) and system of systems (S) entities in a unit volume in the area of operations. In Figure 2, the precision ratio is fixed at 1, which means the probability that an M entity hits an S entity in a simulation period is the same as the probability that an S entity hits an M entity. The resilience ratio is 0.2, which means S entities can stand 5 times more hits comparing to M entities. As illustrated in Figure 2, when the density ratio is greater than 2, both effectiveness and survivability of the mosaic concept become higher than the system of systems concept. When the density ratio is over 6, M entities are able to eliminate all S entities, therefore, the effectiveness of M entities becomes almost 1 and the survivability of S entities goes down to zero. Since many S entities are eliminated before they hit multiple M entities, the survivability of M entities are significantly increased after the density ratio 4.

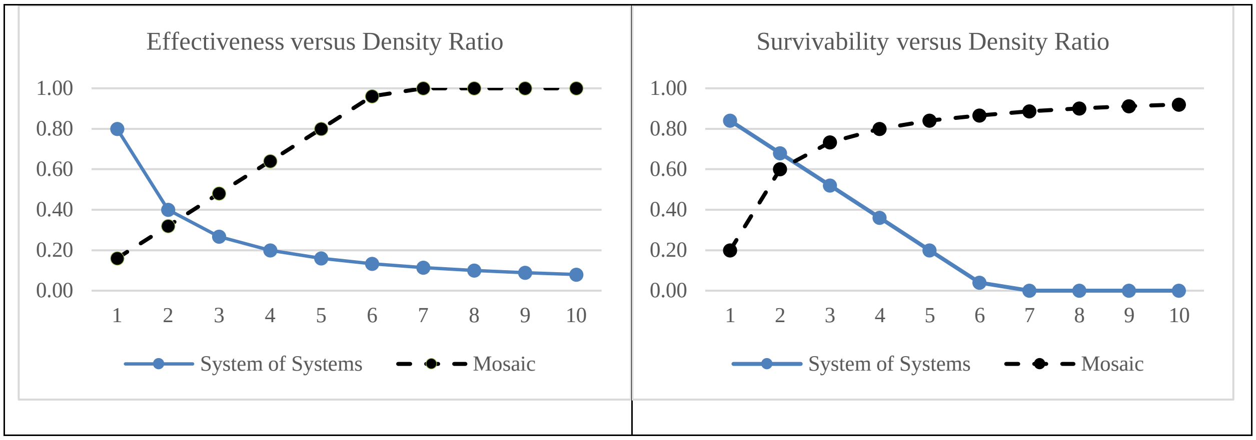

Figure 2: Sensitivity against density ratio ρ when precision ratio ψ*=1* and resilience ratio α*=0.2*.

In Figure 3, the results from the precision ratio experiments are illustrated. When the density ratio is 4 and resilience ratio is 0.2, the changes in the precision ratio has only limited effect on the results. We observed the same also for other density and resilience ratios. As the precision ratio increases, the M entities perform better as expected, however, the change is not very significant.

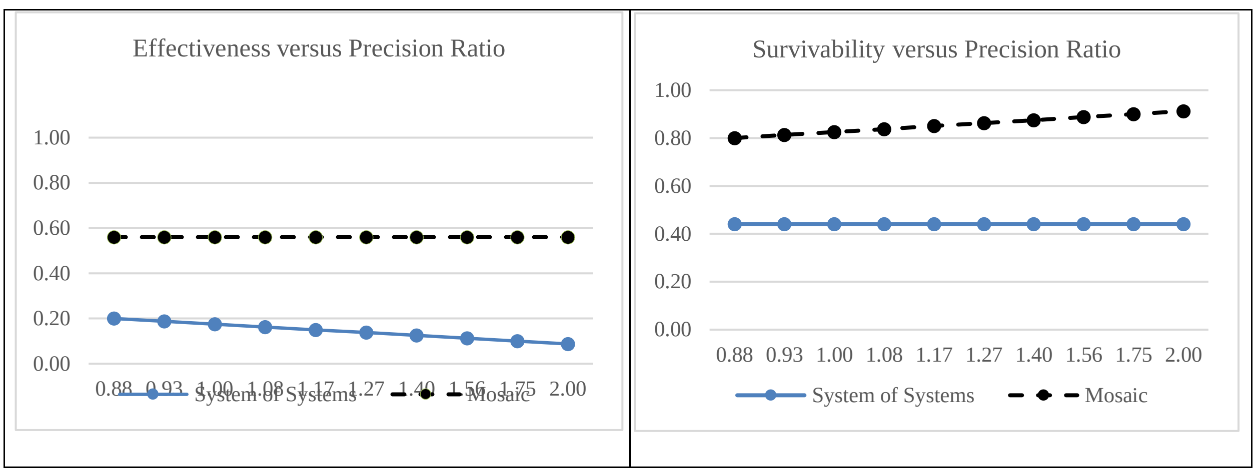

Figure 3: Sensitivity against precision ratio ψ when density ratio ρ=4 and resilience ratio α=0.2.

In Figure 4, the sensitivity of effectiveness and survivability are tested against the resilience ratio when the density ratio is 4 and the precision ratio is 0.2. Obviously, the resilience ratio has a major impact on effectiveness. The lower the resilience ratio becomes, i.e., M entities need to hit more to eliminate an S entity comparing to the number of hits by S entities to eliminate an M entity, the lower the effectiveness of M entities gets. The effect of resilience ratio on the survivability is very limited. That is because all S entities are eliminated when the density ratio is 4 and precision ratio is 0.2 independent from the resilience ratio. In our next set of experiments where we will introduce further complexities such as weather, terrain and morale factors, we plan to further investigate this result and what it means.

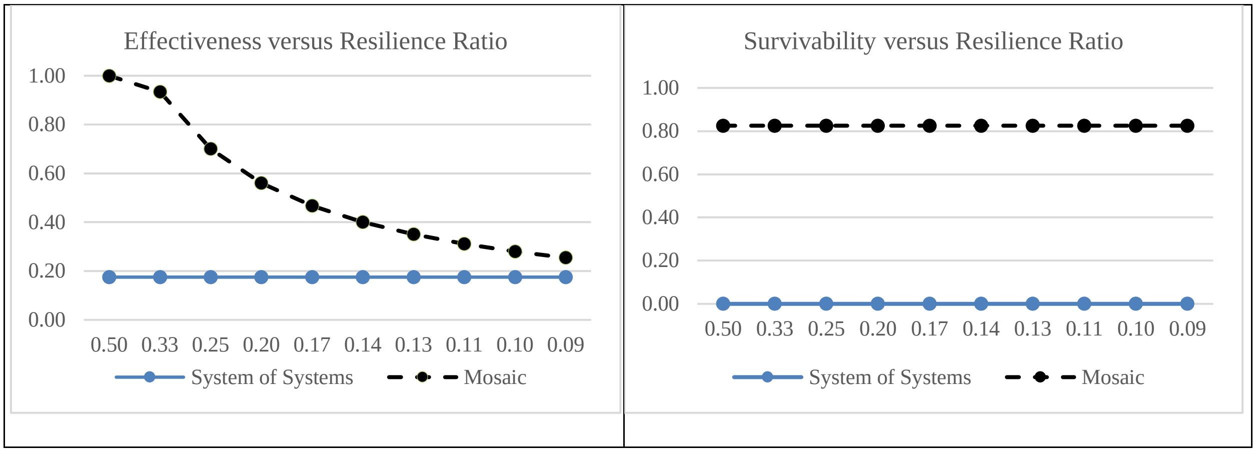

Figure 4: Sensitivity against resilience ratio α when density ratio ρ=4 and precision ratio ψ=0.2

The previous experiments are run only once and the results are analyzed. Figure 5 shows the results from consecutive simulations which are run from the state that the previous simulation ended. In other words, we examine the effect of combat duration on effectiveness and survivability when the density ratio is 4, the precision ratio is 1.33 and the resilience ratio is 0.2. The length of each simulation step (i.e., days or hours) is not relevant because the precision value represent the probability of hit in a unit time. In the following set of validation experiments, all these parameters will become more specific. Figure 5 implies that the longer the combat is, the better the Mosaic concept performs.

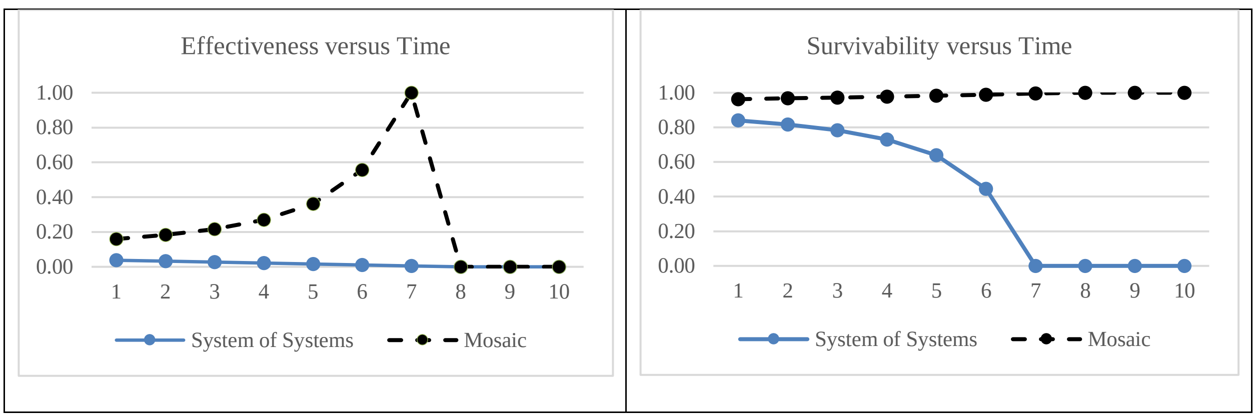

Figure 5: Sensitivity against combat duration when density ratio ρ=4 precision ratio ψ=1.33 and resilience ratio α=0.2.

5 CONCLUSION

An experimentation environment is set and preliminary discovery experiments are run to gain further insight into the mosaic warfare concept and its advantages comparing to the system of systems approach. Proposition 1 and 2 are focused on, and therefore effectiveness and survivability are selected as the measures. The experimentation environment is simplified and isolated from many factors, such as decision making process, C2, morale, various terrain types and weather conditions. Instead the sensitivity of the measures are investigated against the main factoring parameters implied by the propositions, namely density, precision, resilience and duration. Our main conclusions are as the following:

- The mosaic warfare concept is promising and therefore we will further test it with the aim of the concept validation.
- The density and resilience ratios are the main factors that impact on the performance, especially effectiveness.
- The mosaic warfare concept introduces major advantages especially in the combats that last longer. However, the sensitivity against the combat duration depends on the density ratio and may get impacted by the other factors such as production capabilities and resources of the sides, which need to be further investigated.

We have established also a dynamic experimentation framework based on a constructive simulation system and a strong experimentation management tool, and designed our validation experiments in the light of the results from this first set of discovery experiments.

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