Symbiotic Simulation (S2) Based Decision Support

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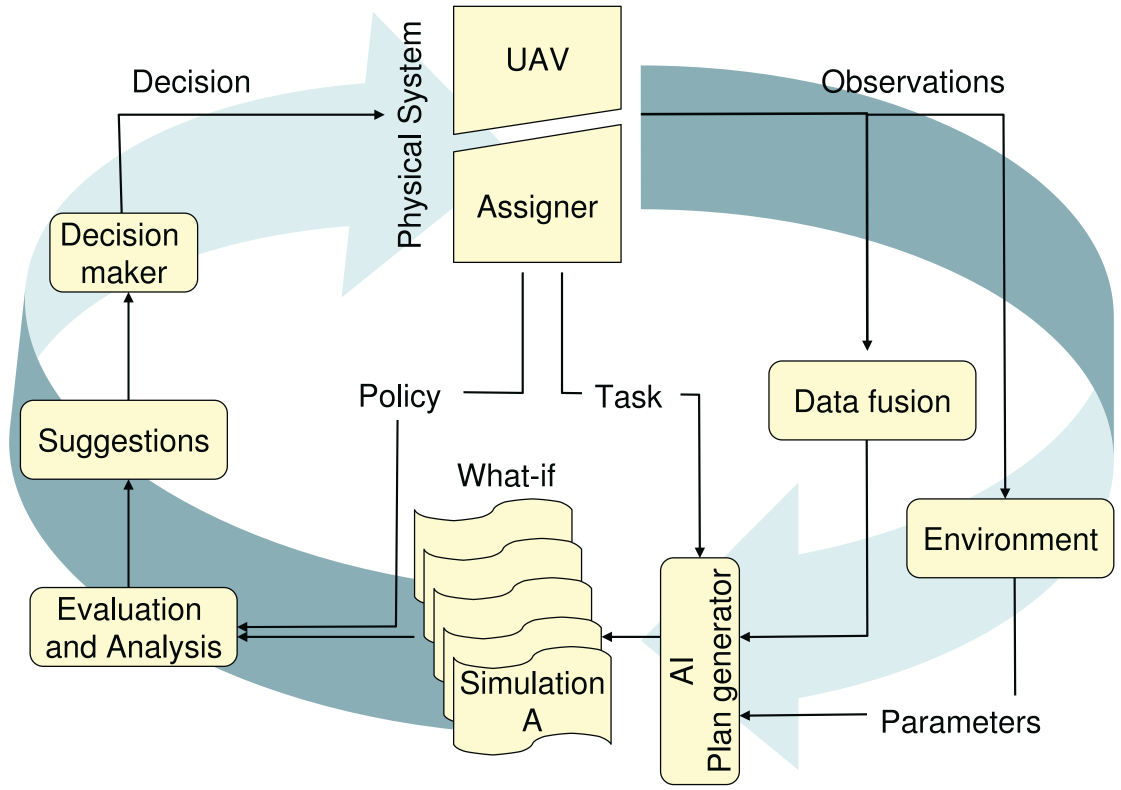

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Abstract

Symbiotic Simulation (S2) based decision support is a relatively new and growing area where simulations are used in real-time to give support to the decision maker. Like embedded systems in the classical context an S2-system is connected to physical systems that it is supposed to simulate. The S2-system receives a constant flow of input data, from the physical systems and other sources, that is processed and used in the simulations. Several so called *what-if* simulations are executed to test different courses of action. The results from the simulations are evaluated, ranked in order of preference and presented in a comprehensible way to the decision maker. The decision maker uses these results, among other things, to choose an alternative and control the physical system. The consequences of these chosen actions are compared continuously with the results of the simulations. In this way the S2-system can validate and refine its models. Thus, there exists a symbiotic relationship between the physical system and the S2-system, hence the name *Symbiotic Simulation*. This report describes the S2-concept and maps related domains and on-going efforts within this area. Further on, examples of how the concept could be applied within a number of domains and the use for the defense are exemplified. One of the suggested applications is sensor management with UAV:s. This is the application the project mainly has concentrated on and that is used as a basis for the concept demonstrator that is currently under development. The report finishes with a discussion of the area, the conclusions that we have been able to draw, and finally a short description of the future work.

Keywords

Modeling and Simulation, Embedded Simulation, Symbiotic Simulation, Decision support, SBBS, UAV

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Simuleringsbaserade Inbyggda System för Beslutsstöd

Sammanfattning
Simuleringsbaserade inbyggda system för beslutsstöd är ett relativt nytt område där simuleringar används i realtid för att stödja beslutsfattare. Likt inbyggda system, i dess klassiska bemärkelse, är simuleringen kopplad till de fysiska system som den ska simulera och får kontinuerligt indata från dem och eventuellt även andra källor. Flera så kallade *'what if'*-simuleringar görs för att testa olika möjliga handlingsalternativ. Simuleringsresultat utvärderas, rangordnas och presenteras på ett lättbegripligt sätt till beslutsfattaren. Beslutfattaren använder bland annat dessa resultat för att välja ett alternativ och kontrollera det fysiska systemet. Konsekvenserna av dessa val jämförs kontinuerligt med resultatet från simuleringarna. På detta sätt kan simuleringssystemet validera och förfina sina modeller. Därför finns det ett symbiotiskt förhållande mellan det fysiska systemet och simuleringarna, därav kommer begreppet *Symbiotic Simulation*, S2.
Denna rapport beskriver S2-konceptet och kartlägger relaterade domäner och pågående ansatser inom detta område. Vidare ges exempel på hur konceptet skulle kunna tillämpas i ett antal problemdomäner och nyttan för försvaret. Ett av dessa tillämpningsförslag är sensorstyrning medelst UAV:er som är den tillämpning som projektet framförallt inriktat sig på och som ligger till grund för den konceptdemonstrator som är under utveckling. Rapporten avslutas med en diskussion av området med de slutsatser som har kunnat dras samt en kort beskrivning av det fortsatta arbetet.

Nyckelord
Modellering och Simulering, Inbyggda Simuleringar, Symbiotiska Simuleringar, Beslutsstöd, SBBS, UAV

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Contents

Executive Summary

The network based defense is a good example of a large and complex system with many subsystems and participants which share information and cooperate to perform different kinds of tasks. The decision making process in such a complex system needs some sort of built-in "intelligence" to produce a basis for decision support. The task of this "intelligence" is to filter, analyze and compile information in real-time or faster as the information must, at the latest, be available at the time of decision making. The result of this information processing can be used in a number of applications, e.g. to control different subsystems, to utilize and guide platforms, to optimize performance of units or to supply decision support in a comprehensible way to the decision makers. Symbiotic Simulations (S2) that interact in real-time with real systems is an example of such an "intelligence".

An S2-system is a system which uses an on-line simulation as a means of supporting, controlling or optimizing a physical system. An on-line simulation is a simulation that interacts and exchanges information in real-time with the physical system. The interaction of the simulation and the physical system is of benefit for both systems. The result of the simulation is used to optimize the physical system and the simulation benefits from the continuous supply of the latest data and the automatic validation of its simulation outputs. The increasing computational power of processors and the overall improvements in software technologies and communications techniques makes it possible to bring this vision into reality.

The project's overall aim has been to study and develop methodologies for integrating simulations within physical systems. These simulations should in real time analyze and optimize the physical system's behaviour and/or supply decision support for a more efficient control of these systems. However, to achieve these goals a number of questions have to answered, e.g. how information from the physical system can be processed to be of use in the simulation, how the results from the simulations are best evaluated to be of use for the decision maker and how alternative plans that should be compared are generated.

The research in this domain is still very new and only a few publications in the area are available. However, symbiotic simulation is a cross-disciplinary area fusing modeling and simulation, command and control, decision support, data fusion, man-machine interface and automatic control engineering. Therefore, we believe that the answer to many of the questions in the domain may be found in these areas.

During the year 2005 the project mainly focused on surveying the area, finding applicable problem domains, finding the general characteristics of these domains and choosing an application for further investigation. Research groups from Singapore, Sweden and USA are active in the area. Despite differences, they all work to use simulations as a control or decision support tool. The research group from Nanyang Technological University in Singapore is pursuing the idea of Symbiotic Simulation as it was first defined in the M&S Dagstuhl seminar. The research group from US Naval Research Laboratory in USA is more concerned with integrating simulations in Command and Control systems. The Decision Support Group at KTH, Information Fusion Group and the Systems Modeling Group at FOI in Sweden are focusing on using simulations for supplying a basis for decision support.

The conceivable domains which may benefit from Symbiotic Simulation have been categorized according to two dimensions: dynamics and degree of distribution of the system. Different problem domains have been studied to make a preliminary assessment of whether they can take advantage of S2, find-

ing some of them more promising: sensor management, traffic system, torpedo defense systems. After having considered these problem domains the project decided to continue with the sensor management application with focus on S2-based decision support for both UAV path planning and predictive situation awareness. For this reason a prototype for studying different methodologies will be implemented during 2006 as a proof-of-concept.

1 Background

1.1 Introduction

Today's systems become more and more complex with many subsystems that have to cooperate. A good example of this is the Network Based Defense (NBD), where platforms, operators, decision makers, technical systems, etc. have to be connected in real-time and share information and help each other to perform different kinds of tasks. To support decision making in complex systems and in real-time, some sort of built-in intelligence is needed. The task of this "intelligence" is to filter, analyze and compile information to produce a basis for decision support and present it in a comprehensible way to the user. These tasks need also to be calculated in real-time or faster as the information must, at the latest, be available at the time of decision making.

There are different ways to implement built-in intelligence, e.g. using different tools and methodologies like mathematical methods, optimization algorithms, game theory, etc. When it comes to dynamic and complex systems with many uncertain and stochastic variables, these kinds of solutions are not always possible to use. In these cases M&S has proven to be an efficient tool and has been successfully used to produce a basis for decision support. M&S involves processing and representing gathered data and analyzing the system behaviour with the aid of simulation models. These analyses are then used by decision makers.

Until now, simulations have been used as off-line processes running with no direct connection to the physical systems (e.g. systems that are simulated). To reach the aims previously described, there is a need for simulations that are part of the real systems and that run on-line. These built-in, or symbiotic simulations (S2) interact in real-time with real systems to e.g. optimize their performance, control or supply decision support. They are called *symbiotic* because both the physical system and the simulation benefit from the connection. The term Embedded Simulation has interchangeably been used for this kind of simulation systems.

A clear example of a system that could benefit from S2 is the future NBD. Information from the simulations could be used both for decision support and to control parts of it. Symbiotic simulations can also be used to control and guide different kinds of platforms, for example, they can be built into airplanes to support pilots in the assessment of different tactical moves and in navigation in combat situations. The same simulations could also be used to control unmanned vehicles, such as UAVs.

To use simulations in this way is no trivial task. A common basis of understanding between the physical system and the simulations is required. Moreover, qualities such as flexibility, adaptability, transparency, efficiency, fault tolerance, security and self regulation are needed to facilitate success. All of these characteristics are of importance and may sometimes be contradictory and thus give rise to conflicts. Hence a number of research challenges exist that must be dealt with to fulfill the promises of S2.

The aim of the FOI project is a preliminary study of the concept and building the foundation for achieving those promises.

1.1.1 Usefulness for the Defense

Symbiotic simulations is a new research area with a lot of potential for many applications. As the NBD becomes more and more a reality and an integral part of the Swedish defense the need for decision support for various kinds of tasks becomes increasingly important. In dynamic and complex systems such as the NBD there is a need for an "intelligence" that has the capability of helping with tasks like optimizing, planning and controlling systems.

Modeling and simulation is a well known methodology for producing a basis for decision support and exploring alternate courses of action. But, until now, simulations have been used as an off-line process running with no direct connection to the physical systems. By connecting M&S-systems to physical systems and allowing them to interact in real-time the mutual benefits should be great.

1.1.2 Research Challenges

The area of Symbiotic Simulations is quite new and a number of research challenges exist. Examples of these are:

- How can information from the physical system be processed to be of use to the simulation?
- How are the results from the simulations best evaluated to be of use for the decision maker?
- What kind of support does the decision maker need?
- How can the interaction between the physical system and the simulation function?
- What kinds of limitations are there?
- How is data supplied to the simulation?
- How are the results presented to the decision maker?
- Which systems may benefit most from symbiotic simulations?
- What kinds of simulations are the best for symbiotic simulations?
- How are the simulation outputs validated?

Some of these questions will be dealt with in this project.

1.1.3 Definitions

In this report a number of terms are used and here we define some of them.

Symbiotic Simulations An S2-system is a system which uses an on-line simulation as a means of supporting, controlling or optimizing a physical system. The simulation and the physical system interact in real-time and both benefit from the interaction. The physical system benefits from the optimized performance that is obtained from the analysis of simulation experiments. The simulation system benefits from the continuous supply of the latest data and the automatic validation of its simulation outputs. The term was coined at the Dagstuhl Grand Challenges workshop in 2002 [1], page 50.

Related terms that can be seen in the literature are *Embedded Simulation Systems* and *Simulation Based Embedded Systems*. These terms generally refer to the same thing and we will not make any major distinction between them.

Embedded System An embedded system is a special-purpose computer system, which is completely encapsulated by the device it controls. An embedded system has specific requirements and performs pre-defined tasks [2].

On-line simulation An on-line simulation is a simulation that is a part of the system it is intended to support, control or optimize. The simulation continuously provides output that can be used in the system.

Real-Time System A real-time system is one in which the correctness of the computations not only depends upon the logical correctness of the computation but also upon the time at which the result is produced. If the timing constraints of the system are not met system failure is said to have occurred.

In a hard real-time system an operation performed after the deadline is by definition incorrect and has no value.

In a soft real-time system the value of an operation declines steadily after the deadline expires [3].

Decision support Decision Support Systems (DSS) are a class of computerized information systems that support decision-making activities. DSS are interactive computer-based systems and subsystems intended to help decision makers use communications technologies, data, documents, knowledge and/or models to complete decision process tasks. Five more specific Decision Support System types include Communications-driven DSS, Data-driven DSS, Document-driven DSS, Knowledge-driven DSS and Model-driven DSS [4].

1.2 Purpose of the project

The overall aim of the project is to study and develop methods for constructing simulations as a part of physical systems. Methods are needed, e.g., to analyze and optimize the physical systems behaviour in real time and/or supply decision support for more efficient control and command of these systems.

1.2.1 Focus and Activities

The project is conducted during three years. The main focus and activities are:

- During the first year (2005) focus lies on making a survey of the area both nationally and internationally, to define basic concepts, to identify different methods and areas of research needed for a realization of S2. Another task is to establish a competence group and network, and to investigate different scenarios where S2 can be applied. To test these scenarios a prototype will also be designed.
- During the second year (2006) the prototype is further developed and and a small implementation is done. Two main challenges are studied, how to connect the simulation with the physical system and what kinds of "what-if" simulations should be simulated at each instance? Related questions are e.g. what initiates a "what-if" simulation, how are the simulation

results evaluated, how are the results presented to the operator and what are the real-time requirements of the decision support systems?

- During the third year (2007) the chosen simulation methods and the prototype are further developed and tested. A proof-of concept demonstration will also be made.

1.3 Outline

The report is divided into five chapters. The first chapter describes the background and objective of the S2 concept and project. Some research challenges and definitions are discussed together with an introduction on how the concept came to be.

Chapter 2 deals with related research and domains. A survey of related papers has been made and a summary of the most important issues is presented here.

In the third chapter an effort is made to map the S2 domain. A preliminary investigation of the kinds of scenarios S2 might be suitable for has been done and some of these plausible applications are described.

The project has decided to continue with the UAV scenario from chapter 3. In Chapter 4 the UAV scenario is further described and expanded. The design proposal for implementing a prototype of this scenario is described.

In chapter 5 a summary of the report is given. The most important conclusions together with future work are also presented here.

Appendix A is a summary of studied papers and other related documents.

2 Related Research

2.1 Related Domains

Symbiotic simulations is a complex and challenging concept. It is still very new and requires contributions from various fields and domains. We found the following domains relevant to Symbiotic Simulation.

Modeling and Simulation Modeling and Simulation is a powerful tool for a number of purposes like training, control, evaluation and analysis of new system designs and modifications of existing systems. In [5] a model is defined as a simplified representation of a system, a process or unit with respect to a specific objective. A model is usually based on mathematics, theoretical laws and principles for the purpose of comprehending and studying a system. Simulation is the imitation of the operation of a real world process or system over time. Apart from difficulties in modeling and simulation in general, M&S in S2 based decision support brings along some new challenges. For example since simulation in S2 is run in parallel with the physical system, the result of the simulation should be validated and analyzed on-line.

Decision Support and Command & Control Command and Control (C2) refers to the ability of military commanders to direct their forces. Decision support is the science of combining and utilizing different kinds of resources to achieve the goals of a given task by choosing between alternative courses of action [6]. Decision support tools usually provide this support by predicting the development of a situation via simulation or evaluating the performance of strategies. S2 is aimed to predict the consequences of an action and its impact on the system. Hence, these approaches are naturally connected. Moreover, the aim of this project is to use S2 as a means of decision support. Therefore studying the relation between S2 and Decision Support is inevitable.

Data Fusion Data Fusion is the science of combining multiple (usually uncertain or conflicting) data, to infer a valuable conclusion. In systems which are stochastic and/or not fully observable, Data Fusion provides irreplaceable support for assessing the state of the system, and the input to the simulation.

Man Machine Interface The user interface that is the layer between the system and the user is of special importance in a Decision Support system. The information from the system should be presented to the user in a correct and understandable way and users' input should be understood correctly by the machine. This is of even more importance in the S2-based Decision Support, since the simulation is involved in the communication and should understand the physical system and vice versa.

Artificial Intelligence Roughly speaking, AI is the computational techniques to automate tasks that require human intelligence and the ability to reason. In

S2 systems, different strategies should be identified and the impact of them on the system be compared. M&S is the tool that mimics the system and compares these different strategies. However, if these strategies are not designed in advance, which is not possible in many cases, some kind of intelligence should identify and suggest them, either human or artificial.

Control Control theory deals with the behavior of dynamical systems over time. When one or more output variables of a system need to show a certain behaviour, a controller manipulates the inputs to the system to obtain the desired effect on the output [7]. In autonomous control systems the actual performance will repetitively be compared with the desired performance and the appropriate action is taken to correct the system behaviour. This repetitive process is in essence similar to the suggested loop in S2 systems which aims to use simulations to optimize or adapt the system to a changing environment.

2.2 Survey Summary

This section contains a summary of the survey of related research made within the project. The survey has mainly focused on published papers that are directly related to Symbiotic Simulation or considered to be of importance for this area. Some of the papers are mentioned here but for an extended summary of all papers see Appendix A. Since the research area is not yet well established, the number of published papers is limited.

After discussing how the term *Symbiotic Simulation* was published for the first time, we try to summarize the ongoing research in the area and provide a review of this research trend. This research is mainly carried out in Singapore, Sweden and USA. In Singapore it is the Nanyang Technological University, in Sweden it is FOI and the Decision Support Group at KTH and in the USA it is the Naval Research Laboratory that has mainly done research within the area.

2.2.1 Dagstuhl Seminar in M&S, Germany

To the best of our knowledge the first time the term "symbiotic simulation" was used in a scientific publication was in the Modeling and Simulation Seminar at Dagstuhl in 2002 [1]. The aim of the Dagstuhl Seminar was to condense ideas and proposals into a set of Grand Challenges that would help further the research progress in modeling and simulation. At the Seminar the participants were divided into several working groups where the group for Parallel / Distributed Simulation presented the idea of Symbiotic Simulations [1]. The group's definition of a symbiotic simulation is as follows:

> Symbiotic simulation is a simulation that interacts with a physical system in a mutually beneficial way. The physical systems benefits by optimized performance and the simulation benefits by having continuous data and automatic validation of simulation outputs. This implies real-time interaction and a control or decision support function.

A proposed high level architecture of how a physical system and simulations interact is depicted in Figure 2.1.

2.2.2 Singapore, Nanyang Technological University

Inspired by the Dagstuhl Seminar, the Nanyang Technological University and Singapore Institute of Manufacturing Technology developed a proof-of-concept

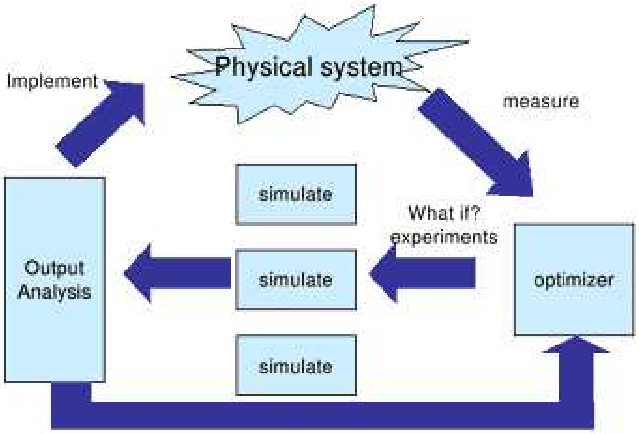

Figure 2.1: A proposed high level architecture view of how a physical system and simulations interact [1].

symbiotic simulation system [8]. The system uses software agents for monitoring, optimization and control of semiconductor assembly.

The background of the problem is the increasing complexity of semiconductor manufacturing which results in a rapidly changing business environment and shortening of the life cycle of products. A typical semiconductor backend and test facility has a large number of process flows with short cycle-times, roughly one week.

Simulation has been an important decision making tool in evaluating scenarios in semiconductor manufacturing. However, since the physical system changes very often the modeling and simulation process cannot cope with these rapid changes. Symbiotic simulation addresses this problem and will enable the system to respond promptly to abrupt changes of the physical system.

The physical system here is a factory consisting of two assembly and test conveyors. Each of these conveyors is a composition of several machines working serially. Whenever the in-house capacity of machines cannot handle the workload, some portion of the workload should be out-sourced to an external vendor. The decision is evaluated considering the penalty cost for order delays and cost of out-sourcing.

According to [8], this approach makes the simulation a tool for not only strategic and tactical but also operational decision making in the semiconductor manufacturing shop floor.

2.2.3 Sweden, FOI

To investigate the possibility of using S2 to optimize a system, FOI developed a prototype for optimizing the performance of a computer network [9]. Running simulation in parallel with the network, the system predicts the effect of different strategies on the network and chooses a strategy that minimizes the occurrence of bottleneck links in the network.

The task of the simulation is to compare three different forwarding policies repeatedly and to choose the most appropriate one for the next period. Both simulation and the "physical system" run in parallel for periods of times and interact at the end of these periods. The simulation is ahead of the "physical system" and predicts the state of the system at the beginning of the next period. When interacting, if the predicted state is validated against the real state of the network, the best policy is given to the "physical system" to be applied for the next period. Otherwise the "physical system" chooses a default policy and the simulation updates its picture of the state of the network.

Another approach at FOI has been to apply S2 for the continuous reevaluation of the situation in a scenario where decision makers face conflicting goals when peaceful demonstrations and protests degenerate into riots [10, 11]. The recently introduced concept of effects-based operations (EBO) in combination with S2 has provided a possible way of handling such situations.

In EBO, the interplay between actions and both direct and indirect effects are emphasized. By modeling these relations one can provide tools that make it possible for commanders to see what indirect effects may result from different choices of actions. This should make it easier to see what actions can be chosen, during an ongoing situation, in order to control the riot while simultaneously upholding the rights of the peaceful protesters. A proof-of-concept prototype of the merger of EBO and S2 has been developed [10].

The third related approach at FOI is the evaluation of sensor allocations using simulations of equivalence classes of possible futures. A new algorithm is introduced in the paper [12] and it is intended to be used for pre-planning of sensor allocations, e.g. for choosing between several alternative deployment sites for ground sensors or for choosing between several alternative flight-paths for UAVs.

2.2.4 Sweden, KTH

The decision support group [6] is an informal network of researchers in Sweden from KTH/Nada, Saab Systems and FOI. The aim of the research in the decision support group is about providing decision support tools for Command and Control applications, focusing on decision theory, information fusion and knowledge representation. Here, we summarize some of this group's efforts that are relevant for S2.

The first approach from this group deals with knowledge representation, and modeling of doctrines and information fusion. In [13] a conceptual model of agent-based simulations is presented as a part of the information fusion process. Information fusion is an on-line process and the agent-based simulation resembles the function of a symbiotic simulation.

The goal of the information fusion process in combination with the agents is to:

1. collect all relevant sensor data and information.
2. combine this information with a priori knowledge, e. g. terrain, doctrines, performance of vehicles etc.
3. represent improved estimates of world state of interest (situation assessment).
4. predict the most likely course of the enemies' actions by agent-based simulation and connect it to the most probable and most destructive outcomes (impact analysis).

The second approach targets simulation-based decision support for command and control [14]. This work suggests that simulations should be part of future C2 systems in order to give the commander the opportunity of simulating tentative decisions and evaluate their consequences during the planning process. In joint operations where different units are involved the commander cannot always predict the outcome of different tentative plans and compare these alternatives due to the complexity of the situation.

Simulation-based decision support in this approach is composed of multi-agent simulations which are used to predict the consequences of a tentative plan and multi-attribute evaluation that compares the multi-attribute consequences of the plan. The S2 support in this example is a network resource that would be connected to other functional units of the C2 system. The aim of this design is that it also could provide decision-making services for training.

The third approach has been to use particle filters to acquire information. In the paper [15] it is described how a stochastic simulation method called particle filter [16] has been used to represent uncertainty in a state and to predict the future state.

Uncertainty arises due to lack of observations. Therefore an agent is represented as a set of possible or alternative states called particles. These state uncertainty particles are depicted in left part of Figure 2.2 (red particles). In [15] each particle represents a state of possible agent's (enemy platoon's) position and velocity.

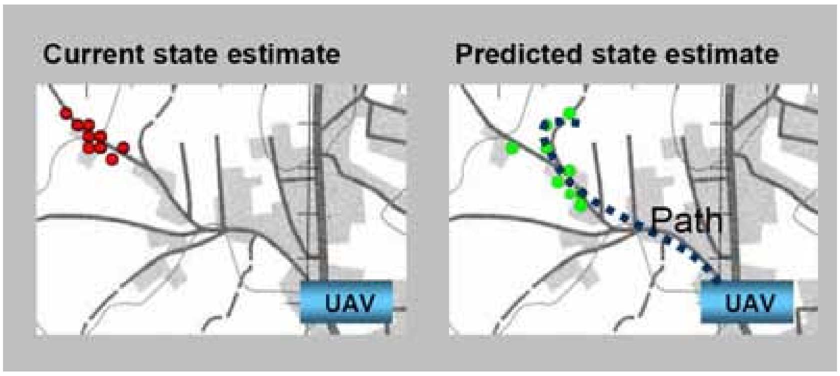

Figure 2.2: State uncertainty particles (red) and prediction particles (green)

Generally, to reduce the uncertainty about an agent's (enemy's) state, position and velocity in this case, sensors are used. In this paper a pro-active approach where an on-line simulation is used to predict a situation repetitively is presented. The prediction time has been set in relation to how long time is required to reach an area of interest. This is done by using a transition model that takes state uncertainty particles as input and simulates an output of the predicted state, see the right part of Figure 2.2. Consequently, by running these simulations the route planning of sensors (e.g. UAVs) can be done with information based on the predicted state when a sensor would enter the area. This process is run repetitively as soon as a new sensor task is assigned. The use of particles for decision making has also been investigated in [17].

2.2.5 USA, Naval Research Laboratory

The US Navy Embedded Simulation Infrastructure (ESI) Program has been established with the objective of facilitating the ability to simulate plans and courses of actions in C4I (Command, Control, Communications, Computers and Intelligence) systems. The main focus is to provide support in the *decide* and *act* phases of the C4I-systems. The group has published a number of papers on their work.

The primary product of current operational C4I systems is a common operational picture (COP) used by decision makers to assess a tactical situation.

According to [18] the COP is an electronic map which displays the terrain, military structures, locations and movements of the forces, etc. By integrating simulations in the operational picture the COP is enhanced to support the commander in the entire command and control process.

In [19] the authors point out that simulation based applications have the ability to process C4I data beyond human cognition, and display it in an intuitive and meaningful way for key tactical decision makers. The COP is proposed to be divided into two parts. The first part is a COP that is based on current processed and aggregated data. The second part, which is based on simulated data, is called simulated common operation picture (SIM-COP). The SIM-COP can also insert simulated data in place of or as a complement of real-world data.

Another effort developed within the C4I ESI program is the Mission Application Software Development Kit (MASDK) [20]. The MASDK is an architecture framework, a set of sharable C4I software components and a composability tool. It is written in Java and integrated with a Common Operating Environment (COE). The aim of MASDK is to reduce the complexity of the design and the developers' workload by composing systems from a collection of reusable elements.

There are few (generic) architectures for combining simulations and C4I-systems. Models are rarely reused and often lack composability. According to [21], one of the reasons for the modest success of integrating models and simulations in C4I system applications is due to the lack of M&S services within the COE. In the paper the authors state that there are three critical elements that are necessary to compose simulation based C4I applications out of common components:

1. Selection and design of sharable software components that can be used within a domain

2. Flexible architecture structure that promotes reuse within a domain or even between domains

3. Development environment that promotes the combined use of the common operation environment and the M&S components.

2.3 Common denominators

The approaches and papers discussed in this chapter differ in starting points and focus; the Dagstuhl Seminar [1] reflects the high ambitions of the Modeling and Simulation community to change simulation into a tool used by the system itself as a means of control and optimization. One of the difficulties of this task is that simulation so far has been a tool used off-line for understanding and analyzing of systems. Validation of the model, interpretation of the outputs of the simulation and inferring optimization parameters is usually done by domain experts after careful consideration and comparison of the simulation results with experiences from the reality. A symbiotic simulation is claimed to automate these processes, since the simulation results could be validated and implemented in the physical system in run time. [8, 9] have been inspired by these challenges and have the same focus. The models in these experiments are discrete-event systems and the objective of the simulations is to compare some single-attribute decisions and choose one. The preliminary aim of these projects has been proof-of-concept, i.e. demonstrating the feasibility of the idea of Symbiotic Simulation, rather than solving a real problem pending solution.

The U.S. Navy's research goal is to enhance existing C4I systems into more powerful tools that support decision and action in the command and control process. Simulations here are not symbiotic and they do not interact with the physical system as described in the Dagstuhl seminar. Simulations discussed in this system are much more complex and can be of different types from simulating weapons of mass destruction to war-games conducted by humans.

However, the common objective of these efforts is to connect the simulations and the real world in a more direct way.

3 Applicable Problem Domains

The range of problem domains that might benefit from Symbiotic Simulation appears vast at the first glance. However, a few dimensions along which these domains can be categorized, would help to identify those problems that are likely to be potential adopters of S2. In S2 the simulations should run faster than the real process, in other words the ratio of the real system time and the corresponding simulation execution time should be larger than one. Two major factors affect this measure, how dynamic the system and the model is and the complexity of the system. The distribution of the physical system is a third factor that can influence the suitability of applying S2 to that problem domain.

- Degree of dynamics, i.e. how often the system changes. Despite the lack of a definition that yields a quantitative measure of the dynamics in a system, it is possible to compare and roughly rank systems with respect to their rate of changes. It should be underlined that when comparing systems only those changes which are included in the simulation models should be considered. In other words, we are merely interested in how often the state variables of a model change.
- Degree of complexity; once again we consider parts of the system that make a contribution to the complexity of the model.
- Distributed vs. Monolithic / Centralized. Systems that are geographically or logically distributed are inherently more complex and dynamic. Furthermore it is not possible to determine the global state of the whole system. A distributed system may be monitored and controlled centrally or in a distributed manner.

Some problem domains were identified and categorized according to the above mentioned criteria, see Figure 3.1. In the following these problem domains are described, among which one (UAV Path Planning) was found most appropriate for conveying the idea of the Symbiotic Simulation. The UAV Path Planning is discussed in the next chapter.

3.1 Sensor Management

Effective use of available resources is strongly significant for the possibility of accomplishing a task. Sensor resources are part of a system that collect relevant data from the real world in order to enable the system to perceive the environment and act rationally. The importance of managing sensors becomes more apparent if we consider the costs related to placement and maintenance of sensors. For instance, in a hostile environment it is not a trivial task to distribute a sufficient number of sensors or supply the power needed by these sensors. The result is that in many situations management of these resources is very critical and the use of symbiotic simulation for optimum placement and

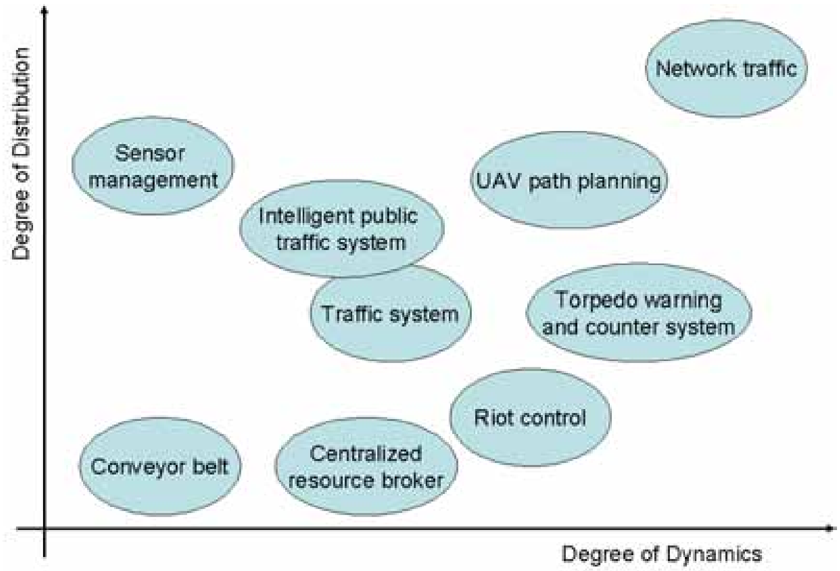

Figure 3.1: Problem Domains

usage of sensors is well motivated. Examples of efforts within this area are [22, 23].

3.1.1 Capabilities and Constraints of Sensors

A sensor is a device that measures or detects a physical stimulus (light, sound, temperature, pressure and so on). Sensors may have different capabilities and constraints. Some of them are described below.

- **Life span:** Sensors may have a limited life span and must be substituted by new ones after a period of time.
- **Limited continuous availability:** Sensors may have limited power supply and the power source may need to be recharged periodically.
- **Coverage area:** Sensors cover a limited geographical area and an adequate number of them is needed for covering larger areas.
- **Usage area:** For example, visible light, infrared radiation, sound source.
- **Sensitivity:** Sensors have different sensitivity and resolution.
- **Communication:** Sensors may be equipped with different level of communication abilities.
- **Collaboration:** Sensors may collaborate with other sensors, communicate only with a central unit or be stand-alone units.
- **Computing power:** Sensors may send raw data or have computational power and process the data to some extent before handing it over.
- **Mobility:** Sensors may be mobile or stationary. Movement of mobile sensors is either self-regulating or instructed from a control unit. The velocity, acceleration and other movement attributes vary greatly between different sensors.

- **Scanning frequency:** Some sensors like satellites scan an area periodically.

3.1.2 Character of the field

Placement of sensors or their movement may be hindered by natural obstacles (such as rivers, mountains, etc) or man-made obstacles (cities, buildings, etc). Sensors may avoid some areas in order to prevent detection or damage caused by hostile actions.

3.1.3 Failure Detection

In case of damage of some sensors or part of the communication system, the possibility of recovering the network of sensors would be a critical issue. The first step toward this goal is to detect such failures. The system should have some means to detect missing sensors, disappeared messages and corrupted data. Comparing different strategies to recover the system and compensate for the missing elements would be a challenging task.

3.1.4 Applications

There are many applications from a wide range of areas that can use symbiotic simulation as a means of managing their sensor resources. Here we mention some which look promising.

- UAV scanning an area for detecting hostile objects. The problem of finding the most appropriate path for UAV will be discussed in more detail in the next chapter.
- soldiers distributed across a region. These soldiers can be seen as a network of sensors.
- planning of distribution and placement of different sensor elements (in order to cover as large an area as possible).
- protecting a mobile object by looking for its potential enemies.

3.1.5 Objectives

The objective of using a symbiotic simulation system in sensor management can be both increasing utility of existing systems and introducing management policies to new areas. Examples of such objectives are:

- given a limited number of stationary sensors, covering an area as thoroughly as possible.
- guiding mobile sensors for accomplishing a mission.
- managing flying sensors.

3.2 Effect-Based Operations

Peaceful demonstrations and protests that degenerate into riots may cause severe damage on infrastructure, cost lives and destroy private property. However, in addition to their mission to protect against damage and loss of lives, the decision makers responsible for keeping security are also tasked with protecting the right to free speech and protest. Thus, the decision makers may face conflicting goals. The recently introduced concept of Effect-Based Operations (EBO) provides a possible way of handling such situations. In EBO, the interplay between actions and both direct and indirect effects are emphasized.

By modeling these relations we can provide tools that make it possible for commanders to see what indirect effects may result from different choices of actions. This should make it easier to see what actions can be chosen during an ongoing situation, in order to control the riot while simultaneously upholding the rights of the peaceful protesters.

By using embedded simulation a continuous reevaluation of the situation can be performed and new (context-relevant) knowledge would be gained in order to support decision making. The main point here is to generate pieces of knowledge given a combination of different decision alternatives, i.e. our actions and possible counter-actions. Such knowledge is further combined with other knowledge fragments and an information model that represents the evolving situation. The information model explains relations and mechanisms between actions and predicted effects. Such a model would be a useful tool for providing real-time EBO analysis to support decision-making on-line.

Mechanisms of EBO are represented in an Influence Diagram by Conditional Probability Tables (CPTs), representing the uncertain causal relation between action and cause. However one conditional probability is required for each combination of relevant potential actions. Moreover, these mechanisms are cumbersome to describe and change as the situation evolves. Hence, the use of embedded simulations is proposed in order to subdivide the problem and automate the estimation of the CPTs [10].

3.3 Traffic System

A traffic system can be viewed as a network of roads in a city where intersections are regulated by traffic signals. The flow of vehicles vary unpredictably over time and it is desirable that the cost of the system is decreased. The cost is a function of some measures of interest such as delay time of vehicles, delay time for public transports, different types of pollution, etc. The cost function, i.e. the possible influence and weight of these measures are defined by policymakers and may vary over time. One can affect the traffic flow and the cost by changing the topology of the road network or modifying the traffic signals. Traffic signals can be either coordinated or not. An example of a partial coordinated traffic signal system is the Green Wave, where traffic signals along a certain path are coordinated in such a way that a vehicle keeping a recommended velocity will not be stopped by red signals. Traffic signals can be adaptive or non-adaptive, i.e. following a fixed scheme that may change periodically during the day. The intelligence in the traffic system can be centralized, distributed over subsystems or across all traffic signals. The area has been subject to intensive research by traffic authorities, researchers and consultant companies leading to different traffic models and software. As an example of a coordinated and adaptive traffic system SCOOT (Split Cycle Offset Optimization Technique) may be mentioned, which is a widely used traffic control system [24]. SCOOT responds automatically to fluctuations in traffic flow using on-street detectors. This system claims reducing traffic delay by an average of 20% in urban areas. Despite successful improvements in adapting the behavior of traffic signals to the input of on-street sensors by SCOOT and similar systems, we believe that there is still work to be done by simulation. For example, the overall picture of the traffic situation in case of important events or collisions may be predicted and appropriate action may be taken. This scenario seems to be an interesting case for using symbiotic simulation.

3.4 Resource Broker

The problem of managing trade between consumers and producers of different types of resources in a federative organization may be solved in different ways depending on the nature of the system and the policies that govern the assignment of resources. Here we consider a distributed system of nodes which share resources for mutual benefit and takes advantage of a resource broker for resource management. This resource broker has a symmetrical relationship with producers and consumers and does not give preferential treatment to any group. For the sake of fairness the resource broker should not own or control any resources. It has an advisory and monitoring role in the system and proposes a transaction between a consumer and a producer according to the current state of the system and an assessment of the future flow of demands and supplies. Both consumer and producer are free to accept the proposals, however they are bound by the transaction once they approve it. The resource broker will possibly assist in exchanging the necessary information for performing the task. It should be underlined that producers and consumers of the resources in general belong to different organizational units with different objectives and interests. A more complicated scenario would be a system where several resource brokers compete with each other.

There does not exist any universal solution to the problem that yields the best result under different circumstances and different strategies and algorithms may do better in different cases. Comparing these different policies dynamically when the input varies and choosing the best policy for the next coming period is a problem suited for symbiotic simulation. Policies that will be compared for matching producers and consumers can be e.g. opportunistic matching (matching the first available supply and demand), best-fit algorithm (searching for best available matches), perfect matching (matching only the supply and demand that have exactly the same attributes and sizes), a mixture of perfect and opportunistic matching (tuning how much difference between the size of demand and supply is allowed) and random matching.

There are some challenges to overcome; simulation is considered to be a tool for understanding the system, and the main decisions about the systems are usually taken by experts rather than automatically. Finding the underlying distribution of the input data and interpreting the output of the simulation is not trivial and usually requires different skills and analytical capabilities. Automating these processes will be the main challenge.

3.5 Torpedo Warning and Counter System

A possible application for using on-line symbiotic simulations could be situations like the following. A navy battleship has the mission of patrolling an area of interest and protecting valuable cargo ships from possible threatening submarines. To achieve this, the naval ship may employ different defensive tactics, such as discharging anti-torpedo torpedoes (ATT), trying evasive maneuvers, deploying torpedo disruptors, using a combination of these alternatives or clearing the area. Assessing the probability of failure or success of these tactics and analyzing the consequences of actions could be supported by the use of simulations. A symbiotic simulation system can continuously simulate all these actions and counteractions and as the situation changes provide decision support to the decision makers based on the latest data and events.

To achieve a good decision support the S2-system should be connected to some form of information hub receiving data from underwater sensors, satellite data, incoming reports and other information sources. To draw conclusions from the information the S2-system would need the help of auxiliary systems like information fusion engines and sensor data interpreters. It would also need to have access to data on the current status of the naval ship, its arsenal, current speed, environment and other relevant information. The described situation could also be made more complex by having multiple adversaries and navy ships.

The S2-based decision support could be supplied at various decision levels. At the most abstract level, support could be given on an operational level by setting up action plans and calculating possible threat situations. Plans could be made for multiple collaborating ships. On a less abstract level, like the tactical level, support could be supplied so that each navy ship has its own S2-system helping the commander with tactical decisions, e.g., suggesting different defensive measures at a given situation. At the lowest level the purpose of the S2-system could be to steer anti-torpedo torpedoes towards their goal. The S2-system would function as a built-in system in the traditional sense by calculating the trajectory as the ATT speeds towards its goal (this is also called receding horizon). These three decision levels have vastly different time requirements and each has its own challenges.

3.6 Conveyor Belt

An oil pump factory that desires to have a smooth flow of products, despite irregularity in the arrival of incoming orders, faces the problem of how to regulate production to deliver products as soon as possible without having large storages. The production pace may be regulated in several ways; temporarily hiring more people, increasing the time of possible production hours by having three shifts or by outsourcing some of the work to subcontractors.

The task of the S2-system is to simulate the consequences of the actions and supply decision support to management.

4 Decision Support for UAV Path Planning

Among the application domains discussed in the previous chapter, Decision Support for UAV Path Planning was chosen to be studied in detail. Our preliminary assessment indicates that the research in this area is far from exhausted and we believe symbiotic simulation may be used to dynamically determine paths for UAVs.

Interest for UAV systems in both civil and military areas shows a considerable growth in recent years. Despite diversity in the systems the trend is moving toward increasing autonomy of the UAVs. For example, the United States Air Force Research Laboratory (AFRL) has introduced the notion of Autonomous Control Level (ACL), and describes ten such levels, ranging from remotely piloted vehicles to fully autonomous swarms of Unmanned Combat Aerial Vehicles (UCAV) [25]. Constructing a framework for highly autonomous UAVs is a very demanding task that cannot be tackled using just one science discipline and technique. One natural way to handle this complexity is decomposition of the problem into a hierarchy of manageable subproblems. For instance, the aerodynamic control of a platform and its long-term path planning belong to different levels in the control hierarchy and can be controlled by different subsystems.

4.1 Scenario

In a static scenario the long-term path planning is primarily deterministic and can be computed off-line [25]. However, in a dynamic situation the long-term path should be re-planned in response to changes in the environment and planning is an on-line process running in parallel with the physical system, i.e. the set of UAVs and their control system with a surveillance mission. Our working hypothesis is that Symbiotic Simulation yields an appropriate decision support tool for utilization of UAVs. An example of how the S2-system loop for UAV path planning and decision support could be designed is seen in Figure 4.1.

Given an Area of Responsibility, a set of UAVs with different attributes and a prior estimation of the position and capabilities of mobile targets, the task is to continuously optimize the paths of the UAVs considering threats, sensor constraints and environment changes. This scenario is a partially observable, stochastic, sequential, dynamic, continuous and multi-agent scenario and thus the hardest case to study among different categories of systems [26]. One feature of simulation models is their ability to handle uncertainty and they may be used with advantage for probabilistic reasoning over time. Special representations such as Dynamic Bayesian Networks and inference methods like Kalman Filtering are appropriate tools which are frequently used in temporal probability models. In these approaches the transition model describes the physics of motion and the sensor model describes the measurement process [26].

For instance, in a surveillance mission the objective is to assess the state

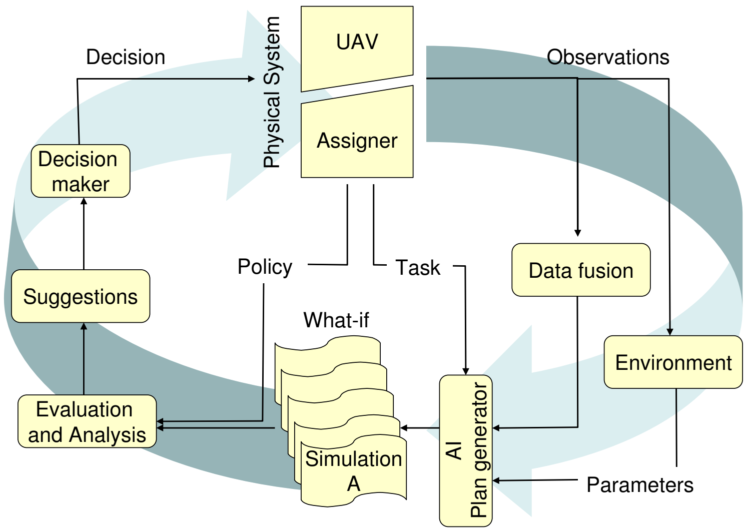

Figure 4.1: S2-system loop for UAV path planning

(position and velocity) of the target objects as accurate and effective as possible from a sequence of noisy and uncertain observations over time. Having accurate transition and sensor models obviously increases the performance of the surveillance system. In fact these models can be modified during the surveillance according to new observations, resulting in a more accurate assessment of the targets, their velocities, movement patterns, etc. But another requirement is to adapt continuously the path of the UAVs to the changes in the environment. If there are a manageable set of alternatives, then simulation can be used to compare these and suggest the most appropriate one.

4.2 Design of a Simulator

In order to test and evaluate the idea of using Symbiotic Simulation for long-term Path Planing of UAVs, we plan to develop a special purpose simulation system. The aim of this simulation which will be called S2P2, is to provide a research tool for experimentation with different methods and techniques and hopefully will be an instructive complement to theoretical research in the area. S2P2 will provide some insight into the possibility of applying theories in the area and will give indications about scalability and complexity of the algorithms.

The primary aim of S2P2 is to be an experimental tool, however in future it may well be developed and function as a prototype and demonstrator working with more realistic data.

We found a number of system attributes that are necessary for S2P2 to fulfill the above objectives as an experimental tool. It should be easy to develop, platform independent, flexible, independent of other (commercial) software and architecturally comprehensive. With these requirements the most appropriate choice would be to implement S2P2 from scratch in Java programming language using object oriented technology.

The system is naturally divided into five parts;

1. a model of the geography of the terrain.
2. a model of the target objects, their movement model.
3. a model of UAVs and their sensor model.
4. a Command and Control system for UAVs.
5. a model of the S2 that aims to optimize the behaviour of the UAVs.

It should be clear that the commander of the UAVs does not have access to complete information of the real world. The commander's view of the world is based on the information acquired by friendly troops and his/her UAVs. However, for simplicity we can assume that both the targets and the UAVs have access to an accurate map of the terrain. Some more details about these models will be given in the following sections.

4.2.1 Terrain Model

Terrain is modeled as a two-dimensional land area and may include the following elements:

- Lake: A body of water surrounded by land. Objects cannot stay in or pass a lake.
- Forest: a connected area with a fixed density of trees, the probability that an object is observed by UAVs reduces by a factor in the forest. This factor is defined by the user for each forest.
- Node: A basic spatial unit of terrain pointed out by the user. Cannot be located in lakes.
- Road: A strip of land connecting two nodes. They are of varying quality affecting the velocity of passing by objects. The road network is the collection of all roads and may be connected or disconnected.

4.2.2 Target Model

Targets have a type, source and destination. Except foot soldiers and tracked vehicles all objects are restricted to the road network and can only move along the roads. Foot soldiers and tracked vehicles can move everywhere on land, but if they are not moving along a road they should try to find the shortest path to their goal. The probability that an object follows the road is defined by the user. A scenario is a configuration of terrain and objects moving on the terrain, during a specified time period.

4.2.3 UAV Model

UAVs are platforms for carrying sensors of various kinds. Reasonably realistic assumptions considering velocity, altitude and motion constraints should be made to model the UAVs. A number of available UAV and types of the sensors are defined prior to the start of the simulation.

4.2.4 Command and Control System

The UAVs are controlled by a central Command and Control System. The objective of this system is to maximize a utility function, defined by the UAV operator. One trivial function is to detect as many target objects as possible, but studying other parameters like cost of the operation, risk of being detected and damaged are interesting as well.

4.2.5 Symbiotic Simulation

Given the state of the scenario in time t_i denoted by x_i, we simulate "all" possible future states x_{i+1} according to the transition model (see below). Having a sensor model (see below), we calculate the utility of the UAVs following different alternative paths, for each simulated future. The path which has a higher average utility over all x_{i+1} will be chosen for the next period. In the next period the prediction (the result of the simulations) will be validated against the real situation and transition model would be modified if necessary, justifying the term Symbiotic Simulation.

Transition model

The transition model is based on the physical laws of the real world and targets' doctrine which are known to the UAV system. This model is neither exact nor complete. The transition model may change during the simulation, either as a direct result of the new observations or under the influence of external information e.g. from analysis of the data in a higher level of data fusion.

Sensor model

Sensor model is the model of observations of the UAV sensors, given the location of the objects. For each object the probability that the object is detected or classified increases with:

1. decreasing the altitude of the UAV.
2. decreasing the distance of the projection of the UAV to the target.
3. increasing the time the target is observed.

This function varies for different target objects. However, the sensor model does not change during the simulation.

5 Summary, Conclusions and Future work

5.1 Summary

The main aim of this report has been to summarize our work in relation to the domain of Symbiotic Simulation. During the year 2005 the project mainly focused on:

- surveying the area
- finding applicable problem domains
- studying these domains and finding the general traits of these domains
- choosing an application for further investigation and use it as as a proof-of-concept

In chapter two, related research domains as well as ongoing research in the area of Symbiotic Simulation were identified. Three independent research groups in different countries, namely US, Singapore and Sweden are working in this area with different approaches. To find problem domains that could benefit from Symbiotic Simulation we categorized the conceivable domains using a few dimensions; how dynamic and complex a physical system and the corresponding simulation model is and the degree of distribution of the physical system. Examples of problem domains that we studied were sensor management systems, traffic systems and torpedo defense systems. After having considered several application areas the project decided to continue with studies of simulation-based threat awareness and the sensor management application. The focus of the application will be on S2-based decision support for both UAV path planning and predictive situation awareness. For this reason a prototype for studying different methodologies was designed as described in chapter 4 and it will be implemented during 2006 as a proof-of-concept.

5.2 Conclusions

Shortcomings of the existing control systems and the need for new approaches that can deal with uncertainty of the increasingly complex systems which embrace stochastic processes are becoming more and more obvious. Modeling and simulation is a well proven tool for analyzing complex systems whenever the equations that rule the system are not known or there is no feasible solution to these equations. However, one obstacle in using M&S widely is the long cycle-time needed to develop the model and validate it, execute the simulation and verify the results, analyze the results and apply them in the real system. Due to improvements in computer power, analyzing tools, simulation techniques and other software tools the M&S community has recently claimed to shorten this cycle-time radically and making it possible to connect the simulation and the physical system in a more direct manner.

The network based defense is a good example of a large and complex system with many subsystems and participants which share information and cooperate to perform different kinds of tasks. To overcome difficulties in the decision making process in such a complex system some sort of built-in "intelligence" that produces a basis for decision support is needed. Symbiotic simulations that interact in real-time with real systems are one example of such an "intelligence". The task of this intelligence is to filter, analyze and compile information in real-time or faster as the information must, at the latest, be available at the time of decision making. The result of this information processing can be used in a number of applications, e.g. to control different subsystems, to utilize and guide platforms, to optimize performance of units or to supply decision support in a comprehensible way to the decision maker.

Research about Symbiotic Simulation is still very new and thus not extensive but it is expected to grow. Experiments performed are in their early stage and challenges to overcome are many. There is no consensus on what an S2-system is, and quite different systems following various architectures and models claim to be an integration of the simulation and the physical system. However, common for these systems is that the simulation is closer to the physical system, spatially, temporally or logically compared with previous M&S systems. We believe that this trend will continue and accelerate in future.

5.3 Future Work

The project's overall aim is to study and develop methods and techniques for integrating simulations within physical systems. These simulations should analyze and optimize the physical systems behaviour in real time and supply decision support for more efficient command and control of these systems.

Following the ongoing research in the area and studying the work of research groups that try to apply Symbiotic Simulation explicitly and completely [8, 27] or implicitly and partly [18–21, 28] would be a valuable source to discover the possible capabilities and boundaries of the method. Symbiotic simulation is an interdisciplinary research domain and the answer to many of the research challenges may be found by taking advantage of settled methods in other communities. Surveillance of related research in command and control, decision support, data fusion, man-machine interface and automatic control is part of this project. In almost all problems in the automatic control field and in a number of research projects in the data fusion field, e.g. [11, 15], a continuous process that runs in parallel and interacts with the real system can be identified and the similarities with the idea of Symbiotic Simulation cannot be ignored. Even though the focus of these communities is different, a deeper study of control designs for stochastic systems and data fusion problems with focus on sensor management will provide a better understanding of the area of Symbiotic Simulation.

Examples of some of the research challenges that the project has decided to focus on are: how predictive situation awareness with simulations can be achieved; how simulation based path planning for sensors can be implemented; and how simulation based threat awareness is assessed. These questions will be the focus of the work during 2006 and 2007.

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A Related Research, Summaries

Related papers and publications that have been studied in connection with this study are found here. This appendix was written in cooperation with the *Embedded Simulation Systems for Network Based Defense* project at FOI.

A.1 Grand Challenges in Modeling and Simulation, Dagstuhl Report

Grand Challenges for Modeling and Simulation Seminar [1] at Dagstuhl in 2002 introduced the idea of Symbiotic Simulation according to the following definition:

> "A Symbiotic Simulation System is defined as one that interacts with the physical system in a mutually beneficial way. It is highly adaptive, in that the simulation system not only performs 'what-if' experiments that are used to control the physical system, but also accepts and responds to data from the physical system. The physical system benefits from the optimized performance that is obtained from the analysis of simulation experiments. The simulation system benefits from the continuous supply of the latest data and the automatic validation of its simulation outputs. Such a definition implies continuous execution of the simulation and real time interaction with the physical system" [1].

The main characteristics of symbiotic simulation in this definition which distinguish it from simulation in general are:

1. It runs in parallel with the physical system.
2. It applies its result to the physical system in run time.
3. It has automatic and continuous validation.

A.2 An Agent-based Approach for Managing Symbiotic Simulation of Semiconductor Assembly and Test Operation

Semiconductor manufacturing experience rapidly changing demands and search continuously for better production management. Simulation of the production process is considered to be the most feasible technique to evaluate the result of different production plans. However, one of the disadvantages of the simulation process is that modeling, implementation, verification and analysis of the result takes a long time which makes it inappropriate for performing "what-if" analysis when the system changes abruptly. In the paper [8] the authors suggest that symbiotic simulation systems remove the problem of long cycle-time process of modeling and simulation and describe the development of a prototype proof-of-concept symbiotic simulation system [8].

In this study the factory consists of two assembly and test conveyors. Each of these conveyors is a composition of several machines working serially. Whenever the in-house capacity of machines cannot handle the workload, some portion of the workload should be out-sourced to an external vendor. The decision is evaluated considering the penalty cost for order delays and cost of out-sourcing.

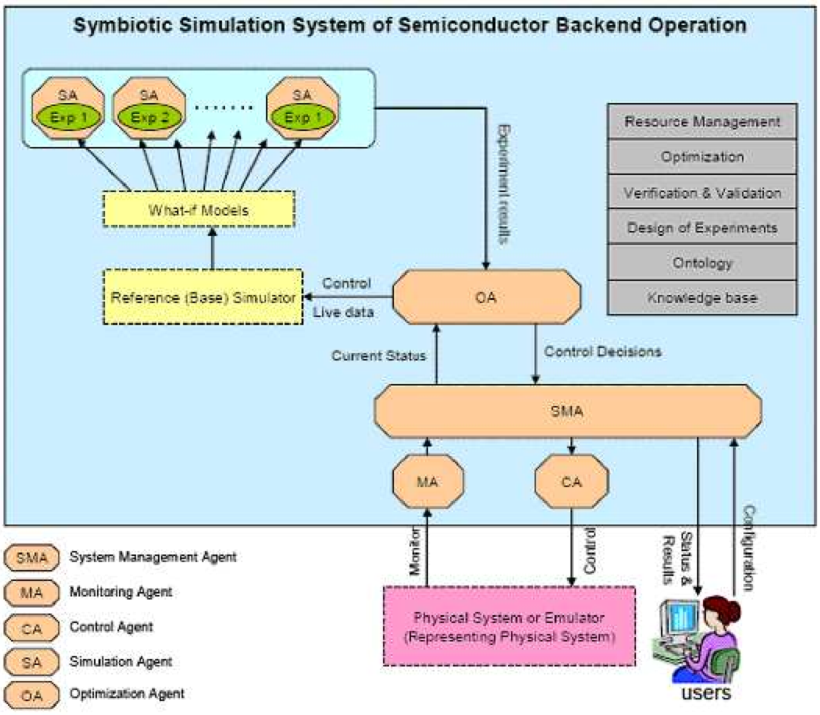

Figure A.1: Symbiotic simulation of Semiconductor Backend Operation [8]

Agent-based technology is used to realize the symbiotic integration between a simulation-based decision support optimization module and a model of a semiconductor backend system. An agent is a software program which is autonomous, proactive, responsive and adaptive. Using a multi-agent architecture where each agent makes decisions based on local knowledge and cooperates with other agents for global optimal performance of the system gives the system the characteristics of distribution of control, resources and experience among different agents. This approach makes the simulation a tool for not only strategic and tactical but also operational decision making in the semiconductor manufacturing shop floor. However, it should be underlined that this symbiotic simulation model is not integrated with a real semiconductor backend factory but with a software model of such manufacture emulated in the commercial software package Witness. Different agents in the system are implemented using the JADE agent toolkit. System Management Agent (SMA) is the central unit of the system, which interacts with operators (human users), the physical system (via Monitoring Agent and Control Agent), and the simulations (via Optimization Agent). Whenever the utilization of the machines exceeds 80%, the Optimization Agent carries out simulation-based optimization by comparing different "what-if" scenarios. The process begins with reading the current state of the system from System Management Agent and creating a Base Model of the system. This Base Model is running in parallel with the physical system and is used by different Simulation Agents to carry out "what-if" analysis. The Optimization Agent summarizes these results and if necessary instructs the Control Agent to make modifications to the physical system [8].

A.3 A Simulation-Based Symbiotic System Prototype

In the Master of Science thesis [9] a simulation-based embedded system is investigated and evaluated. For this purpose a prototype for optimizing the performance of a computer network is developed. Running simulation in parallel with the network, the system predicts the effect of different strategies on the network and chooses a strategy that minimizes the occurrence of bottleneck links in the network. Instead of a real computer network the system is connected to a model of a computer network implemented in Network Simulator 2 (NS-2). Three different forwarding policies are compared: using routing table lookup, choosing one of the outgoing links randomly and selecting the outgoing link with the shortest queue. The parallel simulation interacts with the "physical system" periodically and the best chosen strategy is applied to all "routers". Both simulation and the "physical system" run in parallel for whole periods of times and interact at the end of these periods. The simulation is ahead of the "physical system" and predicts the state of the system at the beginning of the next period. Based on this state three simulations with different routing policies are run and the best routing policy for the coming period is chosen. When interacting, if the predicted state is validated against the real state of the network, the best policy is given to the "physical system" to be applied for the next period. Otherwise the "physical system" chooses a default policy and the simulation updates its picture of the state of the network, see Figure A.2. The test results given by the author does not suggest any improvement of performance of the network using this prototype. However, this project is an interesting experiment that discusses some of the difficulties in developing a symbiotic simulation system [9].

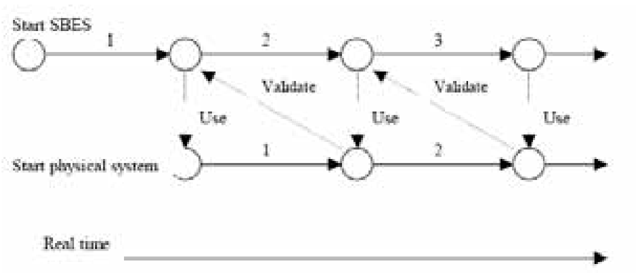

Figure A.2: Time relation between the S2 and the physical system [9]

A.4 Knowledge Representation, Modeling of Doctrines and Information Fusion

A conceptual model of agent-based simulations is presented in the paper [13] as a part of the information fusion process. The process is assumed to consist of agents which store and simulate different behaviors on different aggregation levels, see Figure A.3. Each agent represents a military unit which can consist of other units. It is important to be able to build such a hierarchy in a consistent and reusable way. For example, agent one is in this case a platoon but it can be a company or any other type of agent, see Figure A.3.

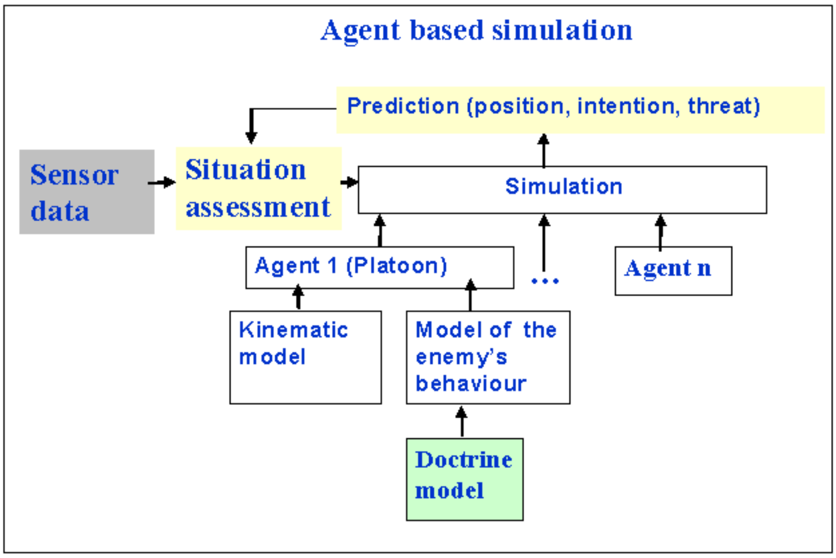

Figure A.3: One conceivable way of using doctrine models and integrating them in an agent-based simulation that is a part of an on-line system (information fusion)

The goal of this process is to:

1. collect all relevant sensor data and information
2. combine this information with a priori knowledge, e. g. terrain, doctrines, performance of vehicles etc.
3. represent improved estimates of world state of interest (situation assessment)
4. predict the most likely course of the enemies' actions by agent-based simulation and connect it to the most probable and most destructive outcomes (impact analysis) [13].

A.5 Simulation-Based Decision Support for Command and Control in Joint Operations

In joint operations where different units are involved the commander cannot predict the outcome of different tentative plans and compare these alternatives since the situation is complex and plans have multi-attributes. Integrating simulations with the future C2 systems gives the commander the opportunity to simulate tentative decisions and evaluate their consequences during the planning process. Embedded simulation-based decision support is here composed of multi-agent simulation (to predict the consequences of a tentative plan) and multi-attribute evaluation (to evaluate and compare the multi-attribute consequences). This embedded simulation support is a network resource that would be connected to other functional units of the command and control system. The aim of this design is that it can also provide decision-making services for training. In multi-agent simulation each resource is substituted by an agent which is an autonomous system that has the capability of performing tasks. A plan defines a set of agents each of which may be involved in different tasks but is associated with only one role. Tasks are composed of several actions.

Besides the agent assemblies other parts of the multi-agent simulation are the simulation environment and an information manager [14].

Multi-attribute evaluation is modeled as a consequence matrix C and a utility matrix R, where; $C = [c_{11}, \ldots, c_{mn}]$ and $R = [r_{11}, \ldots, r_{mn}]$. Furthermore a utility function vector $U = [U_1, \ldots, U_n]$ which maps each c_{ij} to r_{ij} is defined. The elements of the matrix C are consequences of the tentative plan s_i on the attribute a_j. U_j is a function that maps c_{ij} to r_{ij}, where r_{ij} is a real number defining the decision makers' preferences; $r_{ij} \geq r_{kl}$ if and only if the decision maker prefers the consequence c_{ij} before c_{kl}. For each attribute these values can be summarized using a step function with a limited number of utility levels. This will give the commander and staff an understandable situation assessment. However, since other agents may take different actions to meet the commanders' plan the model has an inherent uncertainty that cannot be overcome. The suggested solution to this uncertainty is to calculate one consequence matrix and corresponding utility matrix for every possible opponent plan. Summarizing the probability weighted by these utility matrices yields a total utility matrix which should be used for evaluating the tentative plans [14].

A.6 Particle Filter-Based Information Acquisition for Robust Plan Recognition

In the paper [15] a stochastic simulation method called particle filter, has been used to represent uncertainty in state and to predict the future state.

Uncertainty arises due to lack of observations. Therefore an agent is represented as a set of possible or alternative states called particles. These state uncertainty particles are depicted in left part of Figure A.4 (red particles). Particles in the particle filter can be seen as hypotheses representing alternative states. Each particle represents a state of possible agent's (enemy platoon's) position and velocity [15].

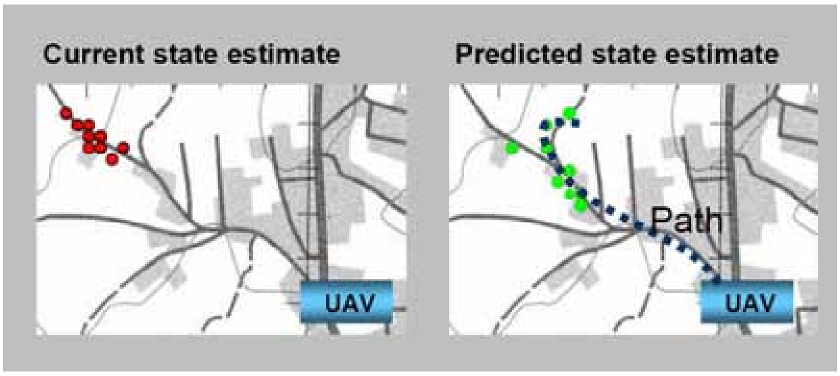

Figure A.4: State uncertainty particles (red) and prediction particles (green) [15]

Generally, to reduce the uncertainty about an agent's (enemy's) state, position and velocity in this case, sensors are used. An on-line simulation can be used to predict situation repetitively. The prediction time has been set in relation to how long time is required to reach an area of interest. This is done by using a transition model that takes state uncertainty particles as input and simulates an output of prediction state, see the right part of Figure A.4. Consequently, by running these simulations the route planning of sensors (e.g. UAVs) can be done with information based on the predicted state when the sensor would enter the area. This process is run repetitively as soon as new sensor tasks are assigned [15].

A.7 Effect Based Decision Support for Riot Control: Employing Influence Diagrams and Embedded Simulation

Peaceful demonstrations and protests that degenerate into riots may cause severe damage on infrastructure, cost lives and destroy private property. However, in addition to their mission to protect against damage and loss of lives, the decision makers responsible for keeping security also are tasked with protecting the right to free speech and protest. Thus, the decisions makers may face conflicting goals. The recently introduced concept of Effects-Based operations (EBO) provides a possible way of handling such situations. In EBO, the interplay between actions and both direct and indirect effects are emphasized. By modeling these relations we can provide tools that make it possible for commanders to see what indirect effects may result from different choices of actions. This should make it easier to see what actions can be chosen, during an ongoing situation, in order to control the riot while simultaneously upholding the rights of the peaceful protesters [11].

By using embedded simulation a continuous reevaluation of the situation can be performed and new (context relevant) knowledge would be gained in order to support decision making. The main point here is to generate pieces of knowledge given a combination of different decision alternatives, i.e. our actions and possible counter-actions. Such knowledge is further combined with other knowledge (information) fragments and a (information) model that represents the evolving situation. The information model explains relations and mechanisms between actions and predicted effects. Such a model would be a useful tool for providing real-time EBO analysis to support decision-making on-line.

The paper [11] describes, conceptually, how Influence Diagrams and different embedded simulation techniques need to be applied in order to implement this functionality and gives an example of how the suggested approach will appear from an operational point of view.

Mechanisms of EBO are represented in the Influence Diagram by Conditional Probability Tables (CPTs), representing the uncertain causal relation between action and cause. However one conditional probability is required for each combination of relevant potential actions. Moreover, these mechanisms are cumbersome to describe and change as the situation evolves. Hence, the use of embedded simulations is proposed to break down the problem and automate the estimation of the CPTs [11].

A.8 Evaluating sensor allocations using equivalence classes of multi-target paths

In the paper [12] an algorithm for evaluating sensor allocations using simulation of equivalence classes of possible futures is presented. The method is meant to be used for pre-planning sensor allocations, e.g. for choosing between several alternative flight-paths for UAVs or for deciding where ground sensor networks may be deployed. The algorithm requires a knowledge of the terrain/road network, in order to evaluate a list of sensor allocation schemes and choose the most feasible one.

Given a current situation picture, the method generates possible future paths for the objects of interest and apply all the sensor schemes to them. This yields a list of simulated observations for each senor scheme that would be the input to a fusion module. Each fusion output is compared to the “true” simulated future to calculate a fitness. Averaging over many possible future paths gives a total fitness for each sensor allocations scheme. The sensor allocations can be ranked based on total fitness.

In order to speed up this process the concept of equivalence classes of futures is introduced. For each proposed sensor allocation, futures are partitioned into equivalence classes. Two futures are considered equivalent with respect to a given sensor allocation if they would give rise to the same set of observations [12].

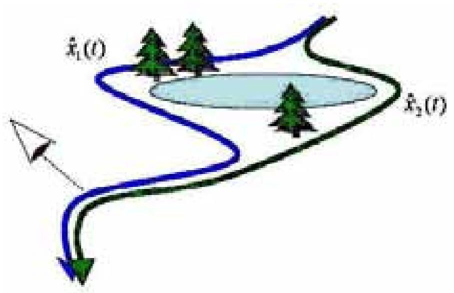

Figure A.5: The concept of equivalent paths. Given the sensor location shown it is impossible to distinguish between the two paths; hence they belong to the same equivalence class [12]

A.9 Bayesian Games Threat Prediction and Situation Analysis

In the paper [29] the authors review developments in game theory and apply them in a decision support tool. The authors propose to use game algorithms together with Bayesian networks and influence diagrams in decision support tools for military Command and Control systems. One of the interesting advantages of game theory tools are that they can deal with uncertainties in enemy plans and deceptions possibilities [29] .

A.10 New Navy Solutions: Integrating Simulations Into C4I

The US Navy Embedded Simulation Infrastructure (ESI) Program has been established with the goal of combining Modeling and Simulation software components within C4I systems to build simulation based mission applications.

The command and control is a continuous, cyclical process that begins with “observe” followed by “orient”, “decide” and “act” and then back to “observe” the results of the decisions and actions and repeat the cycle. So far the C4I systems support “observe” and “orient” phases of the OODA (Observe, Orient, Decide and Act) loop. C4I systems like Common Operational Picture (COP) lack adequate support for command and control phases “decide” (plan operations) and “act” (control operations). ESI Program addresses these demands by developing embedded simulation technologies to get simulations to work with operational C4I. A planned situation is by definition simulated and current C4I systems have neither the means to generate simulated situations or methods to display them. The primary product of current operational C4I systems is a common operational picture (COP) used by decision makers to assess a tactical situation. The COP is an electronic map which displays the terrain, military structures, locations and movements of the forces, etc. Looking beyond the paradigm of the electronic map that C4I offers today and integrating simulations in the operational picture enhances the COP to support the commander in the entire loop of OODA [18].

Generally, the enhanced information processing in C4I enable the development of processes for the use of embedded simulations within tactical applications. E.g., simulated information about electronic sensor performances and atmospheric conditions has been available in stand-alone computer systems. However, their tactical use is limited due to lack of integration with the C4I system. The huge amount of information available in C4I systems makes them ideal hosts for advanced tactical mission applications such as the use of embedded simulations [18].

There are some examples of the use of Embedded Simulation (ES) such as assessing vulnerability of own communications networks, assessing probability of detection of own forces during various conditions, assessing best protection from hostile force activities such as deploying weapons of mass destruction (WMD) [18].

A.11 C4I Tactical Applications Utilizing Embedded Simulations

Simulation based mission applications such as a course-of-action analysis application, or visual representations of complicated operational assessment models, can significantly improve the quality and timeliness of tactical decisions for military operations. Simulation based applications have the ability to process C4I data beyond human cognition, and display it in an intuitive and meaningful way for key tactical decision makers [19].

The task of the C4I system is to provide a COP to the tactical decision maker. Here, the COP is proposed to be divided into two parts. The first part is a COP that is based on current processed and aggregated data. The second part, which is based on simulated data, is called simulated common operation picture (SIM-COP). The SIM-COP can also insert simulated data in place of or as a complement to real-world data [19].

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In order for decision support to serve the commander in tactical situations, a close coupling with the C4I data is required. Tactical decision support can have many different flavors, from "what-if" types of course-of-action analysis, to a commander's inference from using good situational awareness. However, it is important to ensure that simulation results are (on-line) valid. "Simulation based applications have traditionally been used in decision support in a 'what-if' war-gaming type of analysis. While this can be operationally useful, it is also subject to debate on validity of results" [19].

A.12 C4I Mission Application Software Development Kit (MASDK)

Architecture and features of the MASDK; a software developed by Naval Research Laboratory within the C4I Embedded Simulation Infrastructure (ESI) program are described in the paper [20]. The MASDK is an architecture framework, a set of sharable C4I software components and a composability tool. It is written in Java and is integrated with a Common Operating Environment (COE). The aim of MASDK is to reduce the complexity of the design and the developers' workload by composing systems from a collection of reusable elements. A number of applications that have been developed using MASDK sharable software components and composability techniques have passed operational evaluation [20].

The MASDK Host Application shown in Figure A.6, is the start point for composing new applications. It is an application shell containing basic C4I services and serves as a host to simulations and reusable software components. If the application cannot be completely composed of the provided components, one may use one or more Plug-ins or a simulation. Plug-in is defined as a software component that performs a set of related functions. A simulation is a considerably larger software which may be configured as a server embedded within the application. Examples of existing Plug-ins are Mission Editor or COP Capture. Mission Editor can be used to develop a scenario rapidly by creating simulated forces and position them on a map and COP Capture can be used to extract the real-time C4I Common Operational Picture (COP) as a starting point for a scenario. A scenario can be saved as an XML file and be run or modified later. An example of applications which is developed using Embedded Simulation is the Weapons of Mass Destruction Defense (WMDD) which contains the Hazard Prediction Assessment Capability (HPAC) and is capable of predicting down wind contamination and lethality occurring from a chemical or biological release and integrating this information into the COP [20].

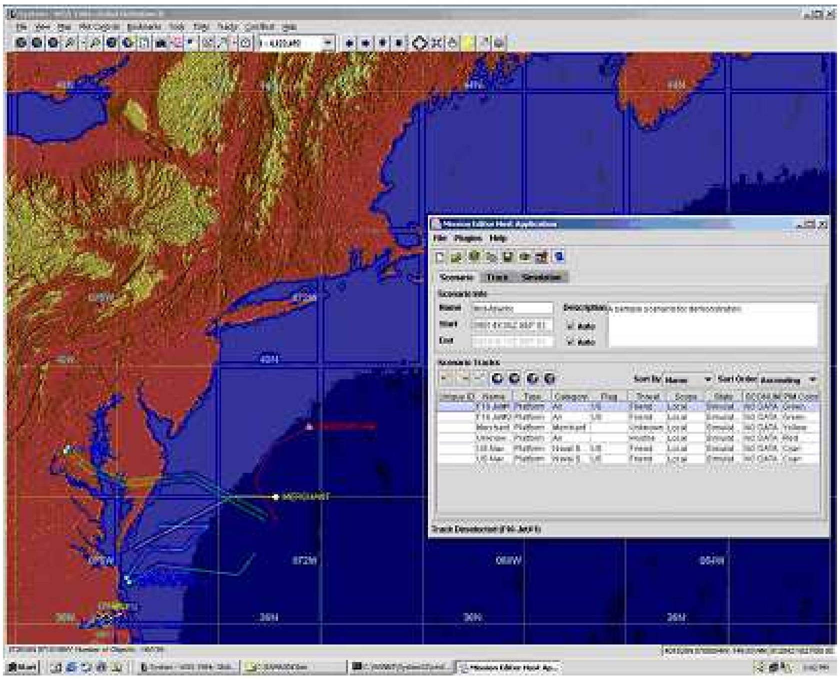

Figure A.6: MASDK Host Application With Default Plug-ins [20].

A.13 C4I Host Applications

Most commonly M&S are poorly integrated into C4I systems. The paper [21] addresses this problem and focuses on designing a common architecture and the issue of simulation model composability.

There are few (generic) architectures for combining ES and C4I. Models are rarely reused and often lack composability. One of the reasons for the modest success of integrating models and simulations in C4I system applications is due to the lack of Modeling and Simulation (M&S) services within the COE. There is a need for M&S software components that are available to generate training and planning scenarios, provide simulations to internal C4I data bases and functions and manage the simulated data within the C4I system. Furthermore these components should also manage variable time bases, display simulated data, integrate simulations with other applications and perform communication tasks [21].

A proper selection and development of M&S components and an architecture that manages complexity and reduces development workload is a way towards efficient integration of M&S into C4I.

There are three critical elements that are necessary to compose simulation based C4I applications out of common components:

1. Selection and design of sharable software components that can be used within a domain

2. Flexible architecture structure that promotes reuse within a domain or even between domains

3. Development environment that promotes the combined use of the common operation environment and the M&S components.

An architecture that is aimed to satisfy the requirements above is proposed. To develop scenarios for planning, analysis or training in the scenario generation part there are features like COP Capture, Mission Editor, Time Line Editor, Virtual Track Manager (VTR) and Scenario Preview.

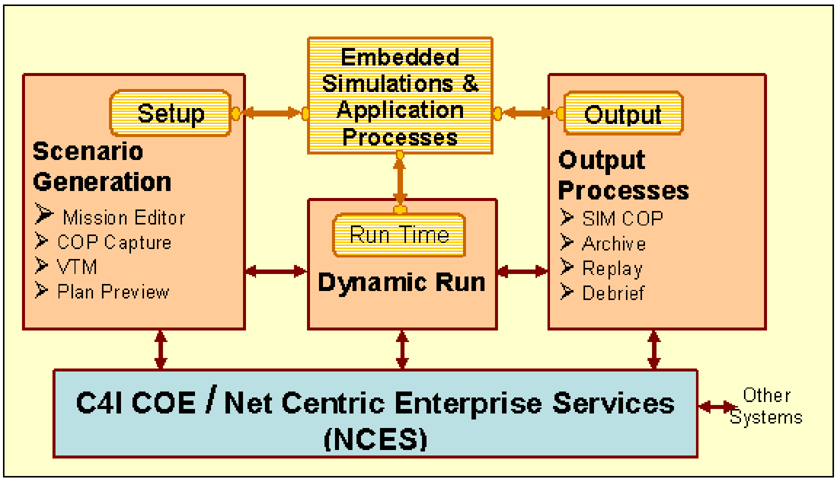

Figure A.7: Host Application Architecture [21]

Many large complex applications can best be developed and maintained using small, limited scope embedded simulations rather than a single large simulation. The Dynamic Run and the simulated COP services interact with the embedded simulations during runtime and the Archive/Replay/Debrief segment to capture and present the application's resulting analysis, see Figure A.7. The Host Applications organize M&S services into shell programs to support a specific application domain. Moreover, the services can be developed to support a wide range of simulation based Mission Applications.

A Host Application has the following characteristics

- Contains a set of M&S services relevant to a particular C4I Mission.
- Hosts one or more simulations or processes
- Is readily modifiable to host additional simulations of the same category. (e.g., Sensor Fusion, Strike Planning)
- Provides interface standards for embedded simulations.

A.14 Simulation Software Component Architecture for Simulation-Based Enterprise Applications

New tools such as CORBA, DCOM, distributed data bases and distributed simulations together with enhanced processing power have facilitated the implementation of embedded simulations. However, one of the remaining obstacles is the low rate of simulation model reusability. From a detailed modeling perspective, every situation is a unique situation, and cannot be modeled generically with a reusable simulation. Most simulations include discrete-event simulation that are viewed as a standalone, project based technology. In previous approaches simulation models were built to support an analysis project, to predict the performance of complex systems and to select the best alternative from a set of well defined alternatives. Single use models where poorly reused in other future applications. In traditional simulation model building, software is designed to handle an infinite use case. However, simulation models that are valid within a particular problem domain are necessary for efficient ES. This constraint originates from the fact that ES do not need to involve direct intervention by humans. Instead, the system can extract data from existing sources and execute simulations as defined by the simulation problem domain and yields results that can be used by humans or by some machine processes. The user who takes an action that triggers a requirement for simulation may not even know that she is asking for a simulation to be run [30].

A.15 Next Generation Vehicle Architecture for Embedded Simulation

"Embedded Simulation is the concept of embedding the capability in the vehicle to allow a 'virtual world' to be displayed to the crew and to have virtual interaction with vehicle subsystems in support of the following missions: Training, Mission Rehearsal, Robotics Mission Planning, Battlefield Visualization and Virtual Test & Evaluation" [31].

Three architectures are possible to add simulation to ground combat vehicles. The first architecture choice is stand-alone, i.e. a completely separate subsystem with its own processing, image generator and software that is connected via a data bus, video-bus and power-bus which is connected to the vehicle. This choice is suited for current vehicles. The second architecture choice is the Integrated Embedded Simulation System. In this approach one would upgrade the vehicles own computer and software architecture for simulation, something that is just possible due to recent technological advances and is a logical choice for the ground vehicle architecture of the future. The third architecture choice is called the Hybrid Embedded Simulation System. The Hybrid approach is a combination of a stand-alone subsystem and an Integrated architecture [31].

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