JOURNAL OF AERONAUTICS AND SPACE TECHNOLOGIES
JANUARY 2007 VOLUME 3 NUMBER 1 (41-50)

THE STATE OF THE ART AND THE FUTURE OF MODELING AND SIMULATION SYSTEMS

Selim TEMİZER

Massachusetts Institute of Technology
Department of Electrical Engineering and Computer Science
Artificial Intelligence Laboratory
Cambridge, Massachusetts, USA
temizer@alum.mit.edu

ABSTRACT
In this document we present a survey of the state of the art of Modeling and Simulation (M&S) Systems, and the anticipation of future technologies in this domain. We provide classifications of currently available M&S technologies and projects from various perspectives using illustrations with the hope that this work will provide as many pointers for developers as possible and serve as a source of reference to future articles on this topic. We will also provide an assessment of Open Source Software (OSS) and its current and possible future effects and uses in the M&S market. Our discussions will slightly emphasize large-scale military M&S projects as these are usually very long-term and the most serious M&S applications that have enormous influence in shaping up both military and commercial M&S markets. Such large projects are also prone to get out of hand quickly; therefore an analysis of potential risks that should be managed as an umbrella activity when undertaking such projects will also be presented.

Keywords: *Modeling and simulation, master plan, open source software, classification, risk analysis*

1. INTRODUCTION

As the computing technology evolves continuously with dazzling speed that enables construction of much faster computers each and every day, the utilization of modeling and simulation (M&S) systems in very diverse application areas also increases. There are almost endless uses of M&S systems from for example simulation based acquisition, decision support and training to analyzing some military war strategies and cost-effective engineering applications. Therefore, availability of more computing power leads to being able to create and simulate more detailed models of objects of interest, and hence highly accurate simulation results that closely reflect reality can be obtained.

In this document, we will present a compilation of information about the state of the art and the future of M&S systems with an emphasis on large-scale military simulation frameworks. We will begin by identifying the major M&S domains and applications including long-term national and/or organizational M&S objectives. Then we will look into an emerging paradigm of software development and distribution, namely the open source software (OSS), and how it contributes to M&S systems. We will also provide classifications of M&S systems from many different perspectives, and make clear what we mean by for example a *simulation framework*. After a thorough examination of how M&S systems are developed, we will conclude with a risk analysis for large-scale military M&S projects.

2. MAJOR M&S DOMAINS

Since the use of M&S is getting very popular, we will present a discussion of three biggest M&S domains in this section which are computer games, academia and military applications.

Computer games are very good and very successful examples of commercial M&S systems that are common to many people today. With the advent of hardware and software technology that can closely imitate many exciting aspects of real life in simulated environments, it becomes possible to get immersed in many otherwise impossible experiences. You might engage enemy and use fatal weapons when you play action games like Counter-Strike™, Doom™ and Quake™. You might drive exotic sports cars like crazy in the game Need for Speed™ or fly planes in Microsoft™ Flight Simulator™. Similarly, many simulation games allow you to drive trains, sail ships, etc. There are even games like Grand Theft Auto™ where life itself is simulated as a whole and you can play gang members that act as local mafia and slowly take over entire cities.

With networking support between computers and the internet, games also allow you to play against other human opponents from diverse geographic locations as well as computer controlled opponents (a.k.a. computer generated forces or CGF). Several commercial massively-multiplayer online role-playing games (MMORPG) like World of Warcraft™ are played by millions of subscribers today.

Common to all addictive games is that they let you experience many scenarios that are otherwise impossible. For example, you can feel danger without risking your life, you can use expensive equipments that you cannot afford or you can assume the role of a fictional character and interact with very large number of other players in a fantasy setting. The gaming industry will keep growing as it is aware of these psychological reasons that make computer games very popular.

Another domain where M&S systems are highly utilized is academia. As researchers expand the frontiers of science, they face many challenges of experimenting with the unknown. For example, before *Sojourner* landed on Mars surface, it was impossible to predict with a hundred percent accuracy what the conditions there will be like. Therefore both hardware and software models of this expensive equipment was tested in many simulation missions before the actual deployment. Similarly, many robotics applications benefit from M&S systems for immensely analyzing the behavior of autonomous robots before they are operated in populated environments. A nice example of this type of robots is Carnegie Mellon University's Minerva [1], the robotic tour guide, which moves daily through crowds at the Smithsonian's National Museum of American History and can be commanded remotely via internet. Similarly, academic research in all areas, from weather prediction to new car engine designs makes use of carefully designed models tested through many simulations.

The biggest M&S market with many ultra-high-budget projects, the one that we put more emphasis in this document, is military M&S systems. There are many players in this market including governments, academic institutions, commercial companies and even big organizations like The North Atlantic Treaty Organization (NATO). Military policies of each government usually define funding strategies, and this in turn impacts academic research areas and industrial involvement. There are many companies specialized in developing military simulation and training applications. To give an example, the software suites Strive® and Items™ of the company CAE come with many military vehicle models and provide the developers with electronic warfare simulations, sensor and communications simulations, weather simulations, etc. to quickly build military M&S systems.

National and/or organizational military M&S policies are usually described in *M&S Master Plans*. These plans describe governmental or organizational visions for the future of M&S applications. These are very long term plans with very large-scale milestone deliveries and aim the development of huge products. Since the impact of M&S master plans to the future of M&S systems is very big, we devote the next section to analyzing them.

3. M&S MASTER PLANS

In order to work on a concrete example, we have replicated the United States Department of Defense (DoD) M&S Objectives and Sub-Objectives from the U.S. DoD M&S Master Plan [2] in Figure 1.

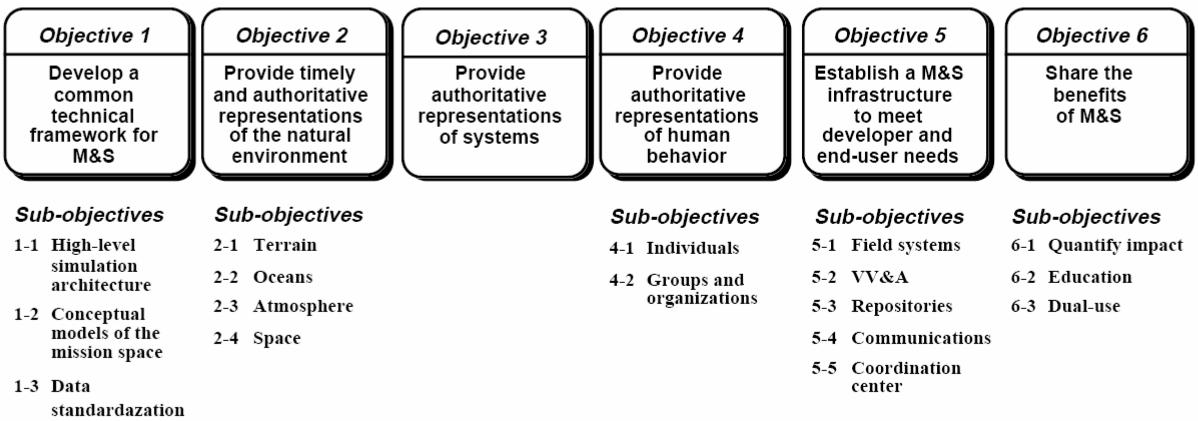

Figure 1. DoD M&S Objectives and Sub-Objectives

It should be noted that NATO [3] and many national military organizations including Turkish Armed Forces (TAF) have quite similar master plans; therefore our discussion here also applies to them.
Although many researchers are working on the objectives shown in Figure 1 in parallel, officially the M&S world is currently somewhere between objectives 1 and 2. Objective 1 addresses one of the biggest challenges of M&S systems: interoperability and reusability. There are many models that have been generated and many simulation projects that have been implemented all around the world. In order to establish a common communication, synchronization and data interchange language between them; the High Level Architecture (HLA) [4] was developed and then standardized [5]. Upon entrance of HLA into the scene, system of simulations that work together or *system of systems* concept started to be spoken of.

HLA is a general-purpose architecture, but in order to realize it, a certain piece of software referred to as Run-time Infrastructure (RTI) is needed. This lead to a new line of software development business and there are currently commercial RTI software available in the M&S market. Two such popular examples are MÄK RTI and Pitch RTI.

HLA has been designated as the standard technical architecture for all DoD simulations since 1996. Other national military organizations and NATO adopted this mandate and adherence to HLA is required almost everywhere for many M&S projects. This example depicts how strong the influence of master plans is and will be to the development of M&S systems.

It should also be noted that it has sometimes been technological advances, and sometimes other reasons that mandate certain products to be utilized in M&S systems. Therefore master plans and their milestone products (tangible hardware and/or software products as well as non-tangible products such as standards) should be considered carefully and watched closely before planning long-term M&S road maps.

Although HLA is standardized and has assumed a nearly solid shape, RTI software is continuously being improved by many scientists, one of the well known being Richard Fujimoto of Georgia Institute of Technology. Prof. Fujimoto and his research group have been working on getting the RTI software more modular and much faster to allow for larger number of simulations to communicate in real-time, and they have developed RTI-Kit, a set of related libraries for developing RTIs [6].

The second objective of DoD M&S master plan aims to unambiguously, efficiently and universally represent natural environment including space. There has been significant progress on this objective and the two technologies that are the most promising candidates to be officially accepted are Master Environmental Library (MEL) [7] and Synthetic Environment Data Representation and Interchange Specification (SEDRIS) [8].
The remaining objectives are still to be researched on for some more time and they do not have any delivered influential milestones yet, but they should be watched closely especially for the future of military M&S projects.

In the next section we will examine other phenomena that are also expected to have a big impact on the way M&S systems will be developed in the future.

4. OPEN SOURCE SOFTWARE AND OPEN STANDARDS

The Linux operating system and the public availability of connections to the world wide internet started a new tradition in software development. In this new paradigm, software being developed is stored openly on the internet, and volunteers (including many scientists, and experts) contribute to the development and also testing on free will. Although this type of development seems chaotic at first, it is actually much more efficient than the closed-walls development of proprietary software, because the contributions to the software are done usually under the control of some concurrent versioning tools such as CVS and Subversion, and there are many free testers out there that voluntarily and massively test and report bugs.

In the open source market, people get free software and pay for value-added services whenever necessary. This new paradigm has had a deep influence on software community including the M&S systems developers. In addition to open software, there are also open standards such as Open Host Controller Interface (OHCI), Open GIS and Open Database Connectivity (ODBC) that facilitate interoperability and reuse of many software and even hardware components that adhere to these standards.

There are many small and large open source software projects available today and the recent success of many open source applications indicates that OSS might define a new software era, and many future M&S systems might choose to adopt a systems engineering approach and assemble open source components rather than implementation from scratch. Since M&S systems are getting larger and more complex and people are starting to talk about system of systems, open source components that strictly adhere to well-defined open standards might therefore prove to be very beneficial.

One major issue concerning OSS is the licensing. There are many OSS licenses in circulation, but most are variants of the following three types:

- GNU General Public License (GPL): Source code licensed under GPL cannot be included in proprietary software. Modifications to the source code must be released back to OSS community.
- Library (or Lesser) GPL (LGPL): This derivative of GPL allows integration of source code with proprietary software.
- Berkeley Software Distribution (BSD): Imposes few constraints to the user and allows integration of source code with proprietary software.

NATO and other military organizations are currently in the process of implementing their own policies in order to systematically exploit OSS market to reduce the total cost of ownership of software components, to be less dependent on proprietary software and single vendors, and to improve interoperability by utilizing open standards.

5. CLASSIFICATION OF M&S SYSTEMS

In this section, we will provide classifications of models and simulations from various perspectives.

5.1 MODELS

In general, we can speak of two general categories.

Conceptual models of the mission space (CMMS): These are simulation-independent hierarchical descriptions of actions and interactions among various entities associated with a particular mission area. These models facilitate interoperability and reuse of simulation components by sharing common, authoritative information between simulations. CMMS is the first abstraction of the real world and can be considered as a high level meta-model.

Simulation-dependent models: When it comes to visualize and employ certain models in simulation systems, there are usually the following aspects that need to be considered:

- Graphics: The simulation software in accordance with the graphics hardware should be able to draw and color the points, lines and polygons that constitute the visual appearance of the models and also special effects such as explosions, fog, etc.
- Audio: Entities and special visual effects such as explosions usually have associated audio that should accompany them in order to create realistic simulations.
- Math: Mathematical models such as Discrete Event System Specification (DEVS) describe the inner workings of single entities and hierarchical systems as rigorously as desired.
- Physics: Simulating dynamics such as gravity, mass and forces for realistic applications is becoming very popular. Designing physical models of entities is much different than designing visual models. As an example, a car wheel may look cylindrical on the outside, yet it might be modeled to behave as a sphere dynamically, because the inertia matrix of a sphere is the identity matrix, and simulating dynamics of a rotating sphere is much easier than that of a cylinder.
- Behavior: Semi-autonomous or fully-autonomous entities in a simulation that should be played by the computer, which are usually called computer generated forces (CGF), must have their behavior modeled.
- Intelligence: On top of simple behaviors, the algorithms and techniques implemented to provide intelligence to semi-autonomous and autonomous entities in simulations are usually called artificial intelligence (AI). Gaming industry is very active in developing competent AI, and many Game AI packages can also be found free of charge on the internet.

5.2 SIMULATIONS

We can classify simulation systems from two different points of view: conceptual and developmental.

Conceptual Classifications

Purpose: Simulations might be developed for many purposes. Most common ones are training, simulation based acquisition (of very expensive ordnance for example), decision support, cost-effective engineering analyses of many sorts, analyzing military strategies, etc.

Structure: Structurally, there are three types of simulations. The following definitions are from the US Defense Modeling and Simulation Office’s web site (https://www.dmso.mil/public/)

- Live Simulation - A simulation involving real people operating real systems.
- Virtual Simulation - A simulation involving real people operating simulated systems. Virtual simulations inject human-in-the-loop in a central role by exercising motor control skills (e.g., flying an airplane), decision skills (e.g., committing fire control resources to action), or communication skills (e.g., as members of a C4I team).
- Constructive Model or Simulation – Models and simulations that involve simulated people operating simulated systems. Real people stimulate (make inputs) to such simulations, but are not involved in determining the outcomes.

Developer/Customer profile: M&S projects developed by and/or for military or non-military personnel might have very different security and reliability demands and many other certain contractual issues.

Developmental Classifications

Serving period (life time): We can broadly classify simulation systems as being short-term and long-term. Short-term simulations are usually prepared to serve for a well-defined purpose such as a simulation based acquisition or a tactical analysis of an attack plan. After the equipment is purchased or the attack is over, the simulation completes its life time. On the other hand, long-term simulations are aimed to be used for much longer periods. Two examples from the civilian and military domains are; the driver training simulator, TRAFİKENT, developed at Meteksan and the stinger simulator, KMS-ES (Kaideye Monteli Stinger Eğitim Simülatörü), developed at Aselsan.

Final product: There are three types of possible final products. The accumulation of source code may lead to a full simulation application, or a (function, library or API) toolkit, or a specialized framework [9].

Size: There are many factors that determine the size of a simulation project (which may include development of certain specific simulation hardware in addition to software) such as the number of members in the development team, the total development time and the budget allocated to the project. We can coarsely classify them into three categories:

- Small-scale systems: Projects that can be completed within months by a development team of 10 to 15 people can be considered as small-scale systems.
- Medium-scale systems: These systems usually require teams of more than 15-20 people, and can take up to 2-3 years to develop.
- Large-scale systems: These systems are generally very big framework projects that require diverse distributed contribution from many development teams, organizations and even civil companies over many years. The realizations of various M&S master plan objectives are good examples of large-scale systems.

Developmental classifications are compactly depicted in Figure 2.

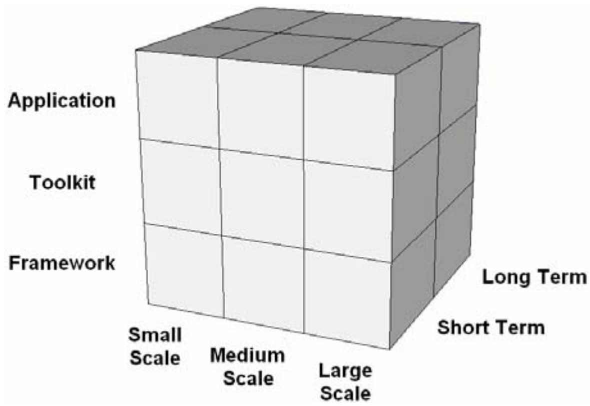

Figure 2. Developmental Classifications

6. COMPONENTS OF M&S SOFTWARE

In addition to their components specialized for the application at hand, almost all real-time 3D simulation software have some common needs that are usually put together in an infrastructure layer. In this section, we will briefly look at how modular M&S software systems are usually synthesized and what goes in the infrastructure layer and what components are usually utilized at a minimum. It should be noted that the OSS paradigm has a great impact in this area, too. It is possible to find many infrastructure entities, many components, and many tools to create/edit them free of charge in the open source domain.

Infrastructure

Mathematics, algebra and geometry: Mathematical computations are always a must in almost all types of simulation projects. Both entity models and the simulation software that will employ those models usually require frequent mathematical computations. There are many high quality open source packages such as Template Numerical Toolkit (TNT) that provide simulations with high precision math support.

Frame management: An operating system neutral frame management utility is also required in order to synchronize real-time simulation events with the actual visualizations. Open Producer is an open source example of such a utility that is in wide use today.

Multi-thread and concurrency support: An easy to use software library that supports threads, mutexes and semaphores such as Open Threads will enable the developers to organize concurrent access to shared resources and manage synchronization between threads.

Components

3D Graphics: The most popular primary engines are OpenGL and DirectX, and there are many (proprietary and open) model formats such as OpenFlight (*.flt*) that can be loaded by these engines. There are also higher level engines such as OpenSceneGraph, CrystalSpace and Irrlicht that are built on top of primary engines. Among the popular 3D modeling tools are 3D Studio Max, Maya and the OSS alternative Blender3D.

Character Animation: Animation of entities can be achieved either by using certain 3D animated model formats such as OpenFlight or ReplicantBody (and associated software that manages these models like CAL3D), or by special animation software tools such as Pixar's RenderMan®.

Audio: Many libraries such as the free OpenAL can load both uncompressed (like .wav) and compressed (like .mp3) audio files and play them in 3D and/or environmental formats with the help of special audio hardware.

Physics: Physical models of entities such as mass, moment of inertia, forces acting on them, etc. can be prepared using libraries such as Open Dynamics Engine (ODE) and Havok Physics™.

Collision Detection: In addition to physical properties of entities, geometric properties must also be modeled and processed using libraries like ColDet for collision detection.

Artificial Intelligence (AI): Many game AI and computer generated forces (CGF) packages are available both commercially and free of charge. These modules might contain simple search algorithms like A*, and more complex algorithms like decision trees.

Networking: Data transfer between M&S systems that run simultaneously is one of the most basic demands and HLA is one standard way that helps developers achieve this goal. There are also many alternatives including high level libraries like The Adaptive Communication Environment (ACE) and low level tools like pure BSD sockets.

7. EVOLUTION AND DEVELOPMENT OF M&S SYSTEMS

In this section, we will check out the ways computer models and simulation systems are developed and the evolution of these processes over time.

7.1 MODELS

Hardware Models

Designing special custom hardware that models the behavior of an expensive counterpart such as a special weapon system, radar or a complex system of many entities such as a telecommunications network is common in military domain. Also cockpit simulators and motion platforms are well-known examples from the civil domain. Hardware simulators are generally referred to as emulators and these are usually very expensive systems.

Conceptual Models

There used to be many common formats (such as data interchange format, DIF) in use, but with the advent of HLA it is expected that formats that favor (Federation, Simulation Object Model) FOM and SOM like data representations will dominate the M&S area. It is foreseen that at least, compatibility with them or the existence of tools that can convert to them will be required. Also, MEL and SEDRIS projects will provide the future M&S systems with authorative and unambiguous representations of natural environment.

Software Models

Graphics and audio models are highly stable as these are the oldest and mostly utilized ones. Most common and popular model formats usually prove to be easily used and efficient to store and decode.

Mathematical modeling is unavoidable in almost all (especially engineering) M&S applications and models like DEVS have always been in wide use.

Physical modeling of entities is rather new. There are no dominant storage formats yet. But highly qualified commercial packages implement their own formats.

Behavioral and intellectual models are also not very mature yet. There are various projects (e.g., The Open Mind Commonsense project conducted at MIT) that aim to openly collect commonsense knowledge and make it available to researchers. As long as military M&S applications are concerned, capturing human behavior (both individual and group behavior) is important, and future research on data mining and data collection will make this possible.

7.2 SIMULATIONS

Hardware

In addition to simulation specific hardware such as Aselsan's KMS-ES stinger weapon training hardware and Havelsan's CN 235 Full Flight Simulators, immersion technologies are getting quite popular since they take virtual reality (VR) systems to much higher levels. Among the immersion products that let us provide *input* to M&S systems are data gloves (e.g., CyberGlove®), GPS trackers, IR trackers (to input motion data for head, body, joints and any other points of interest, e.g., TrackIR™), 3D joysticks (e.g., FreeD) and voice recognition systems (e.g., Verbal Commander). Among the immersion products that provide *output* from M&S systems are head mounted displays (HMD, some also come with integrated head tracking system, e.g., i-glasses, Sony Glasstron, VFX1 Headgear), force feedback devices (e.g., joysticks, Intensor™ Game Chair, Virtual Reality Impact Vest) and haptic devices (that provide users with tactile sensing capability).

There are also some non-conventional hardware devices that were developed as extensions of some software projects that attracted high demands. The most common of such hardware is the graphics processing units (GPU) found in graphics accelerator cards. The demand for near-realistic or photo-realistic visual effects is so big that in order to quickly achieve such results, the computation burden was taken from the shoulders of CPUs and processed on GPUs.

Nowadays, the demand for accurate and realistic simulation of dynamics has lead to the creation of the PhysX™ chip from Ageia. We will briefly examine this interesting piece of hardware in Appendix A.

Another very interesting research in Far East resulted in a special device that can mix certain fluid/gas ingredients to produce various odors.

Today, the immersion technologies and non-conventional hardware currently cover 4 out of 5 of our senses (vision, audio, tactile, smell). There is currently no known work that aims to generate different tastes, but it is theoretically and technologically possible.

It is our expectation that in the near future the new computers in the M&S field will all possess the following components and will have an architecture that looks like the one depicted in Figure 3.

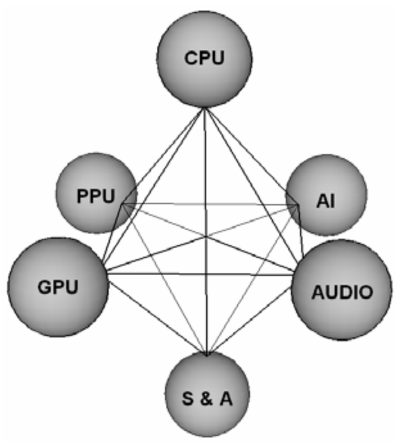

Figure 3. Computer Architecture of the Near Future

CPU – Central Processing Unit, "The Spinal Cord"
GPU – Graphics Processing Unit, "The Eyes"
AUDIO – Audio Hardware, "The Mouth and Ears"
PPU – Physics Processing Unit, "The Body"
AI – Artificial Intelligence Hardware, "The Brain"
S&A – Other Sensors and Actuators, "The Rest"

There are also significant researches on using the human body itself as the simulation hardware. Although massive results have not yet been reached, there are solid advances in this new domain. Professor Kevin Warwick of The University of Reading is considered as one of the bravest pioneers in this field. In his book "I, Cyborg" [10] and on his web site, he describes how a chip implanted in his shoulder helps him operate certain hardware such as doors of his laboratory remotely. Also his experiments on his own body to record senses as they are transmitted through nerves in his arm, and to play them back are reminiscent of the movie The Matrix [11] and theoretically and technologically prove that the famous movie is actually far from being a fiction and solidly provides us with glimpses into the not-so-far future. Professor Warwick has even managed to interchange senses with his wife. Based on the experiments that Prof. Warwick has conducted, we can predict that in the future, direct external (and perhaps non-invasive) stimulation of nerves will become common and digital data from the simulated environment will be played directly to the nerves without the need for immersion technologies.

Another successful experiment in this area was accomplished by connecting a sonar matrix directly to the nerves through a hole in the upper skull of a blind person. The acoustic range data from the sonar matrix allowed the person to perceive a depth field image of his environment and gave hope for providing vision to blinds.

Software

Developing simulation software, especially if hard real-time performance is required, starts with the selection of an operating system. In addition to today's most popular operating systems such as Microsoft Windows and Linux, there are also real-time operating systems (RTOS) available. For example, INTEGRITY® from Green Hills® Software, VxWorks from Wind River and Real-Time Linux (RTLinux) are finding more and more users in the real-time market today.

There are usually the following three approaches followed during the actual development of simulation software:

Development from scratch: Sometimes also referred to as in-house development, this approach is usually applied when total control over the source code is important for security reasons, or when implementing a brand new algorithm. Most military M&S software projects are usually required to be fully national and implemented from scratch. In this approach, in order to avoid additional sources of potential coding errors, it is important to employ software engineering practices such as Temizer Sistemi [12].

Integration of modules: Collecting building blocks (OSS and/or commercial) and working on their integration (rather than developing everything from scratch) using systems engineering approaches is another choice that allows agile project development. In this approach, careful configuration management of utilized modules is very important. Another important aspect is to be careful about the licenses of the modules in order to avoid legal issues.

Mixture of development and integration: Most M&S projects usually employ a mixture of the above approaches. Some modules get developed while others might come from the OSS domain or are either purchased or outsourced. Purchasing and outsourcing also puts the configuration management responsibility on the shoulders of the vendor or the sub-contractor.

8. EMERGING TRENDS IN M&S SYSTEM DEVELOPMENT

Managing development of bulk systems, especially large-scale M&S projects, is difficult. This usually requires expertise in many diverse areas since the work that is to be undertaken is multidisciplinary in nature. Therefore small M&S teams usually find it preferable to integrate available modules and apply agile development techniques if they have to tackle large systems. Otherwise, it is common for small teams and small companies to specialize in the development of some specific aspect of M&S domain such as developing high-performance RTIs.

A nice example of a small team applying systems engineering approach and developing a big M&S infrastructure is the open source Delta3D project (gaming and simulation engine) conducted at the MOVES Institute, Naval Postgraduate School. We will present a case study of Delta3D in Appendix B.

Large companies on the other hand acquire technology relatively easily by for example directly buying small companies and hence enlarging their line of products. There are many such examples in Silicon Valley.

9. DEVELOPING LARGE-SCALE MILITARY M&S FRAMEWORKS – RISK ANALYSIS

Each nation and military organization usually has a big M&S framework development plan. One example is the MÜHATEM project [13] that is undertaken to establish some objectives of the TAF M&S master plan. These huge projects must be planned carefully and their potential risks must be managed constantly.

There are very important lessons that we learned from HLA, the realization of the first objective of U.S. DoD M&S master plan. It is our understanding that once a big project like HLA is completed, it is highly probable that it will become a world-wide standard. Therefore the master plans of certain highly influential organizations like DMSO and NATO should carefully be watched. The estimated times of completions of objectives and milestone products that are delivered might easily cut off certain efforts. There might also be pressures of non-scientific and non-technological origin to have a certain product be adopted worldwide. Countermeasures against these possibilities also need to be addressed in long-term M&S road maps.

Another important point when developing an M&S road map is not to place the development of a very large scale framework project in the critical path of all other M&S projects. Big frameworks are also big responsibilities, and in order to reduce the risks, big frameworks must be designed as modular as possible for easy modifications and maintenance.

10. CONCLUSION

In this document we aimed to present an extensive compilation of as much information as possible about modeling and simulation systems without going into deep details of each. We have provided many pointers to real examples and many publicly available software systems to quickly assimilate newcomers as well as to interest the long-time patrons of the modeling and simulation domain.

APPENDIX A

Case Study – Ageia PhysX™ Processor

The development history of the non-conventional Ageia PhysX Processor is briefly as follows: Physical simulation of entities proved to be very useful in generating realistic simulations. A few commercial products, like Havok Physics™, became available in the M&S market. There have also been open source alternatives to simulating dynamics, like the ODE library. The diverse contributions of developers to ODE project even lead to a 100 times faster execution at some point by the recommendation about a different technique for working with very large matrices (which is another great example that explains the success of open source software development). The simulation of physics phenomenon quickly caught up in the M&S domain and eventually one company looked into a hardware solution to accelerate physics computations. The accumulation of these efforts by Ageia resulted in the PhysX chip.

Physically, the chip is implemented as a PCI card that is attached to the motherboard. There is a special programming language (Dark Physics) to describe the physical entities which is very much like GPU programming. The company even organizes programming competitions to boost the advertisement and widespread use of the processor.

APPENDIX B

Case Study – Delta3D

Delta3D open source gaming and simulation engine is a great integration and systems engineering example. It is basically a collection of most popular OSS modules and an additional layer that provides unified access to those modules. The layer however also permits individual access to components thereby allowing a flexible programming environment. The architecture is briefly depicted in Figure 4.

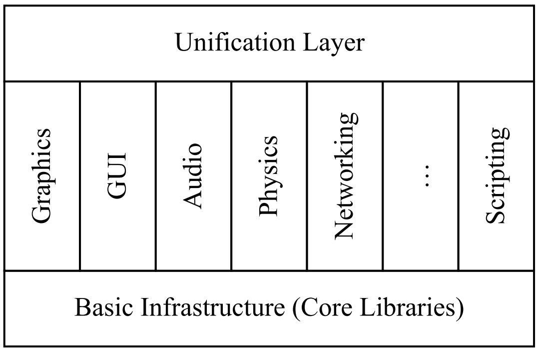

Figure 4. Delta3D Architecture

Delta3D engine also comes with an integrated editor that helps the developer easily and quickly design simulated environments and certain particle system effects. The engine is based on high quality open source software for reliability, and configuration management of dependencies is carefully monitored. Below is the detailed list of all utilized modules:

1. 3D Graphics – OpenSceneGraph
2. Geospatial Data Handling – GDAL
3. Character Animation – CAL3D, ReplicantBody
4. GUI – Crazy Eddie's GUI System, FLTK, Qt
5. Audio – OpenAL, ALUT
6. Physics – Open Dynamics Engine
7. Networking – Game Networking Engine, HawkNL
8. Input Handling – PLIB, InterSence SDK
9. Scripting – Python
10. Configuration System – Xerces-C++
11. Unit Testing – CppUnit
12. Miscellaneous – Boost

REFERENCES

[1] More information about Minerva project is available at http://www.cs.cmu.edu/~minerva/

[2] U.S. Department of Defense (DoD) 5000.59-P, "DoD Modeling and Simulation (M&S) Master Plan", Washington, D.C., October 1995. Copies available at http://www.dmso.mil/

[3] NATO SGMS (Study Group on Modeling and Simulation), "NATO M&S Master Plan, Version 1.0", AC/323 (SGMS) D/2, Brussels, August 1998.

[4] More information about HLA is available at https://www.dmso.mil/public/transition/hla/

[5] IEEE Std. 1516-2000, Std. 1516.1-2000, Std. 1516.2-2000, "IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA)", New York, N.Y., 2000.

[6] Fujimoto, R. et al, "Design of High-performance RTI software", in *Proceedings of Distributed Simulations and Real-time Applications*, August 2000 (DIS-RT-2000).

[7] More information about MEL is available at https://mel.dmso.mil/

[8] More information about SEDRIS is available at http://www.sedris.org/

[9] Gamma, E. et al, "Design Patterns: Elements of Reusable Object-Oriented Software", Addison Wesley, Massachusetts, January 1995.

[10] Warwick K., "I, Cyborg", Century, August 2002 http://www.kevinwarwick.com/ICyborg.htm

[11] Wachowski A., Wachowski L., "The Matrix", 1999, http://whatisthematrix.warnerbros.com/

[12] Temizer S., "Yazılım Yapılandırma Teknikleri: Temizer Sistemi", II. Ulusal Yazılım Mühendisliği Sempozyumu, UYMS'05, pp. 305-313, Ankara, September 22-24, 2005.

[13] Genelkurmay Bilimsel Karar Destek Merkezi Başkanlığı (BİLKARDEM), "Müşterek Harekat Alanı Simülasyon Sistemi Temsili Ortam Bilgi Bankası" (MÜHATEM), started in July 2002.

VITAE

Selim TEMİZER

In 1999, Selim Temizer received his B.S. degree from the Department of Computer Engineering, Middle East Technical University (METU). In 2001, he received his M.S. degree in Electrical Engineering and Computer Science at Massachusetts Institute of Technology (MIT) and continued his education with his Ph.D. at the same institute in The Artificial Intelligence Laboratory. Among his research interests are artificial intelligence, computer vision, robotics, robotic navigation, map-making techniques for mobile robots and simulation systems. He has taken a leave of absence from his Ph.D. studies since February 2004.

He worked at Meteksan Sistem ve Bilgisayar Teknolojileri A.Ş. and Aydın Yazılım ve Elektronik Sanayi A.Ş., leading teams on various high profile projects such as the design of an OpenGL driver for the Joint Strike Fighter (JSF) F-35 Panoramic Cockpit

Displays. He offered a C Programming Language course as an instructor at the Department of Computer Engineering, METU for two semesters.

Since April 2006, he has been performing his military service as a reserve officer in The Scientific Decision Support Center (Bilimsel Karar Destek Merkezi, BİLKARDEM, Genelkurmay Başkanlığı). During his service, he gave support to MÜHATEM and KOZA projects (KOZA is about developing a national RTI). His military service is expected to be completed on March 31, 2007.