

# A High Level Architecture-based Medical Simulation System

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*The Combat Trauma Patient Simulation (CTPS) is a dual purpose training and analysis simulation system that provides an "end-to-end" simulation of the military medical treatment process for combat trauma injuries from the time of occurrence through initial treatment at the field hospital. CTPS was built by integrating a set of existing commercial and military simulations, each specialized for a different part of the process. None of the integrated simulators was initially interoperable, or even designed to be interoperable, with the others. The integration was achieved using the High Level Architecture (HLA), together with interface modules for each of the simulators. The HLA ownership transfer services were central to the system's design.*

**Keywords:** High Level Architecture, HLA, medical simulation, interoperability, ownership transfer, Combat Trauma Patient Simulation

## 1. Introduction

This paper describes the Combat Trauma Patient Simulation (CTPS), with emphasis on how High Level Architecture (HLA) was used in its development. This introductory section, which briefly reviews HLA and states the objectives of the CTPS project, is followed by the two main sections of the paper. The first main section describes the functionality and components of CTPS, and the second details how HLA supported that functionality. Future work and conclusions complete the paper.

### 1.1 HLA Background

The High Level Architecture is an architecture for constructing distributed simulations. It facilitates interoperability among different simulations and simulation types and promotes reuse of simulation software modules [1]. HLA can support virtual, constructive, and live simulations from the training, engineering, and analysis applications domains.

HLA is defined by three components:

1. The HLA Rules [2], which define interoperability and what capabilities a simulation must have to achieve it within HLA;

2. The Object Model Template [3], which is a semi-formal methodology for specifying simulation object classes, attributes, and interactions [4]; and
3. The Interface Specification [5], a precise specification of the interoperability-related actions that a simulation may perform, or be asked to perform, during an HLA exercise.

The HLA Run-Time Infrastructure (RTI) is an implementation of the interface specification, provided as a set of services. The RTI provides services to start and stop a simulation execution, to pass simulation data between simulations, to control the amount and routing of data that is passed, and to coordinate the passage of simulation time among the simulations. Of particular interest here, the RTI provides services to transfer the ownership of specific items of information called attributes about the objects being simulated.

### 1.2 CTPS Project Goals and History

CTPS is a dual-purpose training and analysis simulation system that provides an "end-to-end" simulation of military casualty generation, handling, and treatment. CTPS is the first implementation of a medical federation using HLA. It simulates the emergency medical treatment process for combat trauma injuries from the time of occurrence through initial treatment at the field hospital [6]. CTPS was built using existing commercial and military technology. CTPS is intended to support both training and analysis applications. For training, CTPS can be used to train medical caregivers to prioritize patients, diagnose conditions, select appropriate treatments, and perform the selected treatments. For analysis applications, different medical treatment plans, priorities, and staffing levels can be tested using CTPS.

Successively more capable versions of CTPS are being built in phases. The CTPS Phase 1 system demonstrated basic interoperability [7]. The currently existing CTPS Phase 2 system, which is the subject of this paper, is the first to contain an "end-to-end" set of integrated simulations [6]. CTPS Phase 3, which will add several new federates, is currently in progress. The CTPS Phase 2 system is being evaluated at user sites; delivery of the system to users will likely occur after Phase 3.

## 2. CTPS System Architecture

This section describes the function and system-level architecture of the CTPS system. An overview of the system is followed by descriptions of the system components.

### 2.1 Overview

The simulated objects in CTPS are patients. CTPS may simulate multiple patients at once, limited by the total capacity of the simulation components. The Phase 2

system has been tested with more than 30 concurrent patients.

The CTPS system is composed of a set of distinct integrated components, each of which is a simulation of a different stage or phase in military casualty handling and treatment and/or has specialized capabilities with respect to what aspects of patient status and treatment it can simulate. The exception is the CTPS Executive, which does not simulate patients at all; instead, it provides federation-wide management functions. Each of the components of the CTPS system (the simulations and the CTPS Executive) is an HLA federate. The federates that simulate patients, i.e., those other than the CTPS Executive, will be referred to as *simulation federates*. The essential idea is that each CTPS patient is simulated by the CTPS simulation federates, one after the other, as appropriate for the status or time history of the patient.

A CTPS patient is transferred from one simulation federate to the next depending on certain criteria that include time since the patient was initially wounded and the patient's medical state. To "transfer" a patient means to transfer the responsibility for simulating the patient from one simulation federate to the next. To perform a transfer, the data representing the patient is passed from one simulation federate to another. A patient transfer has nothing to do, other than coincidentally, with the physical movement of a patient around the simulated battlefield; such patient movement is not explicitly modeled in the CTPS system.

Figure 1 shows the general flow of patient transfer among the CTPS simulation federates. It is a design goal of the CTPS implementation that the set of simulation federates can be changed over time to meet changing requirements.

The CTPS Phase 2 system can simulate three different medical scenarios. They are:

1. Blood loss: an injury that involves the loss of a significant amount of blood, such as a severe foot and leg injury resulting from a land mine explosion.
2. Anaphylaxis: a severe allergic reaction to a chemical toxin, such as snake venom.
3. Pneumothorax: a deep puncture wound in the chest cavity involving one of the lungs, as might result from a bullet penetration.

Each CTPS patient is in one of these medical scenarios. The set of patients involved in a particular exercise may include any mixture of scenarios. Within each of these scenarios, a patient may be in one of eleven states that represent distinct stages of the physiological progression of the scenario. Without treatment, a patient will automatically transition from one state to the next as his/her condition worsens. Each transition will normally occur after one minute of simulated time. Treatment can change the default state progression.

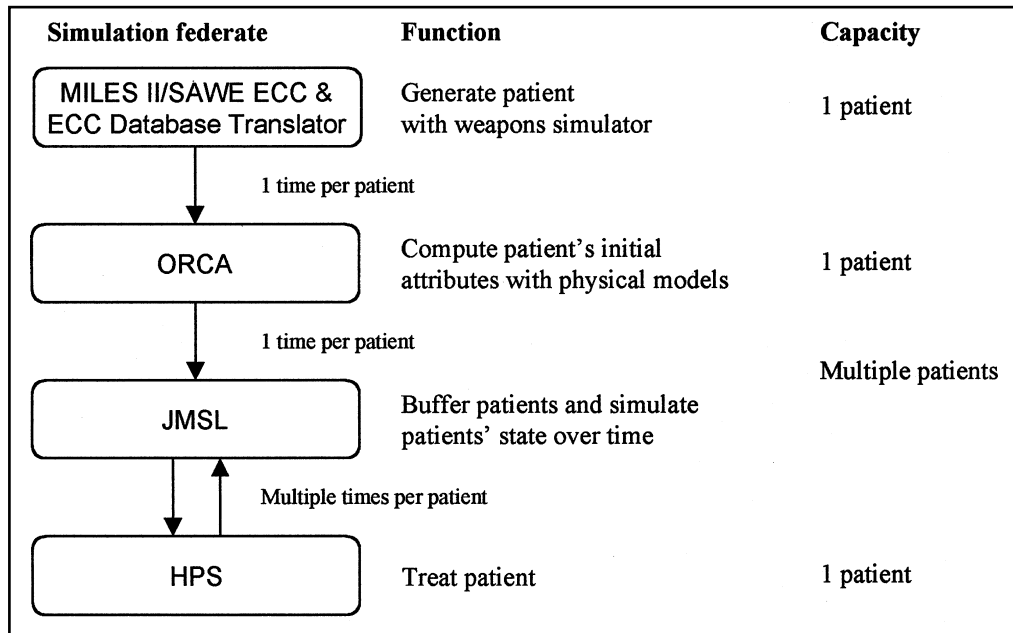


Figure 1. CTPS patient transfer sequence

## 2.2 CTPS Simulation Federates

Each of the four simulation federates in the CTPS Phase 2 system simulates a different stage in the military casualty treatment process. The simulations are:

**MILES II/SAWE ECC.** The Lockheed Martin Multiple Integrated Laser Engagement System (MILES II) and Simulation Area Weapons Effect (SAWE) system uses lasers that transmit encoded signals and sensors that detect those signals to simulate weapons engagements. The associated Electronic Casualty Card (ECC) allows the initial treatment of a wound inflicted by the simulated weapon. In CTPS, the MILES II/SAWE ECC system is used to generate patients by “shooting” the MILES vest with a laser sender.

**ORCA.** The Operational Requirements-based Casualty Assessment (ORCA) system, developed by the Crew Casualty Working Group (CCWG), simulates in great detail the effect on the human body of various types of insults, such as toxic gases or penetrations by bullets and shrapnel. In CTPS, once a patient has been generated by the MILES II/SAWE ECC simulation, the patient is transferred to ORCA. ORCA computes additional physiological details about the wound, completing the setting of the patient's initial state.

**JMSL.** The Jackson Medical Simulation Library (JMSL) is a state-machine tool used by the Henry M. Jackson Foundation (HMJ) to produce training simulations for emergency and medical procedures. After patients have been generated and detailed by the first two components, they are transferred to JMSL. The patients' changing physiological states over time as they await treatment are simulated in JMSL.

**HPS.** The Human Patient Simulator (HPS), a product of Medical Education Technologies, Incorporated (METI), is an instrumented human mannequin. It is a sophisticated electro-mechanical device that is driven by realistic models of human physiology, simulates a variety of medical conditions, and responds to medical treatment procedures applied by a user to the mannequin. HPS simulators are presently in stand-alone use at medical facilities to train nurses, emergency medical technicians, and medics on emergency medical procedures. In CTPS, the HPS allows users of the system to treat patients. Figure 2 shows an HPS.

Each of the simulation federates of the CTPS Phase 2 system, except JMSL, can simulate only a single patient



Figure 2. Human Patient Simulator (HPS)

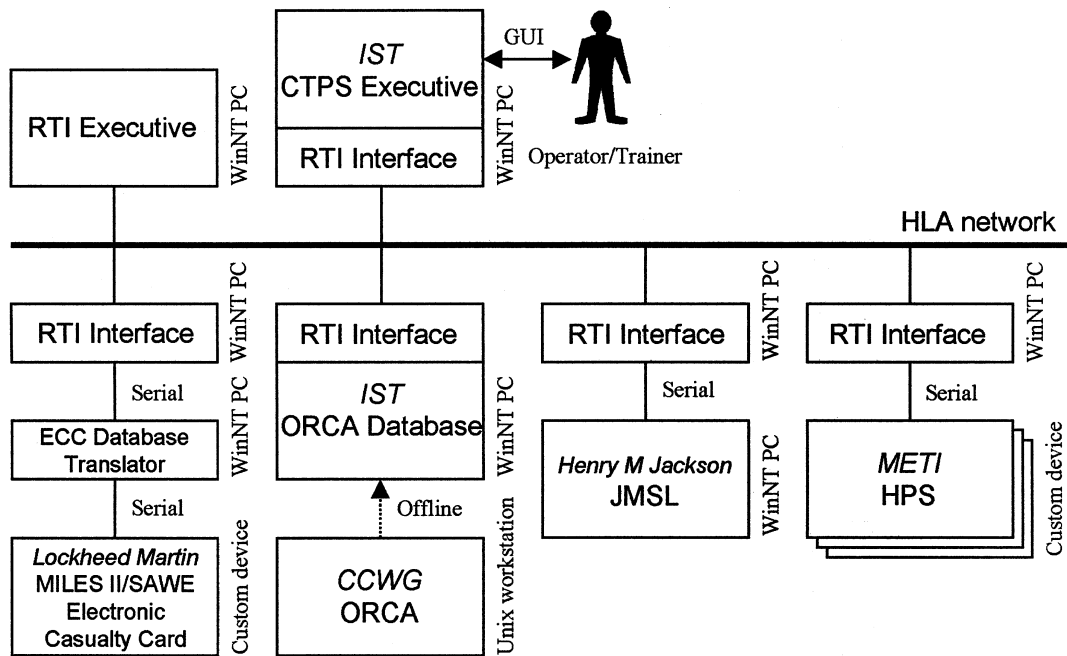


Figure 3. CTPS system architecture

at a time. Because JMSL can simulate multiple patients, as patients are generated they are buffered in JMSL.

When an HPS is available, a patient is transferred into it where the users apply treatment. When a patient is transferred into an HPS, the simulator is initialized with the medical condition of that patient. If the patient is stabilized, or a more urgent patient is awaiting treatment, the patient may be transferred out of the HPS back into JMSL, and a new patient transferred into the HPS. The CTPS system supports multiple HPS federates, so more than one patient may be treated simultaneously.

### 2.3 CTPS Executive

The CTPS Executive is not a simulator; rather, it provides system control functions. It performs typical simulation management functions, including federation management, data logging, save/restore checkpointing, and operator control. However, its most interesting function is the allocation of patients to the simulation federates. As the federation execution proceeds, the CTPS Executive determines which of the federates should be simulating each patient. The criteria that are considered by the CTPS Executive when allocating patients are:

1. Preplanned allocation of patients to specific federates based on treatment sequence.
2. Matching of the patient to the federate best able to simulate that patient's condition.
3. Federate capacity limits.
4. Direct user control via the CTPS Executive's graphical user interface. Users may "drag and drop" an icon representing a patient between panes corre-

sponding to the simulation federates. The CTPS Executive will execute the corresponding patient transfer, if possible.

Based on the allocation algorithm, transfers of patients from one simulation federate to the next are initiated and controlled by the CTPS Executive. The patient transfer sequence in the CTPS Phase 2 system is straightforward, given the specific set of simulation federates, but the allocation algorithm has been designed to be adaptable to different sets of federates. More generally, it can operate in any federation where simulation objects may be transferred between federates based on conditions in the simulation.

The CTPS Executive is an event-driven multi-threaded program. It is the only CTPS federate that is aware of the existence of the whole federation. It continuously monitors activity and provides a graphical interface that shows the state of the federation execution and allows user interventions.

## 3. HLA in the CTPS System

This section reports how HLA was used in the implementation of the CTPS system.

### 3.1 CTPS Integration with HLA

The different components of the CTPS system are integrated into the overall system using the High Level Architecture (HLA), which provides the interoperability framework and communication backbone of the system. Figure 3 shows the overall system configuration. A CTPS Federation Object Model (FOM) containing attributes that describe a patient's physiological state defines the data that is exchanged between the four federates. As the federates simulate the patients,

they update the patients' attributes using the appropriate HLA services.

### 3.2 RTI Interface Modules

None of the CTPS simulation federates was initially interoperable, or even designed to be interoperable, with the others. Each has a unique communications interface that exchanges data formatted according to a custom protocol. Modifying the simulations to directly communicate via HLA was not technically feasible for various reasons, including heterogeneous software and hardware environments, proprietary software internals, and a desire to preserve "off-the-shelf" status for the simulations. Consequently, RTI interface modules for each of the simulations connect the simulation with the federation via the RTI; each simulation and interface pair forms a federate. The RTI interfaces translate the custom non-HLA data of each component into the CTPS FOM data for exchange via the RTI. Though the details vary for each, they have a similar structure; each accepts data from a simulation via its communication interface and custom protocol, and resends that data via the RTI after translating it into CTPS FOM data, or vice versa. An execution control and data management layer links the two communications layers of the RTI interfaces.

Two of the RTI interface modules have special characteristics. First, the ORCA simulation is actually integrated in an off-line manner. ORCA was developed to run only in an interactive manner via a graphical user interface, and modifying it to run in a networked mode was not feasible. The ORCA simulation was used off-line to populate a database of entries corresponding to the CTPS scenarios and states [8]. During a CTPS execution, the ORCA RTI interface accesses that database to get the needed information.

Second, the HPS RTI interface can support multiple HPS simulators, as shown in Figure 3. During federa-

tion startup, the RTI interface announces to the CTPS Executive how many simulators are attached, and the CTPS Executive uses that information when making patient allocation decisions.

### 3.3 CTPS Federation Object Model

CTPS interoperability depended on the CTPS FOM. The CTPS Phase 1 FOM had a small set of physiological attributes for a patient (see [7] for a list). However, even that small set of attributes included attributes that were not commonly usable by all of the simulations being integrated into the CTPS Phase 2 system. Consequently, the CTPS Phase 2 FOM was reduced to just those patient attributes that the least detailed federate could use; it includes two attributes for each patient, scenario and state. For federates that produce more detailed information (e.g., ORCA) that detail is mapped to values for scenario and state by the RTI interface. Similarly, for federates that can accept more detail (e.g., the HPS), the scenario and state are mapped to the detail by the RTI interface. Interactions are not used in the Phase 2 FOM.

### 3.4 Ownership Transfer

In a CTPS exercise, each patient can be simulated by different CTPS federates at different times. CTPS patients are transferred from federate to federate, which means transferring the responsibility for simulating a particular patient. To transfer a patient from one federate to another during simulation execution, ownership of all of the attributes for the patient is transferred using the HLA ownership transfer services.

The precise sequence of transfers for a specific patient during an exercise is generally unpredictable. Nevertheless, the allocation decisions made by the CTPS Executive follow certain rules. First, there are federate capacity limitations. For example, only one patient can be simulated in an HPS at a time. Second,

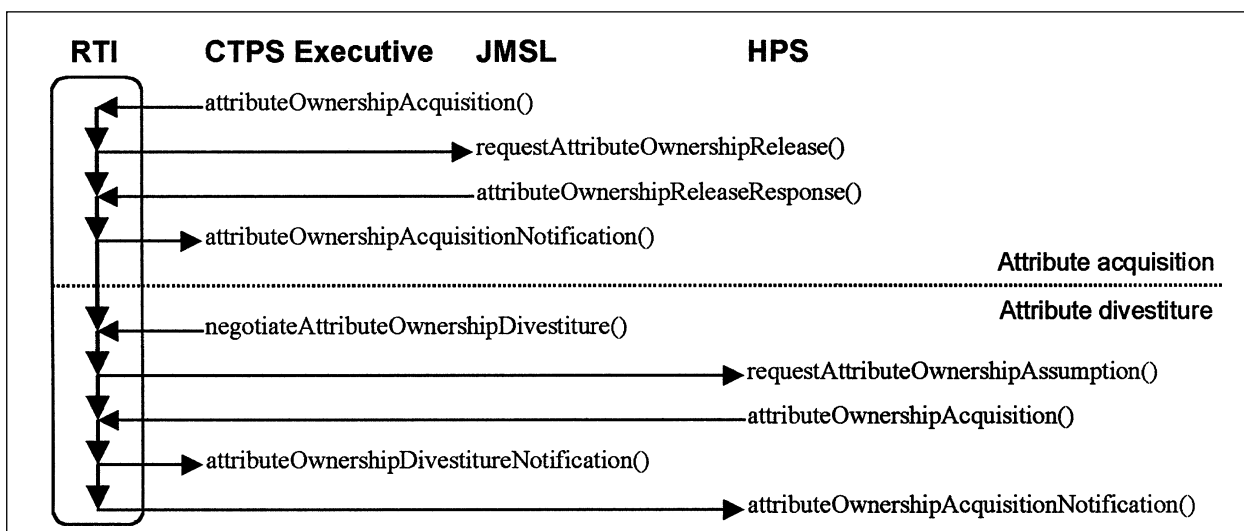


Figure 4. Example patient attribute transfer (JMSL ♦ HPS) via HLA ownership transfer

federate computational load restricts the allocation options in order to assure an acceptable level of federation performance.

If patient transfers were made directly from one federate to another, each federate would need to have some knowledge of what other federates were present in the system. In order to prevent such inter-federate binding and allow for changes to the federate configuration, the patient transfer logic is centralized in the CTPS Executive. In consequence, transferring federates always divests patient attribute ownership to the CTPS Executive, which in turn divests the patient's attributes to the designated receiving federate. Thus, the patient transfer turns out to be a two-stage process in which the CTPS Executive temporarily "owns" the patient. During this time, the CTPS Executive assigns the patient to an internal object. The transfer is accomplished through a discrete sequence of requests and notifications to and from the simulation federates and the CTPS Executive, implemented as system function calls. Figure 4 depicts a typical CTPS patient transfer. In the figure the transfer is from JMSL to an HPS. Other patient transfers are similar.

#### 4. Planned Enhancements

For the CTPS Phase 3 system the following enhancements are planned:

1. Expansion of the CTPS FOM. The Phase 3 CTPS FOM will reverse the "lowest common denominator" approach. The development of the Phase 3 FOM started from two medical object models developed by Mystech Inc., a Physiological SOM and a Human Response to Stimuli SOM [9], and added a large number of new subclasses and attributes. A preliminary version of that FOM had many subclasses and attributes to represent in detail the anatomical, physiological, pharmacological, and pathophysiological state of a patient. The final version of the Phase 3 FOM will have 166 attributes based on those produced by the sophisticated models of the HPS. For federates that cannot use the full set of attributes, the RTI interface modules will provide mappings. No interactions are envisioned for the Phase 3 FOM.
2. Addition of a Triage Control federate. This federate will provide an interface where a user can prioritize patients awaiting treatment.
3. Addition of an After Action Review (AAR) federate. The AAR federate will allow the patients' treatments and outcomes during an exercise to be replayed and reviewed.
4. Addition of a Patient Generation federate. Using this federate, patients may be introduced into an exercise interactively using a graphical user interface, and/or from exercise files created using that interface.

For each of the new federates, a CTPS RTI Interface module will be developed.

#### 5. Conclusions

Interoperability and integration are crucial to the CTPS system. None of the individual components of the CTPS system covered the full range of patient conditions or treatment stages required, nor could any be reasonably modified to do so. Only by integrating a heterogeneous mix of existing simulations could the project's goals be met; HLA provided the capabilities needed to support the integration.

In addition to its intended purposes, medical training and analysis, the CTPS system is significant in two respects. First, the fact that CTPS is itself a heterogeneous interoperable system suggests that its components or integration infrastructure may be reusable. In particular, the functionality of the CTPS Executive may be useful in other federations, especially its function of dynamically controlling the allocation of simulation objects to federates. Second, because CTPS is the first implementation of a medical federation using HLA, it demonstrates the feasibility of medical applications of HLA.

#### 6. Acknowledgments

The CTPS project was sponsored by the Department of Defense Live Fire Test and Evaluation office, under Mr. Jim O'Bryon, and managed by the U.S. Army Simulation, Training, and Instrumentation Command, in particular by Ms. M. Beth H. Pettitt. Their support and guidance is gratefully acknowledged. Medical Education Technologies, Inc., and the Henry M. Jackson Foundation developed CTPS federate simulations. The CTPS Phase 2 system integration was implemented by Sumeet Rajput, Bradley C. Schricker, Fritz W. Feuerbacher, and Kiran Anna. Finally, we appreciate the suggestions provided by the referees, which improved the content and readability of the paper.

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