

## **A Modular Architecture for Blending Virtual and Manikin-based Medical Simulations**

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### **ABSTRACT**

Whole-body medical manikins that respond to interventions through physiological modeling are often considered to be the best available alternative to live tissue for simulation-based medical training. However, a physical manikin that provides essential perceptual cues and supports all of the key procedures and clinical decisions for a complex patient case is not always available or cost-effective. An integrated, blended reality medical simulation system that adds virtual simulations to physical simulations can offer a significant advantage over manikin-only simulation by providing full-body visual and aural cues for the patient's appearance and behaviors, while a manikin or part-task trainer provides the haptic cues needed to train psychomotor skills for targeted procedures. This persistent virtual simulation can maintain and present a coherent representation of the patient while selected procedures are performed on physical manikin modules.

In order to demonstrate the feasibility and effectiveness of this multi-modal approach to medical simulation, a software and data communications infrastructure, in which various aspects of a simulation can be developed as a federation of interoperable, multi-modal modules, was created. The efficacy of this architecture was then demonstrated in multiple module configurations, including through the Center for Research in Education and Simulation Technologies (CREST) team's Advanced Modular Manikin (AMM) Phase I prototype, in which 15 modules of various modalities were successfully integrated. This paper will review the architectural concepts used and results achieved, and describe how the approach to interoperability can be leveraged to close gaps in current medical training.

### **ABOUT THE AUTHORS**

**Ed Sims, PhD** is Chief Technology Officer of Vcom3D, Inc., an Orlando-based company that develops interactive training simulations driven by models of human physiology, behavior, and cognition. Most recently, his focus has been on developing multi-modal medical simulations that blend virtual and physical representations. Prior to co-founding Vcom3D, Dr. Sims held the positions of Chief Scientist and Technical Director for Lockheed Martin Information Systems Company, where he led several projects related to distributed interactive simulation and computer image generation. Dr. Sims received a BS degree in Mathematics from the College of William and Mary and the MS and PhD degrees in Systems Engineering from Rensselaer Polytechnic Institute. He has been awarded five patents in the areas of real-time visual simulation and human behavior modeling.

**Dan Silverglate** is VP of Systems Architecture and Development at Vcom3D and chief architect for Vcom3D's MedSim Modular Architecture. He also led development of Vcom3D's award-winning STAT!<sup>TM</sup> trauma team training that provides opportunities for clinicians to practice making critical decisions under stress throughout the Continuum of Care. He has over 18 years' experience in software development and systems architecture with a focus on character animations systems, serious gaming, and hardware integration. Mr. Silverglate holds a Bachelor of Science degree in Computer Science from the University of Central Florida where he graduated Magna Cum Laude,

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**David Hananel** is Senior Research Scientist and Associate Director of Simulation Research at the University of Washington School of Medicine. He has over 15 years' experience in Surgical & Medical Simulation and Education with a focus on Curriculum Development and Technology Integration. His research goals include developing a deep understanding of surgical and medical education and training needs and integrating the best available modalities to provide breakthrough training models where the sum is larger than the parts. His specialties include educational design, cognitive task analysis, concurrent product and process development, and innovation. Prior to joining the UW School of Medicine, Mr. Hananel held positions at the University of Minnesota Medical School, CAE Healthcare, and METI. He received a BS degree in Computer Science from the Technical University Berlin and MS degree in Electrical Engineering from Southern Illinois University.

**Rob Sweet, MD, FACS** received his medical degree (*alpha omega alpha*) from the University of Minnesota in 1997. After a urology residency at the University of Washington in Seattle in 2003, he became Attending Physician/Acting Assistant Professor of Urology and held a 2-year Scholarship in Simulation Sciences from the American Foundation for Urological Diseases (AFUD). In 2004 Dr. Sweet co-founded the Institute for Surgical and Interventional Simulation (ISIS) at the University of Washington. He currently holds the positions of Professor of Urology and Executive Director, WWAMI Institute for Simulation in Healthcare.

**Troy Reihsen** is the Director of the Artificial Tissue Lab at the University of Washington. Mr. Reihsen has over twenty-five years of military and civilian healthcare experience including extensive use of medical simulation. As the program director for the MEDSIM CCTC contract, he oversaw the administration (staffing, budget, recruiting, hiring, training), operations and execution of the proposed research by implementing effective measures of reliability and consistency for assessment, environmental and physiological conditions, and all technical aspects of manikin design, development, operations, training, and repair for over 1000 subjects.

**Jack Norfleet** is the Chief Engineer for the Medical Simulation Research branch of the Army Research Laboratory Human Research and Engineering Directorate, Advanced Training and Simulation Division (ATSD). He manages a multidisciplinary team of researchers as well as the planning and execution of medical simulation research efforts across the services. Mr. Norfleet has 31 years of experience in modeling, simulation and training as an electronics engineer, test engineer, project engineer and science & technology manager. Mr. Norfleet received a Bachelor of Science in Electronics Engineering from the University of Central Florida (UCF), a Masters in Modeling and Simulation from UCF, and a Master of Business Administration Degree from Webster University. He is a Doctoral Candidate at UCF. He is a member of the Acquisition Corps and is Level III certified Systems Planning Research Development and Engineering.

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### **BACKGROUND: BLENDING MEDICAL SIMULATION AND TRAINING MODALITIES**

Military combat training simulations are commonly, though imperfectly, categorized as Live, Virtual, and Constructive (LVC). Each of these training modalities comes with strengths, limitations, and cost/performance trade-offs. Over the past quarter century, interoperability standards such as Distributed Interactive Simulation (DIS; 2012) and High-Level Architecture (HLA; 2015) have evolved to enable multi-user, multi-entity simulations to combine live, virtual, and constructive simulations into large scale force-on-force exercises. For example, mounted and dismounted infantry can train in virtual simulators while facing adversaries that are constructively simulated as Computer Generated Forces (CGF).

Similar to combat simulation, medical simulation has evolved to include many live, virtual, and constructive modalities, each of which has strengths and limitations. However, there are no widely adopted methods for integrating simulations using these various modalities. As a result, most medical simulation-based training remains limited in scope to one of these modalities. Procedures requiring psychomotor skills are often practiced on part-task trainers without the full context of patient management; patient hand-offs that require transitions to different simulators do not transfer information about the patient's condition that can be used by the next stage of simulation; and nurses, technicians, and physicians frequently practice their skills in isolation using simulators tailored to their individual tasks, since there is no infrastructure for integrating these simulators for collaborative training.

As with combat simulation, several modalities have evolved to provide training that is tailored to specific medical tasks. Common modalities for medical simulation are shown in Table 1.

Table 1. Common Medical Simulation Modalities and their Strengths and Limitations

<b>Modality</b>	<b>Strengths</b>	<b>Limitations</b>
Standardized Patient (SP) Actors	Trained live actors can provide detailed patient histories, ask questions, respond emotionally, and simulate many behavioral symptoms.	For obvious safety reasons, medical interventions can be prescribed, but not actually practiced on an SP.
Part-task Trainer (PTT) Devices	Physical PTTs can provide haptic and visual cues to train psychomotor skills such as catheterization or chest tube insertion.	PTTs focus on one body part or skill and provide limited opportunities to train decision-making or patient management.
Virtual Reality (VR)	Using haptic devices and immersive displays, VR simulations can provide cues for many procedures and are especially effective for endoscopic surgery.	VR simulations do not typically include the impact of surgery on patient physiology or behavior.
Virtual Patients (VP)	A high-performance virtual patient can often provide higher quality visual and aural cues than a physical manikin or PTT. It can also be simulated using standard desktop or mobile computers and network for a multi-user experience.	Virtual patients do not provide the haptic cues required for training many procedural skills.
Manikin-based Simulation	A high-performance, full-body manikin can provide cues for both decision-making and detailed procedures.	Current medical manikins are not modular. Expensive systems may not cost-effectively meet the requirements of specific needs.

It is also possible to blend or mix two or more of these simulation modalities:

- An SP can be fitted with one or more wearable PTTs, such as for training intravenous (IV) injection or emergency trauma surgery.
- An endoscopic procedure trainer can combine an external PTT physical representation of the patient with a VR representation of internal anatomy.

However, no generalized architectures or interoperability standards for integrating the various simulation types into holistic, seamless training have emerged.

## GOALS FOR A MODULAR ARCHITECTURE

The goals of this research and development are to design, implement, and evaluate a modular medical simulation architecture that supports the integration of physical (manikin-based or part task trainer) and virtual modules to meet a wide range of medical training requirements. The architecture should support acquisition and sustainment of a wide range of clinical skills ranging from Role 1 (Point of Injury) to Role 5 (Stateside Definitive Care), including the hand-offs between medical treatment facilities and between teams involved in assuring continuity of care. Such a modular architecture would afford the possibility of “crowdsourcing” best-of-breed simulation modules from multiple vendors that work together to meet specific and evolving medical training needs.

In this paper, the focus is on the software and data architecture required to meet these interoperability needs, and how it contributes to the larger requirements for an Advanced Modular Manikin (AMM) architecture, which also encompasses hardware modularity, and interoperability of learning and assessment content.

## INTEROPERABILITY STANDARDS

In recent years, several specifications have been proposed or adopted as standards for interchanging data relative to medical simulation and training. Most prominent among these have been standards developed and advanced by the Medbiquitous Consortium ([www.medbiquitous.org](http://www.medbiquitous.org)). Medbiquitous standards define Extensible Markup Language (XML) and Web Services specifications for exchanging medical competencies, learning objects, activities, and achievements. There is also a specification for sharing Virtual Patient simulations. The Medbiquitous Virtual Patient

specification defines VP data, media resources, learner activities afforded, and player functionality, but does not define methods for disparate real-time modules to collectively simulate patient conditions and responses to interventions.

Two other organizations, OpenSurgSim ([www.opensurgsim.org/](http://www.opensurgsim.org/)) and Simulation Open Framework Architecture (SOFA, [www.sofa-framework.org/](http://www.sofa-framework.org/)) are developing open architectures for virtual reality based surgical simulation. These architectures define methods and data representations for modeling anatomical structures and surgical interaction with these structures. However, they do not integrate methods for modeling physiology or patient behavior.

Military Modeling and Simulation (M&S) has benefitted significantly from the development of interoperability standards such as the IEEE 1278 standard family defining the Distributed Interactive Simulation (DIS) protocol (IEEE, 2012), and the IEEE 1516 standard family defining the M&S High Level Architecture (HLA) (IEEE, 2015). The DIS standard, in particular, defines Protocol Data Units (PDUs) that capture the possible actions and interactions between live, virtual, and/or constructive simulators representing individual weapon systems. These standards were investigated as possible starting points for defining an open Medical Simulation architecture. Tolk et al. (2013) identify a number of shortfalls of DIS and HLA as a medical simulation interoperability standard. These standards are based on a world view in which object interactions can be modeled using Newtonian physics. They do not scale up to the range of interactions and quantity and types of data required for medical simulation. There may be a role for DIS and HLA standards, or for architectures such as Live, Virtual, Constructive-Integration Architecture (LVC-IA, [www.peostri.army.mil/PRODUCTS/LVCIA/](http://www.peostri.army.mil/PRODUCTS/LVCIA/)) for integrating medical simulation into large scale exercises such as Joint Enroute Care.

## OBJECTIVES FOR THE MODULAR ARCHITECTURE

Primary drivers for the modular architecture were derived from the AMM program, including such documents as the Advanced Modular Manikin User Needs Assessment (MRMC, 2015) and the Advanced Modular Manikin Concept of Operation (MRMC, 2016). Over and above these, objectives were identified that would promote compatibility with future requirements. Combined objectives for the Modular Software Architecture included:

- Support all echelons of care, from Role 1 to Role 5.
- Support PTT, VP, and Manikin-based simulations by enabling any module to be a PTT in its own right.
- Provide the ability to “pause” the physiology, exchange peripherals, and “continue” the physiology so that the next team can train for their specific tasks by using the same patient that was transferred to them.
- Integrate an open-source physiology engine
- Simulate actual medical equipment such as the Propaq patient monitor (vs. devices specific to the manikin).
- Promote the possibility for “crowdsourcing” trainers from multiple vendors by assuring interoperability specifications are as non-restrictive on module implementation as possible:
  - Same interface specifications apply to all simulation modalities
  - Support multiple wired and wireless communication methods
  - Provide a path for integrating legacy simulators
  - Allow vendors to protect proprietary designs while meeting interoperability requirements

To meet these objectives, a multi-faceted team with collaborators from government, academia, and industry was assembled. The AMM project team was led by CREST, who was responsible for the overall systems architecture design and for the specification and integration of the manikin modules, with Vcom3D leading development of the virtual patient and core simulation software and integration of third party PTTs. Other team members provided manikin modules and adapted them to provide the necessary interfaces, as required:

- 7-Sigma, Inc. provided an Advanced Airway Module, based in part on technology developed by CREST.
- Kforce Government Solutions (KGS) provided modifications to their Multiple Amputation Trauma Trainer (MATT) that enabled integration as an AMM module.
- IngMar Medical provided their ASL 5000 Breathing Simulator, which was used as a high-performance lung simulation module, and supported its integration as an AMM module.
- Applied Research Associates (ARA) supported integration of the BioGears physiology engine through their Physiology Engine contract with the Telemedicine and Advanced Technology Research Center (TATRC).

Stratasy, Whiteboard Product Solutions, and several independent contractors provided detailed design and implementation of CREST-specified manikin modules. Col. Robert Rush, MD, provided subject matter expertise for the scenario design, verification, and demonstration.

The US Army Research Laboratory provided overall guidance to the project.

## MODULAR ARCHITECTURE

Figure 1 shows the elements of the modular medical simulation architecture. At the top level, the architecture consists of a Core Computer System and a set of simulation modules, all sending and receiving messages over a Common Data Bus. In totality these components act as a single patient simulation. The core system manages the simulation scenario, patient state, patient physiology, and communications with the modules. The core system also connects to a learning management system to track the learner. Modules generally act as input and/or output devices for the system. For example, one module might register the action of a learner/practitioner and share this with the system, while another might manifest data from the system as a sight, sound, smell, or sensation. Modules may be physical such as a full-body manikin, PTT, or piece of equipment; or virtual, such as a lab report, health record, VP, or virtual patient monitor. Modules exchange data with the data bus through adapters specific to their communication protocols. For example, a generic USB HID (Human Interface Device) adapter was created for Arduino microcontrollers. For legacy systems, such as the Scent Palette Scent Delivery System ([www.scentpalette.com/](http://www.scentpalette.com/)), custom adapters were created that do not require modifications to the existing software or hardware.

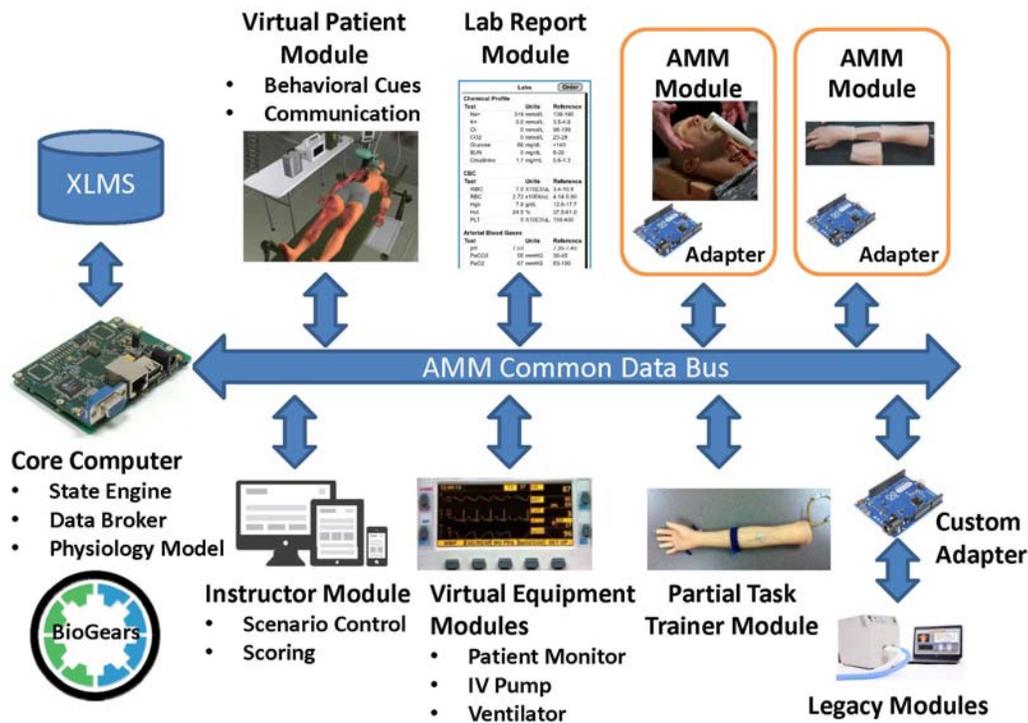


Figure 1. Modular Medical Simulation Architecture

## Experiential Learning Management System (XLMS)

The Experiential Learning Management System (XLMS) prototype enables the student to sign into the system, select a training session, view training content and start the training. The XLMS records results in real time, and is designed to prompt the student as required to perform actual procedures, using embedded sensors to record progress. When the exercise has been completed, the student receives a score and test results are stored for instructor review. The base concept and initial software were developed by CREST under a Cooperative Agreement for the Development of a Modular, Provider Customized Airway Trainer from the Army Research Laboratory.

## Common Data Bus

The Common Data Bus communicates messages among all of the modules using an Application Programmer's Interface (API). Data communicated via the Common Data Bus is required to be clinically relevant data such as that which practitioners would use. Module implementations convert hardware specific messages to clinically relevant data in a standardized format so that this information is readable and meaningful to the system.

### Core Computer System

The Core System provides common communication and simulation services to the other modules of the system. It includes a Physiology Model, State Engine, and Data Broker. For the initial prototype, the Core Computer was implemented on a small, embeddable industrial computer running Windows 7, as shown in Figure 2.

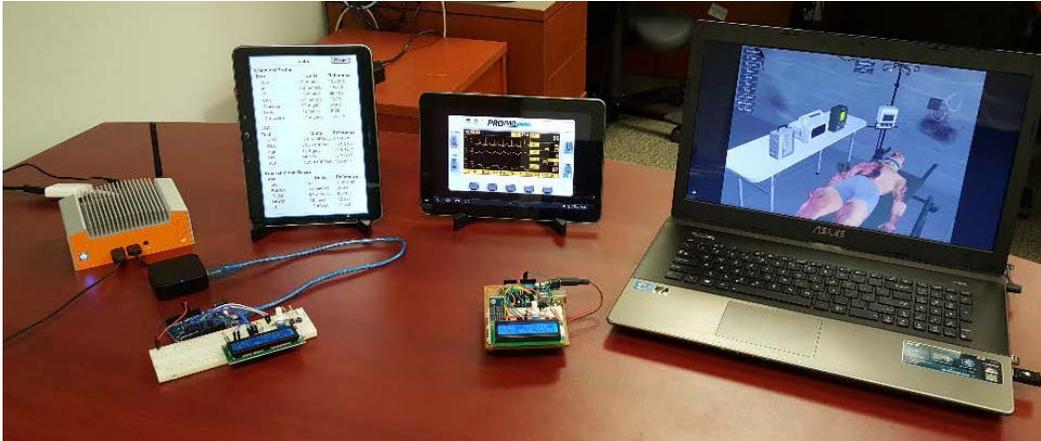


Figure 2. (back, from left) Core Computer, Labs, Patient Monitor, and Virtual Patient Modules (front, from left) Microcontroller Modules with USB and Bluetooth Adapters

The State Engine is responsible for maintaining the state of the patient and the medical treatment environment at all times. This includes instantaneous physiological state as computed by the Physiology Engine, as well as the status of procedures, consumables, medical equipment, and anatomical changes that are not part of the physiological model. The State Engine monitors for actions initiated by the various manikin modules or by the Instructor view and “translates” these into inputs to the Physiology Engine according to Extensible Markup Language (XML) Action Files, where an Action may be an Insult (Injury or Acute Condition), Intervention, or Assessment.

The Physiology Model is built on the open source BioGears Physiology Engine ([www.biogearsengine.com](http://www.biogearsengine.com)), funded by the Joint Program Committee-1 (JPC-1), which is responsible for programming research in: Medical Simulation & Training and Health Information Sciences. The prototype was implemented using BioGears beta version 5.0.0. This engine runs in a constant 90 frames per second loop. The BioGears engine simulates all of the major human physiological systems (including cardiovascular, endocrine, energy, gastrointestinal, nervous, renal, and respiratory) and several anatomical compartments.

The Data Broker manages all modules, receives and disseminates module data, and communicates with the State Engine. The Module Class implements the basic modular functionality. For each hardware interface type, there is a Module Adapter that extends the generic module class and can talk with the hardware interface type, in accordance with the corresponding data communication specification. Adapters implemented for the prototype system include:

- TCP Socket: for talking with modules as a network client using Transmission Control Protocol (TCP)
- REST: for talking with modules as a network client using a Representational State Transfer (REST) API
- Serial: for talking with Universal Serial Bus (USB) or Bluetooth virtual serial port devices
- HID: for talking with USB Human Interface Devices (HID)

Hardware Module developers modify or create devices to these communication specifications. It is also possible to add new Hardware Modules by implementing custom Module Adapters in the C# language. These Custom Adapters can be used to integrate “legacy” manikin modules, while minimizing any changes to the existing devices.

Methods implemented by the Data Broker include:

- Identification: Modules request and receive unique IDs
- Registration: Modules identify the names of messages they wish to receive
- History: Modules identify whether they require the history of all messages for which they have registered that have been sent since the last message was retrieved
- Ready: Modules tell the Data Broker that they are loaded and ready to run
- Get Messages: Retrieve an array of messages asynchronously
- Post Message: Post messages asynchronously to the Data Broker
- Exiting: Modules inform the Data Broker that they are exiting the simulation
- Clean-up: Data Broker tells modules to exit gracefully

For the prototype architecture, all messages have been implemented as name/value pairs. In the future, it is anticipated that more complex data structures will be included.

An Instructor Module was implemented using a Web interface. This interface enables the instructor to intervene to change patient condition or record student actions. In the event that a manikin module is not instrumented to record a student action, the instructor can enter the action based on observation.

Virtual Patient and Virtual Equipment modules were implemented using the Unity Game Engine as a framework. The Unity Game Engine has several attributes that make it attractive for this application, including royalty-free distribution of the player and availability of versions that support all of the following platforms: Windows, Android, Apple iOS, Macintosh, and WebGL. The Virtual Patient module is based on simulations that were funded in part by the Office of the Secretary of Defense (OSD), Defense Health Program (DHP) under a Small Business Innovation Research (SBIR) contract entitled *Serious Medical Game for Continuity of Care*, and managed by the Air Force Medical Modeling and Simulation Training (AFMMAST) office.

The VP provides a cost-effective, high-fidelity 3D representation of the patient in lieu of or as an enhancement to physical representations. For example, the VP module can be used in conjunction with a PTT as a low-cost alternative to a full-body manikin. The VP is capable of manifesting physiological cues such as chest rise, skin pallor, pupil dilation, perspiration, and bleeding. The VP can also be programmed to exhibit behaviors with corresponding audio to convey pain, agitation, level of consciousness, and even dialog in reaction to interventions performed. If medical equipment such as intravenous or intraosseous catheters, airway adjuncts, or masks are detected by the physical manikin, corresponding 3D models appear on the VP. To help immerse the learner in the training and provide a context for treatment, the VP can render the physical environment, terrain, and atmospheric effects. Providing these visual and aural cues allows procedural training to be extended to critical decision-making.



Figure 3. Virtual Patient Module showing Burn Patient

The Virtual Equipment and Reports modules were also adapted from the Serious Games for Continuity of Care project. Specifically, the Propaq patient monitor simulation was modified to run on an Android tablet using the TCP Socket adapter. As shown in Figure 4., the Propaq monitor displays a full range of vital signs as numeric data and waveforms. Electrocardiogram (ECG), arterial or non-invasive blood pressure, and capnography (CO<sub>2</sub>) waveforms were driven directly by variables computed by the BioGears engine at 90 frames per second. Simulated IV pump and ventilator equipment developed for the Serious Games project may also be adapted as modules in the future.

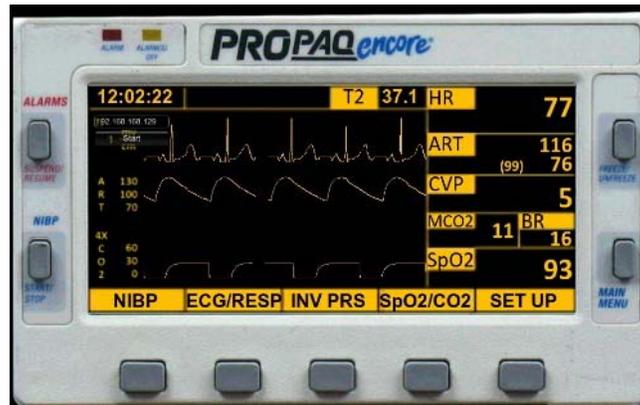


Figure 4. Simulated Propaq Patient Monitor

A Lab Reports module was also adapted from the Serious Games project. The Lab Report included a full set of Blood Chemistry, Complete Blood Count, and Arterial Blood Gases reports, computed using the BioGears engine.

As an initial evaluation of interoperability with PTT Modules, the Core System, VP and Equipment, Lab Reports, and Instructor modules were integrated with an instrumented arm module for training intravenous (IV) infusion. Patient responses to sedatives, pain killers, paralytics, and anesthetics were observed as changes to VP appearance and behaviors, to lab results, and to vital statistics as displayed on the patient monitor.

Under the Advanced Modular Manikin (AMM) program, the Core Computer, Instructor, Virtual Patient, Virtual Equipment, and Lab Reports Modules were integrated with several physical manikin modules and an Experiential Learning Management System (XLMS), as described in the next section of this paper.

## APPLICATION TO ADVANCED MODULAR MANIKIN

Elements of the architecture described in this paper have been applied to multiple projects. However, the primary culmination and initial validation of the research and development has been performed as part of the CREST team's Phase I demonstration for the AMM Project, funded by the US Army Medical Research & Materiel Command (MRMC). The goal of the AMM project is to conduct research and development toward the realization of a "next generation" open-standard manikin platform. As such, the AMM project includes many types of modularity going beyond the software and data modularity described in this paper. This modularity extends to physical, electric, and fluidic connectivity; reference anatomical form; and learning object modularity, as well as the software and data modularity described in this paper. Phase I of AMM culminated with a comprehensive technology demonstration and specifications for the modular system.

### Scenario

A test scenario was developed to have a comprehensive use case that would demonstrate key aspects of the CREST AMM design. The scenario involved a 20-year-old male soldier injured by the explosion of a burn can. This soldier accidentally replaced diesel fuel with gasoline and ignited the pot, exploding the contents immediately, resulting in 2nd and 3rd degree burns across almost 45% total body surface area (TBSA), including full thickness and deep partial thickness burns of his left arm. The accident also resulted in a below the knee amputation (BKA) of the right leg, causing the soldier to be hypovolemic due to loss of blood and capillary leakage from burns. Furthermore, the soldier presented with wheezing and coughing up carbonaceous sputum.

A total of 15 modules were included in the simulation, in addition to the Core Computer:

- Physical Manikin modules:
  - IV Arm, with infusion sensor and pulse (via HID adapter)
  - Rugged Arm, with pulse (via HID adapter)
  - Escharotomy Arm, with incision detection and pulse (via HID adapter)
  - Advanced Airway, with ventilation detection (via HID adapter)
  - Esophagus/Stomach, with ventilation detection (via HID adapter)
  - Multiple Amputation Trauma Trainer (MATT) legs (via custom USB adapter)
  - ASL-5000 lung simulation with spontaneous breathing and mechanical ventilation (via custom TCP Socket adapter)
  - Radio Frequency Identification (RFID)/Proximity detector, for identifying the use of various medical equipment and drugs (via HID adapter)
  - Scent Palette Scent Delivery System/Scent Generator (<http://www.scentpalette.com/>) (via custom USB adapter)
- Virtual modules
  - Patient (via TCP Socket adapter over Wi-Fi)
  - Patient Monitor (via TCP Socket adapter over Wi-Fi)
  - Lab Reports (via TCP Socket adapter over Wi-Fi)
- Administrative modules
  - Administrator (via TCP Socket adapter over Wi-Fi)
  - Instructor (via REST adapter over Wi-Fi)
  - XLMS (via REST adapter over Wi-Fi)

The scenario, shown in Figure 5, unfolds over two days. In the first part of the simulation, the patient is taken to a Battalion Aid Station. The patient receives a tourniquet for hemorrhage control, IV infusion of liquids, pain medication, and successive interventions to protect the airway. Airway interventions include insertion of a nasopharyngeal airway, oxygen via non-rebreather mask, active ventilation via bag valve mask, and finally endotracheal intubation. During the course of the intubation, the patient receives rapid sequence induction (RSI) drugs to sedate him and stop spontaneous breathing. There are then two failed attempts at intubation: the endotracheal tube (ETT) is first inserted into the esophagus, resulting in inflation of the stomach. It is removed and then inserted into the trachea, but it is inserted too far: it passes the carina and enters the right mainstem bronchus, thereby inflating only the right lung. Finally, the ETT is inserted correctly into the trachea, stopping at a position above the carina.



Figure 5. Advanced Modular Manikin Demonstration

The second part of the scenario takes place the next day. Due to burns, the left arm has become edematous and the leathery nature of the burned skin creates a compartment syndrome by restricting circulation. To relieve the pressure, a surgeon performs an escharotomy of the arm, by cutting through multiple layers of tissue, from skin to fascia, to relieve pressure and restore circulation to the distal part of the arm. As the surgeon makes incisions in the arm to relieve pressure, bleeding and oozing are observed. The tissue expands, relieving pressure and restoring pulse to the distal part of the arm and hand. Physiological changes are computed using BioGears, relieving shock over an appropriate period of time. The hand turns from blue to pink and becomes warm to touch. Also, as each of a series of cuts is made in the physical arm, the cuts are sensed and portrayed on the VP. Treatment results are reported to the XLMS.

## RESULTS

The AMM scenario demonstrated results against each of the objectives for the modular architecture, as summarized in Table 2.

Table 2. Results Achieved

Objective	Result
Support multiple echelons of care	The scenario included elements appropriate to point of injury, battalion aid station, and hospital settings.
Support synchronized and correlated physical and virtual simulations	Procedures performed on the manikin were simultaneously observed on the VP. Physiological changes were observed on the patient monitor and in lab reports in response to each interventions and in response to the passage of time. In turn, physiological changes produced corresponding and correlated changes in both the manikin and VP.
Support the ability to stop the simulation and return to the patient at a new treatment facility and a new time	The simulation could be paused and restarted. In addition, the ability to revisit and treat the same patient on the next day was demonstrated.
Simulate actual medical equipment	A detailed simulation of the Propaq patient monitor was demonstrated, including temperature, blood pressure, respiration rate, heart rate, oxygenation, ECG, and capnography.
Demonstrate integration of modules from multiple vendors with minimal impact to existing systems	The demonstration showed the integration of 15 peripheral modules from multiple vendors, including COTS lung, leg, and olfactory simulators that required minimal or no modifications.
Demonstrate integration of open source physiology engine	The demonstration included over 25 injuries and interventions that were modeled using the BioGears open source physiology engine

## LESSONS LEARNED / RECOMMENDATIONS

Over the course of integration and test of the system, several issues were identified and addressed. Although some modules, such as the Propaq patient monitor, required data updates at the 90 frames per second rate of the BioGears Engine, others could not handle this rate and would opt to only retain the latest value. The inadvertent consequence of this approach however, is that some lower frequency but critical messages such as medical intervention actions might get lost. In order to address this, two message types were implemented: high frequency messages, such as physiology data, for which each new message overwrote previous messages, and low frequency messages, such as medical interventions, for which a history of all messages since the last message was retained.

Some needed improvements were also defined for the BioGears Engine. In particular, the Beta 5.0.0 version did not provide a method for serializing and storing patient state such that the state could be retrieved to continue treatment of the same patient at a later time. This required reinitializing BioGears with new conditions, a process that required 2 to 3 minutes. The BioGears team is now developing a capability to save and restore patient state.

## FUTURE PLANS

Based on the results of the prototype, the team has identified several requirements to be addressed in the near future:

- The data model should be expanded and formalized.
- The future version of BioGears, with ability to serialize, store, and restore patient state, should be integrated.
- Interoperability specifications should be refined and published.
- Methods for simulating multiple patient scenarios, and integrating these into larger exercises such as Joint Enroute Care, should be developed.

## **ACKNOWLEDGEMENTS**

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