Simulated Clinical Environments and Virtual System-of-Systems Engineering for Health Care

Frank Boosman
Lockheed Martin GTL
Cary, NC
frank.boosman@lmco.com

Dr. Robert J. Szczerba
Lockheed Martin CE&T
Owego, NY
robert.j.szczerba@lmco.com

ABSTRACT

Our global security environment is increasingly affected by biological systems. From the threats of pandemics and bioterrorism to the exploding cost of health care, developing the means to effectively and affordably solve problems related to biological systems is critical to our quality of life. When considering health care costs, the numbers are staggering. Approximately half of the $2.4 trillion spent annually on US health care can be categorized as preventable costs, and $300 billion of this is attributable to medical mistakes and the defensive medicine they engender. Just as the use of flight simulators and system integration concepts revolutionized the aircraft industry decades earlier, similar concepts can be applied to improve the effectiveness and efficiency of the health care industry today. Our approach is intended to leverage advanced modeling and simulation techniques to accurately represent complex clinical environments. By creating hierarchical simulated models of these systems and then validating these models against their real-world equivalents, we are able to develop a virtual system-of-systems integration laboratory for clinical environments. As with comparable tools in aviation, our goal is for simulation-based tools for health care to make analysis and training fast, safe, measureable, and reproducible. This will be a significant step forward in health care, which has trailed other fields in the adoption of software simulations, due to technological limitations and behavioral barriers. We believe that a holistic approach such as this will pave the way for the next generation of decision support aids, medical devices, and training systems for applications across the health care spectrum. In this paper, we outline our approach with detailed examples of potential savings for a number of complex clinical scenarios.

ABOUT THE AUTHORS

Frank Boosman is a Program Management Director in Lockheed Martin's Global Training & Logistics (GTL) division, where he leads GTL's efforts to improve the efficiency and effectiveness of health care via simulation-based system-of-systems engineering and analytics. He joined Lockheed Martin when they acquired 3Dsolve, a simulation training firm for which he served as COO. He served in a variety of VP-level roles for Be Incorporated, a vendor of software platforms for Internet appliances. He was a co-founder of Red Storm Entertainment, where he served as VP of Product Development and where he co-created *Tom Clancy's Rainbow Six*, the first realistic first-person tactical combat game. He has also served as VP and General Manager of Virtus Studios, which he designed *Tom Clancy SSN*, the first 3D submarine simulation game, and as Senior Product Marketing Manager at Adobe Systems, where he was a founding team member and the original product manager of *Adobe Acrobat*.

Dr. Robert J. Szczerba is a Senior Fellow with Lockheed Martin in the Corporate Engineering and Technology (CE&T) organization. His current responsibilities include leading the Corporation's strategic initiatives in the Systems Biology and Healthcare domains. He has 20 years' experience in assessing, developing, and adapting emerging technologies and accelerating their transition into practice. Dr. Szczerba has more than 100 publications and 40 patents / patents pending in a variety of emerging technology areas including systems biology, health care, autonomous systems, unmanned vehicles, and applied artificial intelligence. He has served as principal investigator and project manager on collaborative research and development programs between government, academia, and industry. Dr. Szczerba received BS and MS degrees in electrical and computer engineering and a PhD in computer science, all from the University of Notre Dame.

Simulated Clinical Environments and Virtual System-of-Systems Engineering for Health Care

Frank Boosman
Lockheed Martin GTL
Cary, NC
frank.boosman@lmco.com

Dr. Robert J. Szczerba
Lockheed Martin CE&T
Owego, NY
robert.j.szczerba@lmco.com

BACKGROUND

Current US health care spending is estimated to be $2.4 trillion per year and rising. As a percentage of GDP, the US spends 45 percent more on health care than the next highest-spending country, France, and spends 80 percent more than the average Organisation for Economic Co-operation and Development (OECD) nation (Organisation for Economic Co-operation and Development, 2009):

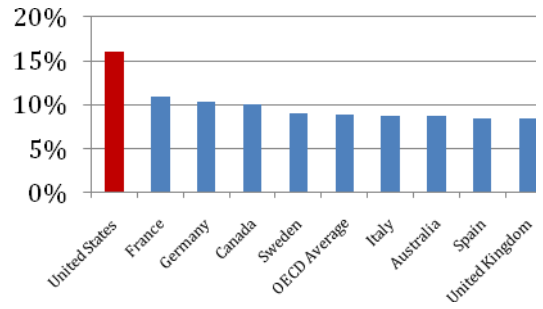

Figure 1. Health Care Expenditures as a Share of GDP, Selected OECD Nations, 2007

Yet despite this spending, the US lags well behind other Western nations in many quantifiable measures of health outcomes. Among 23 countries in a 2006 survey by the Commonwealth Fund, the US was tied for last in "healthy life expectancy at age 60". A 2008 report by the same organization noted that the rate of death due to "curable illness" among persons under the age of 75 was nearly twice as high in the US as in the best-performing countries studied: France, Japan, and Spain (Reid, 2009). The US was last among 19 nations surveyed in "mortality amenable to health care" in 2002-2003 (Nolte & McKee, 2008):

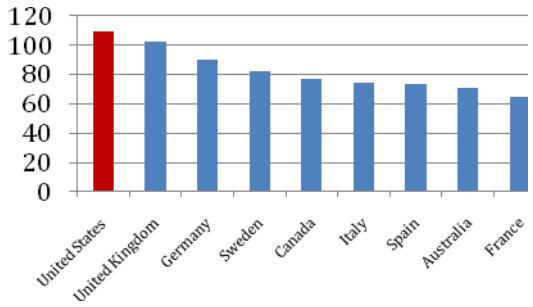

Figure 2. Mortality Amenable to Health Care in Age-Standardized Deaths per 100,000 Residents, Selected OECD Nations, 2002-03

Not only is the US behind other industrialized nations in many measures of health care, it is falling further behind. US health care performance, to quote one study, "is poor at any given moment but also is improving much more slowly than that of other countries over time" (Murray & Frenk, 2010).

It can no longer be considered controversial to observe that the US does not derive the value it could or should from its health care spending.

Clinical Waste

The leading reason for this contradiction between expenditures and outcomes is almost certainly the amount of unnecessary and unproductive health care spending in which we engage. PricewaterhouseCoopers estimates total waste, fraud, and abuse in the US health care system at $1.2 trillion, or approximately half of all spending (PricewaterhouseCoopers Health Research Institute, 2008). Various proposals exist to reduce this wasteful spending. Our interest is in creating and deploying advanced technologies to make health care delivery both less expensive and more effective.

Of the $1.2 trillion spent on waste in the US health care system every year, approximately $300 billion is wasted in the US on medical mistakes and the behaviors they drive, such as defensive medicine

(PricewaterhouseCoopers Health Research Institute, 2008). We believe that medical mistakes and defensive medicine are amenable to reduction via simulation-based system-of-systems engineering and integration.

Medical Errors

The estimates of annual deaths due to medical errors in the US range from 44,000 (Kohn, Corrigan, & Donaldson, 2000) to 191,000 (HealthGrades, 2004). If broken out along with diseases, accidents, and other events as a cause of death, medical errors would rank somewhere between third and tenth in causes of death each year (Centers for Disease Control, 2009):

Table 1. Leading Causes of Death, 2006

Cause	Deaths
Heart disease	631,936
Cancer	559,888
Medical errors (high estimate)	191,000
Stroke (cerebrovascular disease)	137,119
Chronic lower respiratory diseases	124,583
Accidents (unintentional injuries)	121,599
Diabetes	72,449
Alzheimer's disease	72,432
Influenza and Pneumonia	56,326
Nephritis, nephrotic syndrome, and nephrosis	45,344
Medical errors (low estimate)	44,000

ICU Errors

To illustrate the problems of clinical waste generally and medical errors more specifically, we focus on one specific area: intensive care units (ICUs). ICUs pose particular problems in terms of medical mistakes because a) so many procedures are performed on each patient, b) many of the procedures performed are profoundly invasive, and c) by definition, ICU patients are in precarious states of health, requiring active support simply to remain alive.

Central line infections in ICUs are indicative of the problems we face. In the US, ICUs put 5,000,000 central lines into patients each year. 4 percent of these lines are infected within 10 days of insertion. 80,000 people suffer line infections in the US each year, and these infections are fatal in 5 to 28 percent of cases, depending on how sick the patients were prior to infection. On average, line infection survivors spend an additional week in intensive care (Gawande, 2009).

The cost of these and other ICU errors is tremendous. One study estimates the annual cost of ICU errors at $853,000 per unit. With approximately 6,000 ICUs in the US, this puts the cost of such errors at somewhere around $5.1 billion per year (Kaushal, Bates, Franz, Soukop, & Rothschild, 2007). But the actual cost is actually far greater than this. In ICUs, defensive medicine accounts for $27 billion in annual spending (Centers for Medicaid and Medicare Services, 2009). Put another way, if we could wave a magic wand and make ICU errors go away along with the defensive medicine they engender, we could reduce our annual national health care expenditures by over $32 billion, or about 1.3 percent of total spending for one unit in the typical hospital.

The ICU represents one clinical area out of many in the typical hospital. There are other clinical care areas equally in need of dramatic improvements in their efficiency and outcomes—for example, operating rooms (ORs). In the US, we have over 150,000 deaths per year following surgery, with research showing that at least half of these deaths are avoidable (Gawande, 2009). It does not take long to find equally striking statistics for virtually any aspect of modern medical care.

CRITICAL ISSUES IN HEALTH CARE

In the authors' experience, when asked about the most critical issues facing health care today, industry leaders—whether clinicians or administrators, in integrated care or fee-for-service systems, in public or private service—respond similarly. They all point to the need to improve the safety and efficiency of clinical care in an environment of rapidly growing demand for medical services and relentless pressure to reduce costs.

Financial Challenges

In general, US hospitals run with very low levels of profit. In 2008, the median profit margin of a US hospital was zero, and more than half of hospitals studied were losing money. Even successful hospitals operate on profit margins of only 3-4 percent (Fox, 2009). This leaves very little room for errors of any kind.

Never Events

US hospitals have recently begun to focus attention on the so-called "never events," the 28 events that should

never happen within a clinical care environment. One health care organization suggests that hospitals commit to four actions upon a never event: 1) apologize to the patient; 2) report the event; 3) perform a root cause analysis; and 4) waive costs directly related to the event (The Leapfrog Group, 2008). The waiver of costs—which is moving from a recommendation to a mandate—means that errors are more expensive than ever for health care organizations.

Non-Deterministic Systems

Formally, a non-deterministic system is one in which the output cannot be predicted due to multiple possible outcomes for each input. In the context of clinical technology, non-deterministic systems are systems-of-systems in which the complexity of individual devices multiplied by the complexity of their interconnections results in an environment in which the behavior of individual devices can no longer be predicted.

A 2009 interagency government report (High Confidence Software and Systems Coordinating Group, Networking and Information Technology Research and Development Program, 2009) found that "today's medical device architectures are typically proprietary, not interoperable," that "clinicians must monitor [multiple] devices independently, synthesize data, and act on their observations," and that "ad hoc efforts to aggregate data across devices designed to operate separately can lead to unintended or accidental results."

COMPLEXITY, CRITICALITY, AND INTEROPERABILITY

Clinical care—especially in environments such as ICUs, emergency departments (EDs), operating rooms (ORs), and other high-acuity care areas of hospitals—has grown incredibly complex. As one clinician said to the authors, "We have reached a point of complexity in clinical care where we are dependent upon teamwork, prayer, and over-resourcing certain functions." It is not clear that continued increases in such complexity are sustainable in terms of clinical process management.

We have reached this point of complexity because of the nature of technology adoption in clinical care, which tends to be incremental and accretive. In aviation terms, it is as if one set out to build a fifth-generation fighter (such as an F-35) by taking a fourth-generation fighter (such as an F-16) and replacing parts one by one, without regard to interoperability or pilot efficiency, but simply on the basis of whether any given part would be more capable than its predecessor. Such an approach a) would not result in fifth-generation capabilities, and b) would result in an aircraft that was extremely difficult to operate, even for experienced pilots.

The reasons for this approach to technology adoption include culture (this is how it has always been done), safety (misuse or malfunction of a medical device leading to death is a never event), and technology (sufficiently robust simulations suitable for prototype development and testing have not existed).

Complexity and Criticality

In the clinical environment, especially in high-acuity care environments such as ICUs and ORs, the issues of complexity and criticality are tightly linked, making traditional approaches to systems improvement difficult.

Table 2. Complexity and Criticality in the Clinical Environment

	Complexity	**Criticality**
Source or Nature of the Issue	Use of ad hoc, incremental, accretive, proprietary, non-interoperable systems	Failure in care especially high-acuity care, can lead to injury, disability, or death
Effect on Engineering and Integration	Traditional systems processes are incomplete at best, inaccurate at worst	Traditional experimentation processes are difficult at best, impossible at worst

In other words, the particular combination of complexity and criticality in the clinical environment makes traditional approaches to systems engineering and systems integration incomplete (or even inaccurate) and difficult (or even impossible). This is a problem that must be addressed if we are to make significant gains in the efficiency and effectiveness of clinical care.

As the interagency government report referenced earlier concluded, "manufacturers will need access to open, formally composable [verification and validation] technology that relies on computational models unifying cyber and physical systems to help establish sufficient evidence [for the reliability of clinical systems]" (High Confidence Software and Systems Coordinating Group, Networking and Information Technology Research and Development Program, 2009).

The Integrated Clinical Environment

Efforts are underway to improve the interoperability of clinical systems, notably the Integrated Clinical Environment (ICE), which is now an ASTM standard. ICE specifies a clinical environment in which all medical devices are capable of being interconnected in a "plug-and-play configuration that would enable health care to be better managed and patient data to be better shared" (Quigley, 2009). In an ICE-style clinical setting, medical equipment could react to changing patient conditions or device problems by adapting, compensating, or sounding a "smart alarm."

To fully implement ICE and related standards will require software tools that enable manufacturers, regulators, and users to design and test devices and processes in a fast, safe, measurable, and reproducible manner—the "computational models unifying cyber and physical systems" described above. Such simulations do not exist today. When medical professionals use the word "simulation," they most often are referring to hardware-based simulators, especially mannequins, designed for the teaching of clinical care techniques.

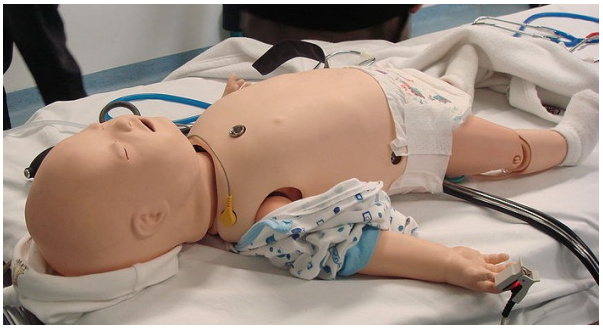

Figure 3. A Typical Medical Mannequin

Software-based simulations of clinical processes are much less common than mannequins and related hardware-based tools. Where such software-based simulations do exist, they tend to be relatively primitive, reinventing software "wheels" over and over again.

APPROACHES TO REDUCING HEALTH CARE EXPENDITURES

The available evidence indicates that improving the efficiency and effectiveness of health care via technological interventions is the fastest, most socially acceptable path to reducing health care expenditures.

Table 3. Approaches to Reducing Health Care Expenditures

	Faster Impact	Delayed Impact
More Desirable	Efficiency & Effectiveness	Prevention
Less Desirable	Rationing	Irrelevancy

Prevention efforts, including investments in education and other public health initiatives, have been shown to sometimes be effective in terms of saving money (Cohen, Neumann, & Weinstein, 2008), though only in a minority of cases. Prevention efforts also tend to be popular with citizens: in a 2009 survey, 71 percent of Americans favored increased investment in prevention, and 44 percent strongly favored such investment (Greenberg Quinlan Rosner Research, 2009). However, even when cost-effective, prevention efforts often take many years to bear results.

Increased rationing (or priority setting) of expenditures is widely seen in the health care community as necessary to the fair and effective allocation of limited health care resources (Sabik & Lie, 2008). However, it is highly unpopular among other stakeholders, including politicians and voters (Singer, 2009).

This leaves improvements in efficiency and effectiveness as the one path to reducing health care expenditures that is a) capable of operating on a near-term time scale and b) is widely acceptable to stakeholders. In fact, the authors' belief is that a health care system perceived as more efficient and more effective by its users would actually be more popular than its predecessors.

SYSTEM-OF-SYSTEMS ENGINEERING IN HEALTH CARE

Systems-of-Systems

The discipline known as systems engineering has evolved over the last few decades. Many years ago, development of a new capability was relatively simple to orchestrate. The design and development of parts, engineering calculations, assembly, and testing was conducted by a small number of people. Those days are long gone. Teams of people, sometimes numbering in the thousands, are involved in the development of systems; and what was previously only a development

practice has evolved to become a science and engineering discipline. Today, engineers and developers have codified processes and techniques for building large, complex systems, and when executed properly, such processes and techniques result in reliable and useful systems that serve users well. The challenges of today involve connecting systems, some of which are themselves complex systems, together into systems-of-systems (SoS) configurations (Saunders, et al., 2005). An SoS approach represents "a collection of task-oriented or dedicated systems that pool their resources and capabilities together to obtain a new, more complex 'meta-system' that offers more functionality and performance than simply the sum of the constituent systems" (Wikipedia contributors, 2010). Examples of systems-of-systems in everyday life that include the Internet (based on the TCP/IP protocol), household electrical appliances (using a common plug), and freight transport using common packaging standards (Saunders, et al., 2005).

Significant experience in aviation and other industries has demonstrated that a true SoS approach can dramatically improve both the efficiency and effectiveness of highly complex systems. This includes both improvements to legacy systems as well as the design and development of new systems from scratch.

For the domain of clinical care, the problem is both critical as well as highly complex. The nature of the environment involves the interactions of numerous heterogeneous, non-deterministic systems, in which the failure of any one of them can easily lead to injury, disability or even death. Historically, the complex, critical nature of clinical care has been a severe impediment to traditional systems integration and system of systems engineering process. The complexity-driven non-determinism of existing systems processes has rendered traditional approaches in this area incomplete at best and inaccurate at worse. Similarly, the criticality of the environment renders traditional experimentation processes difficult at best and impossible at worst. A new, more holistic approach is needed to the address the problem.

Simulation-Based Solutions

Due to the complexity and criticality of the clinical environment, the need exists to develop a suite of tools that allows clinicians to work directly with engineers to rapidly explore and evaluate potential solutions to the industry's most critical problems. Simulation technologies offer a powerful mechanism by which complex Simulation offers environments can be modeled and experiments run within them. However, in the domain world of health care, the simulation models can quickly become quite complex. To address these issues, a multiscale approach to the modeling and simulation of the clinical environment is required. Multiscale model-based design enables the creation of context-specific models at varying levels of fidelity. In such an approach, each model can be modified or replaced by another model to improve the fidelity of the overall system. Where possible, each model can be replaced by a real system to refine and validate the simulation model. The approach allows a tighter integration between real-world systems and their simulation counterparts (Figure 4).

MODELS AND VIRTUAL WORLDS

For simulation purposes, we define clinical care systems as multiscale models consisting of:

1. *Devices*, usually electronic in nature, often computer-based and running complex software programs.
2. *Processes* used by clinicians in treatment, both formal and informal, and both individual and team-

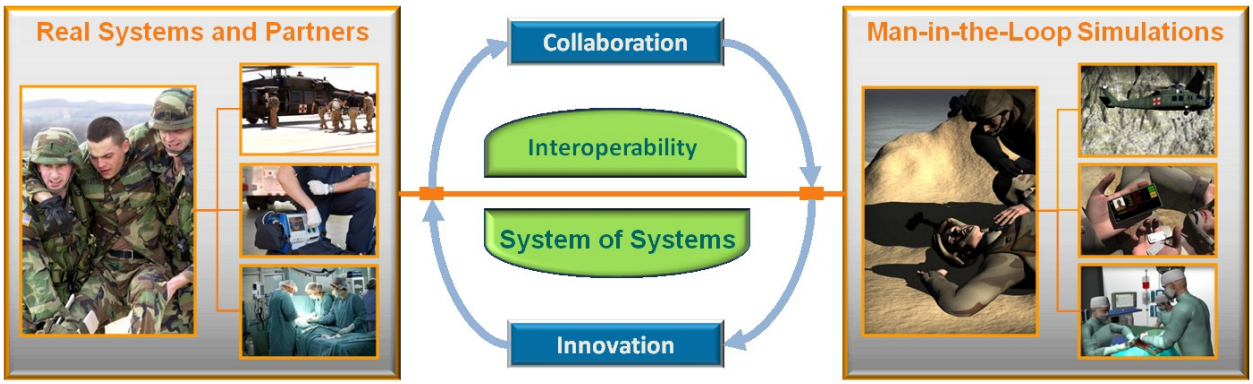

Figure 4. Integrating the Real and Simulated Worlds

based.

3. *Patients*, specifically, their physiology and its responses to medical interventions as well as their psychology and its response to both internal and external physical stimuli and interactions with clinicians.
4. *Clinicians*, primarily their psychology, including process following, clinical mistakes, and responses to interactions with patients as well as fellow clinicians.
5. *Settings*, or the surroundings in which clinical care takes place.

As we develop these models, we will continuously validate them. The typical validation process consists of comparing models to their real-world equivalents, quantifying the differences, and adjusting the models as necessary. This will be true of our project as well. Uniquely, however, and due to our multiscale approach, we will be able to further validate our models by replacing virtual components—typically, but not always, medical devices—with real-world counterparts that we connect to our simulation. We can then test the behavior and results of our simulations in conjunction with actual devices, but in a virtual setting.

As we develop and validate progressively more robust and useful models, we will then use them to prototype systemic improvements using our simulation as a virtual system-of-systems integration laboratory. With point-of-care systems fully modeled and validated, we will have a virtual laboratory for the fast, safe, measureable, and reproducible prototyping of improved and new devices and processes. Our simulation system is designed to enable clinicians to work alongside clinical engineers and specialists in systems integration and decision support. Working together in our simulation system, these teams will be able to quickly modify existing devices and processes for improved performance, as well to create wholly new devices and processes.

Benefits of Simulation

By using advanced simulation techniques to model health care systems, we can investigate inefficient and ineffective clinical practices and create virtual prototypes to test improvements to them, all within a virtual environment that exhibits four key inherent attributes:

1. *Speed*. Exploration, experimentation, and clinical trials can all be conducted far faster in a virtual world than in the real world. This is especially true when the questions being asked are amenable to offline, batch mode, non-man-in-the-loop simulations, which can be run in the thousands, generating data ready for statistical analysis.
2. *Safety*. A virtual environment is by definition a perfectly safe environment. In a flight simulator, after the worst possible accident, the pilot still gets up and walks out. In our simulated health care environment, no patient will ever be at risk.
3. *Measurability*. In a virtual environment, everything that happens (which may or may not be displayed), is generated via software (with or without human input), and so everything can be measured to whatever level of accuracy and detail is desired.
4. *Reproducibility*. As with measurability, since every action in a virtual environment is generated via software, every action can be reproduced precisely. A run of 10,000 iterations of a given experiment could optionally include the generation of all data necessary to perfectly reproduce any single run at any time after the experiment, as long as the data is retained.

Virtual Worlds for Clinical Simulation

When used in man-in-the-loop mode, an accurate portrayal of the the simulated clinical environment is important to enabling users to easily navigate and perform necessary tasks in the simulated world. Even when used in an offline, batch mode, non-man-in-the-loop context, visualizing the results of the simulation is important both for users and for the decision-makers looking to them for input.

For these reasons, we believe that a high-fidelity, three-dimensional, virtual world-style representation of the clinical environment is critical to our project.

Figure 5. An Overhead View of a Simulated ICU

Our virtual world-style environment is designed to be both technically accurate and visually appealing, while at the same time be suitable for rendering at acceptable speeds (30 Hz or greater) on typical desktop computer configurations.

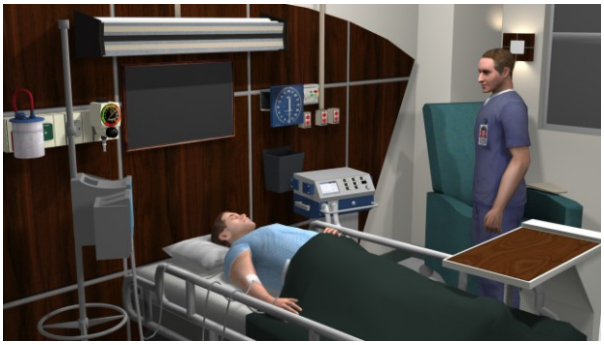

Figure 6. A Simulated ICU Room

As computer hardware and graphics rendering software continue to improve, we believe that it will be possible to achieve progressively higher levels of fidelity in these simulated environments. Within a decade or less, we may take for granted the ability to perform simulated clinical tasks in virtual environments that rival today's film-quality computer graphics in visual quality.

PROJECT DEVELOPMENT

The project described in this paper is proceeding in phases using a spiral development approach loosely derived from the ADDIE (analysis, design, development, implementation, and evaluation). Although ADDIE is primarily used in the development of training tools, we have found it useful in the current project. Using a variant of ADDIE has helped to keep the team focused on clinical care as it is currently practiced and the software tools most likely to lead to its improvement.

To date, we have undertaken the following phases in the project:

1. *Analysis*. The background provided in this paper summarizes our efforts to date to understand the clinical care space and the possibility for applying simulation-based SoS techniques to improving it.
2. *Design*. We have completed the design for the first and second prototype versions of our software tools. Because the problem space of "efficiency and effectiveness in clinical care" is so large, we have paid particular attention to bounding the design, focusing our efforts on critical issues within the larger problem space. Our first two prototype versions are focused on problems specific to high-acuity clinical environments.
3. *Development*. We are currently engaged in software development efforts for our first prototype and expect to have completed the initial spirals of both the first and second prototypes by the time this paper is published.

Industry Cooperation

It is the authors' opinion that the scope of simulating clinical care at a high level of fidelity is so large that it is beyond the capabilities of any single organization, no matter how large, to design and develop a solution on its own.

If, as we suspect, health care is approximately 40 years behind aviation in its use of software-based simulations, this is with good cause. Health care is enormously more complex than aviation and other domains with pervasive use of simulation. The root cause of this difference in complexity is biology, which is dramatically more complex than physics. Simply put, living things are many orders of magnitude more complex than inanimate objects. This biological complexity drives the complexity of health care, which in turn drives the complexity of health care simulations. We can and do abstract this complexity, and multiscale models will be vital to this abstraction process. That said, it will be years before we as an industry have a deep understanding of which areas of health care can (and should) be safely abstracted while preserving the overall fidelity of the simulation.

With the above in mind, we welcome inquiries from organizations—commercial, governmental, and academic—that might wish to cooperate in this endeavor. Only by combining the wide-ranging expertise and capabilities of a diverse group of people and organizations will we be able to fully realize our goal of simulating clinical care at a level of fidelity sufficient to improve its efficiency and effectiveness.

CONCLUSIONS

Simulation-based system-of-systems engineering and integration is an important path forward to improving the efficiency and effectiveness of clinical care. Using simulated virtual environments, we can bring the techniques we take for granted in other industries—notably aviation—to not only design new clinical systems but to improve existing systems. These new and improved systems will be simpler to understand and operate and yet more capable than their current equivalents.

It is apparent that many of the integration challenges facing the health care industry today are quite similar to

the problems faced by the aviation industry 30 years before. If, for a moment, we think of a hospital as an F-35 aircraft, then our objective would be to create man-in-the-loop models that represent how the hospital's team executes their clinical mission. Once we have developed and validated these models, we can then experiment to determine which system integration, data visualization, and procedural modifications can be used to improve efficiency and eliminate unfavorable outcomes.

By combining a system-of-systems integration approach with multiscale simulation frameworks, we now have the ability to essentially develop the equivalents of flight simulators, systems integration laboratories, and intelligent cockpits for clinical environments. Man-in-the-loop simulation and virtual world-based modeling techniques are the critical components for deriving the key cost and performance metrics. The end result is a system that enables clinical subject matter experts to explore some of the most difficult problems of their domain, and to intelligently ask and answer the question, "What if...?"

REFERENCES

Centers for Disease Control. (2009, December 31). *FASTSTATS: Leading Causes of Death*. Retrieved June 11, 2010, from CDC.gov: http://www.cdc.gov/nchs/fastats/lcod.htm

Centers for Medicaid and Medicare Services. (2009). *2007 National Heatlh Care Expenditures Data.* Office of the Actuary, National Health Statistics Group.

Cohen, J. T., Neumann, P. J., & Weinstein, M. C. (2008). Does Preventive Care Save Money? Health Economics and the Presidential Candidates. *The New England Journal of Medicine , 358*, 661-663.

Fox, M. (2009, March 2). *U.S. Hospital Profits Fall to Zero: Thomson Reuters.* Retrieved June 23, 2010, from Reuters.com: http://www.reuters.com/article/idUSTRE5216G320090302

Gawande, A. (2009). *The Checklist Manifesto: How to Get Things Right.* New York, New York: Metropolitan Books.

Greenberg Quinlan Rosner Research. (2009, November 10). *American Public Supports Investment in Prevention as Part of Health Care Reform.* Retrieved June 23, 2010, from Trust for America's Health: http://healthyamericans.org/assets/files/TFAH-RWJFPreventionSurveyII.pdf

HealthGrades. (2004). *Patient Safety in American Hospitals.* Golden, Colorado: HealthGrades.

High Confidence Software and Systems Coordinating Group, Networking and Information Technology Research and Development Program. (2009). *High-Confidence Medical Devices: Cyber-Physical Systems for 21st Century Health Care.* Arlington, Virginia: National Coordination Office, NITRD.

Kaushal, R., Bates, D. W., Franz, C. S., Soukop, J. R., & Rothschild, J. M. (2007). Costs of Adverse Events in Intensive Care Units. *Critical Care Medicine , 35* (11), 2479-83.

Kohn, L. T., Corrigan, J. M., & Donaldson, M. S. (2000). *To Err Is Human: Building a Safer Heatlh System.* Institute of Medicine, Committee on Quality of Health Care in America. Washington, DC: National Academy Press.

Murray, C. J., & Frenk, J. (2010). Ranking 37th-Measuring the Performance of the U.S. Health Care System. *The New England Journal of Medicine , 362* (2), 98-99.

Nolte, E., & McKee, C. M. (2008). Measuring the Health of Nations: Updating an Earlier Analysis. *Health Affairs , 27* (1), 58-71.

Organisation for Economic Co-operation and Development. (2009). *OECD Health Data 2009.* Paris, France.

PricewaterhouseCoopers Health Research Institute. (2008). *The Price of Excess: Identifying Waste in Healthcare Spending.* New York, New York.

Quigley, P. (2009, September/October). F2761 and the Integrated Clinical Environment. *ASTMl International Standardization News* .

Reid, T. R. (2009). *The Healing of America: A Global Quest for Better, Cheaper, and Fairer Health Care.* New York, New York: The Penguin Press.

Sabik, L. M., & Lie, R. K. (2008). Priority Setting in Health Care: Lessons from the Experience of Eight Countries. *International Journal for Equity in Health , 7* (4).

Saunders, T., Croom, C., Austin, W., Brock, J., Crawford, N., Endsley, M., et al. (2005). *System-of-Systems Engineering for Air Force Capability Development.* Washington, DC: United States Air Force Scientific Advisory Board.

Singer, P. (2009, July 15). Why We Must Ration Health Care. *The New York Times* .

The Leapfrog Group. (2008, March 27). *Fact Sheet: Never Events.* Retrieved June 23, 2010, from Leapfrog Group.org: http://leapfroggroup.org/media/file/Leapfrog-Never_Events_Fact_Sheet.pdf

Wikipedia contributors. (2010, April 9). *System of Systems*. Retrieved June 11, 2010, from Wikipedia, The Free Encyclopedia: http://en.wikipedia.org/wiki/System_of_systems