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The newsletter of the Massachusetts Institute of Technology
System Design & Management program

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MIT Space Hotel

Image Courtesy of MIT MARINA Project Team

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sdmpulse

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On the cover: The fully developed MARINA station would feature an eight-room space hotel.

Cover image courtesy of MIT MARINA Project Team

MITsdm

Welcome

As the spring 2018 edition of the *SDM Pulse* goes to press, all of us at MIT System Design & Management (SDM) are hard at work organizing a groundbreaking new conference. The SDM Symposium 2018: Characterizing the Gap, the first international symposium on systems research to address the strategy-implementation gap, will take place on campus at MIT on April 30 and May 1, 2018. We hope to see many of our regular readers there. For more information, see page 25.

The goal of the conference is to promote research into how systems thinking and methods can be used to solve real-world challenges. In this issue of the Pulse, we highlight several examples of this kind of work, including cases in which members of SDM's extended community applied system thinking to:

- develop a plan for commercializing spaceflight via a space hotel;
- address the cybersecurity risks facing healthcare;
- jumpstart systems engineering within an organization; and
- optimize the use of resources within the US Department of Defense.

This issue also contains news on upcoming activities, including SDM's hugely popular webinar series and its upcoming tech trek to the San Francisco Bay Area.

As always, we hope you enjoy this edition of the *Pulse*, and we welcome your feedback and suggestions.

Sincerely,

Joan S. Rubin
Executive Director and Senior Lecturer
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About the Author

SDM alumnus **George Lordos** is a doctoral student in MIT's Department of Aeronautics and Astronautics, where he is researching future architectures for accelerated industrial development on Mars and other worlds beyond Earth. Lordos also has an MBA from the MIT Sloan School of Management and a BA in economics from the University of Oxford.

Systems Thinking Underpins Space Hotel for NASA

The challenge: Last spring, an interdisciplinary team of MIT students responded to a challenge from the National Aeronautics and Space Administration (NASA) to design a commercially enabled habitable module for use in low Earth orbit and potentially for NASA's Journey to Mars program.

NASA's motivation stems from its need to reduce the operating costs of the International Space Station (ISS), which absorbs nearly $4 billion per year, or 19 percent of NASA's budget. Funds released could pay for crew and cargo transportation services to low Earth orbit and for NASA's Space Launch System vehicle and Orion spacecraft operations, which are intended for deep space exploration.

Given that NASA has already tried and failed to place the ISS in private hands, our team used the systems thinking approach taught at MIT System Design & Management (SDM) to address a fundamental question: Is it even possible to shift human spaceflight to a commercial basis?

The history: From the Apollo era up to the retirement of the space shuttle in 2011, the US economic model for human spaceflight featured NASA as prime contractor, the space industry as subcontractors, and the taxpayer as the ultimate customer. Without market discipline, costs soared.

Since the retirement of the shuttle, NASA has been using fixed-price contracts to resupply the ISS. This new model, in which NASA is a customer instead of a contractor, triggered new investment and technological progress in the space industry, significantly reducing ISS resupply costs for NASA—down from approximately $272,000 to $89,000 per kilogram of cargo delivered to the ISS.[1]

However, far higher operating costs are baked into the design of the ISS system, and these cannot be reduced without compromising safety. Since the ISS is scheduled to be decommissioned sometime between 2024 and 2028, NASA launched its challenge to find a new, more affordable successor to the ISS to support further technology development for human spaceflight.

Meeting NASA's challenge to design a commercially enabled habitable module is complicated by the interplay among the technical, managerial, and socio-political aspects that characterize all large, complex, long-lived projects.

- **Technically**, the challenge was to design and build a system that would be reliable and affordable in development and in operation.

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[1] Zapata, Edgar, An Assessment of Cost Improvements in the NASA COTS/CRS Program and Implications for Future NASA Missions, AIAA Space 2017.

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- **Managerially**, the question was how to identify markets and business models that would produce a sufficient return to attract private investors.
- **Socio-politically**, any proposal had to account for a wide range of interests, including old space companies, new space companies, NASA and its international counterparts, Congress, and potential investors.

The approach: From the outset, we felt that a viable business solution would drive the technical solution, and not vice versa. Thus, using the system architecting principles taught at SDM, we reformulated NASA's request from "design a commercially enabled habitable **module**" to the more sociotechnical and strategic charge to "design a viable **business** involving humans in space."

After brainstorming options, it became clear that one of the most attractive opportunities would be a modular space station with a hotel as its anchor tenant.

For this space station to survive as a business, we reasoned that all its rent- and fee-paying tenants should also be viable businesses. We therefore asked: What profitable businesses can be carried out in a space station where the major activity is space tourism? And, what can we do as engineers and system designers to enable these tenants to operate synergistically and add value to each other?

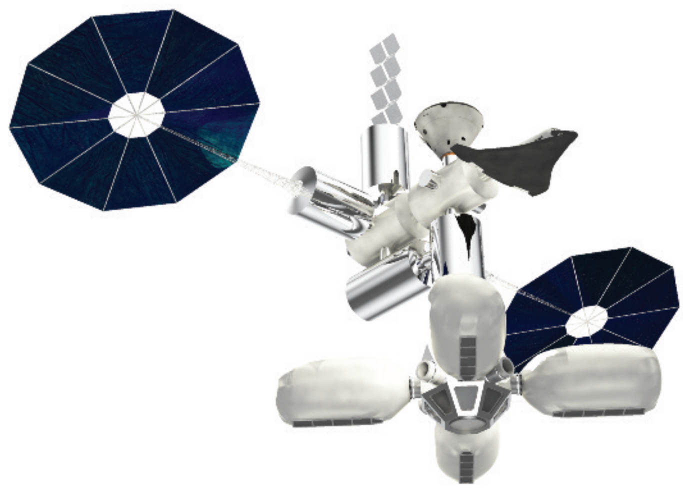

Figure 1.The initial, minimal configuration of the MARINA space station features a four-room, Earth-facing space hotel (below, connected at the two fore nadir docking ports), as well as node modules, habitable modules, and docking ports for use by NASA and other rent-paying customers. MARINA is designed to be easily scalable as demand for commercial activities materializes.

Image courtesy of the MARINA team

The tools: A fundamental principle of the SDM program is that large, complex projects are best studied, architected, and managed as *sociotechnical* systems. Thus our team concluded early on that the best way to meet NASA's requirement for a commercially enabled habitable module was to expand the system boundary using SDM's sociotechnical system-of-systems perspective. Our idea was for NASA to offer a contract to rent space on a private space station for 10 years, stimulating the interest of private investors to pursue a "commercially enabled" business model to build and operate a space station. This offer would provide incentive for a private investor to develop the sought-after "habitable module," without NASA paying for its development.

In the business model we created using the expanded system boundary shown in Figure 2, the orbital space tourism product and in-space manufacturing (e.g., of flawless fiber optic cable) would be the main sources of cash flow, paying for most

For more information about flawless fiber optic cable, visit

spacenews.com/industry-sees-new-opportunities-for-space-manufacturing/

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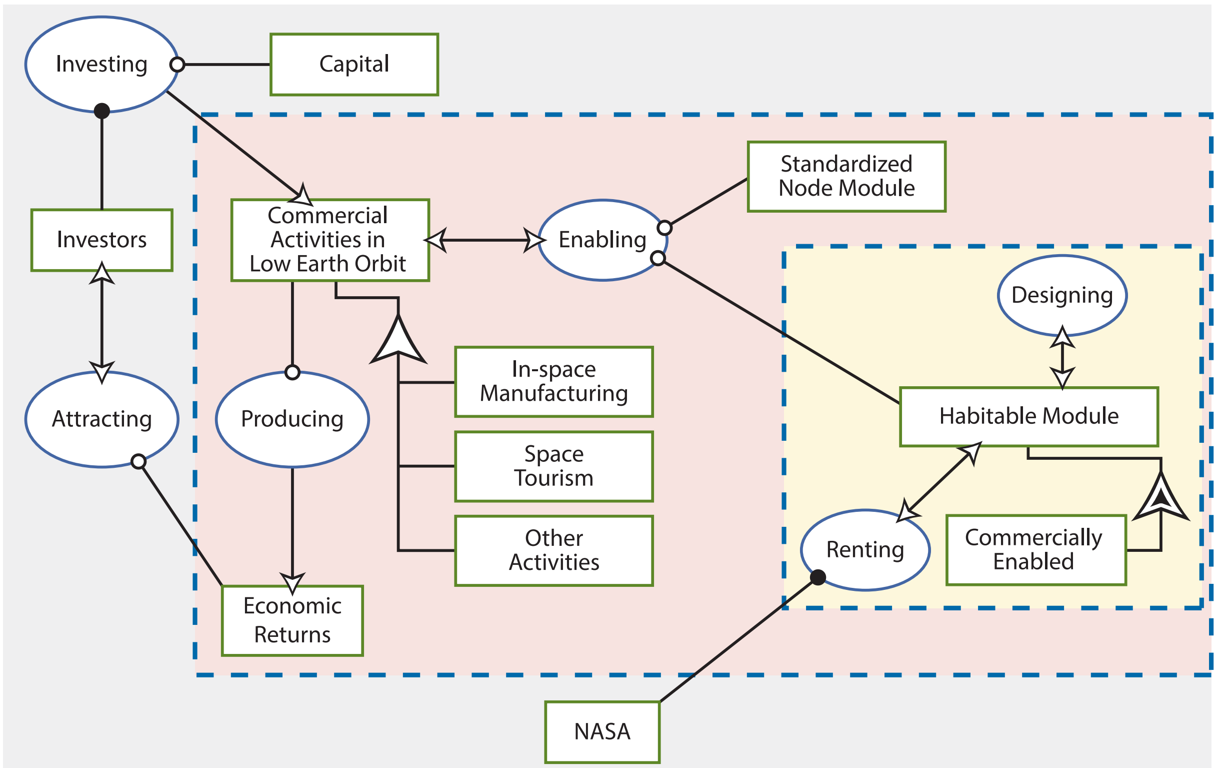

Figure 2. This object-process diagram shows the narrow system boundary implied by NASA's original request to design a commercially enabled habitable module (in yellow) and the MARINA team's expanded sociotechnical system boundary (orange).

Image courtesy of George Lordos

of the development and operating costs. Additional cash inflows would come from leasing docking ports and rack space on the standardized node modules. Our design features standardized interfaces to enable customers to trade among themselves for essential products and services such as clean air, water, waste handling, power, and two-way data links with Earth. We called this concept MARINA, which stands for Managed, Reconfigurable, In-space Nodal Assembly.

Other SDM and systems thinking principles and methods used were:

- **Creative analogs**. This tool guided our architecting. We considered such analogs as malls—which have anchor tenants that draw crowds and other tenants, and marinas—which offer safety, social interaction, and fully serviced berths, attracting yacht-owners to pay dock fees instead of dropping anchor in a natural cove.
- **Aligning the technical and economic planes of decomposition using standardized interfaces**. This technique enabled us to align the decomposition of the form of station subsystems with the decomposition of their potential economic operators, enabling allocation of essential functions to independent private entities and resulting in the emergence of the first market in space.

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- **Targeting the emergence of beneficial network effects**. We sought to maximize the benefits of interactions, such as having station tenants buy and sell products and services among themselves. We expect the resulting competition to produce lower costs and technological innovation.
- **Designing with lifecycle properties in mind**. Since network effects would have to be sustained over the life of the station, we paid special attention to the lifecycle properties (-ilities), particularly modularity and standardization of interfaces. Modularity provides managerial and market flexibility to respond optimally to future developments, including changes in demand or the emergence of new technologies.

Results: Using a method taught by Professor Richard de Neufville in his course Real Options for Product and Systems Design, which is favored by many SDM fellows, we were able to generate a probability distribution of the expected net present value (NPV) of our system architecture using a Monte Carlo model that embraces uncertainty and agency.

The first step was to model the development and operations costs of the entire business plan. The resulting ensemble of models shown in Figure 3 incorporated all structural relationships, uncertain parameters as well as sub-models of "if…then" decision rules by rational agents, based on rules and their virtual "observations" of other endogenously generated variables. Every run of the model ensemble simulates 25 years into the future and

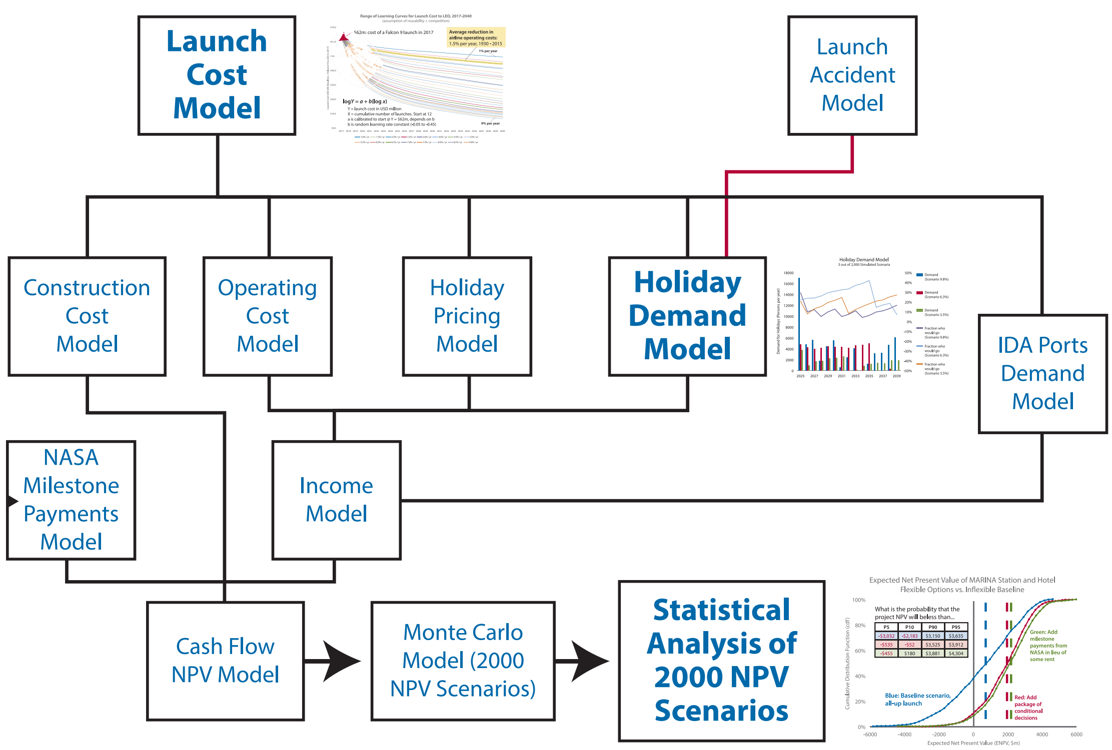

Figure 3. An ensemble of interconnected models was used to model the commercial viability of the business plan. The models included structural relationships, uncertain parameters, and decisions by rational agents based on rules and observations of variables. Every run produces a single net present value (NPV). Thousands of runs with new samples produce a distribution of NPVs.

produces a single NPV. Thousands of runs with new samples for all uncertain variables and new simulated decisions by our rational agents produce a distribution of expected NPV.

Even with a conservative 20 percent discount rate, which is appropriate for high-risk projects such as this one, we found that the managerial flexibility to make follow-on investment and business decisions led to a better than 90 percent probability that the MARINA business model would be a positive NPV project. This result is shown in Figure 4.

For NASA, the development of MARINA using private funds would result in a tenfold reduction in its low Earth orbit human spaceflight operating costs, from about $4 billion to about $400 million per year.

If MARINA can be developed privately, it would greatly accelerate human activity in space. More people, including ordinary citizens, could visit space in the first two years than in the past six decades combined. This would generate learning, reduce costs, and accelerate the development of space technology, including launch, entry descent, and landing and life support systems. MARINA would support the continued dynamism of the private US space industry and would help NASA afford technologies that are essential for humanity's journey to Mars.

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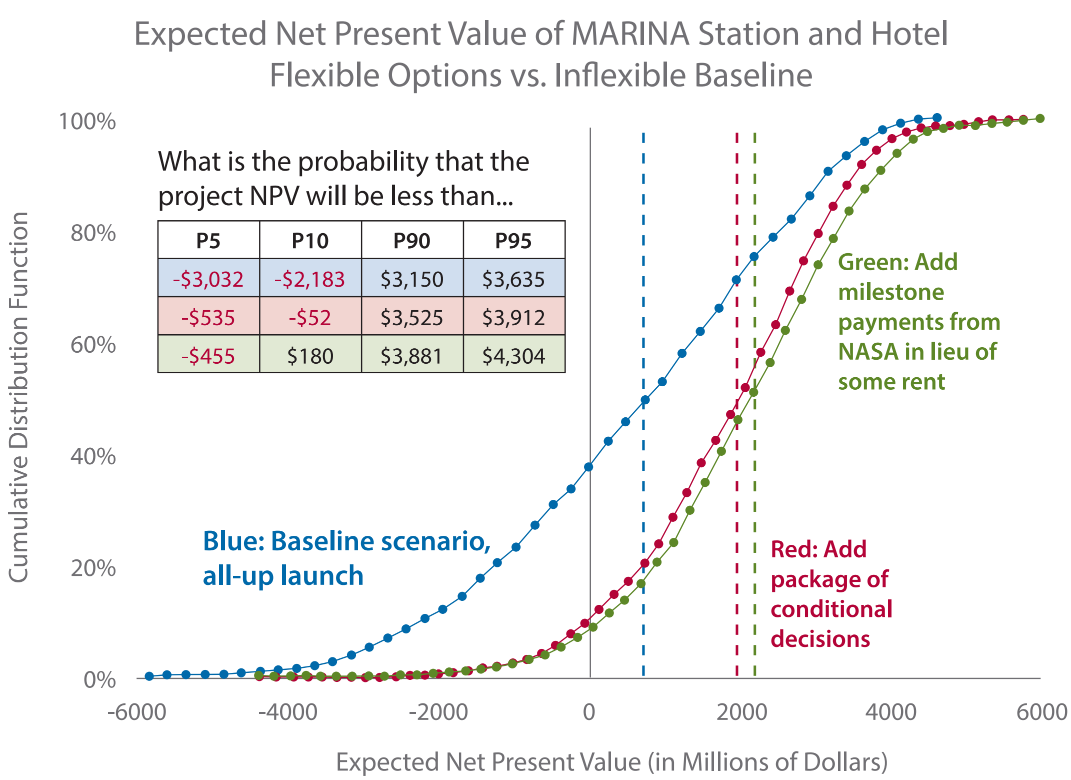

Figure 4. By incorporating flexibility into the system design, using the methods taught by MIT Professor Richard de Neufville, the MARINA team found that MARINA had a better than 90 percent probability of being a positive net present value project.

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Next steps: For NASA, the next step would be to invite proposals from the private space industry to undertake the financing and construction of a privately owned and operated space station, with the understanding that NASA would be a temporary anchor tenant for a period of 10 years for a set amount of rent. For private industry, in-depth modeling, design work, and market research would be necessary to establish the potential of operating in space and to decide how to respond to the opportunity created by NASA's request for proposals. Once NASA selects a developer for the MARINA space station, and the developer selects a partner for the luxury space hotel, funding from private capital markets would enable the project to be realized.

Editor's note: MIT's MARINA received the first-place award in the graduate division of the NASA-sponsored Revolutionary Aerospace System Concepts-Academic Linkage (RASC-AL) Forum held at Cocoa Beach in June 2017. The team was led by Matthew Moraguez, graduate student in MIT's Department of Aeronautics and Astronautics, and was advised by Dr. Caitlin Mueller. Other team members were Samuel Wald, Alejandro Trujillo, Johannes Norheim, Valentina Sumini, Meghan Maupin, Mark Tam, and Zoe Lallas. SDM '16 fellow and team member George Lordos was responsible for the system architecture and the economic and business model of MARINA.

Figure 5. The fully developed MARINA station would have five nodes offering 22 International Docking Adapter ports, two of which would be occupied by the eight-room space hotel on the fore nadir (Earth-facing) end of the space station.

Image courtesy of the MARINA team

About the Author

Saurabh Dutta directs the experience design team at Rapid7. He has worked in design and usability domains across physical and virtual products for more than 15 years. He has also published papers and presented at various usability conferences. He has a master's degree in engineering and management from MIT as an alumnus of System Design & Management. He also has an MS in architecture and design from Mississippi State University and a BArch from Birla Institute of Technology, Mesra in India.

See page 28 for a webinar on this topic.

Addressing Healthcare Cybersecurity Risks in the Internet of Things

The challenge: The Internet of Things, that system of web-enabled devices that can talk to one another, has brought people a wealth of benefits, from quick rides via Uber to the ability to remotely control the heat levels in our homes. But are these devices compromising our privacy—or even our safety?

I considered this question within the critical sector of healthcare, with a specific focus on a device known as an artificial pancreas. Designed to automatically monitor and control the level of insulin in patients with diabetes, this device is capable of communicating all of a patient's vital information to a monitoring physician. To do this, it features a wireless sensor that is always on. This convenience comes at the cost of high security risk, however, since it is possible to tamper with the device remotely—a hack that could have serious consequences.

The question I wanted to explore was: Would be possible to equip makers of Internet of Things (IoT) products with an easy way to evaluate design choices for cybersecurity risks? I focused my research on the artificial pancreas system, but I wanted the work to be applicable to the IoT devices used across a full spectrum of domains.

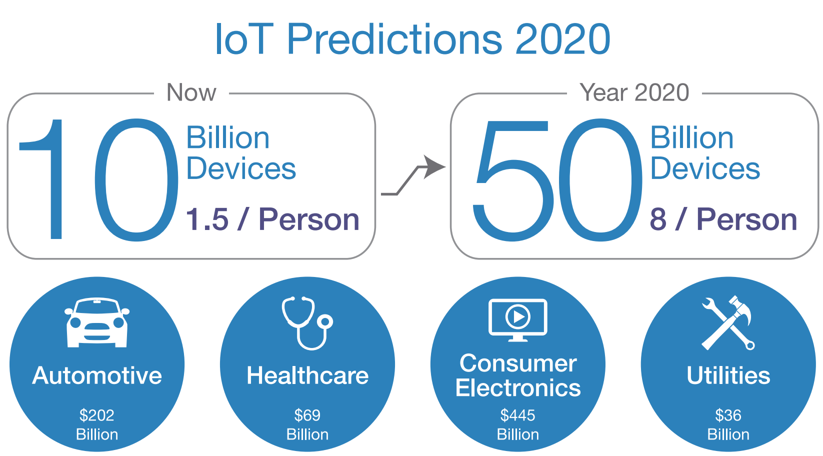

Figure 1. CISCO predicts that by 2020 there will be eight Internet of Things (IoT) devices per person on average across the world. The predicted size of the IoT-related business opportunity is shown for four different industries.

The approach: I began by analyzing the challenges inherent to the usability vs. security paradox that characterizes various systems. I then determined the primary beneficiaries of this study and mapped the product requirements for the artificial pancreas system to 10 usability attributes established by previous studies. Finally, I prioritized a list of IoT security attributes and mapped my artificial pancreas system risk analysis to defined IoT security attributes.

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The tools: I conducted a stakeholder value network (SVN) analysis to determine the system boundaries and understand how a particular IoT security framework might benefit and affect various stakeholders (Figures 2 and 3). For this study. I chose to focus primarily on IoT device makers, but other stakeholders identified during the analysis were kept in mind.

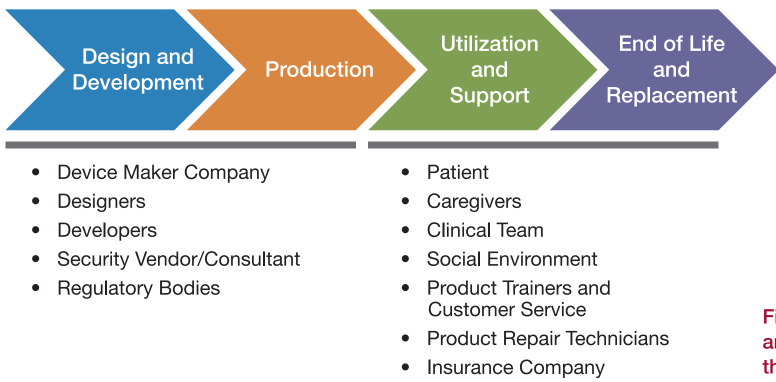

Figure 2. The stakeholders of the artificial pancreas system span the full lifecycle of the product.

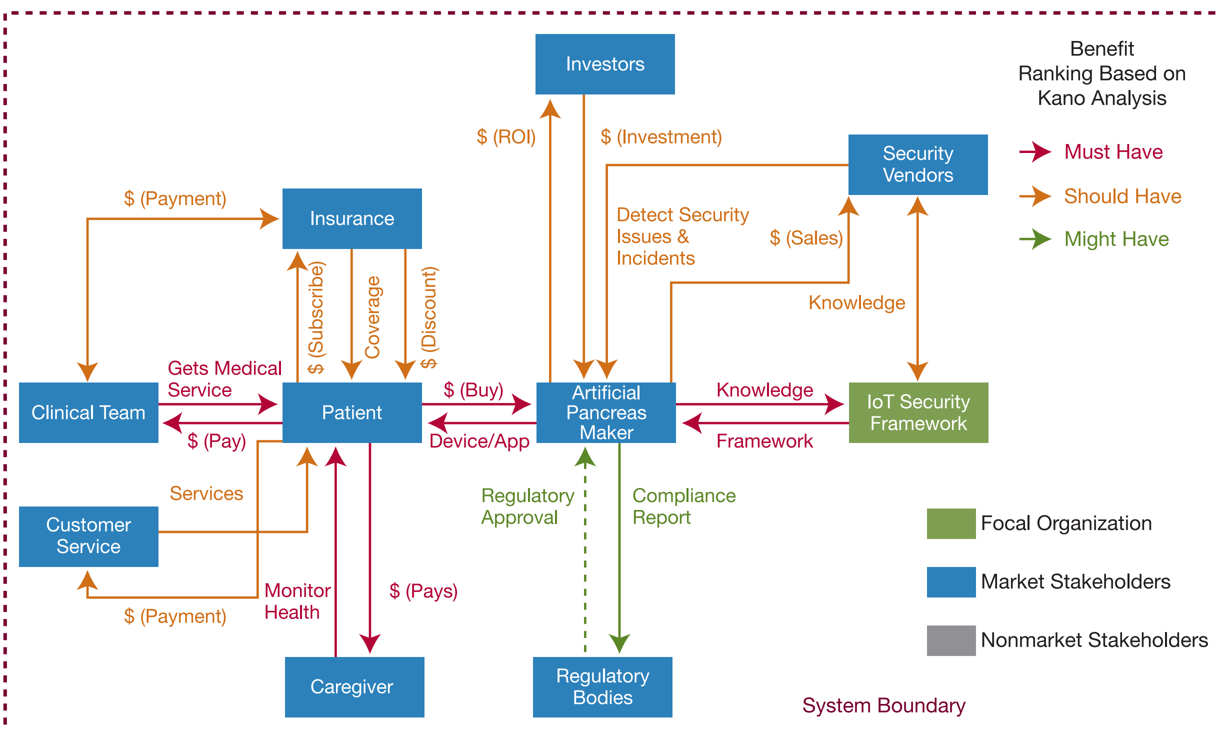

Figure 3. This stakeholder value network analysis of the Internet of Things security framework for an artificial pancreas system shows benefits ranked by 'must have,' 'should have,' and 'might have.'

The goal of the IoT device maker is to ship new features and make the product commercially successful.

However, this person needs to understand the security implications of features before implementation. Therefore, what was needed was an IoT framework that could make developers aware of potential security issues and better protect companies from releasing products that introduce unanticipated risks to customers.

Such a framework could be used to compare designs considering both functionality and security. Ideally, the framework would make it easier to evaluate the risk/reward tradeoffs of a new feature. To accomplish this goal, I mapped the product requirements for the artificial pancreas system to 10 usability attributes established by an existing framework called the Quality in Use Integrated Map. These attributes are:

- efficiency,
- effectiveness,
- productivity,
- satisfaction,
- learnability,
- safety,
- trustfulness,
- accessibility,
- universality, and
- usefulness.

Using SVN analysis and the data collected in 16 interviews with security experts, I next created a prioritized list of product requirements for the proposed artificial pancreas system (Table 1).

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Functional Usability Features	Stakeholder Priorities					Average Priority 1-5, 5 Being Highest	QUIM Most Relevant Attribute
	Patients	Doctors	Caregivers	Customer Service	Sum		
Easy-to-carry device	2	7	6	9	24	2	Efficiency Accessibility
Operate remotely	4	1	2	1	8	5	Productivity Efficiency
Easy interface	3	3	1	5	12	5	Satisfaction Efficiency
Long-lasting on single charge, peace of mind	5	4	7	2	18	4	Safety Trustfulness
Instant notification	8	8	3	6	25	2	Safety Usefulness
Extra drug storage	7	2	4	8	21	3	Productivity Safety
Discreet operation	1	6	5	7	19	4	Satisfaction
Easy access to logs and trends	10	9	10	3	32	1	Learnability Universality
Similar to previous pump design	9	10	9	10	38	1	Learnability
Waterproof	6	5	8	4	23	3	Trustfulness Effectiveness

Table 1. This table shows the top functional usability features required for an artificial pancreas system mapped to the most relevant usability attributes identified by the Quality in Use Integrated Map.

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I also analyzed IoT security risks generally and the specific risks for the artificial pancreas system example. This system contains IoT sensors, communication and storage solutions, processing, and related interfaces. As in all IoT devices, security can affect the confidentiality, integrity, or availability of a system. This analysis enabled me to come up with the following attributes, listed in order of priority.

1. **Physical security**. When referring to IoT systems, physical security is all about making sure people, property, the surrounding environment, and the device itself are not harmed by accident or attack.
2. **Remote control**. Wireless networking systems such as Wi-Fi and Bluetooth are widely used in IoT devices. Improper encryption can lead to data leaks or enable the wrong people to access the device remotely.
3. **Maintenance**. It is critical for IoT devices to allow for regular maintenance, including patches and upgrades.
4. **Authentication**. Authentication involves the mutual verification of peers before they share route information. This ensures shared data origin is accurate.
5. **Authorization**. Access policies are needed that explicitly assign certain permissions to subjects.
6. **Input validation**. Input validation can be used to detect unauthorized input before it is processed by the application.
7. **Cleaning**. This involves sanitization and data validation, tasks conducted to ensure that a program operates on clean, correct, and useful data.
8. **Transport security**. Devices can be “tricked” into sending data to unintended, unauthorized endpoints. All applications must therefore be written to make use of encrypted communication between devices and between devices and the Internet.
9. **Sensitive data**. If a device stores and transmits personally identifiable information or collects passwords or any similar data that can be misused, it is dealing with sensitive data.
10. **Data storage**. Storing data securely involves preventing unauthorized people from accessing it as well as preventing accidental or intentional destruction, infection, or corruption of information.
11. **Encryption**. No data should be stored in clear text. Standard encryption practices should be used to prevent unauthorized access.
12. **Auditing**. IoT environments need to know when their services are accessed, who is making the service request, and when the request occurs.
13. **Error investigation**. In case of an attack or accident, error investigation is crucial to preventing further damage and any recurrence.
14. **Logging**. Keeping a log of data is critical not only for troubleshooting and maintenance, but also to prevent feature abuse and system compromise.
15. **Transparency**. While it may not be practical to use a completely open-source model for every feature and application, software should be reviewable by an independent auditor.

The results: I created an easy-to-use application that enables designers to test the usability-security attribute tradeoffs for the artificial pancreas system and other IoT devices. I accomplished this by organizing the prioritized security attributes into a set of 10 questions. Each question carries equal weight, with every “Yes” scoring a positive point and each “No” a negative point on the proposed “system security scale.” Table 2 shows the scale’s questions and framework.

The application uses the answers to the questions in Table 2 to provide designers with detailed guidance.

System Security Question	Risk Area(s)	Improvement Recommendation	Security Attributes
1. Is it impossible for the feature to affect the health and safety of people or property?	Availability	Provide safety guarantees for failure conditions	Physical security
2. Does the feature require a local, physical interface to access it?	Availability	Lock down all control and data input interfaces	Remote control
3. Can authorized users or devices patch or update the feature in the future?	Integrity	Build and maintain a patch / update service	Maintenance
4. Can only authenticated, authorized users or devices access the feature?	Availability Confidentiality	Construct and enforce authentication and authorization policies	Authentication Authorization
5. Is all received data automatically inspected and validated?	Availability Integrity	Validate all input	Cleaning Input validation
6. Are data transmissions encrypted and mutually authenticated?	Confidentiality Integrity	Use secure transport techniques	Transport security
7. Does the feature avoid storing personally identifying information, tokens, or passwords?	Confidentiality Integrity	Be deliberate and careful with secure storage of credentials	Sensitive data
8. Is any stored data only accessible after authentication by an authorized user or device?	Availability Confidentiality	Consider encrypting data at rest	Data storage Encryption Authorization
9. Does the feature routinely log use and errors in a way that authorized users can inspect the logs?	Integrity	Store log data securely	Auditing Error investigation
10. Is the source code available for inspection by a third party?	Integrity	Adopt open-source principles (where appropriate) and accepted vulnerability disclosure practices	Transparency

Table 2. This framework shows how a series of prioritized questions can be used to test the usability-security attribute tradeoffs for Internet of Things devices. Each question carries equal weight, with every 'Yes' scoring a positive point and each 'No" a negative point on the proposed "system security scale."

Next steps: IoT vendors can use the proposed application to test designs for security resilience and follow some simple guidelines to avoid introducing unanticipated risk to their products. Future work will focus on combining the security and usability scores into a unified metric that can help end consumers make informed decisions about buying products. For example, a security usability score might appear on IoT devices the way nutrition labels appear on food. The application might also one day help governing bodies regulate IoT devices based on minimum standards of security and usability.

Note: Saurabh Dutta's SDM thesis was supervised by Stuart Madnick, the John Norris Maguire professor of information technologies at the MIT Sloan School of Management and a professor of engineering systems at the MIT School of Engineering.

About the Author

Ben Levitt is a consultant at Technology Strategy Partners. He has 15 years of systems engineering experience, including working at Raytheon as a technical product manager, system engineering lead, product test lead, and systems algorithm engineer. He holds an SM in engineering and management from MIT as a graduate of System Design & Management. He also has a BS in industrial engineering from Lehigh University.

See page 28 for a webinar on this topic.

Establishing a Company's Systems Engineering Organization

The challenge: New technologies, big data, and the demand for customization have made system integration increasingly difficult. While firms occasionally foresee this integration dilemma, too often it takes a massive failure to spur an investment in systems engineering and an attendant reduction in complexity.

The fundamental question for companies that wish to get ahead of this issue is, "How do I start a systems engineering organization?"

The common rationales for investing in systems engineering differ slightly by industry, but generally fall into four categories:

- **Past failed projects**. This is the most common reason firms pursue systems engineering. Examples include fatal automotive accidents, aerospace disasters, and unstable mobile phones.
- **Integration of new technologies**. Complexity rises as companies incorporate machine learning technologies, roll out Internet of Things (IoT) sensors, and adopt new software platforms.
- **Risk mitigation**. Systems engineering uses a checks-and-balances approach that helps businesses identify costly defects earlier in a product's lifecycle.
- **Managing multiple configurations**. As product-platform strategies spread across industries, firms are turning to systems engineering, particularly in architecture, to manage the increasing complexity.

The approach: Historically, systems engineering has been most successfully employed in organizations such as the National Aeronautics and Space Administration (NASA) and the Department of Defense, which provide organizational guidance for robust multi-year projects (e.g., space shuttles, airplanes, and naval ships). Unfortunately, commercial businesses facing time-to-market pressures are typically on their own.

To explore the question of how firms can build system engineering organizations, I conducted a wide-ranging benchmarking study that examined two key aspects of systems engineering: the capabilities of systems engineering leaders and successful delivery methods for systems engineering.

The results: I found seven best practices that delivered competitive advantage for leading systems engineering organizations. These are shown in Figure 1 and listed below.

1. **Corporate strategy**. Companies that succeed with systems engineering are organized to support overall strategic objectives. These firms use system engineering to gather data that informs new market entry, erect technological barriers to entry by competitors, and reinforce the firm's pricing structure. Industry leaders: Google and General Electric.

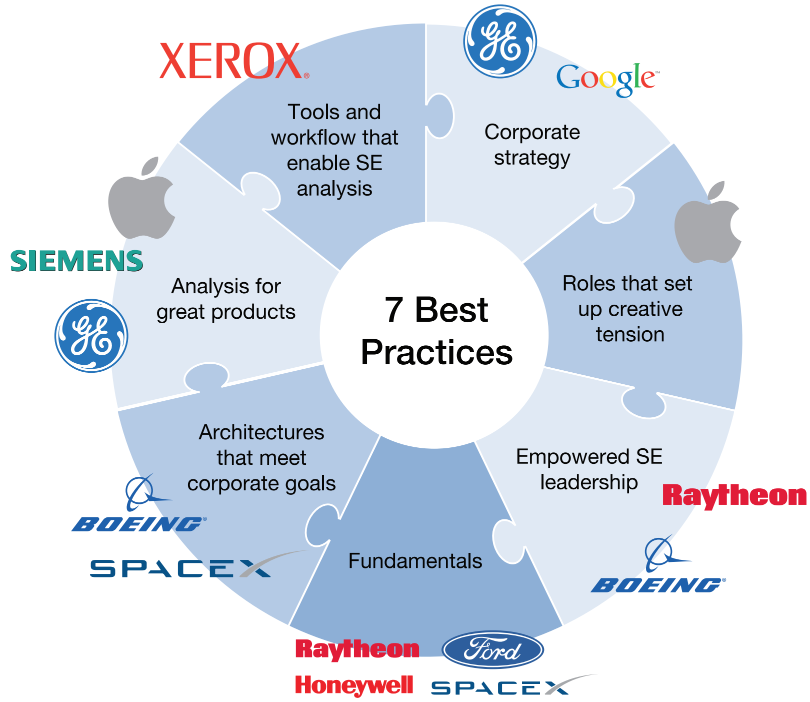

Figure 1: A benchmarking study revealed seven best practices among companies that use systems engineering effectively.

2. **Creative tension**. Great firms construct their systems engineering organizations so that creative tension balances product development efforts with the need for profit and timely marketing. This is often a tradeoff between systems engineering and the profit and loss centers. The creative tension is effective when the organization is comprised of the right systems engineering roles that cultivate a specific talent base. Industry leader: Apple.

3. **Empowered systems engineering leadership**. This advantage is often seen in aerospace and defense firms, which provide systems engineering leaders with both budget and technical control over technology planning and integration. In such cases, systems engineering is integrated into project management, which develops specific targets to measure progress and change propagation throughout the life cycle. Leading firms use systems engineering to capture wisdom from other corporate functions, notably finance, manufacturing, and supply chain. Industry leaders: Raytheon and Boeing.

4. **Systems engineering fundamentals**. Effective use of fundamentals dictates a process for identifying and validating emergent properties—often the most significant challenges for an engineering system. Successful projects often start with top-level requirements and allocate substantial resources to integration, verification, and validation. Some firms focus on need decomposition and verification, while others—SpaceX, for example—specifically focus on iteration, integration, and validation. Industry leaders: Raytheon, Honeywell, Ford, SpaceX.

5. **System architecture**. Architecture serves as a competitive advantage when it meets corporate goals. Successful architects understand the broader context of the system and articulate decisions clearly. Industry leaders: Boeing, SpaceX.

6. **Analysis for great products**. This is the culmination of successful concept development and the pursuit of disruptive innovation. Included in this activity are the identification and management of system trades; system modeling to predict performance and rapidly iterate designs; and advanced methods, such as design of experiments, trade space, hazard analysis, and consolidation. Industry leaders: Apple, Siemens, General Electric.

7. **Tools and workflow that enable strong systems engineering analysis**. It is difficult for systems engineering to be a source of competitive advantage if it is not a daily part of the company's culture. The pursuit of model-based systems engineering for development, verification, and validation have accelerated this area of expertise for some firms. However, it is unwise to focus on this area to the exclusion of more fruitful and difficult changes in organization, roles, and analyses. Industry leader: Xerox.

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In addition to these seven capabilities, I found there are four main types of systems engineering delivery: command and control, system expert groups, system project managers, and service organizations. Figure 2 shows that firms deploy systems engineering differently depending on the level of systems engineering control and the extent of centralization in the organization.

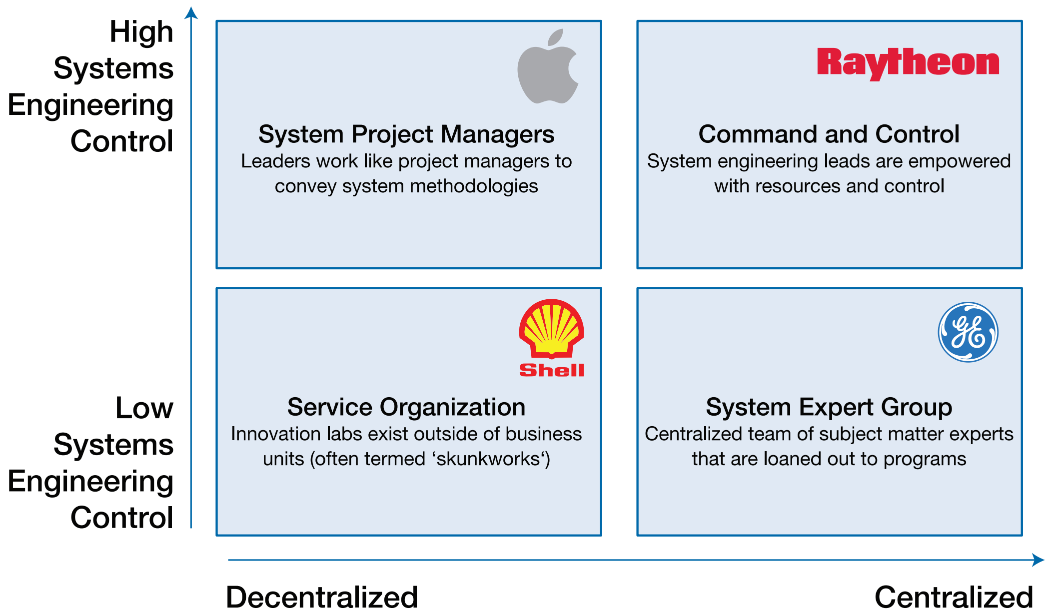

Figure 2: Systems engineering delivery methods vary based on the levels of systems engineering control and centralization in the organization.

1. **Command and control organizations** empower leaders and benefit from strong systems engineering fundamentals and architectures. The leading command-and-control organizations follow NASA's systems model and are prevalent in aerospace, defense, and automotive companies. The organizations make tradeoffs regarding the slower speed to market and lack of innovation outside systems engineering. Industry leader: Raytheon.

2. **System expert groups** are collections of specialists that guide programs at the direction of a central organization, either at an enterprise level or in an engineering system group. These system experts are typically skilled in fundamentals, architecture, and tools, but often lack control of the project. Industry leaders: General Electric.

3. **System project managers** bring the systems view to conventional projects. They act with the control of the project but without a centralized impetus from the organization. Industry leader: Apple.

4. **Service organizations** cultivate innovation in the profit and loss areas of the business. The corporate vision for these firms is often decentralized, with a central entity providing products and services to the business units in a "technology-push" method. Some firms have also used this service approach to inject new technologies into the profit and loss businesses in a "business-pull" manner. Shell's "skunkworks" lab called TechWorks is an example of this model. Firms with service system organizations will typically excel in the analysis, tools, and workflow that enable systems engineering analysis. Industry leader: Shell.

These results indicate that the best way to build a systems engineering organization is to align key capabilities and delivery methods. Figure 3 shows how organizations with a systems knowledge base and a variety of different key capabilities can best implement systems engineering.

Key Capabilities	Delivery Method	Organization Action
Fundamentals Empowered SE leadership	Command and Control	Create a directorate and a power structure that empowers SE leadership
Analysis for great products Roles that set up a creative tension	System Project Managers	Convey system methodologies via project managers
Architectures that meet corporate goals	System Expert Group	Form an organization of experienced system architects who are available to assist the profit and loss programs
Tools and workflow that enable SE analysis	Service Organization	Build an innovation lab outside of business units or Buy a 'skunkworks'
Systems organization that fuels corporate strategic objectives	Essential for all delivery methods	Ensure leadership drives systems to impact strategic objectives

Figure 3: This systems engineering implementation framework reveals how organizations with a variety of capabilities and delivery methods might employ systems thinking to advantage.

Next steps: Building or strengthening a successful systems engineering organization is challenging and requires that companies focus not just on what they produce, but, as importantly, on how they execute internally. As more firms pursue the discipline, systems thinking will spread, enabling an ever-wider range of industries to make their processes more efficient and gain competitive advantage.

For a look at how systems engineering evolved within the US Department of Defense, see page 18.

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A webinar on this topic is available on demand at

sdm.mit.edu/how-to-set-up-a-systems-engineering-organization

http://

About the Author

Austin Page is a major in the US Air Force. He has served as a program manager on various research and development, avionics, electronic warfare, and weapons projects, culminating in his work as deputy program manager for weapons integration in the F-35 program. He is currently a master's degree student in MIT System Design & Management. He has a master's degree in electrical engineering from Wright State University and a bachelor's degree in electrical engineering from the University of Maryland, College Park.

The Evolution of Systems Engineering in the US Department of Defense

The challenge: As the defense budget continues to shrink and the need to innovate continues to grow, the US Department of Defense (DoD) must make better use of its resources. Historically, the DoD has employed systems engineering (SE) to deliver products within cost, schedule, and scope targets. But, the increasing complexity of defense systems makes reaching such targets a constant challenge. The question is, what can the DoD do today to maximize its investment in SE?

The approach: In order to appreciate the DoD's use of SE, it's helpful to understand its origins. According to the International Council on Systems Engineering (INCOSE), the term "systems engineering" stems from the practices employed by Bell Telephone Laboratory in the early 1940s. While the DoD didn't invent SE, it quickly started using the methodology during World War II. After the war, the nonprofit research institution RAND (its formal name was a contraction of Research and Development) was created to connect military planning with research and development decisions. According to RAND, "World War II revealed the importance of technology research and development for success on the battlefield.... Forward-looking individuals in the War Department, the Office of Scientific Research and Development, and industry therefore began to discuss the need for a private organization to connect military planning with research and development decisions."

Over the course of the next several decades, RAND used system-based principles to develop strategic recommendations for aircraft, weapon and ship capabilities, and military basing locations, as well as to determine how to best implement an air defense campaign and how to develop life-cycle cost estimates for budgeting purposes, among other initiatives. While RAND uses a different name for the process, systems analysis (SA), the principles of holistic and system-based planning are very similar in nature to those of SE and have contributed to the body of knowledge we have today. The DoD continued to use these system-based principles to develop missile and missile-defense systems in an effort to stem Cold War aggression from the USSR. While the DoD cannot be credited with inventing SE, it was deeply involved in its evolution and continues to be at the forefront of developing its practices today.

As technology continues to advance, the DoD has evolved from procuring standalone systems to procuring complex and tightly integrated systems of systems. Today, tanks, ships, aircraft, satellites, and ground stations are collecting, processing, and disseminating real-time information to ensure military decision-makers receive the best data as quickly as possible. The interoperability requirements now imposed on project managers have reinforced the need for a disciplined approach to both SE and project management because an ever-increasing number of stakeholders across a wide range of domains must now be served. Figure 1 shows an example of the complex battle space in which the military must currently operate; each system has its own set of stakeholders, timelines, and programmatic risks.

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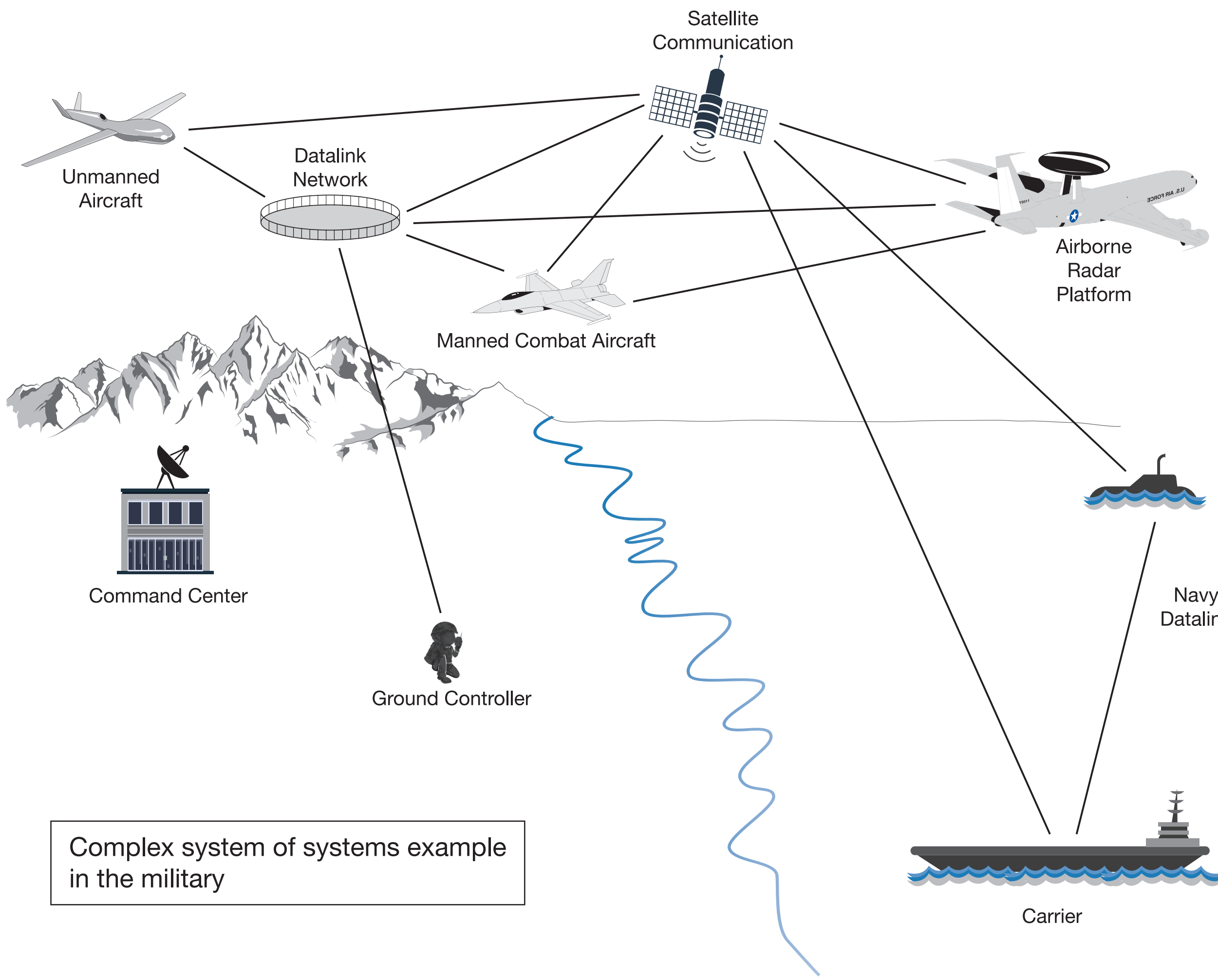

Figure 1. Systems engineering principles are useful in managing military networks such as this one, which links information transmission among US aircraft, partner aircraft, ground stations, and space systems.

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The process: To improve the effective use of SE, the DoD must learn from past experience—both successes and failures.

Over the past 20 years, the DoD has had several successful, high-profile programs. This is largely thanks to adherence to sound SE principles. For example, according to a 2005 RAND study on the Navy's F/A-18 E/F program, "The unparalleled success of the F/A-18 E/F acquisition program emerged from the Engineering and Manufacturing Development (EMD) functions meeting all of the products' performance requirements, on budget, on schedule, and underweight by 400 pounds. All of this was confirmed in Operational Verification testing (the final exam) and described as an unparalleled success, passing with flying colors and receiving the highest possible endorsement."

This same study stated that the F/A-18 E/F program's success can be attributed to many factors, most related to good SE discipline. The report cited many examples of why the program was successful, including:

- "Structuring the contractor team according to prior experience on the F-18 A/B/C/D programs. Specifically, lines of responsibility were clearly defined, with a designated prime contractor ultimately responsible for contract performance."
- "Cost and schedule estimates were relatively accurate and stable."
- "The airframe weight had only minor increases, reflecting a stable design."
- "Using the Navy's evolutionary development approach for the moderately risky avionics technologies, which was funded outside of the Engineering and Manufacturing Development program."

By funding the new avionics outside the main development program, the program manager was able to compartmentalize his risk and undertake a new development project without impacting the rest of the program. If the new avionics failed, he could rely on the existing F-18 C/D avionics as a backup solution. While not all programs are designed in the same way, and risk tolerances vary across systems, understanding the advantages of these approaches can inform future development programs.

Despite increased emphasis on SE, the DoD has also learned important lessons from several significant failures to deliver weapons systems on time, on budget, and with the requisite capabilities.

In the cost domain, these failures can be measured in terms of Nunn-McCurdy breaches (Figure 2). According to the Government Accountability Office, "A Nunn-McCurdy breach occurs when a program's unit cost exceeds certain thresholds. When that happens, DoD must notify Congress of the breach." A significant breach is experienced when a program exceeds 15 percent of its current baseline cost (or 30 percent of its original cost), while a critical breach is when a program exceeds 25 percent of its current baseline cost (or 50 percent of its original cost). As part of the 2009 Weapons System Acquisition Reform Act, any program that experiences a critical breach is terminated unless it is certified by the secretary of defense. Programs that are certified typically undergo a restructuring, a revocation of previous milestone approvals, and require a written explanation as to the root cause of the cost growth.

Here are two recent and high-profile examples of Nunn-McCurdy breaches:

- **The F-35 Lightning II Program in 2010**. This program saw significant cost growth in the per-unit price of the aircraft, causing it to exceed the 2002 baseline by more than 57 percent. One of the root causes was the discovery of a significant weight and design issue in the first prototype. If proper SE principles of risk management had been in place, this technical deficiency could have been caught before significant rework was required.

- **The Global Positioning System Next-Generation Operational Control System in 2016**. "Air Force Secretary Deborah Lee James declared the breach on June 30 [2016] after quarterly reviews showed inadequate systems engineering at program inception, Block 0 software with high defect rates, and Block 1 designs requiring rework." From 2012 to the time of the breach, program cost estimates rose 22 percent from $3.4 billion to $4.2 billion.

In both cases, lack of proper SE played a central role in the cost overruns.

The process and tools: Organizational changes have been made at the DoD to emphasize the importance of SE. To help manage increased complexity within DoD programs, the Office of the Deputy Assistant of Defense for Systems Engineering, ODASD(SE), was chartered in 2011 as "the point of contact for policy, practice, and procedural matters relating to DoD System Engineering and its key elements including technical risk management, software engineering, manufacturing and production, quality, standardization, and related disciplines." This office provides continued workforce development and ensures security across platforms and proper technical risk management. Additionally, it has ownership of the Systems Engineering Plan (SEP),

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Number of Nunn-McCurdy Breaches Since Calendar Year 2007

Calendar Year	Critical Breach	Significant Breach
2007	1	4
2008	3	1
2009	7	1
2010	4	4
2011	4	-
2012	1	-
2013	2	2
2014	1	1
2015	1	-
Total	**24**	**13**

Figure 2. This chart shows the number of critical and significant Nunn-McCurdy breaches in the Department of Defense between 2007 and 2015. Such breaches reveal failures that could be addressed through systems engineering.

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a document required by all major defense acquisition programs that gives the project manager a framework for identifying the important SE components to execute a program. The SEP template addresses:

- system architecture and interface control;
- risk and opportunity management;
- technical schedule and schedule risk assessment;
- technical performance metrics and key performance indicators;
- stakeholder management;
- configuration and change management;
- technical reviews and their associated entrance and exit criteria;
- engineering tools; and
- many other topics.

While templates and documentation are important in instilling SE discipline across an organization, it is equally important to ensure that their intent is carried out by the project team.

To accomplish this, ODASD(SE) oversees education, training, and competency screening. The office reviews the content of classes offered by the DoD's source for project management and SE training, Defense Acquisition University, and staff members serve as subject matter experts in updating core competencies and the experiential requirements necessary to successfully execute core SE activities across the DoD. By establishing this office, the DoD is making a concerted effort to acquire, train, and retain the best SE talent possible.

Instilling sound systems engineering principles across a large enterprise requires both structural and cultural change. In addition to the organizational change mentioned above, the DoD established an initiative called Better Buying Power (BBP) in 2010. The intent of this initiative is to improve acquisition efficiency in the face of declining defense budgets. Architected by the former assistant secretary of defense for acquisition, technology, and logistics, this initiative consists of 23 principles aimed at increasing DoD efficiency and productivity. BBP has been revised twice since then, with BBP 3.0 expanding to focus on 36 goals in eight core areas:

- achieve affordable programs;
- achieve dominant capabilities and controlled lifecycle cost;
- incentivize industry and government productivity;
- incentivize industry and government innovation;
- eliminate unproductive bureaucracy and processes;
- promote effective competition;
- improve tradecraft in services acquisition; and
- improve professionalism of total acquisition workforce.

Several of these core areas are dependent on the development and execution of SE principles, specifically: controlling lifecycle cost, spurring and incentivizing innovation, removing unproductive processes, and improving the tradecraft and professionalism of the workforce.

Results: According to the 2016 Annual Report on the Performance of the Defense Acquisition System, "The Department of Defense (DoD) is making continuing progress in improving acquisition. The overall series [of reports] presents strong evidence that the DoD has moved—and is moving—in the right direction with regard to the cost, schedule, and quality of the products we deliver. There is, of course, much more that can be done to improve defense acquisition, but with the 5-year moving average of cost growth on our largest and highest-risk programs at a 30-year low, it is hard to argue that we are not moving in the right direction."

Specifically, from 2011 to 2015, the growth of contracted costs for major development acquisition programs (MDAP) shrunk from 9 percent to 3.5 percent, its lowest growth in 30 years. Additionally, it was mentioned in the discussion above that Nunn-McCurdy breaches are an indicator of cost growth that could be attributed to poor systems engineering discipline. In the years since BBP was implemented, these breaches have significantly declined. Figure 3 shows the decreasing trend in the percentage of breaches vs. the overall number of MDAP programs.

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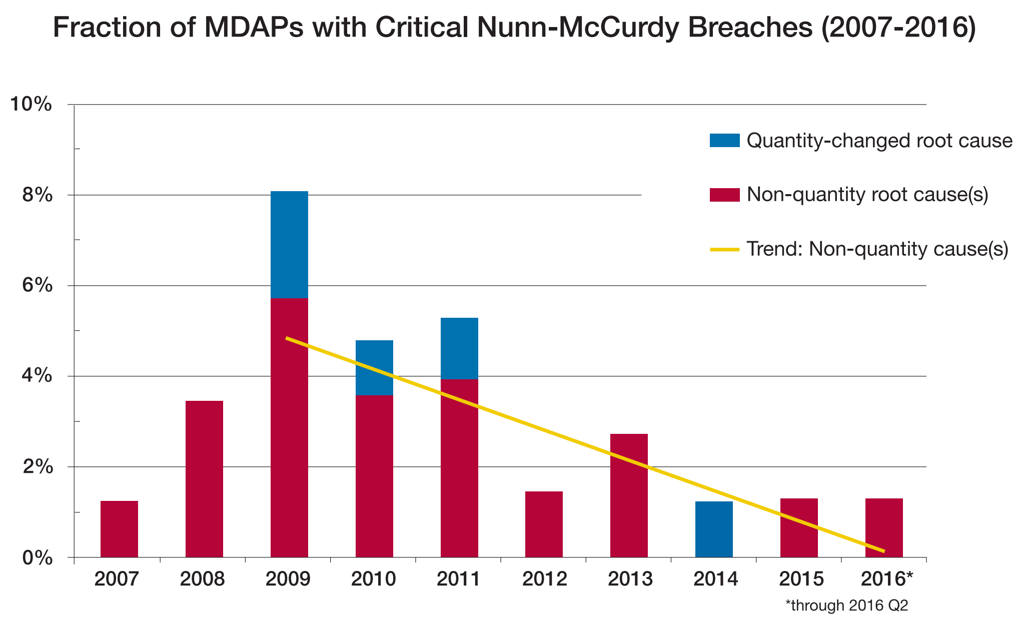

Figure 3. The Department of Defense (DoD) has seen a decrease in Nunn-McCurdy breaches since its Better Buying Power effort was initiated in 2011.This DoD chart shows the downward trend in breaches attributed to quantity changes.

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While cost growth seems to be moving in the right direction, schedule growth metrics show mixed performance in the report. The outcome of the metrics is largely based on the data that's included (completed vs. active programs, etc.). In some cases, there is a decrease in schedule growth, while in other cases there is zero, or even an increase in schedule growth. This emphasizes the fact that continual improvement is required, and the DoD must continue to develop its workforce to instill the systems engineering discipline needed for success. It should be noted that independent of schedule overruns, the DoD has seen a significant increase in planned schedule duration, from an average of three years in 1980 to an average of six and a half years in 2016. This data directly correlates with the complexity of the systems the department is procuring. As the DoD moves from independent systems toward systems of systems, this duration will continue to grow, reinforcing the need for proper program control.

Next steps: While there have been many successful acquisition programs throughout the DoD's history, there have also been numerous examples of programs that failed to deliver their product within cost, schedule, and scope targets. By implementing structural, cultural and strategic changes, the DoD can gain significant returns on its investment in SE—from basic research, to weapon development, to the integration of systems of systems. It is up to us, the future leaders, to help transform this vision into a reality.

The views expressed in this article are solely those of the author and do not reflect the official policy or position of the US Air Force or Department of Defense.

For more on getting a company's systems engineering organization started, see page 14.

http://

To see the references for this article, please visit

sdm.mit.edu

SDM Plans International Symposium to Address Strategy-Implementation Gap

The MIT System Design & Management (SDM) program is pleased to announce SDM Symposium 2018: Characterizing the Gap, the first international symposium on systems research to address the strategy-implementation gap. This ground-breaking symposium intends to establish a new research track, leveraging systems thinking and methods to better align implementation with strategy in complex business and government initiatives. Organizers hope the event will launch a major series of working research symposia.

Slated to take place at MIT on April 30 and May 1, 2018, the symposium is expected to draw 150 to 200 attendees. Prospective presenters are invited to submit original research characterizing the gap between strategy and implementation, including theoretical and applied work. Organizers are particularly interested in work related to new research frameworks and crosscutting themes.

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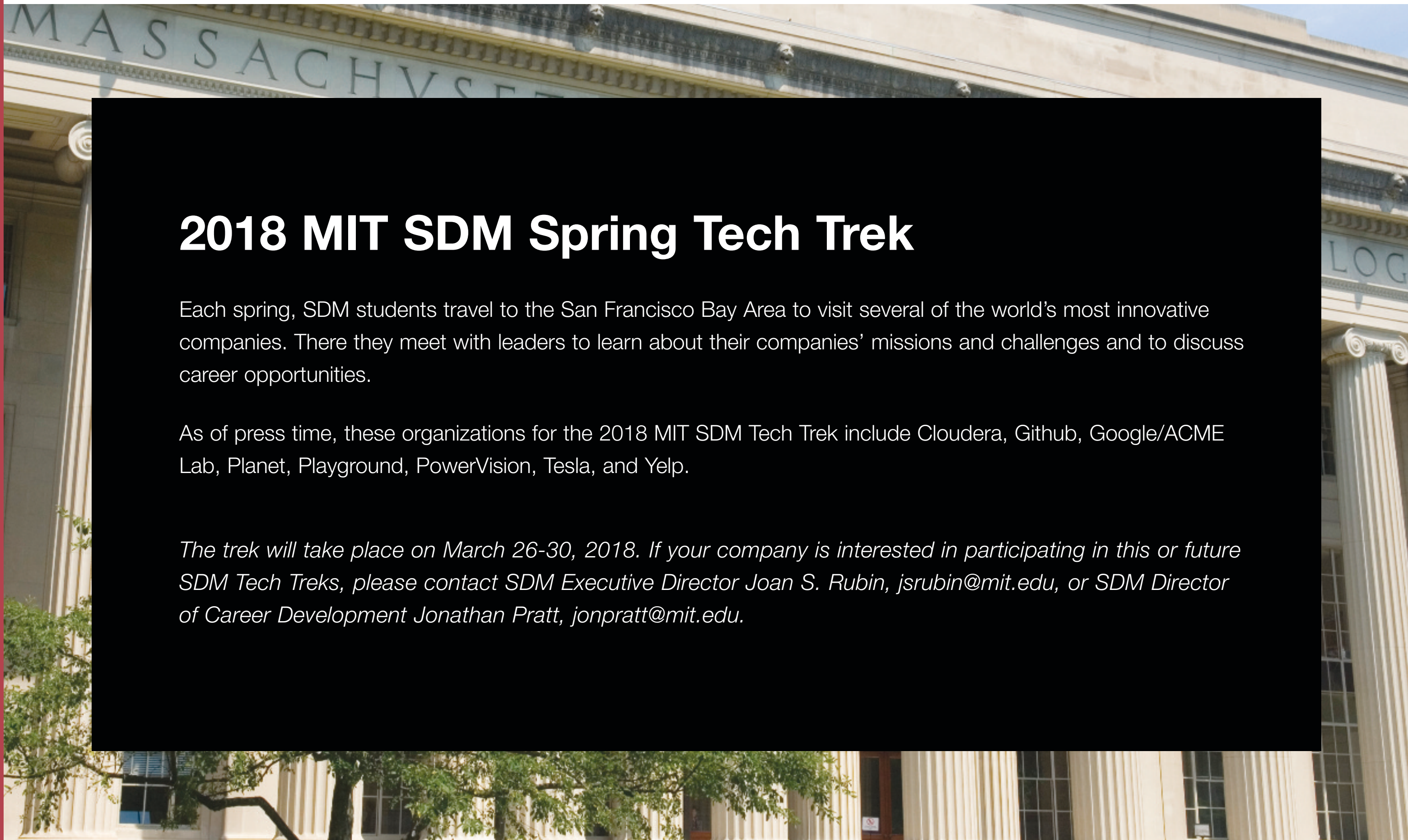
For further information, see

www.sdm2018symposium.org



2018 MIT SDM Spring Tech Trek

Each spring, SDM students travel to the San Francisco Bay Area to visit several of the world's most innovative companies. There they meet with leaders to learn about their companies' missions and challenges and to discuss career opportunities.

As of press time, these organizations for the 2018 MIT SDM Tech Trek include Cloudera, Github, Google/ACME Lab, Planet, Playground, PowerVision, Tesla, and Yelp.

The trek will take place on March 26-30, 2018. If your company is interested in participating in this or future SDM Tech Treks, please contact SDM Executive Director Joan S. Rubin, jsrubin@mit.edu, or SDM Director of Career Development Jonathan Pratt, jonpratt@mit.edu.

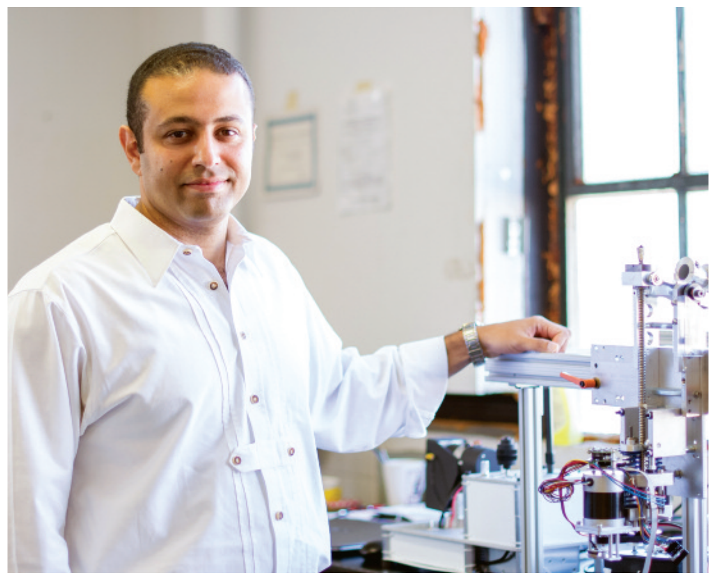
SDM Alum's Robotics Nonprofit Awarded $2.5 Million Grant

MassRobotics, a nonprofit startup escalator co-founded by MIT System Design & Management (SDM) alumnus Fady Saad, has been awarded a $2.5 million grant to expand operations in Boston's Seaport District.

Massachusetts Gov. Charlie Baker announced the grant on February 8, 2018. The award to MassRobotics was among nearly $7.5 million in MassWorks Infrastructure Program awards given to support projects in the Boston neighborhoods of Dorchester, Mattapan, South Boston's Seaport District, and Roxbury.

"These projects will lead to long-lasting, positive benefits for their neighborhoods and the City of Boston," Baker said. "Our administration is committed to economic development programs like MassWorks that help cities and towns invest in public infrastructure and unlock opportunities for private investment, housing, and new jobs."

The four projects are part of the 2017 MassWorks Infrastructure Program award round, which totals nearly $85 million in infrastructure investments across the commonwealth. According to Baker's office, the MassRobotics project alone is expected to support the creation of 3,000 new jobs within 10 years and attract more than $1 billion in venture capital funding and corporate investments to the commonwealth.



MassRobotics co-founder and SDM alumnus Fady Saad
Photo by Mimi Phan

Growing robotics business

Centered on encouraging the growth of robotics and artificial intelligence companies, MassRobotics opened 15,000 square feet of shared workspace in the Seaport District in February 2017. Since then, it has grown to house more than 30 companies and organizations, including startups, mature robotics companies, and university teams, with more than 70 people working in the space.

MassRobotics leaders said they are excited about getting support from the city to expand their operations. "This grant opens the door to more robust partnerships and sponsorship, and the space for robotics in Boston to grow," said Saad, SDM '13, who was named to the *Boston Business Journal's* "40 Under 40" list last fall. "The value of MassRobotics to Massachusetts and the industry is clear."

MassRobotics' Executive Director Tom Ryden added, "Year one has been a tremendous success. MassRobotics is busting at the seams, with every office and lab bench taken. We provide a center of gravity to Boston's robotics community and are truly becoming the epicenter of robotics innovation. To support that growth, we need to expand, and we are excited about the cooperation and support from the City of Boston in this process."

Incorporated in 2015, MassRobotics helps startups move from working prototype to marketable product by providing offices, a machine shop, and a robot testing platform; access to high-tech equipment such as electronics testing tools and a 3-D printer; and connections to partners. Saad co-founded MassRobotics with Stephen Paschall SM ’04; Tye Brady SM ’99; Daniel Theobald SB ’95, SM ’98; and Joyce Sidopoulos.

MassRobotics has said it plans to use the new grant to build out up to 35,000 square feet of additional space, which will include private offices; an open shared lab, prototyping and test space; a machine shop with 3-D printers, laser cutters, and other tools to help make parts; an electronics lab; and dedicated labs for advanced manufacturing robots and university-supported research. There will also be public event space and a dedicated STEM lab where students and others can learn about the latest technologies that will impact and inspire them.

SDM Webinar Series Welcomes Expert in Innovation

Established in 2010, the MIT SDM Systems Thinking Webinar Series is designed to disseminate information on how to employ systems thinking to address engineering, management, and socio-political components of complex challenges. The series features research and lessons drawn from real-world experience presented by SDM alumni, students, faculty, and academic and industry partners.

Hideyuki Horii

This spring, the series welcomes a new speaker. **Hideyuki Horii, PhD,** a recently retired professor in the University of Tokyo’s Department of Civil Engineering. Horii, who is now serving as executive director of the Japan Social Innovation Center, has been running an innovation education program named i.school since 2009. Horii will present a webinar on April 3, 2018, titled “Examining the Science of Innovation Education.”

See page 28 for more information on this and other upcoming webinars.
All live SDM webinars are free and open to all with pre-registration. Recordings and presentation slides are available at www.youtube.com/user/MITSDM.

http://

Recorded webinars can be accessed at

sdm.mit.edu/news-and-events/webinars/

2018 spring sdm calendar

> Available on the SDM website

Virtual SDM Information Session
sdm.mit.edu/virtual-sdm-information-session

Recorded webinars
www.youtube.com/user/MITSDM

Current and past issues of the *SDM Pulse*
sdm.mit.edu/pulse

Details and registration information for all events can be found at **sdm.mit.edu**.

MIT SDM Information Sessions

Learn more about MIT's System Design & Management (SDM) program and its master's and certificate offerings at an information session.

March 29, 2018

Press Club, 20 Yerba Buena Lane, San Francisco, CA, 3 p.m.
Details/registration: **sdm.mit.edu**

June 6, 2018

Live on campus at MIT
Details/registration: **sdm.mit.edu**

MIT SDM Symposium 2018: Characterizing the Gap

April 30, and May 1, 2018

First international symposium on systems research to address the strategy-implementation gap
For details, visit **www.sdm2018symposium.org**

MIT SDM Systems Thinking Webinar Series

This series features research conducted by members of the SDM community.
All webinars are held on **Tuesdays** from noon to 1 p.m. ET and are free and open to all. Details and registration for live webinars as well as recordings and slides from prior presentations can be accessed at **sdm.mit.edu/news-and-events/webinars/.**

April 3, 2018

Examining the Science of Innovation Education
Hideyuki Horii, executive director, i.school

April 10, 2018

Establishing a Systems Engineering Organization
Ben Levitt, consultant, Technology Strategy Partners; SDM alumnus
See page 14 for an article on this topic.

April 24, 2018

Balancing Cybersecurity and Usability in IoT Devices
Saurabh Dutta, director of usability and user experience, Rapid7; SDM alumnus
Tod Beardsley, senior security research manager, Rapid7
See page 9 for an article on this topic.

May 8, 2018

A Systems Approach to Challenges and Opportunities Generated by High Integration of Renewables in Electricity Systems
Jorge Moreno and Donny Holaschutz, partners, inodú; SDM alumni

Massachusetts Institute of Technology

Event listings contain all details available at press time. Final information is available at **sdm.mit.edu** two weeks prior to each event.

sdm.mit.edu