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A Systems Approach to a Research University's Research and Innovation Strategy

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Abstract - **The Georgia Institute of Technology (Georgia Tech), a major research university in the United States of America, has a legacy culture of embedding innovation throughout its education and research programs and thus an important role in facilitating economic development within its region. A new strategic vision introduced in 2010 to guide Georgia Tech's role nationally and internationally, included a systems approach to support faculty-led research concurrently with a focus on maximizing industry and societal benefit. The systems approach guides research infrastructure investments into core research areas and institute-wide support for discovery, application, and deployment functions. It also provides a venue for students to discover and explore disruptive innovations. This paper explores the similarities and differences between systems engineering in an industry setting and in the implementation of a university-based research strategy. Examples are cited from ongoing research in robotics, energy systems, health care technology, and advanced manufacturing.**

Keywords – **systems engineering, research strategy, innovation**

I. INTRODUCTION

Georgia Tech is ranked as one of the top research-intensive institutions in the world.[1] Its broad research focus includes world class expertise in research, education, and application of systems engineering. The authors have 65 years of combined experience in systems engineering. They have also served as leaders of large scale university research programs for many years. Lessons learned from this collective systems engineering experience have proved useful in leading and managing large scale, university-based research programs. A systems engineering mindset has also proved useful in leading work spanning basic and applied research coupled with technology transition and economic development programs. Interestingly, approaches for supporting innovation in a research-intensive university, and in fact in cultivating a culture of innovation, suggests important differences in the implementation of key systems engineering functions typically used in an industrial setting.

This paper explores the similarities and differences between systems engineering in an industry setting and in the implementation of a university-based research strategy. While research is largely an activity that resides with individual faculty investigators, the overall strategy is managed based on systems engineering principles where the entire enterprise is viewed as a system. Key similarities involve four key functions in systems engineering: system description, requirements definition, risk management, and team leadership. Differences involve the approaches taken to implement these functions. These differences are explored both through the authors' transformation of the research enterprise and current research projects. The paper will begin with a review of the conventional systems engineering approach and then a description of the Georgia Tech research strategy. Key similarities and differences in key systems engineering functions will then be explored based on this strategy with illustrations from ongoing work in robotics, energy systems, health care technology, and advanced manufacturing.

A primary finding is that a systems engineering approach is a useful means by which to manage such a diverse program, but that the key functions differ from the conventional systems engineering approach in a typical industrial setting.

II. SYSTEMS ENGINEERING IN AN INDUSTRIAL SETTING

Systems engineering is defined as "… an interdisciplinary approach and means to enable the realization of successful systems."[2] It has been characterized as both art and science [1]. As discussed by Bayhill and Gissing [2], a depiction of a conventional systems engineering approach is shown in Fig. 1. This approach, sometimes referred to by its acronym SIMILAR, highlights the typical functions of systems engineering.

- **S**tating the problem is the most important and often most challenging aspect of systems engineering. It entails creating a description of an end product that will meet the needs of users and other stakeholders.

[1] http://www.timeshighereducation.co.uk/world-university-rankings/2011-12/subject-ranking/subject/engineering-and-IT

[2] http://www.incose.org/practice/whatissystemseng.aspx

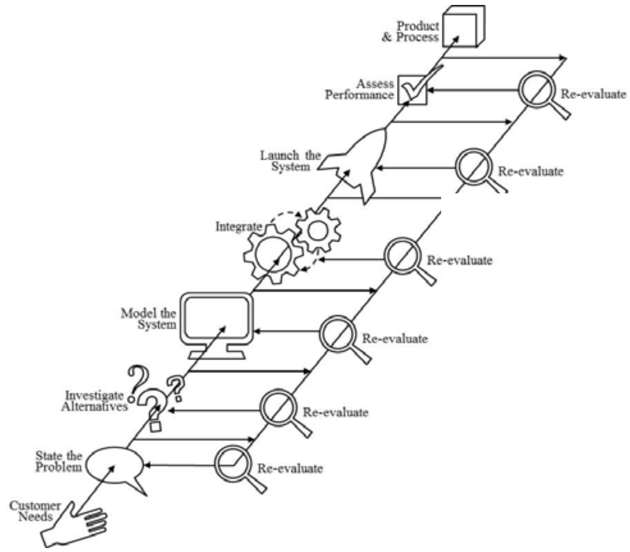

Fig 1: Systems Engineering Process

- **I**nvestigating alternatives involves the identification of mandatory and desired requirements and means for achieving them with known technical, cost, and schedule risk. Approaches for achieving the requirements are often pursued in parallel (often referred to as system decomposition).
- **M**odels of the system are used to communicate with clarity and to analyze the system description and alternatives for realizing the system.
- **I**ntegration involves the design of interfaces and protocols for combining different approaches for achieving individual requirements into a unified whole.
- **L**aunching the system requires the test and evaluation of the realized system in a realistic environment similar to that which will be experienced by end users.
- **A**ssessing performance means collection of data for comparison to evaluation criteria based on the system requirements.
- **R**e-evaluation is a continual process as systems engineering is not a linear process, but rather an iterative one with continuous feedback loops.

A key skill of the systems engineer is the ability to translate and decompose a description of a system vision, based on customer need, into realizable modules and requirements, each with a known technical solution and with predictable implementation risk, cost, and schedule. The "science" involves the use of well-established tools and methods to aid in the decomposition, modeling, integration, and testing of the system [3,4]. The "art" is often compared to the skill of an orchestra conductor who is sufficiently knowledgeable about the various instruments though perhaps not as talented with any one instrument as any given musician. But the successful conductor is able to coax the best from each musician in order to achieve an overall desired performance.

There are many variations of this systems engineering approach. For example, an evolutionary approach (e.g., intensive interaction with end-users to understand the requirements throughout the systems engineering process) is described at [5]. It presents a case study following the SIMILAR steps. A system description was created based on intensive interaction with users. This description was decomposed into key functional modules spanning user interface, data integration, data processing as well as requirements concerning training for use of the system and its maintenance. Designs were then pursued where each had predictable technical risk, schedule, and budget. Integration and testing followed individual subunit design and test. Regardless of the approach, the four key functions listed in Section I are the basis of good systems engineering. These functions will be further explored after a discussion of the Georgia Tech research strategy.

III. GEORGIA TECH RESEARCH STRATEGY

Georgia Tech was created in 1888 with the mission to educate a cadre of technical leaders to build a manufacturing and economic base in the State of Georgia. Georgia Tech's strong engineering culture resulted from the blending of two standard approaches for engineering education of that era. Commonly called the school and the shop approaches, they differed in the order in which theoretical and practical work were introduced (i.e., theoretical work was mastered first in the school approach; practical work was mastered first in the shop approach). Georgia Tech sought to blend these two approaches by having students study science, mathematics, engineering, and the humanities simultaneously with practical work in its shops and foundries. Thus from its beginning, Georgia Tech pursued a concurrent approach to theory and practice. This has resulted in a culture where education, practical problem solving and discovery-focused research co-exist.

Today, Georgia Tech consists of six colleges (engineering, architecture, computing, business, science, and liberal arts). The Georgia Tech Research Institute (GTRI), an outgrowth from the original shops and foundries, was created in 1934 to conduct applied, industry focused research. In addition, the Enterprise Innovation Institute (EII) supports economic development. EII houses the first and largest incubator in the United States. Through 2009, the colleges, GTRI, and EII largely pursued their activities independently. Research results were deployed through a slow, linear, and often frustrating process.

In 2009, a new president was selected to lead Georgia Tech. He directed that a new strategic vision[3] be developed that, in part, would create synergy between the colleges, GTRI, and EII. As part of this strategic vision, Georgia Tech defined an industry-facing research and innovation strategy focused both on leading-edge research and economic development. The strategy sought to bring a systems approach to the vast array of faculty-led research projects across Georgia Tech. This was done both to create more synergy between the colleges, GTRI, and EII and also to more efficiently and effectively fund research infrastructure and support processes. For example, Georgia Tech uses a shared services model to support the acquisition, use, and maintenance of research equipment. Such equipment is situated in administrative units, called interdisciplinary research institutes, reporting to the central administration outside the colleges and other units. This is done, in part, to promote interdisciplinary work. Another example is the simplification of contracting and intellectual property processes in order to become more "industry friendly." In addition, 12 core research areas, as shown in Table 1, were defined to represent the breadth and depth of research competencies.

These core research areas were selected because they are appropriate aggregations of core competencies represented in over 300 research centers, groups, and laboratories at Georgia Tech, their interdisciplinary nature, the alignment with strategic markets within the region, and the existence of industry and other partners interested in working with the Institute. The process to arrive at this aggregation involved a year-long discussion with faculty, administrators, and regional stakeholders in an effort to achieve shared understanding and agreement on how to best provide an effective "industry face" for research programs and their economic development potential.

A concurrent approach to research, innovation, and economic development means that teams of faculty, graduate students, application and economic development experts, and professional staff work together to define and pursue important problems, to foster earlier engagement with industry, and to accelerate the deployment of research results. It should be noted that to accomplish this, creative tension and a balance is required between high-risk, discovery focused research and development activities. The pursuit of discovery-focused research does not mean that every outcome will be successful in terms of usable outcomes for what is learned from creative pursuit and exploration must be a key focus. Research is an experimental pursuit where new insights and fundamental learning often come from failed attempts. The balance sought is to engender and support a culture that blends high risk, discovery-focused research with early identification of commercialization potential.

TABLE I

GEORGIA TECH CORE RESEARCH AREAS

"Big Data"
Bioengineering and Bioscience
Electronics and Nanotechnology
Energy and Sustainable Systems
Manufacturing, Trade, and Logistics
Materials
National Security
Paper Science and Technology
People and Technology
Public Service, Leadership, and Policy
Robotics and Autonomous Systems
Systems

Central to the successful implementation of such a strategy is a philosophy of maximizing collisions, reducing friction, and prudent risk taking. This requires a culture and a work environment where novel ideas can be explored and where faculty have the freedom and support to do that with minimal administrative burden. It also requires that work is done in ways that are meaningful to the pursuit of scholarship while responding to the needs of industry and other important external stakeholders. As a result of these observations, Georgia Tech's research and innovation strategy has three objectives: *create transformative opportunities, strengthen collaborative partnerships, and maximize economic and societal impact.*

- Transformative opportunities occur when members of the faculty pursue high-risk, interdisciplinary research linked to important economic as well as societal impact. Members of the faculty are encouraged to provide thought leadership at the national and international levels. An example includes the creation of a national robotics roadmap by Christensen [6] cited by the President of the United States when he announced an advanced manufacturing partnership initiative in June 2011. These and other initiatives are pursued in ways where the Georgia Tech campus and the surrounding region serve as a living laboratory to support scalable and relevant research on real world problems. Another important aspect of the strategy is to assemble professional support in licensing, industry contracting, commercialization, business development, communications and marketing, and development into commercialization impact teams.
- Partnerships with other universities and technical colleges, national and international universities, major corporations, local nonprofits, and State agencies are

[3] www.gatech.edu/vision

essential. Through these partnerships an innovation ecosystem is formed and sustained. Strategic partnerships now exist with major companies including AT&T, Boeing, Chevron, Children's Healthcare of Atlanta, Coca Cola, Dow Chemical, Exxon-Mobil, General Electric, General Motors, IBM, Kimberly Clark, NCR, and the Southern Company. A strategic partnership is one in which Georgia Tech and the company commit to each other's success. Along with improvements in industry contracting and intellectual property management, a customer service model was introduced to better serve strategic partners and to cultivate deep understanding into the needs of the partnered company.

- Maximizing economic and societal impact means that research success is not measured solely by standard metrics associated with scholarly productivity, as important as they are to the academy. Success is ultimately based on research results being deployed beyond the laboratory and classroom into the real world. Success measures include companies formed, licenses issued, outside industry investment achieved, and new jobs created. The value Georgia Tech's strategic partners attribute to the work conducted under this strategy is ultimately most important.

As a result of this strategy, Georgia Tech's sponsored research awards have increased 12% per year over the past three years and commercialization activity has also advanced. In 2012, Georgia Tech helped create 150 new companies, six times the number from 2010. It ranks third in the State of Georgia in patent production, out distanced only by AT&T and Kimberly Clark [7].

IV. RESEARCH STRATEGY COMPARISION TO AN INDUSTRIAL APPROACH

Research is a much more individual endeavor than commonly experienced in a large systems engineering project. Especially within a research university, a faculty member is an independent entrepreneur with freedom to conduct research as she or he sees fit. But within the university, common research themes emerge and decisions need to be made by administrators about investment into research facilities and the very areas of research upon which the university seeks to base its reputation. To complicate this further, research universities are increasingly expected to both engage in leading edge research for reputational and scholarship purposes and also to realize economic benefit from the research. The research process described in the previous section is illustrated in Fig 2.

At the core of the strategy are grand challenges. These are the equivalent of the system description in an industrial systems engineering project. Grand challenges are

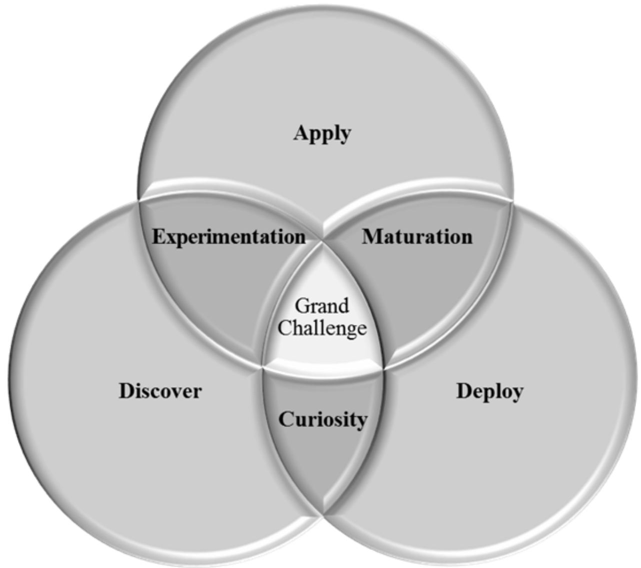

Fig 2: Research Process

futuristic system descriptions that excite and motivate communities of researchers to work together to achieve some seemingly impossible capability.

A famous grand challenge was expressed by US President John Kennedy in a speech at Rice University on 12 September 1962.[4]

> But if I were to say, my fellow citizens, that we shall send to the moon, 240,000 miles away from the control station in Houston, a giant rocket more than 300 feet tall, the length of this football field, made of new metal alloys, some of which have not yet been invented, capable of standing heat and stresses several times more than have ever been experienced, fitted together with a precision better than the finest watch, carrying all the equipment needed for propulsion, guidance, control, communications, food and survival, on an untried mission, to an unknown celestial body, and then return it safely to earth, re-entering the atmosphere at speeds of over 25,000 miles per hour, causing heat about half that of the temperature of the sun--almost as hot as it is here today--and do all this, and do it right, and do it first before this decade is out-- then we must be bold.

In President Kennedy's own words, this bold vision clearly communicated a system description which could be decomposed into subsystem technological solutions required to develop the subsystems that had not yet been created, hence the motivation for a generation and more of discovery, applied, and deployment research. In a similar vein, grand challenges have been used in many other fields over the past decades. Roland and Shiman [8] describe the quest of the Defense Advanced Projects Agency to create intelligent machines in the 1980s. The

[4] http://er.jsc.nasa.gov/seh/ricetalk.htm

computer science community also stated several famous grand challenges in speech understanding, speed translation, and robotics which accelerated progress in artificial intelligence [9]. The US National Academy of Engineering maintains a description of engineering grand challenges in engineering.[5] More recently both the mathematical and biological science communities have stated grand challenges that have and are proving useful in facilitating progress in their respective fields [10,11].

Grand challenge descriptions are part of each core research area at Georgia Tech. For example, four health care technology challenges are the cure of single gene defect diseases, regeneration of growth plate function, and a significant reduction in health problems associated with asthma, and use of robotic technology as an automated care assistant for the elderly.

A useful technique for arriving at community assessment for and articulating requirements related to grand challenges are roadmaps. Such requirements represent needs for which there are no known technical solutions, hence a research opportunity. A roadmap is a device for helping a community to arrive at a shared understanding of the key problems that must be solved to make progress toward a visionary capability. For example, the previously mentioned US robotics research roadmap was developed by leading research universities and industry in 2009.

The key processes that create synergy between discovery, application, and deployment involve supporting curiosity, experimentation, and maturation. Each play a key role in providing a bridge between two of the key research processes.

- Curiosity is a key attribute linking interesting and challenging societal problems to basic research. Curiosity is also an attribute of a more individualized research process called use-inspired research as described by Stokes [12]. Louis Pasteur was perhaps the most successful practitioner of this research approach. He exceled in both basic (discovery focused) and applied (translation and solution focused) research. The goal of use-inspired research is to maximize the generation of new knowledge and solutions to important societal problems. This is illustrated in Figure 3. Grappling with the societal problems (curiosity) often leads to insight into new fundamental research questions. For example, Pasteur's industry funded research on behalf of the beet industry (the goal was to maximize alcohol production) led to new insights and unanswered questions that in turn led to the discovery of fundamental insights in microbiology, and in fact the creation of microbiology as a field of science. Legendre [13] and Linder [14] have also explored support for curiosity driven research. At Georgia Tech, faculty councils are used to facilitate discussions across academic disciplines in ways that promote discussion with outside partners who seek to deploy research results. For example, in the area of health care technologies, a faculty council works closely with health care providers from Children's Health Care of Atlanta and biomedical device companies in order to understand clinical problems and to use that understanding to guide research in nanomedicine, regenerative medicine, and health systems.

- Experimentation is crucial for both providing a laboratory or test bed in which to support discovery focused research and in supporting the applied research needed to test research discoveries and to integrate them into a systems solution [15]. At Georgia Tech, facilities for interdisciplinary work with shared equipment are used in the core research areas. Such facilities provide "intellectual crossroads" where faculty can explore new ideas and their potential application. Disruptive innovations often arise from this work. Such experiments incorporate a challenge-competitive environment to maximize depth of innovation and exploration. As an example, Georgia Tech has a smart grid laboratory as part of its energy systems programs. This lab is used both to educate students and to conduct research. It is also used to stage a competition between student teams supervised by a faculty member and an industry representative. Industry challenge problems are presented for which there are no known solutions. The student team that produces the most useful results receives a cash prize (and a good grade!). Over the past three years, companies have hired many of the students who have competed in the competitions. One company produced 26 patent applications with a return on investment (ROI) six times their own internal ROI.

- Maturation activities involve the use of expertise from commercializing experts engaging earlier in the research process to look for promising ideas that have market potential. At Georgia Tech, technology may be deployed through creation of new companies, licensing technology to existing companies, or conducting value added services for a company interested in accelerating the maturation. Risk management differs in a large research university from that in a typical systems engineering process. While in a systems engineering process, one wants to mitigate technical, cost, and schedule risk; in research one wants to promote risk taking to promote the discovery and application of game changing ideas. Senior leaders often find themselves in the position of "giving permission to take risk." Risk taking in discovery-focused research and related experimentation is crucial, yet more managed approaches are prudent in maturation pursuits. Common practices used in discovery and applied research include use of "seed grant" funds to provide initial support for exploring a new idea. Systems engineering techniques have proved directly applicable in the maturation of

[5] http://www.engineeringchallenges.org/

promising research ideas into widespread use. One method involves the use of readiness levels as typified in Technology Readiness Levels or TRLs[6] and Manufacturing Transition Levels (MRLs)[7]. Levels 1-3 typically deal with basic and applied research and Levels 7-9 deal with more application ready technologies. Universities typically deal in the Level 1-3 area and industry is more committed to Level 7-9. Often called "the valley of death," Levels 4-6 deal with the risk reduction issues necessary to migrate a technology from promise in a laboratory or test bed application to hardened industrial use.

Wang [16] is exploring how existing technology and manufacturing readiness levels can be combined with business case and market acceptance readiness measures as an aid to risk mitigation accelerating deployment. This work presents a different view of the research strategy as shown in Fig 3. To fully operationalize this view, synergy and alignment is required across the Georgia Tech enterprise (e.g., the colleges, GTRI, and EII working together as a team across discovery, application, and deployment functions). The significance of this work relates to revitalizing a manufacturing ecosystem in the Southeast United States focused on lightweight materials. Georgia Tech is working to deploy additive manufacturing methods to strategic partners and smaller companies in their supply chain in the aerospace, automotive, biomedical device, and natural gas combustion markets

Lastly, the authors have found that leadership style, while often a matter of individual style, differs in terms of successful application in leading a systems engineering project versus leading a university's research program. In a commercial systems engineering project, especially in a large undertaking, a top down management style is often appropriate where system management tools ranging from Gantt charts, modeling, and formal design reviews are appropriate means for ensuring progress towards realizing the desired systems capability. In a university research environment, where grand challenge statements are used to motivate and guide research investment and progress, a much more personal and supportive leadership style often proves to be more appropriate. Sometimes called servant leadership, it is important that leaders lead from behind, letting the faculty and students take center stage.

The leadership model successfully employed is a variation of servant leadership as described by Kouzes and Posner [17]. As they describe an attitude of success of others and the organization over self, encouragement, and process improvement are key attributes. Also the ability to gently influence others to pursue goals, perhaps involving more risk than one might normally feel comfortable with (e.g., as in a grand challenge statement) and in anticipating

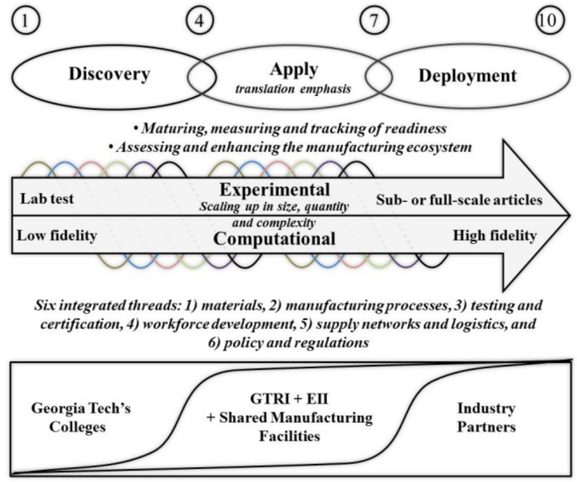

Fig. 3: Accelerated Research to Deployment Via Readiness Levels 1-10

and creating conditions that make it possible for others to achieve these goals is embedded in this style of leadership. For example, in pursuing ongoing work in pediatric health, university leadership anticipated the opportunity and secured a major philanthropic gift with a key strategic partner. This enabled senior faculty to build interdisciplinary teams, and initiate leading edge research faster than might have been possible through normal grant application means. Significantly, it also empowered faculty to state grand challenges, to decompose those challenges into key open problems to guide the research, and to define translational programs to concurrently mature and migrate promising results into use. Thus, a leadership style based on putting others first, gentle influence, and anticipating future opportunities is as important in a diverse research intensive environment as a more directive style is in an industrial systems engineering environment.

The authors' experience in leading both systems engineering projects and large scale research projects highlight the importance of the four systems engineering functions listed in Section I. Yet there are subtle contrasts in each function as highlighted in Table II. The approaches most often used in systems engineering are well codified as previously suggested in Section II. The authors' experience in implementing the systems engineering functions in a research setting suggest six key lessons.

V. KEY LESSONS

The "Georgia Tech as a system" approach based on key systems engineering functions has proved to be very

[6] http://esto.nasa.gov/files/trl_definitions.pdf
[7] http://www.dodmrl.com/MRL_Deskbook_V2_21.pdf

TABLE II
CONTRAST OF KEY FUNCTIONS

Attribute	Systems Engineering Approach	Research Strategy
System	End product description	Grand challenge description
Requirements	Decompose into statements of what is needed; define known approaches for addressing them	Decompose into statements of what is needed; define open research issues to address in order to eventually achieve needs
Risks	Select technical viable approaches with predictable cost and schedule	Promote risk taking in exploration, experimentation, and evaluation of novel ideas; pursue accelerated maturation using a risk management approach
Team Leadership	Disciplined management approach, often directive	Anticipatory, influencing, and support others

effective. As noted, research sponsorship has increased as have economic development outcomes. There are six key lessons.

- ***Scholarly output is still important***: The excellence of faculty, students, educational programs, and research are all linked inextricably to high quality scholarly output. While critically important in today's academy, it should be viewed as a necessary condition. The sufficient condition becomes success at translating that scholarly output into deployable outcomes that have economic development impact or otherwise solve an important societal problem.
- ***Communication and trust are fundamental:*** A faculty member's education stresses the importance of reasoning, questioning, and independent work. A team-based approach, common in large engineering projects, is more challenging in a research university environment. Frequent communication (including active listening) is crucial in order to gain support from faculty.
- ***Innovation happens in such an interdisciplinary environment***: It has long been recognized that "break through ideas" often occur at the boundaries of different points of view. The approach implemented at Georgia Tech supports interdisciplinary research (across academic disciplines) and across the life cycle of discovery, application, and deployment. Price [18] has recently made a similar observation.
- ***Alignment is necessary throughout the system:*** As described in [19], alignment with the enterprise between vision, strategy, process, culture, and outcomes is very important. Moving dedicated teams of support professionals into faculty research areas to focus on offloading administrative burden and to support the functions related to curiosity, experimentation, and maturation have enabled faculty to spend more valuable time on their research while others focus on transition to use. Further, alignment of core research areas with strategic markets important to the State of Georgia and to Georgia Tech's strategic partners has both produced support for research and for deployment activities.
- ***Nothing trumps leadership**:* Scholarship is a necessary condition for earning the respect of faculty when assuming a university leadership position. But there are many cases in numerous universities where the most gifted academic has failed to provide effective leadership or management of a research program or department. Arguably, leadership capability is a discriminator between successful and non-successful programs in the academy. Servant leadership puts the success of the organization and others who support the organization first. Such leadership skill can be learned. At Georgia Tech, faculty with these kinds of leadership skills are sought to lead the core research areas.
- ***A systems approach has proved effective***: Transforming the Georgia Tech enterprise by viewing it as a system and tailoring key systems engineering functions such as system description, requirements definition, risk management, and team leadership have led to an effective approach for promoting more synergy between discovery, application, and deployment activities.

VI. SUMMARY

The Georgia Institute of Technology is a major research university with a strategic vision that spans discovery-focused research, applied research, and deployment. While research is largely an activity that resides with individual faculty investigators, the overall strategy is managed based on systems engineering principles where the entire enterprise is viewed as a system. Intentional support for curiosity, experimentation, and maturation create synergy between previously disconnected units. Key principles include the articulation of futuristic systems based on grand challenge problem statements, the strategic investment into research capabilities based on unresolved open issues (requirements) related to these descriptions, an intentional approach to pursue big ideas (taking risk), reduction to practice and deployment (managed risk), and a leadership approach in support of all activities and the people who conduct them. The work is aligned with strategic markets being developed in the southeast United States. The results to date have been encouraging, A primary finding is that a systems engineering approach is a useful means by which to manage such a diverse program, but that the key functions of system description, requirements management, risk management, and team leadership differ from the conventional systems engineering approach in a typical industrial setting.

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