Grand Challenges for Systems Engineering Research

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Abstract
Systems engineering is rapidly becoming recognised as a key discipline in a number of sectors including Aerospace & Defence, Automotive, Construction, Energy, Transportation, Consumer Electronics, IT, Pharmaceutical & Healthcare and Telecommunications. This trend is driven by growing system complexity and the need for optimal integration of people, processes and technologies. Consequently, the sheer scale of future system complexity is likely to exceed our current understanding of systems engineering and the associated tools/techniques we employ. The number of overall system parameters to be controlled as part of the overall design process (as various system optimisations are undertaken) is likely to be overwhelming. Whilst systems engineers will be expected to manage system complexity the underpinning understanding of systems science, technology and tools must evolve to take account of the increasing systems complexity. Unless enabling research is undertaken there is a growing risk that available tools will be inadequate for the future. This paper builds on feedback from numerous research presentations, industry discussions (across different sectors) and various subject matter expert data collection exercises. From this work it has been possible to propose a number of Research Grand Challenges in systems engineering in order to inspire a research agenda for systems engineering. In this context, a Research Grand Challenge pursues a series of goals that are recognised as being one or two decades in advance; their achievements are regarded as major milestones or breakthroughs in the advancement of knowledge or technology.

Keywords – systems engineering, grand challenge, research

1 Introduction
Systems engineering is rapidly becoming recognised as a key differentiator for the successful architecting, development and deployment of complex systems. Distinguishing features of a complex system include many factors such as:
1. A set of components which when combined have additional qualities (emergent properties) over and above those present in any of the individual components themselves.
2. Existence of complex relationships between the components that determine how the system as a whole behaves.
3. Iteration of the design is required to align the customer and other stakeholder expectations of performance and capability.
4. Synthesis of an optimal solution is a trade-off between component performance, cost and risk. Also there might be more than one solution.
5. Modern systems are typically very complex and interact with other systems in a manner that components cannot be optimally designed without consideration of the whole.
6. Requirement to balance requirements against conflicting constraints through the full life of the system.
7. The systems architecture design involves a multi-disciplinary approach within a framework that ensures cost, timeframe and delivered system performance can be controlled.
8. End user or customer system capability requirements are likely to require a different approach to traditional engineering methodologies.

Consequently, there is a need to formulate a research roadmap to tackle the research questions that might at first seem to be intractable. This paper will look at research requirements at the lower end of the Technology Readiness Level (TRL) scale (refer to Figure 1) with a view to advancing knowledge and technology transfer through a series of Research Grand Challenges. At the heart of this process is the need to bridge from TRL 1-3 to TRL 7-9 via TRL 4-6 the so called ‘valley of death’ in order to ensure effective knowledge and technology transfer.

Figure 1: Technology Readiness Levels: Source - Courtesy of NASA.
Managing the necessary research pipeline to bridge the gap is not as straightforward as might be first thought. The academic community strives to make new breakthroughs and achieve scientific impact whereas the industrial sector typically wants exploitable results in the short term. It is crucial for the academic community to get a clear understanding of industrial needs at an early level and similarly the industrial sector needs to share its research needs with academics in a way that stimulates longer term research. The sharing of technology insertion roadmaps can go a long way to help communicate the research need. However, this requires a great degree of trust on both sides for it to work. Establishing a set of Research Grand Challenges that are owned by the community can also be of significant value.

A Research Grand Challenge pursues a series of goals that are recognised as being one or two decades in advance; their achievements are regarded as major milestones or breakthroughs in the advancement of knowledge or technology. However, to be regarded as a Grand Challenge the systems engineering community needs to endorse the challenge. This does not guarantee success but the challenge serves to focus research effort towards a shared understanding of where the breakthroughs are required. An advantage of this approach is that it is vitally important for the systems engineering community to define the long-term aims of the systems engineering discipline, independently from the short-term pull and technology push. It is hoped this paper will help stimulate such a debate and create a research roadmap that will identify the requirements of systems engineering research and focus attention on key scientific challenges. To initiate this process this paper represents an attempt to gain a larger perspective on our efforts, to suggest directions in which our energies and talents could be used for the advancement of systems engineering, and to underscore the long-term technological issues that must be resolved for this to be successful.

In any endeavour which tries to predict future needs, it is very easy to stay within a comfort zone and think only about short to medium term challenges. Whilst these are clearly important in terms of market readiness, it is perhaps more important to define a longer term research agenda without restricting innovative thinking. It is not surprising there is a degree of asymmetry between an industrialist’s perspectives of what research needs to be undertaken compared with an academic view, which is usually a longer term perspective. Unfortunately, being too close to market by trying to think of solutions at the same time as developing Grand Challenges is likely to inhibit the process [1]. In the future, we can expect systems engineering to offer a very impressive range of social and economic benefits as more products, applications and services become even more complex. However, it’s not the complexity that necessarily provides the benefit; rather it is the ability of more complex systems to offer greater capability. The UK Royal Academy of Engineering recently published an enlightening report ‘Creating systems that work’ [2] which identified six principles for integrated systems design, refer to Table 1. These cover the continuum from a single discipline to multiple disciplines as part of systems engineering. Moreover these principles allude to the systems engineering process and do not describe the state of, or how mature our level of systems understanding is in any particular area.

<table>
<thead>
<tr>
<th>Principle</th>
<th>Purpose</th>
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<tr>
<td>Debate, define, revise and pursue the purpose</td>
<td>The system exists to deliver capability, the end justifies the means</td>
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<tr>
<td>Think holistic</td>
<td>The whole is more than the sum of parts – and each part is more than a fraction of the whole</td>
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<tr>
<td>Follow a systematic procedure</td>
<td>Divide and conquer, combine and rule</td>
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<tr>
<td>Be creative</td>
<td>See the wood before the trees</td>
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<tr>
<td>Take account of the people</td>
<td>To err is human</td>
</tr>
<tr>
<td>Manage the project and relationships</td>
<td>All for one, one for all</td>
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Table 1: Six Principles for Integrated System Design (adapted from [2])

Whilst the Royal Academy of Engineering report is very good at describing the process of systems engineering it does not explain why things are important. Examination of the wider systems engineering literature highlights a number of gaps between current systems theory and practice. Many activities take place within the systems engineering field as a result of best practice rather than through a verifiable scientific process. Unfortunately, this makes it harder to transfer techniques from one sector to another, especially where systems engineering is not a common term. Perhaps not surprisingly in these sectors other almost identical ‘systems approaches’ are employed but are not called systems engineering. This raises the debate of needing a common framework or language within which to discuss systems engineering across different sectors.

2 An Initial set of Research Grand Challenges for Systems Engineering

The desire to establish a research agenda for systems engineering is particularly appealing because it could have the potential benefit of focusing effort and bringing about key changes where they are most needed. Due to the multi-disciplinary nature of systems engineering it is very difficult to propose a single Research Grand Challenge, instead an initial interrelated set of challenges are proposed in this paper. This approach enables us to identify a set of deep technical problems that apply to several of the Research Grand Challenges. Also solving similar problems in different application contexts will encourage solutions that are far-reaching and durable. Although these Research Grand Challenges incorporate problems that are already the focus of some research, these challenges set goals that are
broader than most typical research agendas and move far beyond what has been demonstrated by today’s research. An alternative approach would be to look at a given application domain and try to define the longer term research need. However, this approach has the potential of excluding important cross domain challenges – i.e. solutions to a problem in one domain may be the perfect answer to one in another domain.

In many cases, it is the scale of the vision that makes it challenging. To be regarded as a Grand Challenge each goal will require typically a decade of concentrated research effort in order to make significant progress or achieve a substantive breakthrough. Consequently, the value is such that each is deserving of substantial investment by government and industry because each challenge, if successfully achieved, will significantly advance the capabilities of the product, application or service. We can all take inspiration from part of John F. Kennedy’s September 12th 1962 speech “We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too. “

The goal behind defining Research Grand Challenges is to develop a consensus as to where the major research challenges lie, and thereby to encourage greater coherence, communication and collaboration across the research community. As a result of this coherence we anticipate an increase in the quantity and quality of systems engineering research activity. Achievement of any of these Grand Challenges will represent a breakthrough for the systems research community. Consequently, this is highly likely to require sustained world-class research involving international and inter-disciplinary collaboration.

It is important to note the establishment of these Research Grand Challenges is an ongoing process and it is expected that the community will wish to revisit these proposals to refine, develop, and redefine their nature and scope on a regular basis.

In formulating an initial set of Research Grand Challenges (to start the ball rolling) it has been necessary to focus on generic challenges that are applicable to different systems engineering sectors. Obviously, each sector (e.g. aerospace, medical, construction etc.) have their own specific challenges.

2.1 Research Grand Challenge (RGC 1) – Ultra-scalable Heterogeneous Systems

Over recent years systems have grown from single user to include geographically distributed multi-user systems. The advent of high bandwidth networks has further enabled data intensive connectivity to be achieved between heterogeneous systems (with mixed hardware and software stacks) that are globally connected. Whilst the internet is a good example of an ultra-scalable system this has led to a phenomenal plethora of uncontrolled/unregulated connected computing resources. Consequently, we are only too aware of the impact of security breaches that result from such an ‘open system’. On the other hand grid computing whilst being based on similar network architectures [3–5] is not so vulnerable and less prone to attack because security certificates have been built in from the outset. Unfortunately, as complexity has scaled up there are growing numbers of examples of where complex systems have failed to deliver. For example, the National Programme for IT in England was designed to reform the way the National Health Service (NHS) uses information, and hence improve services and the quality of patient care. The estimated cost of the Programme is £12.7 billion (including £3.6 billion of local costs) and requires substantial organisational and cultural change if it is to be successful. At the outset of the Programme, the aim was for the implementation of the systems to be complete by 2010 but latest forecasts [6] suggest it is likely to take (a further four years more than planned) until 2015 before every Trust has fully deployed the new care records systems which will support the creation of detailed care records.

“Little clinical functionality has been deployed to date, with the result that the expectations of clinical staff have not been met.” [6]

Over the next decade or so we will see other requirements for ultra-scale systems emerging. Cloud computing has recently appeared as a computing architecture in which dynamically scalable and often distributed computing resources will be loosely-coupled to create a virtual computer comprising a cluster of networked computers, acting in concert to process extremely large tasks as a service over the Internet. Also, it is anticipated the demand for networked assets could increase further because of the number of invisible computers embedded in everyday objects around us. Many of these will have the capability to communicate with each other which will in turn create new complex systems.

Such systems present significant challenges in terms of security and privacy of the data because systems on such a large scale need to be open (in terms of standards) in order to be able to take account of rapidly evolving technology. Additionally, this presents a significant challenge with regard to legacy equipment and their useful lifetime due to inter-operability. Significant research effort is required in defining an open systems architecture that supports a truly scalable system from one to many hundreds of nodes with the required level of security and integrity. The issue of where the data resides will be an important aspect for the designer of the overall system architecture – this raises all sorts of issues concerning data synchronisation, resilience etc. Questions such as, what are the key features of the infrastructure to support ultra-scale network enabled systems? Also at the ultra-scale level will it ever be possible
to exhaustively test and validate the whole system to ensure it does not behave erroneously.

Human interaction with ultra-scale systems will present particular challenges though this depends on the task and whether the human is part of a very large distributed team or whether the human is overseeing the operation of the ultra-scale system. History tells us that humans are prone to make errors when least expected with some disastrous results (there is plenty of evidence to support this) – For instance in the UK “Hospitals around the country admitted to security breaches as part of an investigation into data protection in all areas of public life, triggered by the loss of 25 million child benefit records by HM Revenue and Customs. They include the loss of data on 160,000 children, after City and Hackney Primary Care Trust reported that a disc failed to arrive at St Leonard’s Hospital, east London.” [7]). Consequently, any ultra-scale system must be designed to cope with human error either accidental or deliberate.

The aim of this Grand Challenge is the development of a trusted open systems architecture that is independent of the number of interconnected nodes, their location, time of access and which is resilient in terms of loss of one or more nodes and the inherent network whilst still being human error free.

Areas for research include:

- Trust, security and privacy
- Resilience to system failure and external denial of service attack
- Ubiquitous communications and user access
- Auto-configuration – a flexible architecture to deal with system failure and upgrade
- Management of ultra-scalable data – ensuring only relevant data of interest is accessed
- Data provenance – knowing the exact status of information
- Accessible and manageable by humans through the widest possible interaction technologies
- A robust system architecture that supports the above
- A systems engineering design environment that permits the design, evaluation and testing of an ultra-scalable system
- A framework in which an ultra-scalable system can undergo VV&A

### 2.2 Research Grand Challenge (RGC 2) - Ultra-scalable Autonomous Systems

The deployment of autonomous systems to replace human based systems is appealing because they have the potential to remove humans from hazardous situations or environments, be more cost effective and require less infrastructure because the human does not need to be integrated into the system and decisions can potentially be taken faster and without emotion.

This Grand Challenge is concerned with the same issues as RGC 1 except that the true autonomous system has little if any reliance on human operator intervention to ensure they act responsibly when performing tasks. At its core is the concept of autonomous systems interacting with one another for their individual and/or collective good. To function, an autonomous system incorporates disciplines including artificial intelligence, distributed computing, object-oriented systems, software engineering, economics, sociology and organisational science. Currently, the field of autonomous and multi-agent systems is receiving a great deal of attention and represents a rapidly expanding area of research and development. However, this challenge is particularly concerned with ultra-scalable autonomous systems which can exist as a single autonomous entity at the scale of one to a large civilization of autonomous systems working co-operatively. The form and function of individuals in the civilization need not be all the same and would diversify according to need. Clearly, autonomous agents and multi-agent systems represent a new way of analysing, designing, and implementing complex systems.

The aim of this Grand Challenge is the design and construction of an ultra-scalable autonomous system architecture which automatically reconfigures itself to tackle new tasks and is able to evolve as its tasking changes or the enabling technology evolves. The autonomous aspect of the system is that it is required to think for itself and make decisions based on intelligence data it collects during the course of its existence. The key challenge is to build a large scale system comprising a large number of smaller autonomous systems that are collectively fully aware of their environment and undertake tasks co-operatively with neighbouring systems and agents. The ultimate goal is for such systems to intelligently respond to events and situations with the same (or better) outcome as corresponding human based systems would achieve. In some respects these systems will have capabilities and decision processing times that is significantly better than a human.

Areas for research include:

- Context awareness in terms of self and the whole autonomous community
- Trust, security and privacy in a way that humans will pass total authority to the autonomous system
- At what point will we be able to completely and totally trust and autonomous system and allow it to do its own thing?
- Secure communication between autonomous systems and agents in the community
- Self-configuration and adaptation to changing situations
- Self-healing in the event of system failure (either complete or intermittent)
- Information provenance – an ability to take full accountability for actions

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• Integration of the autonomous system in an environment where human controlled systems coexist.
• Support tools and theories (including autonomous cognition models)
• A systems engineering design environment that permits the design, evaluation and testing of an ultra-scalable system
• System architectures supporting totally autonomous agents

2.3 Research Grand Challenge (RGC 3) - System Verification, Validation and Assurance (VV&A) of Extremely Complex Systems

In today’s world, the cost of a malfunctioning system can be staggering when considering the aftermath of a large scale disaster caused by the failure of the system. Unfortunately, some system faults are not detected until in service and then only after an incident occurs. One only has to read the Air Accidents Investigation Branch (AAIB) reports and their recommendations available online from (http://www.aib.gov.uk/home/index.cfm) to get a perspective of the need for even more verification, validation and assurance.

The increasing scale and complexity of future systems will only add to the problems of system verification, validation and assurance. Important factors include functional correctness issues (such as conformance to functional specification, type correctness, consistency of data, numerical accuracy etc.) and many non-functional issues (such as dependability, safety, security, timeliness of response, availability, maintainability etc.) that need to be addressed. Unless, the system has been designed for reliability from the outset a single bit error can have catastrophic consequences for the whole system.

Unfortunately, building in high levels of system redundancy quickly escalates the cost of the whole system. Can we learn from other systems in nature? Biological systems exhibit graceful degradation and self-healing in some cases - whether we can learn from this remains to be seen.

All systems (whether human in the loop or autonomous) will need to undergo VV&A before they can go into service. As system complexity increases so too will the need for more VV&A.

A key challenge will be the development of an integrated suite of tools to support all aspects of verified system construction: requirements capture, specification, validation test-case generation, refinement, analysis, verification, and run-time checking.

Areas for research include:
• How to undertake VV&A on ultra-scalable systems?
• Impact of legacy systems in a VV&A activity
• Metrics and techniques for assuring system trust
• How to deal with learning in multi-agent systems – can we accept VV&A of such systems?
• How to deal with self-optimising system VV&A?

2.4 Research Grand Challenge (RGC 4) – Modelling & Simulation (M&S) - Total System Representation

Modelling and simulation is integral to the systems engineering process by supporting the design process, evaluating architectural solutions, supplementing testing, and enabling the assessment of the system performance envelope where system testing on real equipment is not cost effective, or where additional data is required. Modelling and simulation techniques allow the systems analyst to concentrate on the critical parameters and system behaviours and consolidate the results of their effects. Moreover, modelling and simulation is playing an increasing role in allowing system properties to be investigated at all stages of the life cycle. Some simulations are so realistic they are virtually indistinguishable from the real thing (e.g. a flight simulator) from the user’s perspective. Consequently, as the complexity or scale of the system increases so does the problem of developing an accurate and validated model. When dealing with complex cognitive systems (involving humans in the loop), modelling and simulation has often played a role in supporting the development of theories and understanding of systems when controlled by humans, rather than predicting the human behaviour. The major weakness today is that we don’t yet have comprehensive models of human behaviour and cognitive performance. It would be a great asset if we could reliably predict human behaviour under all circumstances – this probably represents another Research Grand Challenge in its own right. At a system level many techniques exist, such as hierarchical decomposition, object-oriented modelling and programming, graphical depiction of system behaviour, visual analytics and more recently agent-based modelling have enhanced our ability to build and use complex models. Supporting multi-paradigm, multi-resolution modelling and modelling at different levels of abstraction presents a significantly advancing modelling and simulation challenge in such diverse application domains. The desire to accurately model/simulate a complex system and its environment in minute detail to a higher level of abstraction still remains the ultimate challenge.

The challenge of re-use of system models seems largely unresolved. The high level of investment in system models to date is such that many users will want to re-use their existing codes – this further challenges the system modeller.

Modelling and simulation is a specialized area requiring high levels of knowledge and skill within the application domain. As system models become more complex and multi-disciplinary, the challenge extends to requiring the support of domain and subject matter experts in order to interact with model components and their respective output. Coupled simulations will need to be built to take address the more complicated problems – requiring heterogeneous models.
Unfortunately, a standard modelling notation (such as the Unified Modelling Language (UML)) does not exist for capturing the full range of information critical to system engineering, including aspects of system configuration, behaviour, requirements traceability and verification results. This makes it difficult to integrate different models together in a seamless manner.

The key challenge of any model and simulation activity is how accurately it depicts the system it is supposed to represent. The verification, validation and assurance (VV&A) of models and simulations will always be top on any list of requirements, as system scale and complexity increases, so too will the VV&A. The trustworthiness of modelling and simulation is essential to its acceptance to support decisions within a systems engineering context. Understanding this characteristic of a model or simulation is important when considering its potential reuse across the system life-cycle or by other organisations.

A particular Research Grand Challenge is the development of a modelling and simulation framework that allows a full system and its environment to be modelled effectively and in a way that allows a designer to explore system properties from different perspectives. Examples include trading system performance against cost and configuration. Other dimensions will allow the systems engineer to investigate the impact of the supply chain throughout the life of a product. The UK Defence Industrial Strategy [8] has introduced the requirement for capability based acquisition – this substantially changes the emphasis away from equipment and performance based assessment to the procurement of higher level capability. This has a profound effect on the modelling and simulation tools used to reach design decisions.

A quest for the modelling and simulation community is to strive towards executable systems models that can start as abstractions of the system design and which can evolve into full representations of the system. The final step is the desire for these system models to be compiled into executable code and downloaded into the required target hardware. Model based systems engineering (MBSE) is a step in this direction but has a long way to go. A key challenge is the use of automated systems tools that allow systems engineers to establish abstract representations of the system and its architecture. These tools are essentially modelling environments that permit the systems engineer to analyse requirements, develop architectures and specify constraints.

Areas for research include:

- How to use heterogeneous modelling tools within a multi-organisation enterprise?
- Accurate representation of the human (physical, cognitive and performance)
- An open systems architecture supporting integration of models
- Generation of executable code from model based representations
- Use of agent technology to facilitate decision making process
- Appropriate abstraction methods permitting fine grained models to course grained representations
- Coupled models that execute in real-time

2.5 Research Grand Challenge (RGC 5) - Through Life Information and Knowledge Management

Most complex systems have a product lifespan that exceeds two or three decades. During this time information and knowledge relating to the product can expand considerably. This can consist of the original design, the decisions taken during the design iterations to the final product and in service context data. At a micro level such information could potentially include all the email traffic associated with the product, telephone calls, meeting memos, diagrams, photographs and other forms of data. Consequently, there is a vast landscape of information which contains the inherent design and aspects of system operation during a long service life. Also within this timeframe the designers of the system are likely to have moved to other jobs or even retired. An important aspect of the eventual systems design is that certain decisions are taken set against a specific requirement or context. Over a long period of time there is a danger that these assumptions are forgotten and the original basis for the design is lost leaving future engineers to wonder why the design emerged as it did. In addition, as systems become even more complex the amount of data that needs to be stored and retrieved throughout the lifetime of the product is set to escalate. Even if all the information could be captured it will still be a challenge to search through the data and select the areas of interest. In order to do this it would be necessary to annotate and tag documents, diagrams and all data so they lend themselves to search later on.

The development of a system that allows the searching, storing, securing this information in addition to methods of annotating the information in a way that permit rapid retrieval is a significant challenge. However, it does not end there - even if the information could be accessed there is a need to support the systems engineer in terms of interpreting the data through knowledge management. Is it possible to construct an information advisor based on agent technologies?

The main aim of this Research Grand Challenge is the ability to efficiently store and retrieve important information relating to a given complex system. It should be possible to access data at the lowest possible level as well as a high level abstraction to satisfy a particular query. Given the potential for vast amounts of data the use of agent based technology to facilitate the search should be considered. These tools will need to be pre-emptive and try to anticipate the needs of the user.
Areas for research include:

- Ensuring the data is secure and reliable
- Information provenance – ensuring what is real remains real data
- How to retrieve information in an intelligent and usable manner
- Development of a diagnostic consultant that is able to search the data for relevant information
- Development of an information agent tool
- Reliable and efficient storage of data
- How will legacy systems be incorporated into the system
- Impact of distributed databases – How is the data managed and what happens if it changes

2.6 Relationship between the Research Grand Challenges

The five Research Grand Challenges are inter-related as shown in Figure 2. Whilst each challenge could be tackled in isolation the real benefit comes if these are regarded as an integrated set of challenges. For example, more advanced modelling and simulation will only be of value if the techniques can be validated, not only against expected or predicted model output but also against real system behaviour. Similarly more sophisticated modelling techniques in the future will rely on greater amounts of data that demand efficient access to a smart information and knowledge management database. The data model behind the whole process will constantly evolve as a given system matures from early concept to in service product.

Articulating grand challenges and scoping them in a way that academia understand is challenging in its own right.

One way in doing this is through industrial – academic partnerships where industry is prepared to share their low TRL requirements with academia. Often insight into real-world problems can be a motivator for many academics especially where funding can be obtained. It’s all very well academia taking on these challenges but if the mechanism for knowledge transfer is not in place then the benefits will be lost. In the UK and US the way forward has been the development of strategic research partnerships between academia and industry. This can be extremely cost effective in terms of accelerated research activity, knowledge transfer or technology pull through, people development and risk reduction. Unsurprisingly, this process is highly dependant on establishing a funding stream for the academic research.

4 Conclusion and Next Steps

This paper has stressed the importance of the systems engineering research community keeping in sight and maintaining a set of Research Grand Challenges that will encourage researchers (who do not normally collaborate) to work together. To construct a roadmap of community agreed Research Grand Challenges requires considerable effort to reach consensus. In particular, the Grand Challenge statements will need to articulate clear criteria for success. These statements must also be endorsed by the various stakeholders including the industry sector. The formation of a roadmap will help to develop a dialogue between systems engineering researchers and industry to promote the emergence of shared systems engineering research agenda with industry impact. This will serve as both a research roadmap, and also an application roadmap of industry relevance. It is hoped this paper will stimulate such a debate that will either agree with the Research Grand Challenges presented in this paper or be encouraged to join the debate and suggest other Research Grand Challenges.

If we don’t try – we may never know.

5 References


