A National Approach to Systems Integration of Large Complex Systems

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ABSTRACT

Large-scale systems, such as rail networks, air traffic control systems, and networked defence systems are vital to national well-being. However, modern systems are becoming increasingly complex in nature and their development is proving problematical both in Australia and around the World. The paper opens by describing the nature of the problem and the best-practice approach taken to overcome the difficulties. From here, the Australian needs for systems integration research and skills development are discussed and finally the paper outlines a proposal to form a defence centre of excellence in systems integration that will form a coherent basis for a national response to the Nation's systems integration research and skill-base capability requirements.

Introduction

Figure 1, extracted from GSAMS (2000), illustrates the increasing complexity of modern electronic systems. Both the civilian and defence sectors have distributed command and control systems that exhibit a high degree of complexity (Athans, 1987) and of which their construction and management challenge the current engineering expertise of even the most experienced companies. Moreover, there is an increasing trend to having the functionality of defence systems determined by software and for complex systems to be integrated into systems of systems and families of systems that underpin defence transformational concepts such as Network Centric Warfare (Cebrowski and Garstka, 1998). Unfortunately, Jones (1995) and others show that there is a very strong correlation between complexity and project failure probability.

While it is fair to say that Information Technology (IT) now underpins our society, it is also fair to say that systems and software development projects are not renown for delivering project success (as defined by stakeholder satisfaction that the right systems has been delivered, on time, to budget, with the agreed functionality). The Defence sector in Australia is not immune from these challenges (DoD, 2001; ANAO, 2000) and the issues that arise are mirrored by similar difficulties across the world.

A scientific crisis (Khun, 1970) is evident: the entrenched management paradigm consistently fails in large, complex, technical projects. There are many reasons for this and they have been well documented but suffice to say that the reasons for failure can be as complex and interdependent as the systems in question and span management, process, technical, and social aspects (Cook, 2000; Dept of the Air Force, 2000).

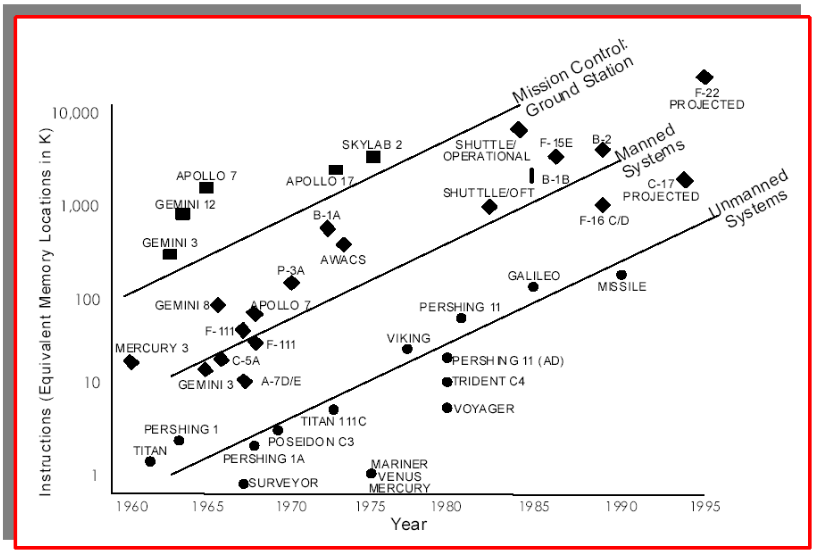

Figure 1: Projected military system complexity (Dept of the Air Force, 2000)

Difficulties of this magnitude do not go unaddressed. For over fifty years the systems engineering (SE) community has been devising scalable methodologies, tools, and techniques that can be applied to projects of all sizes. A significant body of knowledge has been collected, that, when applied effectively, does improve project outcomes as Figure 2 from Honour and Mar (2002) indicates.

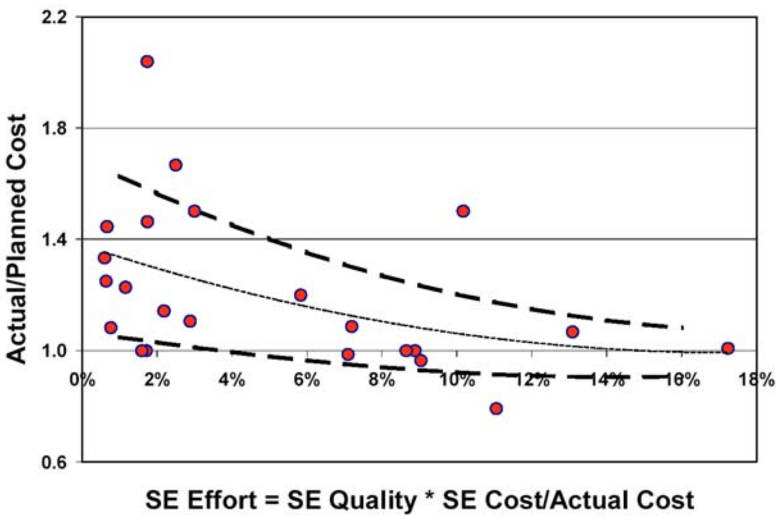

Figure 2: Project cost overrun as a function of SE effort.

What this figure says is that if an enterprise invests in systems engineering, the overall average project cost goes down! To illustrate, a company at world's best practice has an SE Quality index of 1.0 and if 14% of the total project cost is devoted to systems engineering, then the project is liable to be completed on time, within schedule, and will achieve the performance expected. Remember, however, it takes a bold manager to spend $140m in say a

$1 billion task on activities that may simplistically be thought of as technical management overhead. Consider an average, internationally-competitive organisation. It would have an SE Quality index of 0.5 and invest say 4% of a project budget on systems engineering – equivalent to an SE Effort of 2%. The expected overrun will be 30% or around $300m on a $1billion task (a commonly cited overrun percentage for US aerospace contracts). The dotted lines on the graphs in Figure 2 are the 10th and 90th percentiles; hence on 10% of projects meeting the specified criterion, the overrun will be $600m.

The response for informed executives is obvious, invest in systems engineering education, training and utilise it in practice. Indeed that is what the world's large, successful technical organisations have done and they often proudly quote their Capability Maturity Model rating; a metric that reflects their working knowledge of how to handle complexity.

At this juncture it is important to note that not only has the complexity of modern systems increased but the way they are designed is also changing. Traditionally, complex systems were custom-designed from the top-down and built from the bottom-up out of low-level components such as integrated circuits, resistors, capacitors, connectors, etc. About twenty five years ago reuse of assemblies began to become a popular cost and risk reduction strategy. This trend has now become mature to the extent that leading systems engineers advocate extensive use of commercial-off-the-shelf systems components (Hitchins, 2003) at the level of computers, operating systems, sensing systems, application software, etc. This level of systems engineering is frequently referred to as "systems integration".

The integration of large-scale complex systems involves a wide set of skill bases including systems engineering, project management, customer engagement, and deep technical expertise. Although there is growing recognition of the problem, Australia is facing a reduction of indigenous expertise in electronic technology development and industry research and development. This phenomenon is not peculiar to Australia but seems to be a general trend in Europe, the US.

It is not possible to develop systems integration expertise through textbook learning alone. The process requires deep technological expertise and experience in product and system development as well as a robust R&D base. In the electronics sector this translates into depth in microelectronics, embedded real-time software, network technology, photonics, etc. A strong national technology base implies that there is substantial activity in industry in the development of high technology products and that there is sustainable industry research and development. Globalisation and the information economy simply mean that today's competition – economic and military - is based on 'speed and reliability of supply'. Failure to maintain pace with international developments will place Defence in Australia at a global disadvantage. There is an urgent need, therefore, to build integrated military demand and supply chains that support speed and reliability of supply at the highest levels, within and across platforms (ie: systems of systems). International best practice in electronic systems integration, supported by a similarly integrated acquisition process, will contribute substantially to Australia's competitive capability by:

- Reducing acquisition risk.
- Increasing procurement efficiency and reducing capability risk, thereby releasing funds for:
  - Increasing functional capability.
  - Increasing systems interoperability.

Technological advancements are now influencing defence supply chains and directly increasing the complexity of platform and combat systems. As the complexity of systems increases, so does the need (but not necessarily the capability) for integration within and across platforms. Large Defence procurement projects are now resulting in longer lead times, a greater number of project suppliers, and increased acquisition and capability risk associated with systems integration.

This paper discusses the nature of the skills needed to enable effective systems integration and a proposed research centre to ensure that the necessary skills are available within the country to ensure that large, complex systems can be successfully engineered.

Systems Integration Technical Skills

Systems integration: the creation of large, complex technical systems from largely pre-existing, substantial components, requires skills that are not found in the product-level engineering courses taught in the majority of engineering programs. For the purposes of this paper, we have divided the needed system integration skills into three areas: systems architecting, systems engineering specialty disciplines, and detailed technical knowledge.

Systems Architecting

Maier and Rechtin (2000) define systems architecting as “The art and science of creating and building complex systems. That part of the systems development most concerned with scoping, structuring, and certification”. The role of the systems architect is to apply architectural methods analogous to those used in civil works. Such a person concerns oneself about meeting the overall client needs, directing the high-level design, focussing on keeping the interfaces between contractors manageable, and working for the client to ensure that the resulting system satisfies the client’s expectations, even if these are not clearly articulated.

Maier and Rechtin (2000, Chapter 1) state that the foundations of modern systems architecting are:

- The systems approach: systems are collections of different things that together produce results unachievable the elements alone.
- A purpose orientation: systems architecting is process-driven by a client’s purpose.
- A modelling methodology: the creation of abstractions or representations of the system to predict and analyse performance, costs, schedules, and risks, and to provide guidelines for systems research, development, design, manufacture and management.
- Ultraquality: the level of quality so demanding that it is impractical to measure defects. It is a limiting case of quality driven to an extreme beyond statistical quality control that requires a zero-defect approach to design, engineering, manufacturing, assembly, test, operation.
- Certification: a formal statement by the architect to the client or user that the system, as built, meets the criteria both for client acceptance and for builder receipt of payment.
- Insight and heuristics: the ability to structure a complex situation in a way that greatly increases the understanding of it, insight is strongly guided by heuristics that capture the lessons learned from experiences and observations.

Systems architecting is an emerging discipline that draws on the practical experience of creating complex systems that employs qualitative and quantitative reasoning and knowledge in the form of heuristics. The opportunities to practice systems architecting are limited in Australia compared to many other countries because of the modest level of large systems developments that occurs within the country. Fortunately, protagonists such as Rechtin and

Maier have demonstrated, firstly at the University of Southern California and now elsewhere, that the skills of systems architecting are, indeed, capable of being taught effectively at postgraduate level.

The emphasis of systems architecting on meeting client needs and achieving certification is aligned with that of Operational Test and Evaluation which seeks to validate that a system meets the user needs (as opposed to the specification) and as such the early T&E activities such as the creation of Test Concept Documents is part of the system architecting function. Similarly, experimentation that seeks to establish what the user or customer really needs also fits well into systems architecting.

Maier and Rechtin (2000) consider systems engineering as having a different emphasis from systems architecting: the building of complex systems wherein science and analysis takes a higher emphasis than is prevalent in architecting. This is shown below in Table 1.

Table 1 Architecting versus Engineering (adapted from Maier and Rechtin (2000: Preface).

Characteristic	**Architecting**	**Engineering**
Situation	Ill-structured	Understood
Goals	Satisfaction	Optimisation
Methods	Heuristics Synthesis	Equations Analysis
Interfaces	Focus on "misfits"	Completeness
System integrity maintained through	"Single mind"	Disciplined methodology and process
Management issues	Working for client Conceptualisation and certification	Working for builder Meeting project requirements

The difference in the two approaches can be illustrated through the Sydney Opera House. The architect was most concerned in providing the stakeholders with an iconic building and in this instance many of the concerns of the civil engineering team became secondary considerations. (This situation would have been reversed were value for money the driving project success criterion.)

Systems Engineering Speciality Disciplines

Systems engineering harnesses a considerable number of specialist disciplines that are not in evidence at the equipment level, see Figure 3. Systems integration, (which can be thought of as an instance of systems engineering wherein the components from which systems are composed are substantial equipments) draws on these disciplines.

Technical skills of interest in this context would include systems analysis disciplines such as performance analysis, reliability analysis, safety engineering, risk assessment, electromagnetic compatibility analysis, maintainability analysis, etc. All of these are well established and many are taught at postgraduate level in Australia although not in a dedicated systems integration context.

Deep Technical Knowledge

The traditional route of formation for a systems architect or engineer is through substantial experience as a detailed design engineer followed by further experience as a project engineer responsible for managing a design team. It is in this activity that the systems practitioner gains the practical hands-on knowledge that refines the heuristics that will be used later to structure and synthesise systems. Such knowledge is crucial to predict various system-level properties from the knowledge of the properties of the subsystems. As an example, in order to predict the level of service, say, that a communications systems architecture or a mission system will be able to provide to the user community, one would need to have extensive knowledge of the behaviour of the subsystems and their interfaces. In order to arrive at the performance estimate, it is also necessary to draw on systems-level techniques such as information theory, queuing theory, network analysis, etc.

- Engineering Management
- Organisational Architecting
- Requirements Engineering
- System definition and requirements analysis.
- Functional analysis.
- Requirements flow down and allocation.
- System synthesis.
- Trade studies.
- Modelling and simulation.
- Specification generation.
- Configuration management.
- Risk analysis and management.
- Test and evaluation.
- Reliability.
- Availability.
- Maintainability.
- Interoperability.
- Compatibility.
- Logistics supportability.
- Transportability.
- Human engineering.
- Systems integration.
- Safety.
- Manpower supportability.
- Training.
- Electromagnetic compatibility.
- Parts engineering.
- Survivability and vulnerability.
- Integration.
- Contamination and corrosion.
- Value engineering.
- Diagnostics.
- Power efficiency.
- Integrity.
- Capital costing.
- Tempest.
- Trusted systems.
- Test design.
- Verification and validation.
- Production engineering.
- Team building and working
- others

Figure 3: Example systems engineering specialty disciplines (Cook, 2004)

Systems Integration in Australia

Major infrastructure in both the defence and civilian sectors is characterised by deep complexity and consists of distributed interacting electrical and information systems. In Australia however, some of the high profile systems integration projects have been in the defence sector, with a number of major $1B projects experiencing significant problems during design and integration.

The defence sector in Australia has similar traits to overseas defence sectors, however what is different is the number of projects and the size of system integration companies. There may be only one or two large projects going at any one time in Australia. As a result Australian companies are not being exposed to the larger issues and high-level system technologies and techniques which will likely influence a high percentage of future system acquisitions. There is a danger, therefore that Australian electronics industry capabilities will not grow in accordance with Government aims but rather they will be further marginalized, placing Australian electronics industry involvement at the lower levels of the defence systems enterprise.

A second factor, noted in a number of defence reviews and hearings, has been the poor track record of Defence and Defence Industry in a number of recent major electronic systems projects - the Collins Submarine Combat System being one such high profile project. Further, even for relatively successful projects, there have been problems in sustaining adequate levels of systems expertise within industry and government for the duration of the project. This has led to an apparent consensus within the Defence Material Organisation and industry that there is an urgent need to "raise the capability bar" in electronic system skills, especially integration skills, within both Australian industry and Defence.

The recent Australian Defence Electronics Sector Plan "Investing in the Knowledge" (DoD, 2004), in acknowledging these deficiencies, has recommended particular focus on developing the system integration capability in government, industry and academia. The Electronics Sector Plan indicates it is important to foster collaboration between industry, government and universities to "increase defence industry knowledge and sustain a national skill base in technologies critical to the integration, through-life support of sub-systems, systems and systems of systems".

In line with international developments, Australian defence and civilian infrastructure and assets are becoming more complex as they become more interconnected and dynamic in nature. The capability of the nation to undertake the system design and integration is dependent on the nation's skill base in a wide range of disciplines. The problem with not having a constant stream of similar projects (e.g. satellite communications, ship construction) is that the skill base becomes fragmented and there are limited numbers of very experienced people. This does not mean those who are recognised as leaders in an area are not experts. It means there is limited opportunity for them to capitalise on that technical and project experience in follow-on projects.

Another important demographic feature of Australia is the cross fertilisation of engineers between the defence and civilian sectors. This means practitioners will attempt to stay involved in their disciplines (e.g. mechanical, electronic, software engineering) by moving to where the large projects are. The advantage is Australian engineers experience a wide range of projects and environments. However, this is at the expense of significant technical depth in important engineering disciplines. For example, once a large software project is successfully completed, what happens to the team, the team leader or the project manager? These experienced people may well move on to a smaller project and may never undertake as large a project. This is essentially lost "knowledge capital".

Addressing the nation's ability to undertake large scale complex projects needs to be tackled at a national level and encompass both the defence and civilian sectors. This implies a more proactive approach in addressing systems integration skill base development. Later we discuss the elements that make up this proactive approach. However, at this point it is important to understand that Australia needs to be addressing this problem in a number of dimensions and that unless there is a coordinated approach, the nation may be unable to maintain a viable engineering base to successfully undertake large scale defence and civilian projects.

The Role of DSTO in Systems Integration

At present, the Australian Defence Science and Technology Organisation (DSTO) is the pre-eminent organization within Australia for operational analysis, experimentation, modeling and simulation and electronics systems R&D. It is to be expected that any major attempt at military transformation by defence and industry, particularly in areas such as future systems integration, will need a high level of DSTO support.

The DSTO's laboratories at Edinburgh, South Australia constitute a major national resource in electronic systems R&D, as well as in Information and Communication

Technologies (ICT). There are also within the broader DSTO substantial (by national standards) capabilities in modeling and simulation, experimentation, and operational analysis. At Edinburgh are also major facilities for R&D in systems analysis and integration, for example the Combat Systems Research Centre, the Mission Systems Research Centre and others. There are also burgeoning programs, such as Automation of the Battlespace, which will introduction requirements for new methods of systems integration.

In addition DSTO is a major collaborator in international defence R&D programs, especially with the US and UK, but also with other significant players including Canada, France, Sweden and Singapore. These collaborative programs, in terms of size and achieved outcomes, outstrip any similar international R&D programs in the Australian civil sector.

DSTO is thus well placed to assist in transferring to Australia new knowledge in systems development and integration, particularly in electronic systems. Also, it is and will continue to be a significant player in international R&D programs with other nations, and is well positioned through its in-house R&D programs to assist in co-development activities involving industry.

Following recent reviews of Australian Defence acquisition projects, DSTO was identified as the key technical advising agency and the key to identifying technical risks in all of the ADF's projects. CDS is now required to sign off on risk assessments for all projects progressing through the formal approval processes. The assessments will be against Technical Risk Levels for technology issues and System Readiness Levels for integration related issues.

One of the difficulties in DSTO undertaking this critical role is the breadth of technologies that DSTO must support, the significant reduction in size of DSTO over the past 20 years, and the need to maintain a world-class research environment with an emphasis on excellence in science and technology. It is this very excellence that the ADF calls on for technical expertise that is under threat if DSTO is required to support all projects in the ADF at a more detailed engineering level, i.e. not addressing the deep science and technology issues.

Hence, there is a need to develop a national approach that can build on the science and technology skills of DSTO as well as the national support base (academia and industry) to address the systems integration risks. DSTO can then continue to play its critical role in providing advice to the ADF helping to build expertise in industry and academia in critical technologies for future defence projects as well as supporting the national research base for future Australian products and technologies.

DSTO also plays a critical role at defining the future capabilities of the ADF (out to 20 years) and that a diversion to more short term (1-2 year) engineering design and engineering integration will only reduce the ADF's ability to address future technologies.

Already, DSTO is integrated into the Capability Development Group, which looks at the "pre-1st pass" capability options for the ADF projects. DSTO brings to bear the R&D modelling and simulation infrastructure to help define the future capabilities.

Systems Integration Skill Base Development

It is useful to identify the types of knowledge we wish to instil and hence the personal competencies we wish to create when considering skill-base development. Biggs (1999) uses four interactive categories. The first is declarative or propositional knowledge that refers to knowing about things. Biggs goes on to say that this type of knowledge accrues from scholarship and not from personal experience but it is public knowledge that is subject to rules of evidence that make it verifiable, replicable and logically consistent. It is in text books and it is what teachers declare in their teaching. This is exactly the type of knowledge one expects to be transferred in a university setting.

In contrast to this, procedural knowledge is skill-based and lacks the high-level declarative foundation. It is about knowing what to do in a given situation in terms of the sequences to follow and actions to perform and the competency to perform both correctly. The teaching of procedural knowledge requires a different approach to the teaching of declarative knowledge. Procedural knowledge is more strongly workplace-related and learning requires experience of a sequence of practical examples. The master-apprentice model comes to mind as a well-used method of imparting this form of knowledge whether it is to a research student or a trade apprentice.

Biggs' third category is conditional knowledge that incorporates both procedural and declarative knowledge at a theoretical level so that one knows why, and under what conditions, one should take a particular approach.

Biggs' fourth category is functioning knowledge that is within the experience of the individual who can put declarative knowledge to work by solving problems, designing systems solutions, and understanding how well they can be expected to perform before they are built. Functioning knowledge requires a solid foundation of declarative knowledge, mastery of relevant procedural knowledge (knowing how to do things), and knowing when to do which things (conditional knowledge).

In order to reduce the risk of undertaking systems integration activities, it is imperative to have a corps of staff that has a strong functioning knowledge of the relevant skills. The formation of engineers with these characteristics requires a rather more rich teaching and learning environment than is commonplace in Australia. Firstly, the necessary declarative knowledge must be available and this requires the contribution of interested academics over a period of years to select and develop the collection of materials and to build a "school" of thought. This knowledge would reside in university libraries, within active systems engineering and research departments, and specialist knowledge repositories such as the one maintained by the Systems Engineering and Evaluation Centre at the University of South Australia, that holds systems engineering manuals, guideline documents, and unpublished material that captures lessons learned from the practice of the disciplines. Secondly, the teaching staff must have an intimate knowledge of what needs to be done and how to go about it. This procedural knowledge takes many years to accumulate. Thus the teaching staff need to be unusually experienced as well as being highly-qualified academically. Moreover, current practice is rapidly evolving and it is essential to intimately involve industry to capture this dimension as well as to provide access to contemporary facilities and realistic problems.

The development of functioning professional knowledge also requires considerable exposure to systems integration problems. This is often hard to achieve in the Australian defence industry because the scale of operations is such that it is not uncommon to find staff who have only worked on a few projects in their working life. The solution is to create a centre of expertise that meets Australia's unique circumstances; one that can draw many industries together with the academic and DSTO research communities to create a valuable pool of people with functioning knowledge and the infrastructure needed to support it.

A National Approach to Systems Integration

The recent Defence Electronics Sector Plan "Investing in the Knowledge", has recommended the creation of a National Centre of Excellence in Electronics Systems Integration (NCEESI). The purpose of the Centre would be to foster collaboration between industry, government and universities to "increase defence industry knowledge and sustain a national skill base in technologies critical to the integration, through-life support of sub-systems, systems and systems of systems".

The Defence Science and Technology Organisation (DSTO) of Australia has a mandate to investigate the deep technological issues that arise in the integration of complex defence projects. To do this, DSTO has established a number of virtual environments to support the development of complex mission systems (for aircraft such as Airborne Early Warning and Control), Air Warfare Destroyers, ANZAC frigates, Electronic Warfare integration, and submarine combat system architectures. These facilities are now being linked in order to develop understanding of the networking requirements and the systems integration issues that will arise from distributed command, decision and control systems.

DSTO has in recent years established Defence Centres of Excellence (known as Centres of Expertise) that focus and align DSTO science and technology investigations with universities and industry. The scale of DSTO's systems integration work in the past five years has increased significantly, to the point that expertise across Australia is being built in core areas that will underpin SI research and skill base development in Australian Industry.

DSTO is planning to establish a Centre of Excellence in Systems Integration that addresses the issues raised in this paper, supports its mandate to address SI aspects of defence projects, and provide a national support base in core systems integration expertise. This national support base will over time play a crucial role in supporting DSTO, the Australian Defence Force's acquisition body (DMO) as well as the civilian industry base.

Clearly, such a Centre would have the potential to address many of the issues concerning Australian capabilities in military electronic systems integration, especially industry capabilities, providing a stakeholder group can be formed with the will and incentive to direct and support the Centre's programs. A recent consultant's report indicates that there is support for the concept from DSTO, DMO, defence and civil industry, the South Australian Government, and the Systems Engineering and Evaluation Centre (SEEC) at the University of South Australia. The Centre would provide a nucleus to systematically address perceived deficiencies in national system integration capabilities, and to pursue opportunities for greater Australian involvement in electronic systems projects.

Consultation with industry has revealed that industry would be interested in receiving the following services from the Centre:

- Post Graduate Education and Training (including short courses, seminars and conferences) to generate more experienced, highly skilled and international-standard software and systems engineers (development of an enduring skills base).
- Systems integration research and development in support of projects identified in the Defence Capability Plan.
- Provision of, or access to, Systems Integration Facilities in support of education and training, modelling and simulation, consultancies (especially to SMEs), etc.
- Access to DSTO laboratories and facilities to facilitate, for example, pre-bid kit testing (i.e: company test and evaluation)

Conclusion

Systems integration skills are becoming increasingly recognised as vital if Australia wishes to remain active in large-scale, complex-system development. A case has been made about what these skills comprise and a national response has been outlined in the form of a centre of excellence in systems integration to provide services to Australian Defence, defence industry, civil industry, and to individuals. These services to be provided can be broadly described as systems integration research and consultancy, skills development, and organisational capability improvement.

Currently, the advocates for a Centre of Excellence in Systems Integration are preparing a business plan. Further details can be obtained from the authors.

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