Systems Architecting for

3G SAF Transformation

ABSTRACT

The transformation of the Singapore Armed Forces into a fully networked force operating with network-centric system of systems is a strategic imperative for the Third Generation Singapore Armed Forces (3G SAF). Systems architecting has been identified as one of the effective means to coherently realise system of systems capabilities. The successful application of this strategic competency will enable us to realise our potential and create an even more capable 3G SAF.

This paper presents a working understanding of Systems Architecting (SA), a seven-step SA methodology and the architectural framework currently adopted by DSTA's Directorate of Masterplanning and Systems Architecting. It also highlights some of the well-known heuristics and principles in systems architecting.

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INTRODUCTION

"The transformation of the SAF to exploit rapidly emerging technologies and concepts is a strategic imperative for the 3G SAF. These will lead to changes in organisation, less demand for conventional platforms, more demand for less visible technologies like information systems, precision weapons, electronic warfare systems, unmanned platform technologies, and a new type of soldier who is trained to exploit these capabilities." Minister for Defence Teo Chee Hean said this in Parliament in March 2004 when he introduced Transformation and the Third Generation Singapore Armed Forces (3G SAF).

Systems Architecting was identified as one of the effective means that will facilitate this new thrust of Transformation and help realise our capabilities in building a system of systems. Within DSTA, the Directorate of Masterplanning and Systems Architecting (DMSA) has been formed to spearhead the build-up of this strategic system competency and work with the SAF to create and build a system of complex systems.

WHAT IS SYSTEMS ARCHITECTURE?

Systems architecture is a structure comprising key entities or components, interconnections and interactions (Hastings, 2005). In other words, it provides the structure or skeleton of the system, as well as the principles, rules and guidelines governing the system design, creation and evolution. It also provides the broad framework, system level constraints as well as relationship for the sub-structures and modules of the system. It determines the options available for future development.

Systems architecture is essential for order, effectiveness and efficiency. It typically shapes systems behaviour and may provide clues on possible emergent behaviour. It is also a useful tool to address systems attributes such as complexity, flexibility, interoperability, modularity, robustness, vulnerability, scalability, sustainability and impact on the environment (physical, political, social, etc). Varying the systems architecture allows one to address alternate forms that the system can take. Ideally, the architecture should be enduring and robust for a long time so that it can absorb future developments.

Systems architecture is different from a design concept, which describes an engineering system in terms of abstract concept that involves symbolic attributes and possibly also relations among design components. A design concept is an outline or an illustration whereas systems architecture goes further and provides a structure of conceptualisation, description, or design of the system, its components, their interfaces and relationships with internal and external entities, as they evolve over time.

WHAT IS A SYSTEM OF SYSTEMS?

Generally, a system can be defined as a set of different elements so connected or related that it performs a unique function that cannot be achieved by the individual component elements alone. Incomplete or erroneous integration of the component elements will result in the system becoming incapable of performing its required functions. A system can be described as simple or complex, small or large in scale. Our focus on systems architecting for the transformation of the 3G SAF is naturally on the complex systems.

A complex system comprises many mutually interacting and interwoven (complex) parts or entities which, either by design or function or both, are difficult to understand and verify.

Figure 1. Examples of complex systems in defence

The complex relationships among the component parts or entities may also evolve over time or in accordance with system states. The interfaces between the component elements are mainly software-driven. Any incomplete or erroneous integration of these component elements will trigger the complex system to malfunction in varying degrees. Figure 1 shows examples of defence systems that are considered complex.

The integrated air defence network as illustrated in Figure 2 is a good example of a system of systems (SoS) comprising advanced jet fighters, early warning aircraft, either standalone or platform mounted advanced radars and surface-to-air missile systems, anti-aircraft artillery and Command and Control (C2) network. The loss of any part or component of the SoS may degrade the performance or capabilities of the whole SoS. An SoS typically exhibits five principal characteristics (Maier, 1996):

Operational Independence

The various component elements in the integrated air defence system are able to operate independently and usefully on their own.

Managerial Independence

The component elements are separately acquired and integrated, and continue to maintain an operational existence independent of the SoS.

Evolutionary Development

The development and existence of an SoS is evolutionary, with functions and purposes either added, removed or modified as time goes by.

Emergent Behaviour

An SoS performs functions and carries out purposes that do not reside in any of its individual component systems. It is the socio-technical aspects of the SoS that are dynamic in nature, involving multiple time scales and uncertainty, and likely to have emergent properties. Voluntary and collaborative interactions among the components often result in new emergent properties or behaviour that are desired and fulfill the primary purpose of the SoS. For example, the component elements (fighter jets, ground radars, AWAC platforms) of an integrated air defence network interact with one another to achieve the goal of defending a nation s airspace, which cannot be achieved by the individual components.

Large Geographical Distribution

As an illustration, an integrated air defence network does not reside within a building, a localised area, nor an airbase. Instead, it spans a wide ground coverage in the order of tens or hundreds of miles, and components can be separated by thousands of feet in altitude. Such a vast geographical coverage means that the component elements exchange only information and not substantial quantities of mass or energy.

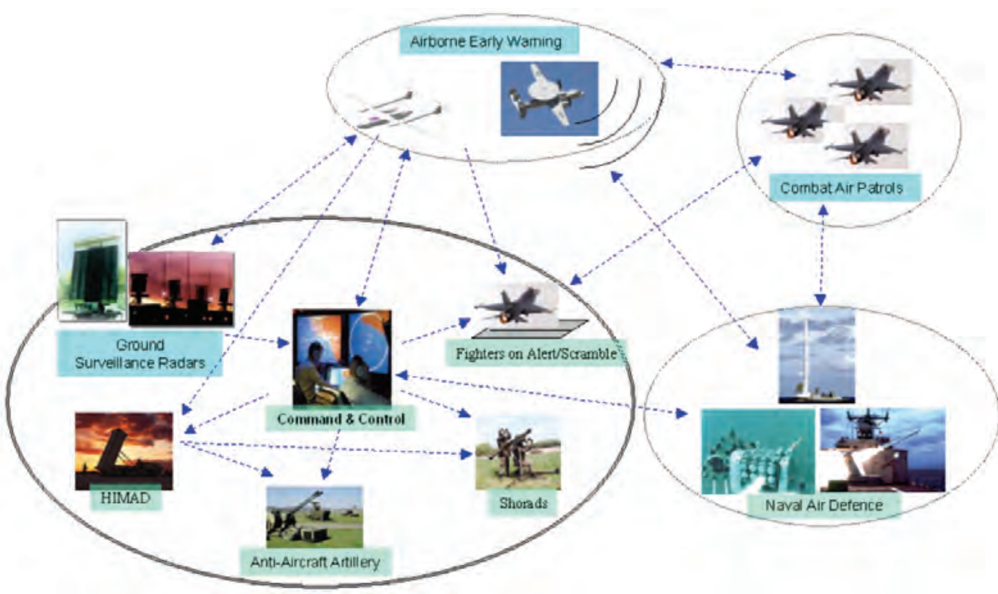

Figure 2. Integrated Air Defence Network - A System of Systems

WHAT IS SYSTEMS ARCHITECTING?

Systems architecting can be introduced as both an art and a science, of designing and building effective, efficient SoS (Rechtin, 1997). It is an art because it aims to balance local needs in the interest of a global optimum and strives for qualitative worth, i.e. client satisfaction. It is a science because it uses architecture as a tool for addressing global integration, consistency and integrity in design.

An SoS is simply too complex to be treated by quantitative engineering analysis alone. The optimal configuration and deployment of various air defence assets, such as advanced jet fighters, early warning aircraft and surface-to-air missile systems, as an effective and efficient integrated air defence SoS is an example of the complex problems involved in such an SoS.

Systems architecting is hence employed to visualise, conceptualise, plan, create and build such an SoS. It aims to bring together various systems with the purpose of achieving operational capabilities greater than the sum of what each individual system could provide. It deals largely with non-measurables using non-quantitative tools and guidelines based on practical lessons learnt. For example, by combining the sensing picture of both ground and air surveillance assets, an integrated time-coherent air picture can be formed with overlapping coverage for greater robustness. Experiences from air combat exercises with other air forces may help us identify the minimum relative combat power for effective engagements, which is an important consideration in providing an SoS architecture for an effective integrated air defence capability.

Systems architecting is an art because people are an important but not necessarily predictable factor. More often than not, it is not possible to arrive at the SoS architectural solution through analytical or concrete mathematical derivations. Indeed, the solution is often derived through intellectual discussions and engagements with key decision-makers and stakeholders, and by leveraging holistic experiences of leading domain experts and thinkers, senior commanders, as well as other established large-scale systems engineering practitioners. In the process, the systems architecting team may have to persuade and bring certain stakeholders onboard, communicating using animation or demonstration to put across new ideas and developing a consensus on the utility and effectiveness of new warfighting concepts.

On the other hand, systems architecting can also be an analytical exercise to determine the optimal combination of resources (people, organisation, equipment, weapon), systems (hardware, software, network), and their interactions to achieve the desired outcome. For example, a more capable air surveillance network may reduce the need for more fighters on alert, thereby reducing the stress on ground resources. Modelling and simulation may be carried out to analyse the relationships and determine the optimal combination.

Systems architecture provides a holistic view of how various systems interact with one another across space and time, for example, how the various air defence assets and the C2 network react and interact with one another in the face of approaching air threats. This is essential for planning and the identification of gaps. It establishes a framework for identifying existing and desired technical capabilities relevant to the systems development, and develops an understanding of how they complement one another. It examines and develops the desired interfaces and the relationships between sub-systems.

Effective systems architecture helps to maintain overall systems integrity and balance conflicting demands in design, engineering and development, as the system grows in complexity. It also takes into account factors like the fiscal, social, organisational, cultural and safety aspects of people and society and the drivers of performance in the SoS architecture. This will ensure that the SoS developed would be operated in an integrated and coherent manner by the operators and their organisations in a real environment, leading to a quantum increase in warfighting capability.

VALUE OF SYSTEMS ARCHITECTING IN DEFENCE

Systems architecting is an effective means to coherently realise a network-centric SoS capability. The mutually reinforcing relationships within an SoS reduce the weaknesses of each component element and enhance "jointness" and the overall effectiveness. This results in the creation of emergent capabilities out of the SoS, leading to a higher order of asymmetric capability or warfare. For example, at the individual system level, an Apache helicopter engages its own tank targets. At the SoS level, the combined radar coverage of a number of Apaches as well as an integrated datalink network among them and other ground forces can actually allow the helicopters to perform their anti-armour missions more effectively, and be part of the ground surveillance network.

The systems that the SAF needs for its transformation into a 3G armed force will be increasingly complex, versatile and intertwined. In the 3G transformation, the SAF will be adopting new concepts that the more developed countries are now experimenting with. To do this well, we will need to examine these concepts from an SoS approach. Looking at the various systems in a holistic manner will allow many of the non-obvious compatibility and interoperability problems to be surfaced at an early stage. Options can be generated when the unknowns are discovered and studied using a wide spectrum of analytical techniques and tools. It would be very costly to all stakeholders to wait for the unknowns to be manifested during implementation, integration testing or during subsequent operations.

In the 3G SAF s transformation journey, systems architecting will be both an enabler and a catalyst. As an enabler, it identifies the necessary conditions for us to embark on the journey and to fuel the journey itself. As a catalyst, it stimulates us to review the way we think, organise, equip, train and fight the future war. As an ongoing process, it creates new relationships, and through matching, balancing and compromising proposed functions and forms, it helps to enhance or create new operational concepts to meet the challenges of the changing environment.

Through systems architecting, we will be able to better leverage disruptive technologies and new warfighting concepts. It will enable us to better leverage the high educational profile of our national servicemen and the excellent inter-Services rapport the SAF enjoys. With effective systems architecture, a new generation of capability would be built for the 3G SAF transformation, which would be adaptable, flexible, sustainable, scalable, responsive and robust. The SoS level of defence capability is uniquely indigenous and cannot be easily duplicated or matched. It is the synergy gained from integrating different platforms, sensors and weapons at the SoS level guided by robust warfighting concepts that will give the SAF greater potency in the battlefield.

A significant qualitative measure of the worth of systems architecture is the satisfaction enjoyed by MINDEF and the SAF. They will be more aware of the architecture s enhanced effectiveness and hence have greater confidence in its optimised capabilities at the SoS level.

WHEN DO WE NEED SYSTEMS ARCHITECTURE?

Systems architecting to build up a new capability based on SoS architecture may be triggered by an actual or anticipated change in the nature of threats, or the expected availability of revolutionary technology that may allow a more effective SoS architecture to be constructed. Typically, this is carried out in conjunction with the long-term strategic planning processes in MINDEF and the SAF. On the other hand, a review of current SoS architectures may become necessary when the underlying assumptions or considerations change. This can be due to feedback of shortfalls in key component systems during implementation or limitations and gaps of existing SoS architecture identified through exercises or periodic Operations and Technology reviews (Geritt, 2000a). Figure 3 illustrates the three key phases to realising an SoS architecture: namely, Planning and Analysis phase, Systems Architecting phase, and Implementation phase. The establishment of clear processes and governance in each of these phases will help the many programme teams working on a capability programme to adhere to the systems architecture during project implementation in order to arrive at the desired SoS capability in the theatre of operations.

PRE-REQUISITES FOR SYSTEMS ARCHITECTING

Partnership between Operations and Technology personnel is vital to the success of systems architecting. The involvement of Operations personnel provides valuable domain knowledge and their participation throughout the systems architecting process will facilitate their subsequent endorsement

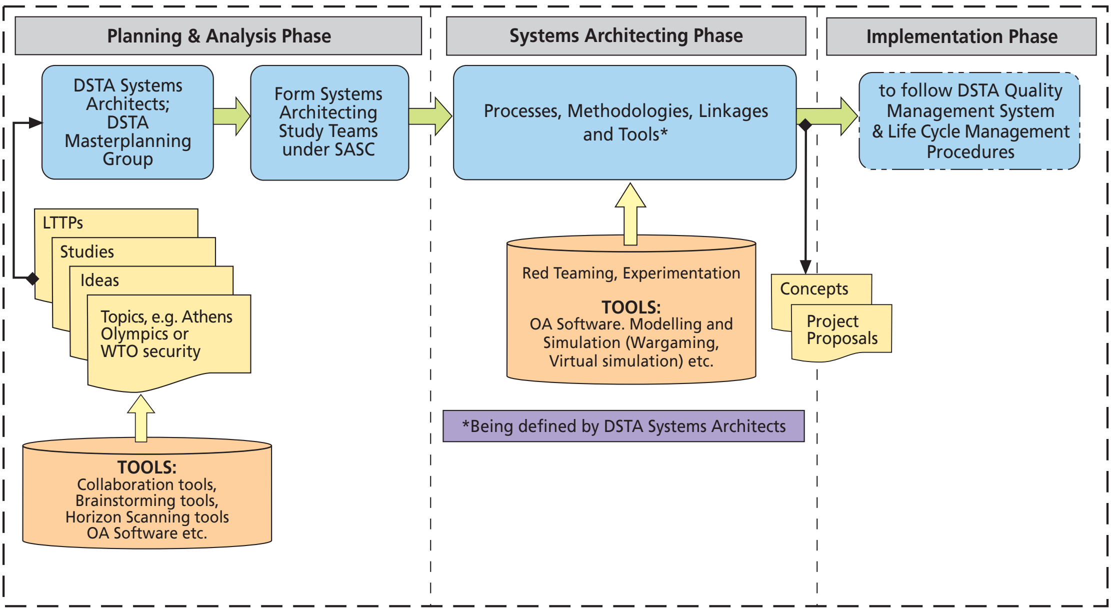

Figure 3. Three key phases in realising an SoS architecture

of the architectural solution. The combined knowledge and creativity of the Operations-Technology team will lead to the innovation of an operationally sound and realisable Concept of Operations and SoS architecture.

A Red Team is important in the formulation of the systems architecture. A Red Team plays not only the adversary, but also the devil s advocate and related roles. Aggressive red teaming challenges emerging operational concept for weaknesses before a real adversary does. A Red Team can also temper complacency that usually occurs after success.

Systems architecting requires a multi-disciplinary and integrated team of Operations, Technology and Red Team subject matter experts (SMEs) to collaborate and work on a comprehensive range of issues. For more integrated operations across Services, the Operations group could include relevant SMEs from the various Services. Likewise, the Technology group could include relevant SMEs from the various technological domains. In this way, the integrated systems architecting team would have the necessary expertise and experience and this will facilitate the generation of innovative yet practical ideas to arrive at an SoS architecture that could offer robust capabilities to meet the operational objectives.

It is also necessary to establish clear objectives in order to stay focused. The objectives could be defined as a form of capability, whether enhanced or new. The objectives may be specific (as in "to reduce battle procedure planning time by half") or it may be general (as in "the development of a new capability or operational concept"). The former involves transforming current capability where current conditions are known and the outcome is more measurable. In the latter, the experience, knowledge and creativity of those involved are important.

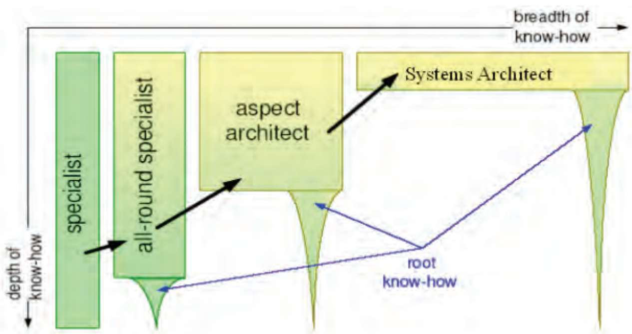

Figure 4. Profile of a Systems Architect (Geritt, 2000b)

ROLE OF A SYSTEMS ARCHITECT

Having a team of competent and experienced Systems Architects is another important factor for successful systems architecting work. Figure 4 illustrates the profile of a Systems Architect (Geritt, 2000b). The Systems Architect is the ultimate judge and coordinator of the integrated systems architecting team. He is an expert of experts. He knows which talents should be brought in to join the team. In order to visualise goals and yet exercise control, he has to exert authority. He has to be conceptual and pragmatic at the same time. This is a demanding role which requires him to be a good communicator, a multi-tasker, a generalist, and also a person who is open-minded, absorbs knowledge quickly, and is able to give constructive criticism. The Systems Architect understands and designs at a global level, acting as the single focused mind behind the SoS architecture. At the same time, he possesses wide-ranging knowledge including ongoing acquisitions and R&D programmes, so that he can identify solutions for the SoS. He serves the clients (key stakeholders) and not the builder (the technical teams), but he works jointly with both clients and builders on problem and solution definition. He converts the clients' needs into the systems architecture and is mindful of the unarticulated needs. Through the architecture, he creates both opportunities and constraints for future development. Playing a pivotal role in trade-off decisions, he is therefore the protector of future generations from today's decisions. (Lui, 2005).

HOW DO WE GO ABOUT SYSTEMS ARCHITECTING?

As an initial answer to this question, we propose a seven-step methodology as illustrated in Figure 5. This methodology is expected to evolve as we accumulate experience through practice and collaboration with external agencies. The seven steps are as follows:

a. Establish the Objectives for Systems Architecting and Measure of Effectiveness

The objective of a systems architecting project can be to construct a new SoS architecture to counter a new threat. For example, Japan's Self Defence Agency may view Theatre Ballistic Missiles as a new threat that requires a new SoS to deal with it. Alternatively, the objective can be to review the existing SoS architecture to enhance responsiveness and robustness. An example would be enhancing Singapore's Island Air Defence against terrorist attacks. With respect to the objectives, it would be necessary to establish the measures of effectiveness (MOE) for the architectural alternatives to be identified (through the systems architecting process) and evaluated. The top level MOEs are typically in operational and resource dimensions.

b. Create the Framework

The framework establishes the key local and global constraints, as well as key enablers required in achieving the objectives of the systems architecting project. Examples of constraints are current architecture and boundaries of operations. It is important to

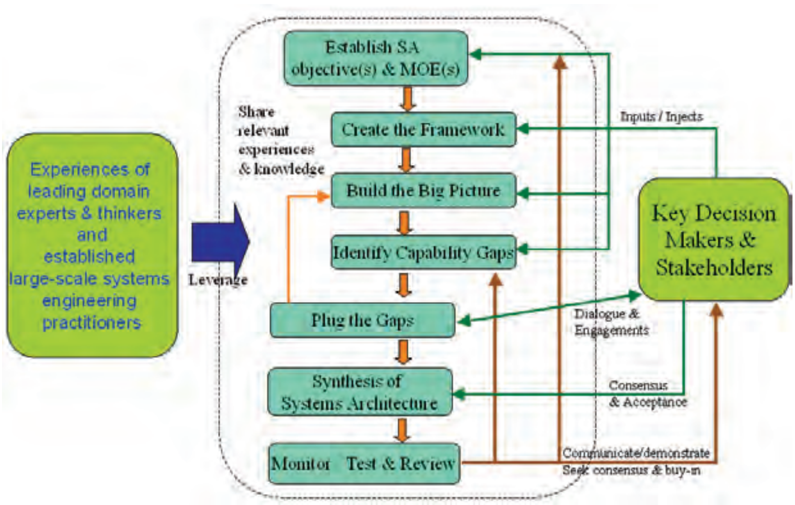

Figure 5. A seven-step methodology for Systems Architecting

review whether such constraints can be overcome through other means such as policy changes. The enablers could be technologies that are building blocks for a global solution.

c. Build the Big Picture

This means constructing an SoS architectural solution with various building blocks and components so that every component operates coherently to achieve the desired capability. Tools for building systems architecture such as Popkin, Vensim and Concept MAPs may be used. The DMSA Architectural Framework described in a subsequent section defines various Operations-Technology views that may be generated to describe the solution.

d. Identify Capability Gaps

It is important to review the solution and analyse the system dynamics to identify gaps in areas such as coverage, range, survivability and vulnerability. Besides red teaming, sensitivity checks on key underlying assumptions and considerations should be carried out to ensure the robustness of the solution.

e. Plug the Gaps

This may mean an adjustment or refinement of the SoS architecture. In some cases, to close the gaps identified, it may be necessary to review the constraints and re-optimise where necessary and possible, either at the global or local level. Such optimisation may even have to be carried out across SoS architectures at the SAF level for the various capabilities. In some cases, the SoS architecture may even have to be reconstructed.

f. Synthesis of Systems Architecture

Proper documentation of the appropriately endorsed architectural solution must be carried out to consistently facilitate promulgation, communication, governance and systematic implementation.

g. Monitor, Test, Review

It is important to monitor the implementation of the SoS architecture and to subject the SoS architecture to varying levels of tests and experimentation at each phase of implementation to check and verify performance against the MOEs and other important systemic attributes. A core group of the systems architect team may remain to serve as the architectural configuration manager. A review of the SoS architecture may become necessary when underlying assumptions change (for example, performance shortfalls in key component systems during implementation).

It is necessary to solicit inputs from key decision-makers and stakeholders in the early stages of the systems architecting process, so that the objectives, MOEs and framework are better aligned. The customer may also have strong views based on heuristic and field experiences on what the architectural solution should or should not be, which may help to quicken the process of finding a solution. The 'intuitive architecture alternatives' of decision-makers or experienced operators should be evaluated and useful insights should be documented as part of the process to arrive at the final architectural solution. Such early dialogue and engagement will lay a good foundation for eventual consensus and acceptance of the recommended architectural solution.

Relevant experiences and knowledge should be shared whenever necessary. This helps to create a common system reference model among the systems architect team. It facilitates collaborative thinking and consensus within the team during the process. It would also be helpful to establish heuristics and principles that are deemed relevant to the objectives of the systems architecting project. The team should also leverage the diverse and in-depth experiences of leading local and international domain experts and thinkers, senior SAF commanders, as well as other established large-scale systems engineering practitioners.

GENERAL PRINCIPLES AND HEURISTICS FOR SYSTEMS ARCHITECTING

It is essential to have a global understanding of the entire problem or requirements. However, it does not mean that localised problems are totally ignored. It is important to strike a balance - between conflicting interests and requirements; short and long-term goals; efforts and risks; effectiveness and costs. Most importantly, from a global outlook, the SoS architecture must be consistent and remain focused on its objectives, possess a certain degree of systems integrity, be simple yet elegant in function. It must be remembered that complexity does not always serve the required function or efficiency.

It is important to ensure that the SoS architecture possesses stable intermediate forms (Maier, 1996). There may be occasions, in the heat of a battle for example, when certain component elements fail or are lost suddenly. An architecture that is stable and robust will not fail catastrophically in such an event, but will instead be able to effectively fall back on less complete yet operational configurations capable of achieving all or some of its objectives. It also allows a more rapid development and phased implementation of the SoS within the overall architecture. Hence, each of the intermediate forms or configurations should also be technically, economically and politically self-supporting.

The emergence of SoS capabilities occurs through the interaction of its component elements at the interfaces. It is important to pay attention to and leverage the interfaces. Such interfaces define the entire architecture, especially when component elements are highly independent operationally and managerially. For example, the Command and Control, Communications and Intelligence network in an Integrated Air Defence SoS defines and provides the architecture in which independent elements of sensors and weapons and command elements reside. On the other hand, it is important that each element imposes minimal essential requirements for the others to avoiding stifling one another.

Communication between component elements, which are typically dispersed geographically, is the principal enabling technology for an SoS

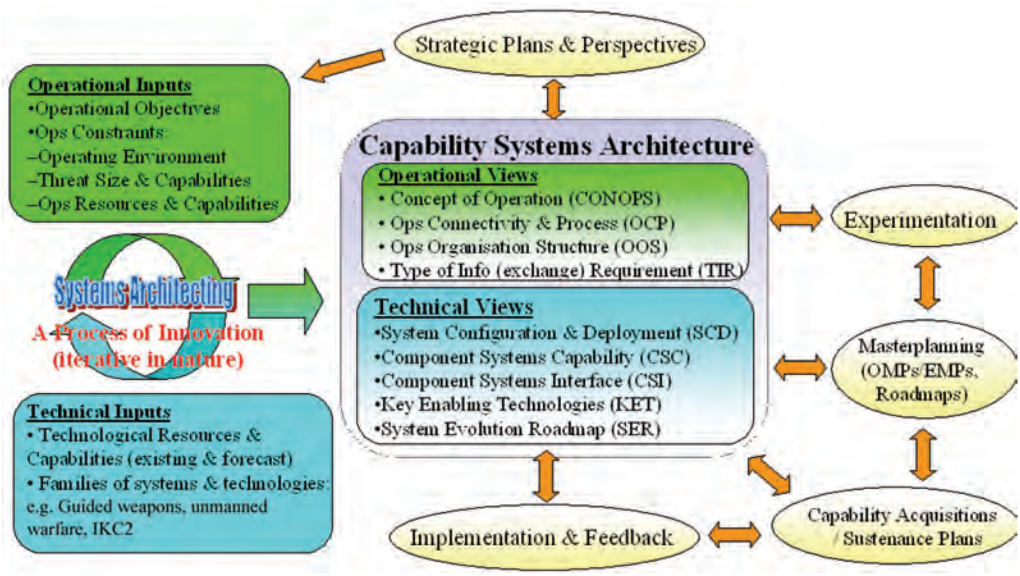

Figure 6. DMSA Architectural Framework

architecture. Emergent behaviour at the SoS level can only appear if there is sufficient information exchange taking place between the component elements. For example, an information feed from sensor to shooter does not result in shooter response if the information is not adequate enough to be acted upon. Adhering to military specification standards may help, but may not ensure full interoperability within the SoS, given the possibility of varying levels of interpretations and adherence to such standards by the equipment manufacturers.

DMSA ARCHITECTURAL FRAMEWORK

Building an effective systems architecture involves innovation and is iterative in nature. Inputs from the Operations and Technology domains are important ingredients but it is the creativity of the integrated systems architect team in exploiting new technologies and devising new and realistic concepts of operations that will determine the effectiveness of the systems architecture.

Figure 6 illustrates the architectural framework currently adopted by DMSA. The Operational-Technical views provide a comprehensive description of the SoS architecture. Where necessary, studies and/or modelling and simulation experiments may be conducted to refine the Operational-Technical views, resulting in a more robust, versatile and optimal SoS architecture. The Operational views would guide the formulation of various Operation Master Plans. The Technical views would serve as the technical blueprint for the implementation of the SoS architecture via various Engineering and Technology Master Plans. We expect the DMSA Architectural Framework to evolve as we accumulate experience in this area.

CONCLUSION

It is the network-centric SoS capability that will give the SAF greater potency on the battlefield - a capability that will not be easily matched or duplicated. The SoS capabilities are higher-order force multipliers that we must seek for the transformation of the SAF into a third generation fighting force. Systems Architecting is one of the effective means to coherently realise such SoS capabilities. The adoption of a holistic Systems Architecting and Masterplanning approach is DSTA's systemic response to add value and support the SAF in front-end planning and operational concept development and evaluation. The successful application of this strategic competency will enable us to realise our potential and create an even more capable 3G SAF.

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