Systems Engineering Role and Importance in Weapon Development

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Abstract

Defence industry is involved in numerous weapon development programs to meet the requirement armed forces. Aerospace platforms, underwater systems and other major systems often comprise a large number of interacting subsystems that have to collectively satisfy a set of specified goals. Moreover, these requirements often evolve throughout the development cycle and improvements during the life of the system. Additionally, these may be contradicting requirements. Systems Engineering (SE) provides designers the capability to manage complex relationships within a subsystem design and across the rest of the subsystems. Systems engineering ensures that, the primary system complies with the most challenging requirements from concept development through production and then the extended service life.

The purpose of this article is to share my experience in Systems engineering during the design and development phase of weapon systems. The concept of connectivity diagram is used here.

Keywords: *Systems Engineering (SE), Systems Analysis (SA), System of System (SoS)*

1. Introduction

Defense Research Development Laboratories (DRDL) is involved in design and development of weapons for armed forces. These weapons are in general, highly complex and involve multidisciplinary systems to meet the mission objectives. Mission of DRDL is stated as:

- Develop the state-of-the-art infrastructure and technologies for different classes of missile. Transfer the technology to production agency for guided missile products.

System is defined as an integrated set of elements, subsystems, and assemblies that accomplish a defined objective. These elements include products (hardware, software, and firmware), processes, people, information, techniques, facilities, services, and other support element. The main characteristics of systems are interaction of the different elements in it. In general, a system is the product of several disciplines makes it interdisciplinary characteristics.

Highly sophisticated weapons are outcome of System of System (SoS). The general understanding of the SoS is it is a large-scale interdisciplinary system involving multiple, heterogeneous, distributed elements. Design and development of large-scale complex system becomes the union of several systems as indicated in Fig. 1. Realization of such systems is a tough task as extremely tight feasible design space is available. Following challenges which influence the development of systems of systems:

- System elements may operate independently.
- System elements have different life cycles.
- The initial requirements are likely to be ambiguous in some cases where user itself not able to define what he/she want.
- Complexity is a major issue for initial modelling, visualization and prototyping.

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- Management can overshadow engineering as the budget constraints, schedules, interfaces, and technology upgrades further complicate the development of SoS.
- Fuzzy boundaries cause confusion while specification generation.
- System of Systems engineering is never finishing, continuos improvements and changes may be needed. Project management must continue to account for changes in the various system element life cycles.

Systematic approach required to design and develop such complex and large-scale products. A unique design environment to address the above issues is "Systems Engineering"

2. Overview of Systems Engineering

There is no commonly accepted definition/approach for systems engineering, often confused with "System Analysis", "System Science", "Operations Research" or other.

A suitable definition which reflects the nature and type of work carried out by DRDL, DRDO is given in military standard MIL-STD-499A [3]:

System engineering is the application of scientific and engineering efforts to:

1. *Transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test and evaluation;*
2. *Integrate related technical parameters and ensure compatibility of all physical, functional and program interfaces in a manner that optimizes the total system definition and design;*
3. *Integrate reliability, maintainability, safety, survivability, human engineering, and other factors into the total engineering effort to meet cost, schedule, supportability and technical performance objective.*

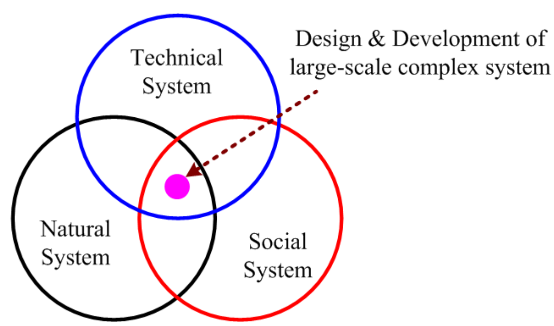

Figure 1: SoS - An extremely tight feasible design space

The above definition and terminology of systems engineering may look very complex but it is a very useful tool to accomplish the objective. An alternative and simple definition of SE in my view is "*Systems engineering is a logical approach taken by multidisciplinary team/teams to engineer and integrate a system to ensure that the product meets customers need*".

Equipped with this definition of a systems engineering, one can expand on the systems engineering methodology in the following steps:

1. Definition of the objectives or goals of the system
2. Elaboration of the interdependencies between the processes of the system
3. Clarification of the roles of the constituent system elements necessary to achieve objectives (thereby reducing cross-functional barriers)
4. Definition of the system's capabilities
5. Establishment of performance expectations prior to operational employment

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6. Measurement and evaluation of performance to continually improve the system through measurement and evaluation

From the above requirements it is clear that, systems engineering is a unique discipline that concentrates on the design and development of the whole system as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect. Systems engineering is an iterative process of top-down synthesis, analysis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system [2]. It is a tightly coupled interdisciplinary approach and meant to enable the realization of successful systems. It focuses on defining customer needs and required functionality at initial stage of the development cycle, documenting the requirements and qualitative requirements, and then only proceeding with design synthesis, analysis and system validation while considering the complete problem. In addition to design and development SE also considers the cost and schedule for product development, training needs and future product/spares support, and safe disposal of life out products.

Waterfall Process Model (WPM) is the first SE model was introduced by Royce in 1970 for software development activity [4].

The waterfall model is a sequential (non-iterative) design process, used in product (mainly used in software) development processes, in which progress is seen as flowing steadily downwards (like a waterfall) through the phases of conception, initiation, analysis, design, construction, testing, production / implementation and maintenance. Fig. 2 indicates the schematic representation of waterfall process model. The main disadvantage of this model is the feedback at the end of development cycle. Clients may not know exactly what there are getting against their requirements before they see working product and so any change leading to redesign, redevelopment, and retesting, and increased costs [5].

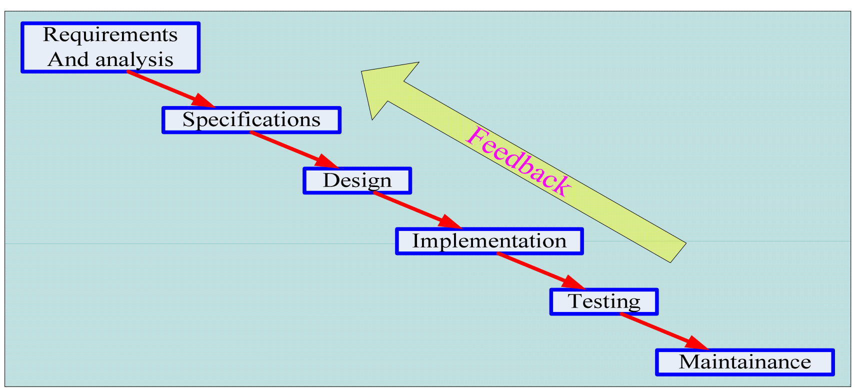

Figure 2: Waterfall Process Model

In 1986, Barry Boehm proposed a new system engineering model called Spiral Process Model (SPM). It is a combination of a waterfall model and iterative model. Each phase in spiral model begins with a design goal and ends with the client reviewing the progress [6]. This model has four phases called, planning, risk analysis, engineering and evaluation. Risk analysis is the main advantages of spiral model over waterfall model. In the risk analysis phase, a process is undertaken to identify risk and alternate solutions. A prototype is produced at the end of the risk analysis phase. If any risk is found during the risk analysis then alternate solutions are suggested and implemented. The main limitation of this model is risk analysis requires highly specific expertise and project's success is highly dependent on the risk analysis phase.

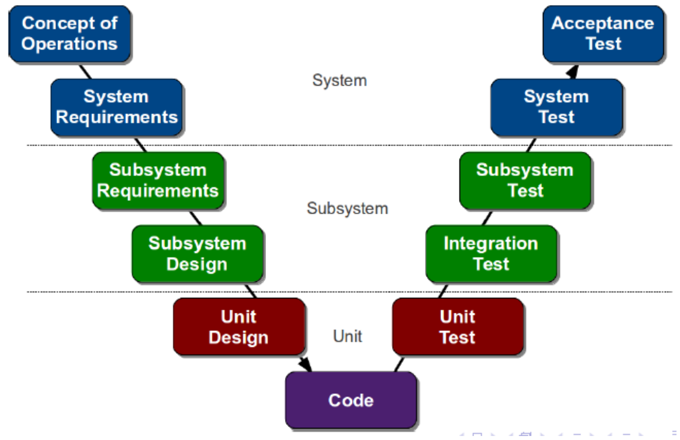

Figure 3: Vee Systems Engineering Process Model

Many different process models have been developed over the years that specify a series of steps that make up the systems engineering approach. Among these models, the “Vee” model is used where requirements are clearly defined and practically fixed. It should be chosen when ample technical resources are available with needed technical expertise. Fig. 3 shows the Vee model used for missile development process. The Vee model is used to visualize the system engineering focus, particularly during the concept and development stages. The Vee highlights the need to define verification plans during requirements development, the need for continuous validation with the stakeholders, and the importance of continuous risk and opportunity assessment.

3. Role of Systems Engineering Team

Exactly the same is performed *by System Engineering Team or Committee (SET or SEC*) of different projects of missile complex. The primary function of the SET in my view is to provide the basis for integrating the technical effort and communicating what will be done, by whom, when and why it is being done. In addition, the SET identifies the roles, responsibility and interfaces of the technical effort and how those interfaces will be managed. Managing this systems architecture and providing traceability and impact during the design lifecycle is an important activity of SE. Forcing designers to articulate testing scenarios as allocated requirements get owned is another important task of systems engineering team.

A general high-level picture of the systems engineering process is indicated in Fig. 4. This process is often repeated multiple times during the course of a complex system design and development process. Its repetition is a function of the system's complexity, system composition and confidence levels on subsystems adopted. Technology Readiness Level (TRL) is plays vital role in number of iterations. In my experience, a project like missile system needs at least three iteration. Submarine launched long range ballistic missile project took just four iteration. For the first two years, we were concentrated on understanding user needs and constraints, current technology and future needs, generated top-level specifications, and initiate the parallel programs to bridge the gap between the technologies available currently and required to meet the user needs. This particular project was in mission mode and supports to research and development activity to build the required technologies. After four iterations, mission review (Conceptual System Design) was conducted and design was cleared for further detailed studies and preliminary designs of different subsystems.

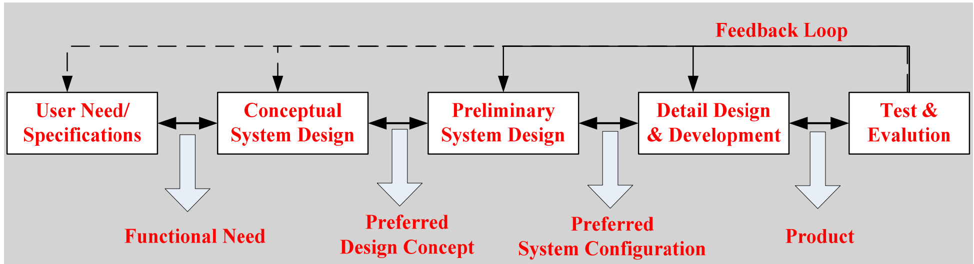

Figure 4: Simplified view of System Engineering Process

SET Work Load: Till this stage system engineer will be having maximum work load. He/she should interact with users, project team and subsystem designers to home on to an optimum system concept. Several times, subsystem designs may be getting rejected due to technical reasons but situations may lead to egotistic problems. Under such situations he/she will face some non-technical pressures additional load/burden on them. Leaving those non-technical issues, typical work load on SET at different stages of design and development phases is shown in Fig. 5.

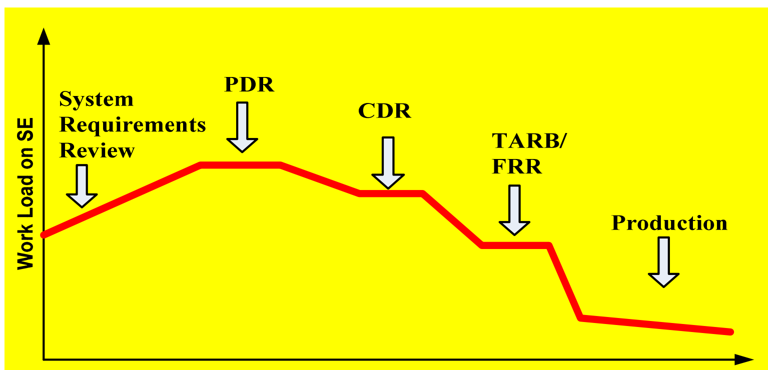

Figure 5: Typical work Load on SET at different phases of development

As it is clear from Fig. 5, most critical and complex stage is the generating overall system requirements which include user needs, constraints from user and designer.

- **Requirements Engineering:** A systems engineer should evolve well-stated requirements which exhibit the following attributes:
  1. The requirement is Necessary **-** What would happen if you didn't include this requirement. ?
  2. The requirement is Verifiable **-** How will you know you have met the requirement. ?
  3. The requirement is Attainable - It should be with the current technology or in near future can be developed.

In simple, requirements should be concise and unambiguous. Most of the cases, systems engineers face difficulty in convincing contradictory requirements. Ideally, one should generate consistent (non- contradictory) requirements, but some of the missile systems will have contradictory requirements in performance and safety. Systems engineering team only can visualize the complexity and generate some trade-off solution to meet both performance and safety. In some complex situations, user may not have clear picture of what they want. For example, Indian Navy looking for some state-of-the-art weapon available with USA, but they don't have any information other than end functionality.

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In such situations, joint team can do some sort of R&D to evolve user needs. SE also concentrates on history of changes and change rationale (if required) is as requirements gets evolve. It also keeps track of change history of design in terms of configuration/data control [10].

- **Risk Assessment:** It is more important aspect of any project. Risk involved from conceptual stage to design, development, production and storage needs to be visualized and necessary step to be initiated at the early stage of project life cycle.
    1. A system engineering demands risk assessment at the beginning of project for all subsystems and also monitors at all critical design stages [9].
    2. Specifically, wherever safety of man is involved, systems studies should bring out different types of possible failure modes and its criticality on safe mission.
    3. When it is important to minimize risk, high fidelity models are required to simulate the failures. Special processing tools are required to analyse the data.
    4. Systems engineering team covers these aspects and generates guidelines for fail-safe system with sufficient redundancy at different subsystems.

During the systems engineering process, peak work load comes when designer starts designing to incorporate system requirements to realize the end goal. Though, preliminary design starts with a simple concept, it goes through different phases and cycles of design, realization, integration, quality control, repeatability/reliability assessment, testing & performance evaluation, life assessment and so on. All these aspects are addressed to the extant at PDR stage itself.

- **System Engineer:** The responsibility of System Engineer *(in DRDL and Missile Complex also called as **System Manager***) plays a vital role in total SE process of a missile design, development, production, testing and delivery i.e., each and every stage of weapon development life cycle. System manager should focus on interaction of all other subsystems with his own subsystem. The system manager (technical team) works with and for the project / project manager to accomplish the goals of the project. Here, is the list of typical characteristics of a good systems engineer.
    1. Intellectual Curiosity – ability and desire to learn new things and update him self
    2. Ability to make system - wide connections/ thinking
    3. Comfortable with uncertainty and unknowns -
    4. Proper Paranoia – expect the best, but plan for the worst
    5. He/she should be a strong team member and leader
    6. Self Confidence and Decisiveness – short of arrogance
    7. Appreciation for Process - rigor & knowing when to stop
    8. Exceptional Two-way Communicator
    9. Diverse Technical Skills – ability to apply sound technical judgment
    10. Comfortable with change - Rigidness may lead to failure or non-optimal system
    11. Ability to see the big picture even when things are not frozen or yet get into the details

In simple, a system manager should know many things (don’t have to be the expert in every field). He must work with many people in different levels and from different disciplines. He should be challenging in nature.

- **Benefits of Systems Engineering:** Implementation of this systems approach will enhance core engineering, management, and scientific capabilities and processes to ensure safety and mission success. At the same time systems engineering also helps to increase performance and reduce cost and time. This systems approach needs to be applied to all elements of a system and at all hierarchical levels of a system over the complete project life cycle. Model-based approaches are now available for doing this. Merely what needs to improve in DRDL context is regular and focused interaction of SET teams. The ultimate goal of a good Systems Engineering Efforts (SEE) is to

    1. Address system integration issues as early as possible, and reduce late design changes.
    2. Good understanding of the system interactions
    3. Good coordination among users, designers, production agencies, working teams, and others organizations

4. Modeling and Simulation Tools

Technical team generally generates the system specification by *modeling* dynamics of plant and *simulating* in most realistic environment. These tools have very high importance in the whole SE process from problem statement to specification generation, preliminary design, detailed design, testing and performance evaluation. For highly complex problems like aerospace applications, there is a need of using high fidelity models at concept feasibility stage itself.

Trajectory simulation model (in general called as 6-DOF package) is one such critical mathematical model used in Directorate of Systems (DOS) of DRDL. These models should be used appropriately based on its applicability. Table 1 summarize the general guidelines for fidelity of model vs its applicability. Similarly, every small and big sub-system should have reasonably representative mathematical models to evaluate its performance before going for real field testing. This is generally a mandatory requirement for aerospace applications.

Table 1: Fidelity of model vs its applicability

DOF	Applicability
1 DOF	Missile Dynamics on launcher
2 DOF	Missile Dynamics on Launcher with Normal force
3 DOF	System design & optimization, Guidance
6 DOF	Complete Missile Dynamics Simulation

5. Data Management

In a complex area like missile system design, it is very difficult to assimilate the input data requirements of various subsystems participating in the design process. Data from one subsystem forms input for the other subsystem. Huge amount of data gets generated during design iterations and convergence. Further, for the chosen variant, considerable amount of fine-tuning takes place in almost every subsystem in order to meet the mission requirements. Data management becomes utmost importance so that the correct and appropriate data is used by the concerned subsystems designer. Data management is the key element of systems engineering process and it is treated as a one of the technical management process. The efficient data management essentially provides technical insight and supports management activities as well as decision making. General attributes of data management are as follows:

1. Proper acquisition and structuring of data from various sources and working groups
2. Efficient access and retrieval of the “right” data at “right” time
3. Enable sharing and integration of data between user, designer & manufacturing industry as and when needed
4. Every set of should be identified by a unique number for easy of traceability and utility

6. MISSILE SYSTEMS ENGINEERING PROCESS

Design, development and flight testing of a missile system is highly interdisciplinary activity involving various subsystems like aerodynamics, propulsion, structures, control, guidance, navigation, warhead, on-board electronics etc., Each of the said areas have the complexities/intricacies of their own. Hence, it is not possible for a small team like Project Team to have an overall picture of design and development process. It will be highly beneficial, if whole of the mission scenario is divided into various design activities and connectivity can be provided between various parameters that could influence the particular design. Especially, if the criticality of the influencing parameters in the design process is established, it will forewarn the project team as well as the designer during the initial stage itself to take necessary steps for controlling the same. Systems engineering team generates list of such critical parameters for each system and subsystem. Doing so, the foremost task of systems engineering is capturing requirements of all stakeholders and documenting them by paying attention to the best practices. Then comes the top-down systems architecting by involving stakeholders (in case of weapon development, Armed forces and production agency are the stakeholders) who are to be internal to the design team.

In order to achieve user’s multipurpose requirements for "guided missiles" of high kill probability, a hierarchal top down system design methodology has been evolved. This approach will take care of user defined threat profiles, system coverage/kill zone, fire power, mobility, low observability in the presence of constraints of launch platform, safety of launch platforms such as aircrafts and underwater vehicles, availability sensors and actuator and realization time frame and unit cost of missile. The following steps are carried out as part of systems engineering for missile design and development at Directorate of Systems (DOS) of DRDL in consultation with other designers.

1. Stakeholders Requirement Analysis
2. Threat Scenario Definition and Synthesis
3. Generation of System Requirements (also called as "base line specifications")
4. Design Constraints
5. System Architecture Evaluation
    a. Evolving Mission Definition in terms of range, CEP and damage potential
    b. Sizing Propulsion System based on maximum range requirement
    c. Designing Aerodynamic configuration based on lateral acceleration requirement to shape trajectory
    d. Ensuring launch platform safety
    e. Generating Guidance, Control and Actuator requirements
    f. Assess the sensor need and generate specifications
    g. Trajectory design and analysis
6. System Characterization and Sensitivity Analysis
7. Failure Mode Effects and Criticality Analysis (FMECA)

8. Methodological Review Mechanism (Mission Review, PDR, CDR, FRR, TRAB and so on)
9. Testing and Evaluation
10. Documentation of design and learning during development.

Normally measure of merit and effectiveness are derived from the mission need statement and used to evaluate the system architecture. It now becomes essential to bring out the *inter-connected connectivity chart* between the various models as indicated in Fig. 6. The result of all these exercises is a System Architecture leading to efficient and faster development. Systems engineering also helps in creating the work breakdown between different subsystems designers. While all the above are the parts essential systems engineering, creative part comes in investigating technology alternatives and supporting decision making through risk analysis.

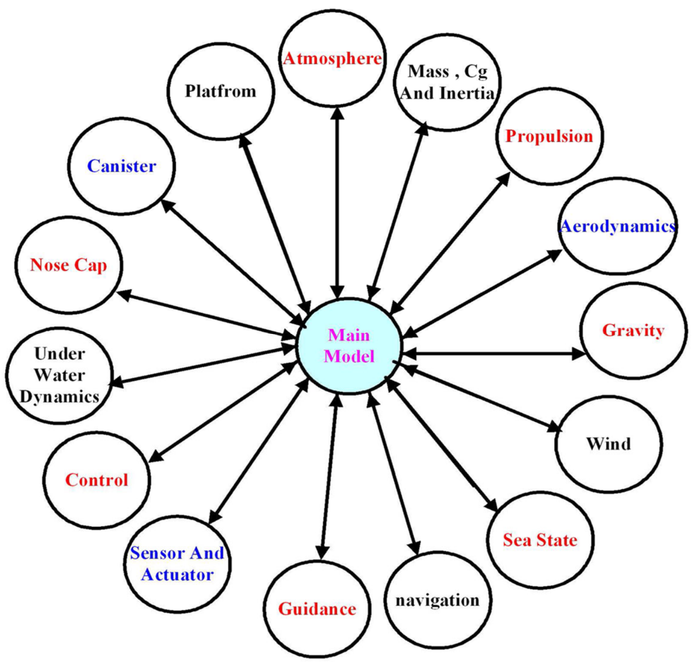

Figure 6: Inter-connected Connectivity Chart

7. CONNECTIVITY CHART

Based on user and mission requirements, subsystem specifications have been evolved by applying systems engineering process. Based on mission profile, critical design areas have been identified that need to be further elaborate as connectivity charts with associated influencing parameters. Connectivity charts is a chart which shows the relation between the outcome and influencing parameters at different degree of interaction levels as indicated in Fig. 7 for one of critical subsystem. Connectivity charts have been developed in a layered approach manner. Outcome of the design activity are indicated on the rightmost side with influencing parameters placed in different layers. Parameters in the innermost 2 layer, i.e., L1 directly influence the outcome of the design process. Parameters that affect L1 are placed in layer-2 (L2) which in turn influenced by the parameters of Layer-3 (L3). These charts are developed to such an extent that a reasonable degree of interaction levels have been achieved. However, it is always possible to further expand the charts or make further connectivity to the parameters in the outermost layer based on complexity of a given subsystem.

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One of such complex sub-system is explained here as a case study. Control Surface (CS) unfolding is essential to stabilize and control the missile. A powerful pnuemo-hydraulic CS opening mechanism is designed and the operation of this mechanism is greatly effected by an external loads acting on the CS and this needs to be studied in detail. The opening mechanism has got stringent requirements on synchronization of all four fins, angular speed at the time of locking and others, under the conditions where external flow counteracts the opening. The performance of this subsystem depends on missile dynamics as well as pneumatic opening mechanism. Here hydraulic damping system plays vital role to reduce the structural loads. Fig. 7 indicates the connectivity chart for this system. Total five layers provide degree of interaction of different influencing parameters and at the end outcome on system performance.

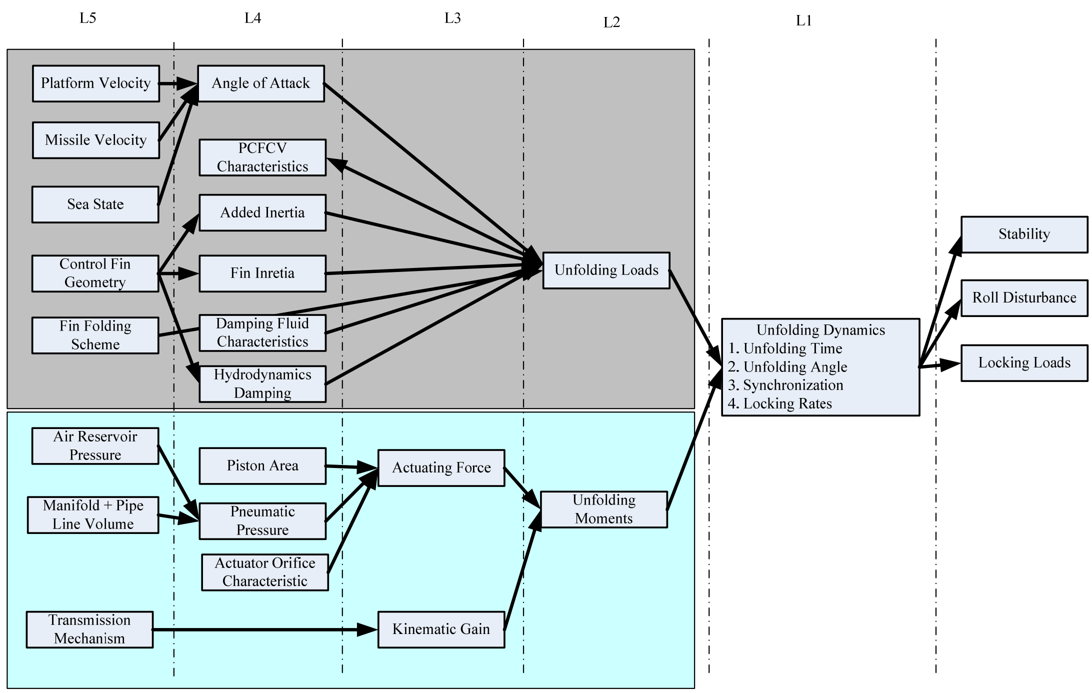

Figure 7: Connectivity chart for CS Unfolding Mechanism

In DRDL the task of systems engineering is accomplished by forming Systems Engineering Teams who discuss on regular basis the various mission requirements and workout the designs to meet them. The designs are discussed in detailed to bring out any shortfalls so that those can be rectified at the right time during the development process. Experience shows that the projects who instituted such forums and followed it up meticulously have experienced minimum problems during flight trials and the overall success rate is very high compared to those who did not follow it meticulously. In my view SET contribution is very high in any successful project.

8. SUMMARY

1. Systems engineering is the art and science of creating a product, it needs dedicated efforts. As there is no unique methodical approach to apply SE on our day to day problems, we (DRDL) should evolve a SE process and articulate it. We must have a curriculum to support individual development in best SE practice for all scientists.

2. Need to develop a human resource to eliminate "insufficient understanding of both the individual and System-of-System interdependency of product and process".
3. It is the time to use standard SE tools to properly define the various environments.
4. There exists a large gap in India's technical capability for catering the demands of indigenous production in Aerospace and Defence sector. Indian manufacturing needs to upgrade capabilities in precision engineering, micro engineering to take a big leap into the Aerospace and Defence sector.

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