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Establishment of System Engineering Procedure for Two-Stage Sounding Rocket

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Abstract

The growth of the space economy and the success of space missions rely heavily on the development of space transportation technology. The continuous and effective development of space transportation technology relies on the education of human resources nurturing practical talent with both theory and experience. The SLV·ST project was started to provide graduate students with hands-on experience developing launch vehicles through systems engineering. Present paper presents a case study of the application of system engineering principles in the development of systems of SLV·ST project. The SLV·ST project requirements were established using a tree structure referring to the open resources, those will be followed by the development, test and launch of two-stage sounding rocket. The SLV·ST project will provide valuable experience in systems engineering to future aerospace professionals and enhance their understanding of the process. This work would serve as a foundation for the continued growth and development of the spacecraft and space transportation industries.

Keywords: *System Engineering, Sounding Rocket, Rotating Detonation Engine (RDE)*

1. Introduction

Over the past few years, South Korea's space development has achieved notable progress, with the successful development of the Nuri (Korea Space Launch Vehicle, KSLV-II) space launch vehicle leading the way. This success has spurred further research in the rocketry field, utilizing the technology and systems of both Naro (KSLV-I) and Nuri rockets for various projects. These include studies on lunar exploration launch vehicles [1,2] scientific rocket missions [3,4], water rockets [5,6] and examinations of new rocket technologies [7,8]. Additionally, research based on the design of the Nuri rocket has been conducted on the conceptual design of large geostationary orbit launch vehicles [9], improvements in Nuri rocket performance [10], and high-performance small launch vehicles [11,12]. Research aimed at developing systems engineering procedures for small launch vehicles has also been carried out by authors' research group at the graduate level [11]. As the global launch vehicle market evolves, there is an increasing interest in reusable launch vehicles in South Korea, necessitating a thorough evaluation of the viability and utility of reusable launch vehicles.

The importance of space transportation capabilities has been recognized in Korea since the successful test launch of KSLV-II (also known as Nuri) in October 2021, which has opened up various opportunities for space development. In response, Korea has announced a comprehensive roadmap for the development of launch vehicles, satellites, satellite navigation, and space exploration, which includes the Fourth Basic Plan for Space Development Promotion [13]. This plan provides a long-term vision for Korea's space industry and acknowledges the need to cultivate interdisciplinary expertise and facilitate international exchange in the field of future space transportation technology in anticipation of the future

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expansion of the space industry. As a result, the 'Future Space Education Center' project has been launched to address this need.

The aim of this study was to develop a sounding rocket based on system engineering, conducted by Pusan National University, which was selected by the Future Space Education Center as the 'Space Launch Vehicle·Space Transportation Education and Research Center (SLV·ST ERC)'. This paper describes how students apply the systems engineering process for the first time with the open resources of systems engineering like the NASA Systems Engineering Handbook

2. Systems Engineering Procedure

In the SLV·ST ERC, graduate students are taking the lead in system development as a project by applying systems engineering. Given the intricate nature of aerospace systems, which require the integration of various disciplines such as structures, propulsion, control, and aerodynamics, effective system engineering integration becomes imperative for systematic development and research. In this paper, these system developments are called the SLV·ST project. It can enable efficient interdisciplinary integration across academic domains.

A. Life cycle of SLV·ST project

The first step in system engineering is to establish a process based on the development target's life cycle and ensure that subsystems perform their tasks according to milestone schedules. Figure 1 illustrates the system engineering process proposed in this study. The system life cycle is typically classified into phases starting from Pre-phase A to Phase F. When transitioning from one phase to the next, stakeholder reviews are conducted through milestone reviews to assess project readiness and make 'go' or 'no-go' decisions. Milestone reviews and phase-specific deliverables are referenced from the NASA Systems Engineering Handbook [14]. The SLV·ST project, being of a smaller scale compared to NASA and Korea Aerospace Research Institute(KARI)'s, tailored the scale of documents and reviews according to its budget, manpower, and other resources. The results of this tailoring are presented in Table 1. The SE process established in the SLV·ST project referred to NASA System Engineering Handbook, INCOSE, DoD, KARI, and other materials [15-20].

Unlike other projects, the SLV·ST project conducted Pre-phase A and Phase A simultaneously at the project initiation stage. This was due to the research on system planning and critical technologies being conducted separately by each institution during the proposal phase. Therefore, during the SLV·ST project's Pre-phase A and Phase A, preliminary system-level requirements, cost estimates, and schedules were established, alongside the essential technology research and development needed for system configuration. The stakeholders decided to 'go' during the milestone review of System Requirements Review(SRR) and System Design Review(SDR). Currently, the SLV·ST project is in Phase B, focusing on the preliminary design of the system.

B. Functional decomposition process of SLV·ST project

The functional decomposition should precede for the definition of system requirements, especially for configuration, and interface identification. In the functional decomposition process, the scope of the system function is initially determined based on the requirements of the project's stakeholders and the mission of the system. This involves outlining the system's design and manufacturing constraints and enumerating sub-functions that can be implemented within these limitations. Subsequently, these are linked to performance parameters, forming the basis for constructing system requirements and verification methods. In Phase B, system architecture development and interface identification are performed.

The ultimate goal of the SLV·ST project is the development of a two-stage sounding rocket system that reaches an altitude of 3 km, along with the verification of a rocket-type Rotating Detonation Engine(RDE) functionality. One of the final goals of the SLV·ST project is RDE operation, and by possessing RDE technology, our laboratory has lowered the risk of completing development [21-28]. The initial configuration of the system being developed in the SLV·ST project was identified during the proposal phase, with a hybrid engine for the first stage and RDE for the second stage. The project identified the ultimate goal as a requirement of stakeholders. Then, it established a mission baseline, referring to the launch sequence. Additionally, to narrow down the scope of system functions, three main objectives were identified. Subsequently, some key functions required to achieve objectives were identified:

1) The rocket must be capable of flight.
2) Stable operation of the RDE and achieving target performance.
3) Stable communication and data collection for monitoring.

The functional decomposition will become more detailed as the project progresses. At the current project stage, the system's configuration for performing the mission while implementing these five functions has been concretized and documented in the Part Breakdown Structure (PBS), as illustrated in Fig. 2.

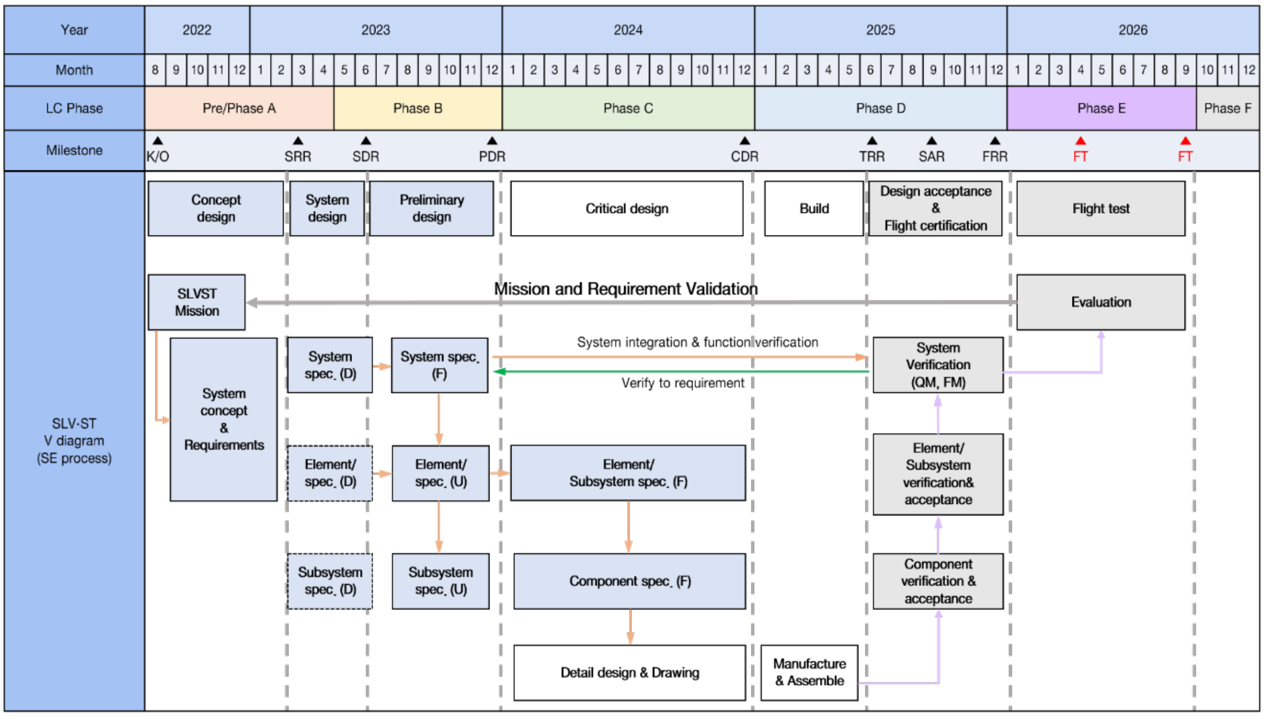

Fig. 1 System engineering process of SLV·ST ERC

Table 1. Life Cycle Phase of SLV·ST project

System life cycle	Activities	Milestone review of NASA	Milestone review of SLV·ST project
Pre-phase A	Concept study	MCR	Kick-off (K/O)
Phase A	Concept and Technology Development	SRR/SDR	SRR/SDR
Phase B	Preliminary Design and Technology Completion	PDR	PDR
Phase C	Final Design and Fabrication	CDR/SIR	Pre-CDR, CDR
Phase D	System Assembly, Integration and Test	ORR/FRR	TRR, SAR
Phase E	Operations and Sustainment	DR	FRR
Phase F	Closeout	DRR	FT, Evaluation

C. Requirements definition and management

The rocket system is composed of various subsystems, including propulsion, control, and structure, making it subject to complex development requirements. Moreover, the interpretation of these requirements can vary significantly depending on the engineer, necessitating the need for clarity and consistency in defining requirements. Defined requirements should be managed to maintain traceability between upper-level and lower-level system requirements. Requirements are initially defined as system requirements based on the ultimate goals and functionalities of the system, as derived from the top-level stakeholders.

NASA manages system and subsystem requirements separately in large-scale system development projects to ensure bidirectional traceability between subsystem and system requirements [14, 29]. The SLV·ST project comprises two main components: the rocket system and the ground system. To ensure the effective development of this complex system, a requirement tree structure and identifiers, as illustrated in Fig. 4, have been established to link lower-level requirements to upper-level requirements. Level 1, representing the SLV·ST system that encompasses the entire project, is composed of the rocket system and ground system, sharing the same identifier 'SYS000'. Given that this project is executed with a team of fewer than 30 students, smaller in scale compared to projects in aerospace system development with over 100 engineers, the hierarchical structure has been streamlined to manage identifiers concurrently.

Level 2 requirements, referred to as Element Requirements and denoted as 'EL,' are assigned unique numbers for each element. Similarly, subsystem requirements inherit identifiers from element requirements to maintain the tree structure. System requirements for the SLV·ST project have been defined in alignment with the ultimate goal of the project. These system requirements will also be utilized for the verification of the system's success in the milestone review, Flight Test(FT) in Phase F. The verification methods have been categorized as Inspection(I), Analysis(A), Demonstration(D), and Test(T), following the Verification Cross Reference Index (VCRI) method [14]. Some of the SLV·ST project's system requirements and verification methods are presented in Table 2.

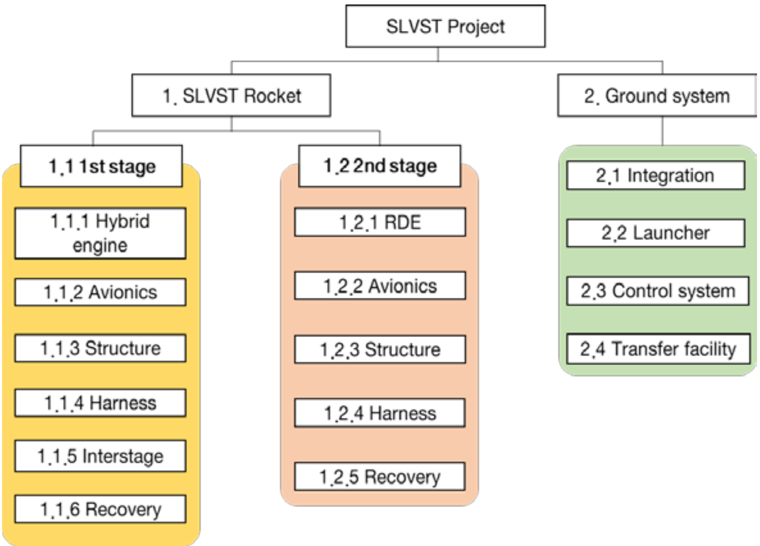

Fig. 2 Part Breakdown Structure of SLV·ST project

Table 2. SLV·ST project rocket system requirements and VCRI method

System ID	Requirement	VCRI
SYS001	The final flight altitude must satisfy the range of 2.5 ~ 3 km.	A, T
SYS002	The rocket must consist of two stages.	I
SYS003	The rocket must have flight stability during flight.	A
SYS004	Designed with rocket diameter xxx cm (TBD)	I
SYS005	Designed for gross weight less than 150 kg (TBD)	I
SYS006	Each stage of the rocket must be retrieved by parachute.	D
SYS007	Each stage of the rocket transmits and stores the collected flight and status data to the ground system.	D
SYS008	The rocket must abort flight upon receipt of an abort command.	D

D. Overview of the specifications of the sounding rocket

As previously mentioned, the rocket system under development in the SLV·ST project follows a two-stage configuration with a hybrid engine for the first stage and an RDE for the second stage. The detailed configuration of the system emerges as a result of the functional decomposition and requirement definition phases discussed earlier. Additionally, the project team employed in-house code to determine the mass and propulsion performance that meet these requirements. Through the systems engineering process, the preliminary specifications for the SLV·ST project's rocket system are presented in Table 3.

Table 3. Preliminary specifications for rocket system of SLV·ST project

System specification	1st stage	2nd stage
Engine type	Hybrid engine	Rotating detonation engine
Propellant (Fuel / Oxidizer)	HDPE / N_2O	C_3H_8 / N_2O
Thrust (N)	4,000	600
Total stage mass (kg)	110	40
Length (m)	1.8	1.2
Diameter (m)	0.2	
Target altitude (km)	3	

Among the system specifications, particular consideration was given to the specifications for the upper-stage RDE. This emphasis was driven by the project's goal of demonstrating a rocket-type RDE. The reason is the goal was to demonstrate a rocket-type RDE. Instances of applying RDE (Rocket-type Rotating Detonation Engine) in rocket propulsion are relatively rare worldwide. Notable examples include the use of RDE in sounding rocket launches by Nagoya University in Japan and the Institute of Aviation in Poland. Given this trend, it is evident that utilizing RDE as a rocket engine in this project presents a significantly challenging endeavor.

3. Conclusions

In the aerospace industry, research on subsystems such as engines and structures is going on continuously. In the meanwhile, it is necessary to integrate these disciplines through a multidisciplinary approach and manage the development process toward a defined goal to develop a working system. Thus, it is crucial to have human resources capable of performing systems engineering for the development of various aerospace systems. As systems engineering is a discipline that requires tailoring according to the system being developed, the institution involved in the development and the level of performance required, it is essential to tailor and integrate it effectively. In this study, we have applied systems engineering for successful project execution, and presented detailed processes and outcomes related to it. These processes can potentially lower the entry barrier to systems engineering for students who are new to the field. Also, this system could serve as the foundation technology of spacecraft and space transportation industries.

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