Conceptual Design of Mission Scheduling Software for Small Satellite Constellation

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ABSTRACT

This paper introduces the design of 'Mission Allocation & Planning Software' (MAPS) under developing software for satellite mission scheduling in South Korea. As the country embarks on launching around 130 satellites by 2030, predominantly small satellite constellations, there is a pressing need for a domestic solution to optimize these complex operations. The current dependence on foreign software, without prospects for collaboration or technology transfer, underscores the importance of developing a homegrown system. MAPS addresses this by offering a comprehensive framework that streamlines the scheduling of satellite missions. It integrates multiple modules, including a user-friendly interface for easy parameter input, a data management system ensuring efficient information flow, compatibility with existing orbit propagation tools, and a powerful optimization engine designed to handle various mission constraints. The software also features intuitive visualization capabilities, making complex scheduling data easily interpretable. MAPS design is nearing its final stages, with a full release expected by year's end. This development is poised to enhance South Korea's autonomy and efficiency in space operations.

Keywords: Mission scheduling Software, Optimization, Small satellite constellation, Conceptual design

1. INTRODUCTION

Remote sensing (RS) offers numerous advantages, including the ability to monitor and analyze the Earth's surface and atmosphere with precision and consistency [1]. By leveraging satellites, RS can provide continuous, large-scale, and high-resolution data that is invaluable for various applications, such as environmental monitoring, disaster management, and national security [2]. This capability has led to a significant increase in demand for satellite-based RS services [3].

With the growing demand for RS, there has been a notable trend towards the deployment of satellite constellations, particularly small satellite constellations [4]. These constellations provide enhanced coverage, reduced revisit times, and greater flexibility in mission planning, making them an attractive option for various stakeholders [5]. Among these, small satellite constellations have seen the most substantial growth due to their cost-effectiveness, rapid development cycles, and the ability to perform complex missions that were once only feasible with larger, more expensive satellites.

However, operating a constellation of small satellites presents its own set of challenges. The numerous number of satellites, combined with their high maneuverability, significantly increases the complexity of mission scheduling [6] [7]. This complexity arises from the need to optimize satellite tasking, manage limited resources, and ensure mission objectives are met efficiently. As a result, there has been extensive research focused on optimizing satellite mission planning. Various approaches, including mathematical algorithms [8] [9], meta-heuristic algorithms [10] [11], and dynamic programming techniques [12], have been proposed to address these challenges.

Building on this body of research, our team has developed a Modified Dynamic Programming (MDP) approach specifically tailored for optimizing small satellite constellations [3] [5]. This new algorithm represents a significant advancement in satellite mission planning. Aiming to extend the benefits of the MDP algorithm beyond seasoned mission

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planners to include those unfamiliar with advanced optimization techniques, we have designed the ’Mission Allocation & Planning Software’ (MAPS). This software integrates the MDP algorithm into a user-friendly interface, revolutionizing the way mission planners operate and manage satellite constellations.

MAPS comprises five fundamental modules, each contributing to a robust and user-centric experience. The ’User Interface Module’ offers an intuitive graphical user interface (GUI) that allows users to easily input mission parameters. The ’Data Management Module’ serves as the software’s data repository, ensuring efficient and reliable data flow. The ’External Interface Module’ enables interoperability with other orbit propagation tools, while the ’MAPS Core Module’ houses the optimization algorithms that generate mission schedules. Finally, the ’Result Visualization Module’ presents the optimized schedules in a clear and accessible format.

As of September 2024, the critical system design of MAPS is nearing completion, with module-specific functionalities being implemented and tested. With the goal of finalizing the software by the end of the year, the development team is committed to delivering a tool that will significantly enhance South Korea’s satellite operations. The deployment of MAPS is set to redefine satellite mission planning, ensuring greater independence and efficiency in handling complex constellation management tasks.

The structure of this paper is as follows: Section 2 will cover the operation concept of MAPS, focusing on the system architecture, interfaces, and other system-level aspects. Section 3 will provide a detailed explanation of the design for each of the five key modules within MAPS system. Finally, Section 4 will present the conclusions and discuss the future development plans for MAPS.

2. OPERATION CONCEPT OF MAPS

2.1 MAPS Overview

The development of the MAPS originated from the need to shift away from planning missions for a few large satellites independently toward more effective operation strategies for numerous clustered satellites. Specifically, the intent was to integrate mission planning across multiple clustered satellites while applying optimization algorithms to derive optimal solutions for the inherently complex problems associated with managing satellite constellations. As mentioned in the introduction, our research team developed the MDP algorithm based on a deterministic dynamic programming [3] [5], which is particularly well-suited for clustered satellite operations. MAPS is a GUI-based software that incorporates the MDP algorithm, an advanced optimization solution designed to streamline the scheduling of optimal imaging and communication tasks for satellite constellations. The system is structured into five distinct modules, details of which will be discussed in subsequent sections. Fig.1 represents a conceptual visualization of MAPS. This image was created to depict the process of optimal scheduling for Earth observation satellite constellations as they capture images of ground targets and communicate with ground stations.

Fig. 1: Conceptual illustration of the Mission Allocation & Planning Software (MAPS)

2.2 System Hierarchy

The system hierarchy of MAPS deviates from the traditional work breakdown structure of system-subsystem-module, opting instead for a more streamlined hierarchy organized as system-module-sub-function. This restructured approach reflects the scaled nature of MAPS, which, unlike larger systems, does not require segmentation into multiple subsystems. Our research team's intention was to enhance the system's manageability and operational efficiency by focusing on functional modularization and minimizing system complexity.

At the system level, MAPS functions as the central framework orchestrating the overall mission planning process. The module level is comprised of five primary modules: the Data Management Module (DMM), External Interface Module (EIM), MAPS Core Module (MCM), Result Visualization Module (RVM), and User Interface Module (UIM). Each of these modules is designed to perform distinct and critical functions within the mission planning cycle, thereby facilitating a robust but flexible operational environment.

Specifically, the modular design allows for rapid updates and maintenance, enabling each module to be independently modified or enhanced without disrupting the overall system functionality. This aspect is particularly vital in adapting to new mission requirements or integrating technological advancements quickly and efficiently.

Illustrated in Fig.2, the primary functions assigned to each module highlight their individual contributions while also showcasing the cohesive operation across the system. For example, the User Interface Module facilitates direct interaction with end-users, ensuring ease of use and accessibility, whereas the External Interface Module manages data exchange with external systems, crucial for real-time decision-making and system responsiveness. By adopting this simplified but effective hierarchy, MAPS ensures that all components work in harmony to achieve optimal mission planning outcomes, demonstrating a balance between functional independence and system-wide integration.

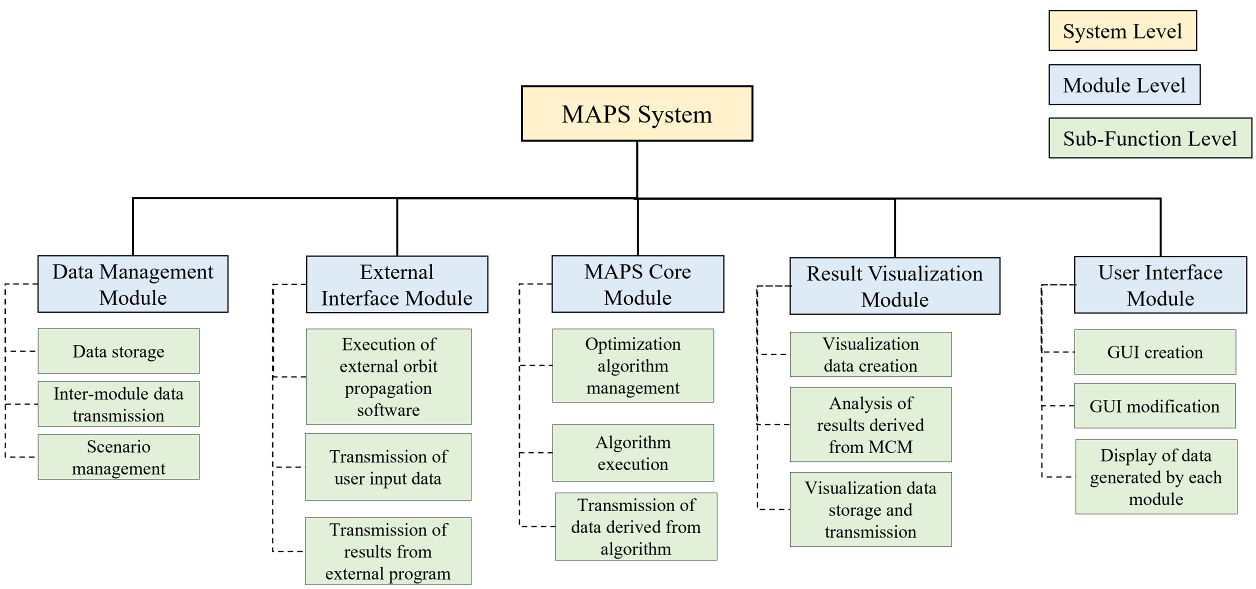

Fig. 2: Breakdown chart of system hierarchy

2.3 System Architecture

The system architecture of MAPS is divided into three main components. Firstly, the User Display, which allows users to enter desired information through a display interface and to view the final results. This is integrated with the UIM, enabling direct interaction with MAPS, facilitating the easy input of desired parameters and retrieval of mission results. The interface is intuitively designed to support users ranging from mission planners to technical staff without requiring extensive training.

Secondly, at the core of MAPS, which incorporates all five system modules, user inputs are processed, sophisticated optimization algorithms are applied, and mission planning results are generated. This setup is engineered to handle complex calculations and data management tasks efficiently, ensuring robust performance even under demanding scenarios.

Thirdly, the EIM manages communications with external orbit propagation programs, such as the System Tool Kit (STK). This integration is crucial for importing essential baseline data necessary for accurate mission planning. The data exchanged typically includes orbital parameters, satellite status information, and environmental variables, which are vital for accurate trajectory modeling and task scheduling.

The decision not to include an internal orbit propagation module aligns with the project's goal of optimizing mission planning processes while maintaining system simplicity and user accessibility. Instead, MAPS leverages existing, proven external programs to provide critical data, enhancing the system's reliability and reducing developmental complexity.

Fig.3 in the document illustrates this architecture, clearly showing the workflow and data flows within MAPS, highlighting the strategic integration points and the flow of information across the system.

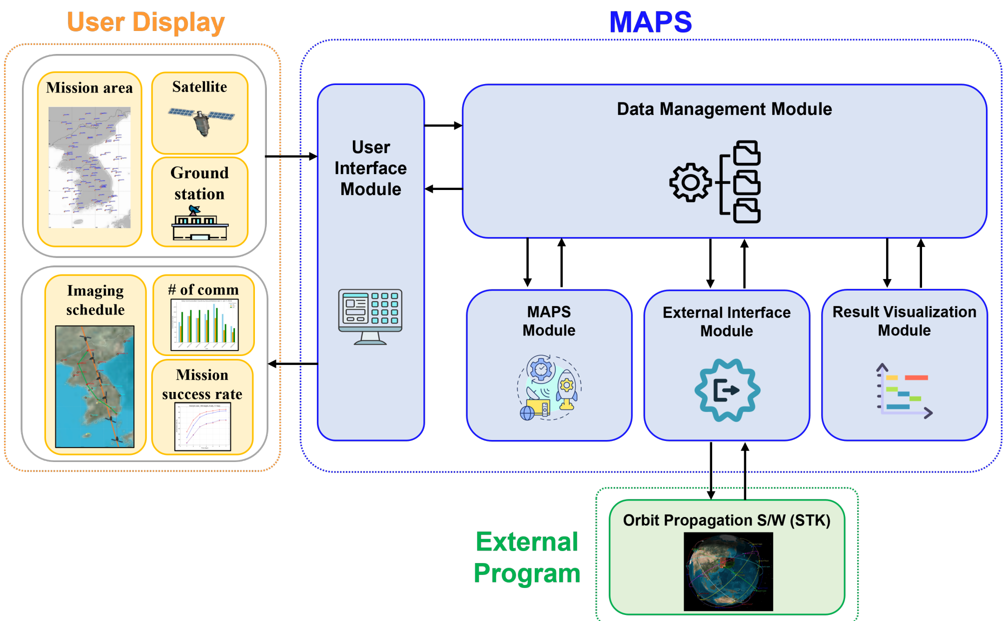

Fig. 3: Workflow of system architecture

2.4 System Interface

The connectivity and data flow among the five key modules that constitute the MAPS system are detailed in Fig.4, which presents the data flow in a matrix format, illustrating movement in a clockwise direction. This figure effectively shows how each module interacts within the system to facilitate comprehensive mission planning.

In the UIM, users input critical data such as the locations and numbers of ground stations, orbital elements of cluster satellites, target locations, priorities, and the selected optimization algorithms. Users can also specify the desired outcomes and the formats in which these should be presented. This information is then compiled and forwarded to the DMM, which acts as the central hub for data distribution within MAPS.

The DMM plays a pivotal role in sorting and categorizing the information received from the UIM. It distributes relevant data to the EIM, MCM, and RVM based on their specific operational requirements. Each of these modules processes the data according to its function—EIM handles external data interactions, MCM performs mission calculations, and RVM generates visual outputs from the computed data.

After processing, the results from EIM, MCM, and RVM are relayed back to the DMM. Here, data is reassessed and reorganized to ensure efficient coordination between modules. This cyclical data flow continues until the final mission planning outputs are formulated. These results are then sent back to the UIM, where they are displayed to the user in a user-friendly format.

The system's design ensures that all data transitions through the DMM, minimizing direct inter-module communication, which helps in reducing complexity and potential data handling errors. By centralizing data processing and distribution through the DMM, MAPS enhances system reliability and operational efficiency. Additionally, standardized protocols and software tools are employed across the modules to ensure secure and seamless data transmission, further mitigating the risk of errors and enhancing system responsiveness.

Fig.4 not only illustrates these interactions but also emphasizes the streamlined and systematic approach to data handling in MAPS, highlighting the strategic integration points and the robust architecture that supports the flow of information across the system.

UIM (User Interface Module)	Ground/Satellite/Target (GST) info Algorithm selection info Result selection info			
STK output MAPS output Visualized results	**DMM (Data Management Module)**	GST info	GST info Algorithm selection info STK output	Algorithm selection info Result selection info MAPS output
	STK output	**EIM (External Interface Module)**		
	MAPS output		**MCM (MAPS Core Module)**	
	Visualized results			**RVM (Result Visualization Module)**

Fig. 4: Inter-module interface matrix

2.5 System Operation

The operation of MAPS, designed for simplicity and clarity, centers around the creation of optimized schedules for cluster satellite missions. Unlike more complex systems that accommodate multiple scenarios, MAPS focuses on efficiently executing a single, well-defined scenario. Fig.5 depicts a flowchart of the system's operations, illustrating the scenario-based approach to cluster satellite mission scheduling.

Users initiate the process by entering various parameters and desired outcomes through a GUI-based display. This user input is processed via the UIM and forwarded to the DMM. The DMM acts as the central hub for data coordination, ensuring that inputs are correctly prepared for subsequent processing stages.

To support the calculations of the optimization algorithms, the EIM establishes connectivity with external systems, notably the STK, to fetch foundational orbital and access data. This interaction is facilitated by secure and reliable communication protocols, ensuring that data integrity and confidentiality are maintained. The acquired data are then relayed back to the DMM.

The integrated data, including user inputs and STK-derived information, are then sent to the MCM. Here, optimization algorithms are applied to compute the necessary scheduling outputs. These outputs are meticulously checked for errors before being passed back through the DMM to the RVM.

The RVM takes responsibility for analyzing and visualizing the computed data, transforming them into intuitive formats for review and storage. This module employs advanced visualization tools to present data in a user-friendly manner, enhancing the decision-making process. The visualized results are finally circulated back to the user through the DMM and EIM, completing the operational cycle.

Throughout this process, MAPS employs robust error handling and data verification protocols to detect and correct any discrepancies, thus ensuring the reliability and accuracy of the mission planning results. This comprehensive approach not only streamlines operations but also reinforces the system's capability to handle complex satellite mission planning tasks efficiently and reliably.

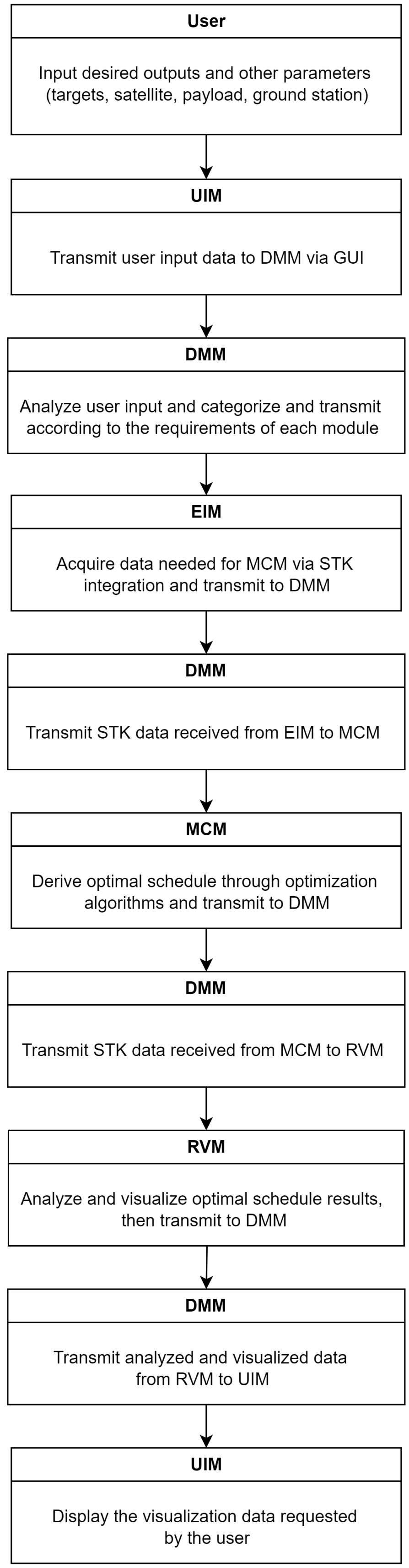

Fig. 5: Example flowchart of system operation

3. MODULE DESIGN

The MAPS comprises five key modules, each developed to function autonomously yet harmoniously within a unified framework facilitated by the Python programming language. This choice ensures seamless system-level integration, enabling easier maintenance and streamlined updates across modules. Python's adaptability and the extensive support provided by its libraries also significantly enhance the system's ability to interface with other technologies, thus increasing MAPS's versatility in diverse operational environments.

This section details the conceptual design of each of MAPS's five modules, explaining their individual roles, functionalities, and how they interact within the broader framework of the software. These modules include the DMM, EIM, MCM, RVM, and UIM. Each module's design and operational strategies reflect MAPS's overall objective to optimize satellite mission planning efficiently and effectively.

3.1 Data Management Module (DMM)

The DMM is pivotal in orchestrating the flow of data within the MAPS system. It serves as the primary repository for user inputs and manages the inputs and outputs necessary for the EIM and MCM. A crucial function of the DMM is the collection of output values from various modules. Specifically, it collects outputs from the UIM for the EIM, from the EIM for the MCM, and from the MCM for the RVM.

Additionally, the DMM is responsible for storing and categorizing the collected data. It archives raw data from each module and sorts this data according to the specific needs of different modules, ultimately storing the final products derived by the RVM. Another significant feature of the DMM is its capability to create and save scenarios. Based on the mission planning parameters entered by users, the DMM crafts files in a "scenario" format which can be saved and later retrieved for modifications, enhancing user convenience and interaction with the system.

Fig.6 illustrates these roles of the DMM, providing a schematic view of how it integrates and manages data across MAPS, ensuring efficiency and coherence in handling the complex data flows essential for optimized mission planning.

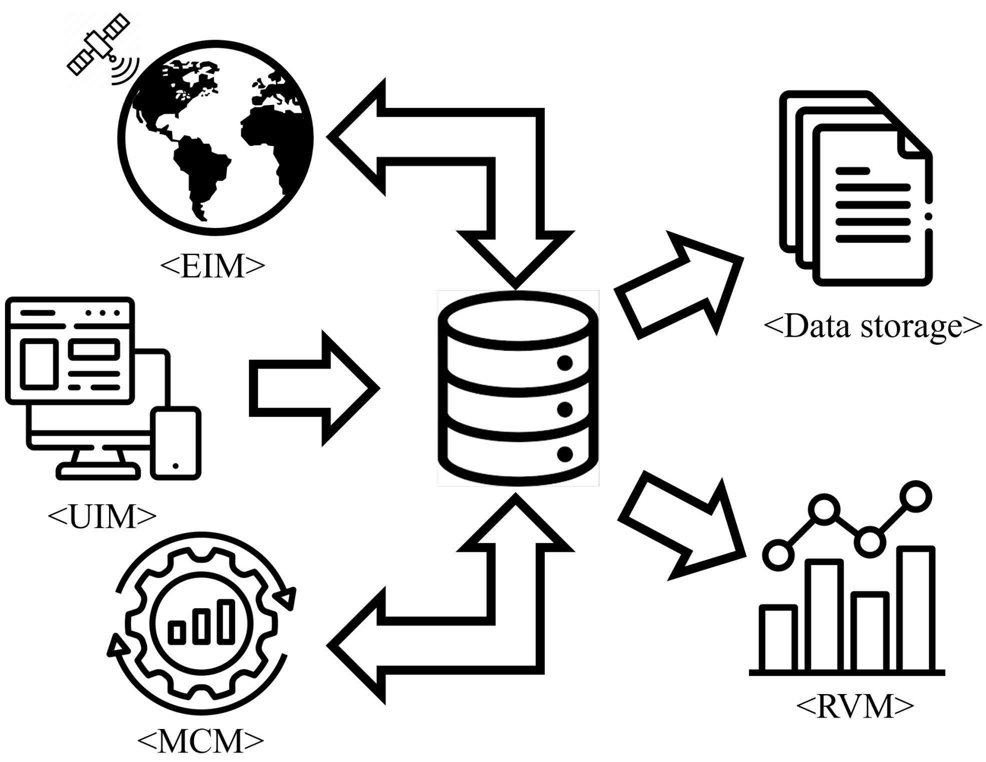

Fig. 6: Schematic illustration of DMM

3.2 External Interface Module (EIM)

The EIM is a critical component of the MAPS system, uniquely designed to interface with external orbit propagation programs. Its primary function is to automatically activate these external programs in accordance with user-defined parameters. This automation ensures that parameters such as satellite orbits, payload configurations, ground station details, target locations, and sensor ranges are precisely implemented in the orbit propagation simulations.

Additionally, the EIM is responsible for receiving foundational data generated by these external programs post-execution. This data includes vital information such as satellite coverage, satellite access times, duration times, and antenna access coverage. Once received, the EIM processes and forwards this data to the DMM, ensuring seamless integration and availability for further computation.

The EIM supports flexible data handling capabilities, allowing it to store raw data in various formats including txt and csv. This flexibility facilitates easy access and transfer of data to other necessary modules within MAPS, such as the MCM and the RVM enhancing the system's overall efficiency and responsiveness to mission planning needs.

Fig.7 provides an example illustration of the EIM's operational workflow, showing how it interfaces with external programs and manages the data flow within the MAPS framework. This figure helps visualize the overall processes involved, offering a clear depiction of how the EIM enhances the satellite mission scheduling efficiency by integrating external data sources.

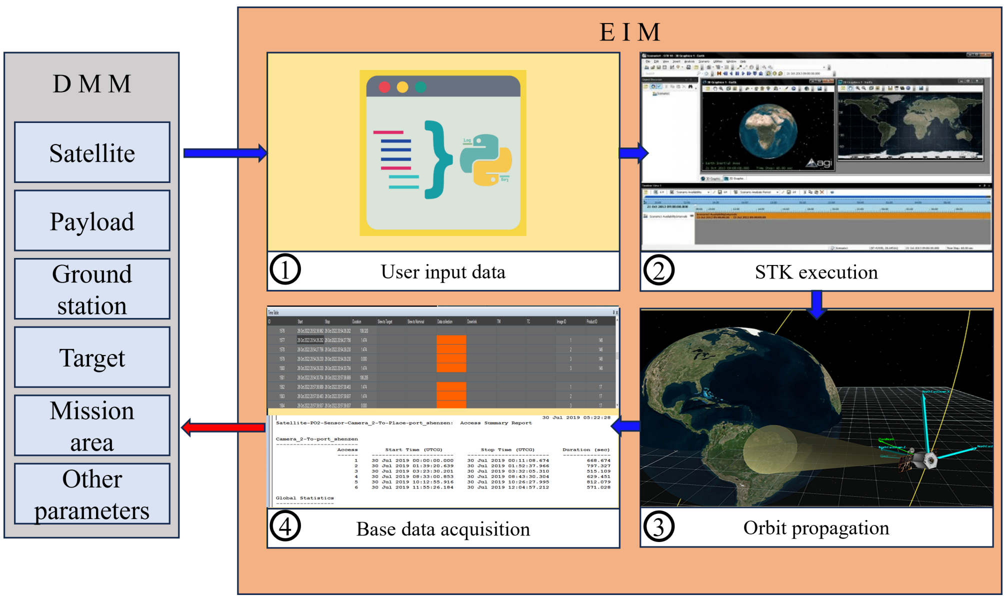

Fig. 7: Example workflow of EIM operation

3.3 MAPS Core Module (MCM)

As its name implies, the MCM plays a central role within the MAPS system. It is the module where the Modified Dynamic Programming (MDP) developed by our research team is implemented. The MCM utilizes orbital propagation information relayed from the EIM and user inputs delivered from the UIM through the DMM. These inputs are essential for defining the optimization algorithms and mission planning parameters that drive the computations within the module.

The primary function of the MCM is to construct the data structures required by each optimization algorithm, thereby generating the foundational information necessary for optimization. It also computes the schedules for imaging and communication missions based on user inputs. This module not only ensures the execution of complex optimization routines but also manages the integration and processing of all input data to produce final mission planning outcomes as shown in Fig.8.

An additional consideration in designing the MCM is its scalability. The initial development goal was to incorporate at least two optimization algorithms; however, with scalability in mind, the MCM's architecture has been modularized.

This modular approach to algorithm implementation ensures that additional optimization algorithms can be easily integrated into the MCM in the future. As a result, the MCM is well-prepared to adapt to and incorporate more advanced or better-performing algorithms as they are developed, enhancing the overall capability of the MAPS system.

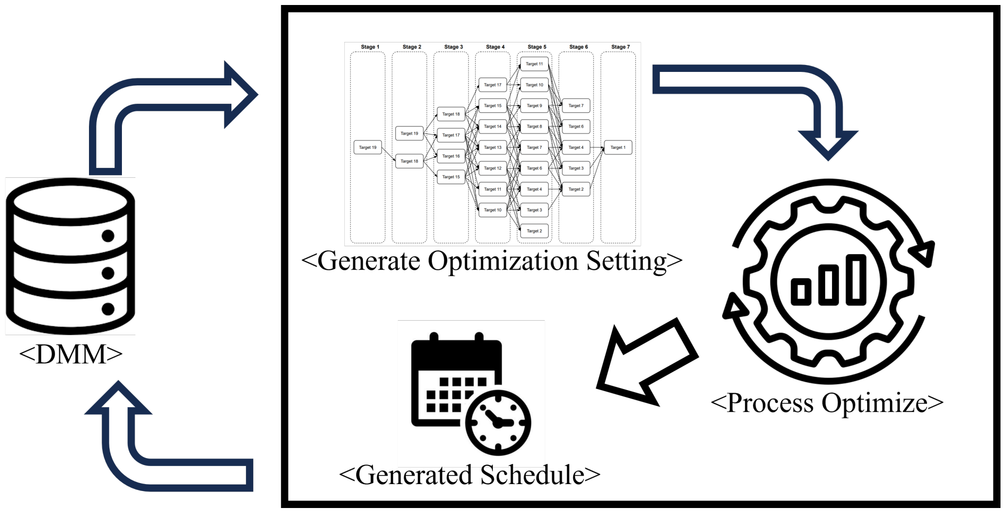

Fig. 8: Schematic illustration of MCM

3.4 Result Visualization Module (RVM)

The RVM serves a pivotal role in the MAPS system, transforming complex output data from the MCM into easily interpretable visual formats. This transformation is crucial for ensuring that the intricate data generated by sophisticated scheduling algorithms can be understood and utilized effectively by users. The RVM processes the raw data, which is typically outputted in txt or csv file formats, and aligns it with specific figures of merit (FOM) defined by the users according to their operational needs.

One of the primary functions of the RVM is to conduct a detailed analysis and preprocessing of the data. This involves sorting, filtering, and organizing the data based on the optimization algorithms used by the MCM to ensure that the visualizations reflect accurate and relevant information. The goal is to tailor the output to meet the specific demands and criteria set by the users, allowing for customized analysis that fits the mission's objectives.

Following the data preparation, the RVM employs advanced visualization tools to create a variety of user-specified formats, such as graphs, charts, or tables. These visual outputs are designed to provide users with intuitive and actionable insights. For example, Gantt charts are used to illustrate detailed scheduling for imaging and communication tasks, allowing users to see the timing and duration of each activity. Other key visualizations include mission success rate graphs, which help assess the effectiveness of the missions; revisit time analyses, which optimize satellite coverage; downlink analyses by ground station, which assess communication capabilities; and trends in memory and electrical power usage, which are critical for long-term mission sustainability.

Fig.9 illustrates examples of the RVM outputs and the functional flow of this module, demonstrating how data is effectively transformed into visual formats that enhance the understanding and usability of the mission planning results.

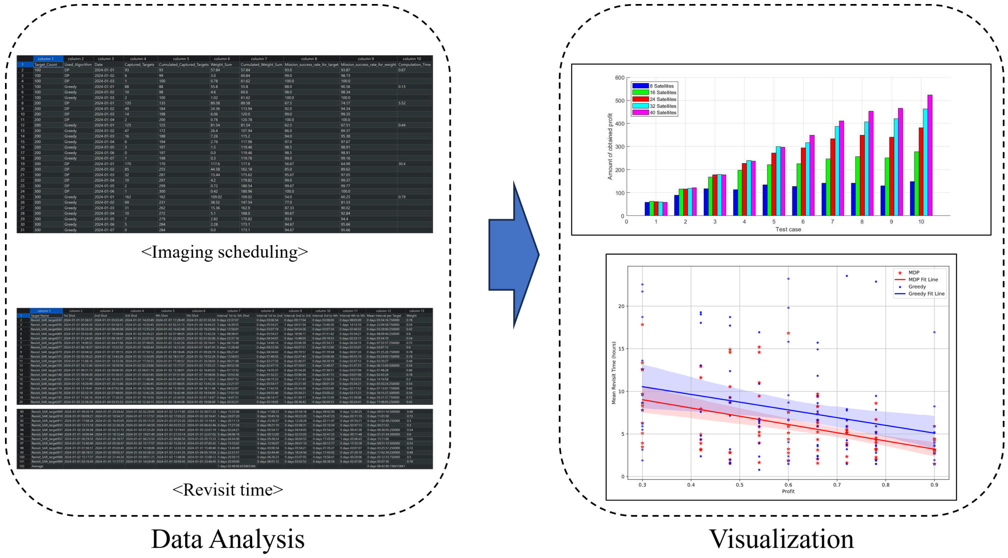

Fig. 9: Example outputs of RVM

3.5 User Interface Module (UIM)

The UIM is crucial in the MAPS as it serves as the primary interface for users engaging in mission planning. The UIM enables users to input essential details such as targets, satellites, ground stations, and mission duration, which are fundamental to orchestrating a successful mission schedule.

A key objective in the design of the UIM is to create an intuitive and accessible module that allows users of all levels, particularly those with limited technical knowledge of satellite operations, to efficiently plan missions. To achieve this, the UIM has been developed using PyQt, a robust tool that supports the creation of a user-friendly graphical interface.

The UIM is meticulously designed to streamline the data input process, guiding users to enter all necessary information in a structured manner. It adapts dynamically, displaying relevant fields and options tailored to each mission scenario, and is equipped to visually present outputs in user-friendly formats like detailed tables, dynamic charts, or comprehensive graphs. These features not only allow users to verify and refine mission parameters effectively in real-time but also align the final results with the user's expectations through structured menus. This adaptability and clarity in data presentation enhance user satisfaction and increase the efficiency of mission planning operations.

Fig.10 offers a schematic illustration of the UIM, demonstrating its role within MAPS and highlighting how it effectively bridges the gap between complex mission planning tasks and user-friendly operation.

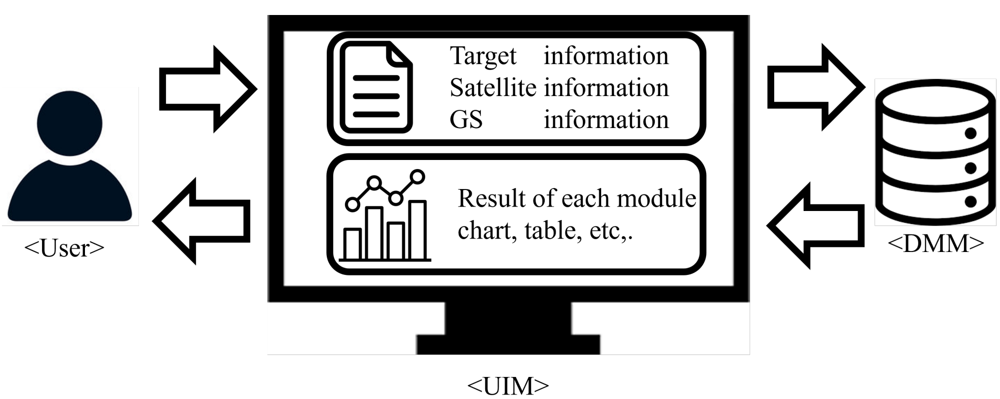

Fig. 10: Schematic illustration of UIM

4. CONCLUSION

This paper has presented the conceptual design of the MAPS, a comprehensive tool aimed at enhancing the planning and execution of missions for small satellite constellations. Through the development and integration of five distinct modules—DMM, EIM, MCM, RVM, and UIM—MAPS facilitates the optimization of satellite operations with a focus on accessibility and efficiency.

The significance of this research lies in its approach to streamlining complex mission planning processes, making them more accessible to users with varying levels of expertise. By incorporating sophisticated optimization algorithms within a user-friendly interface, MAPS stands to significantly enhance the capability of small satellite operators to execute more efficient and effective missions. However, the study acknowledges its limitations, particularly in the scalability of the current system architecture to incorporate future advancements in satellite technology and mission complexity.

Future work will concentrate on completing the principal design by September 2024, with subsequent phases of validation and testing leading to a final software release by the end of 2024. We will also work on expanding the system's algorithmic capabilities and adaptability to support a wider variety of mission scenarios and satellite technologies. These efforts aim to keep MAPS adaptable and relevant in various satellite mission demands.

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