EOMPA – A service-based prototype using Artificial Intelligence in support of Multi-Mission Planning and Analysis for Earth Observation Constellations

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Abstract

Over the next decade, hundreds of Earth Observation satellites are expected to be launched as part of mega-constellations, providing intelligence for a multitude of applications. The planning for multi-missions within a constellation presents a new challenge for operators to ensure that the data-throughput from each satellite is maximised, while at the same time not violating the temporal and resource constraints. Traditional mission planning systems are unsuitable for this task as they are typically developed for single satellite missions and would incur high costs to adapt for multi-missions. The mission planning systems for future constellations need to be autonomous, scalable and capable of fast re-planning. As such, a new and advanced mission planning system is required.
Under the frame of ESA's EOMPA study, GMV investigated the complexities associated with constellation planning and has developed a prototype system to address the issues associated with planning for Earth Observation multi-missions. The main objective of this study was to build an optimized planning system for multi-missions, based on existing tools that would integrate seamlessly into existing ground segments. The development focused heavily on the re-use and adaption of existing capabilities from different mission planning systems to combine classical workflows with Artificial Intelligence technologies to create advanced functionalities, ultimately introducing a new satellite tasking workflow. The prototype has been designed to manage multi-missions and to include a solver component to run optimization algorithms.
Focusing specifically on the problem of resource allocation, two optimization algorithms were chosen for implementation in the prototype based on their previously demonstrated success in similar optimization scenarios. The algorithms selected, Ant Colony Optimization and Squeaky Wheel Optimization, offer two differing approaches to solving the same planning problem. The algorithms were validated against the scenario detailed in this paper using real mission data from the Sentinel-1A and B satellites.
A secondary goal of the prototype was to demonstrate the Mission Planning service standards as defined by the CCSDS. Aiming to increase interoperability in the ground segment, this part of the study focused on the implementation of standard service-based interfaces for mission planning functionalities including planning request, plan distribution and plan editing services.
This paper presents the design of the EOMPA prototype and its operational concept within the ESOC workflow. The merits of the optimization algorithms used in the frame of the planning scenarios will be discussed, as well as the implementation of the mission planning standards and the outcomes of the project.
Keywords: Mission Planning, Constellation, Optimization

Acronyms/Abbreviations
ACO - Ant Colony Optimization
CCSDS - Consultative Committee for Space Data Systems
EOMPA - Earth Observation Mission Planning and Analysis
EGOS - ESA Ground Operations System
MPS – Mission Planning System
SWO - Squeaky Wheel Optimization

1. Introduction

The next decade will see an unprecedented increase in the volume of Earth Observation satellites launched, as the trend towards operating mega-constellations continues. Multi-satellite missions will be used to support hundreds of applications such as climate monitoring, disaster response planning and the tracking of maritime vessels. This increase in the number of spacecrafts operating in concert will increase the complexity of payload planning as the resources and tasking grows exponentially. Traditionally, operators can predict the utilisation of an on-board resource to plan for the image acquisitions. However, this activity is time-consuming and unfeasible to manage for large numbers of satellites concurrently. The mission planning systems available on the market today are typically developed for a single spacecraft system and are not capable of managing multiple satellites. Adapting these systems would be very costly and would not result in a truly optimized system. To support future applications and achieve the maximum possible value from EO constellations, while at the same time reducing the operator load, new advanced mission planning systems are required.

Considering these points, the Earth Observation Mission Planning and Analysis (EOMPA) study aimed to design and develop a scalable mission planning framework that would combine traditional mission planning workflows with advanced optimization techniques. A key objective of the study was that the prototype should build on existing capabilities to reuse existing software components and minimise the development time. Emphasis was placed on automating the low-level work currently carried out by operators as much as possible and to use well-defined interfaces so that the resulting prototype could be integrated into existing ground segments with ease and interface with international and national EO space assets.

The study was divided into three separate phases. The first phase was to define the requirements and use cases, the second phase to design the system architecture and development, while the third phase was to validate and evaluate the resulting prototype. Each phase is described in the following sections.

2. Requirements Definition

The initial tasks of the EOMPA study were to define the technical requirements of a state-of-the-art mission planning system by analysing the functionality already available in existing systems and to form a group of mission planning experts and stakeholders to collect user requirements for a new constellation planner.

1.1 Existing Planning Systems

A thorough review was carried out to identify existing mission planning systems that could either be fully or partially used as a baseline for the prototype, enforcing the re-use aspect of the development. This involved the completion of a survey of the available state-of-the-art systems for planning and tasking, with a particular focus on identifying systems that are used for planning multi-missions. This analysis was used to identity any gaps in the current technical solutions offered with respect to constellation planning needs. Both commercial and institutional mission planning systems were assessed and a trade-off was performed by comparing existing systems in terms of its planning capabilities, its organization and management of data, any nominal or advanced functionalities available in the system and most importantly, its genericity.

Ultimately, the ESA Ground Operations System MPS (EGOS MPS) [1] was selected as the baseline for EOMPA as this system was developed from the beginning with re-use in mind, with the intention of having a single mission planning system available which could be adapted to any mission by means of configuration. This approach to the development means that the system components are very generic and it does not contain any mission specific development. EGOS MPS is used by the Flight Control Team as ESOC for the planning and scheduling of the space and ground operations during routine mission phases and can send data to and receive data from several different subsystems in the ground segment by using standard interfaces.

1.2 Stakeholders

An important objective for EOMPA was to contribute to the resolution of typical planning problems faced by constellation operators and to improve the planning processes overall. To achieve this aim, Planet were involved in the project as a consultant to provide both user requirements and to define realistic use cases based on their operational experience. Planet own and operate the largest Earth Observation constellation in existence, with more than 150 satellites providing multispectral high and medium resolution imagery their customers daily. As such, they were uniquely qualified to act as the Earth Observation constellation planning experts for the EOMPA activity.

Additionally, a stakeholder expert group was created consisting of experts from both the commercial and institutional space sectors to support the definition of the user requirements and use case scenarios. This group consisted of mission planning operators, mission managers and ground segment engineers who provided inputs on the requirements of a multi-mission planning system based on their experience in terms of satellites constellation modelling, satellite planning and tasking management, operator interfaces and functionalities, required automation capabilities and expected satellites data throughput.

This approach to gathering user requirements proved to be very successful as it encouraged open discussion and fostered a collaborative environment with the developers. The technology requirements for the prototype were driven by the heterogenous use cases and requirements defined during this stage to offer a robust requirement framework for future exploitation of the tool. The use cases defined during this phase were used later in the study for the evaluation of the prototype and its performance.

1.3 Findings

Discussions with the stakeholder expert group yielded many user requirements which the project developers reviewed and analysed in collaboration with ESA, before determining the selection to be considered for the prototype. While numerous possible functionalities were discussed, the need for optimization and a flexible Rules Engine were highlighted most frequently.

Participants indicated that optimization algorithms and machine learning techniques are not widely used within the currently available mission planning systems. While it was unanimously agreed that optimization would be required for efficient constellation management, many of the participants commented that they were not currently using these techniques within their own systems and did not see any benefits in applying complex algorithms for the planning of single satellite missions. In the case where a mission planning system were to plan for both single and multiple satellites, the suggestion was that the application of optimization techniques should be optional for single satellites to avoid unnecessary complexity.

Most participants indicated that a flexible Rules Engine was the most imperative requirement for any mission planning system, one which enabled operators to define planning rules independently and in real time. It was reported that some rules engines are not as flexible as is necessary and that it can be cumbersome to make changes to planning rules as the mission may require throughout its lifetime. A Rules Engine that offers flexibility to the operator to manage different planning policies and evaluate different constraints for conflict detection and resolution was thought to be imperative for the management of large constellations of satellites. The incorporation of the Rules Engine also offers the ability to increase the automation of planning decisions which can significantly reduce operational costs.

3. System Design and Development

The system architecture aimed to cover the technology gaps identified during the analysis phase and to reuse the components of the baseline MPS where possible. The design of the framework was based on Service-Oriented Architecture (SOA) at its core so that the focus was on the development of services, rather than individual components and would be interchangeable. This was achieved by having the services loosely coupled and to then combine them with standard interfaces and protocols so that they may communicate through a service bus. The service bus integrates the components into an entire system, allowing for cross platform integration. Having each component provide well-defined inputs and outputs and having them loosely coupled means that they can couple or decouple to the system as needed, allowing for a flexible and scalable design as the prototype evolves. Additionally, this also allows for existing systems to be integrated into the defined service layer, meaning that less components must be developed from scratch. This approach promotes a high degree of interoperability, reusability and scalability making it suitable for an evolving constellation planning prototype.

The SOA was implemented using two software engines: an Application Server (AS) and an Enterprise Service Bus (ESB). The AS oversees the handling of business logic and delivering application access to end-users on a client device, while the ESB handles all communication between the interfacing services. As part of the analysis phase, a survey was also carried out on the available technologies to determine which would be suitable for the EOMPA prototype. Based on the ease of deployment, performance, scalability and documentation available offered by these tools, the Wildfly AS [2] and Mule ESB [3] were selected respectively.

The components selected for inclusion within the service bus were based on the feedback received during the initial phases of the activity. A Rules Engine was integrated based on the Drools Rules Engine which allowed operators to define planning rules, conflict rules and resolution rules. A solver component was integrated which could launch multiple optimization algorithms in parallel. On top of this, a simple front-end was designed to be user-centric and adaptable so that application-specific versions could be developed in the future. The HMI included a dedicated Request Editor from which users could make planning requests to the system, a New Satellite Editor to allow operators to input new satellite configuration information and a launcher to launch the planning rules for either a single or multi-satellite scenario.

2.2 Algorithms

The most important development aspect of EOMPA from a constellation planning perspective was the inclusion of a solver component to enable the integration of optimization algorithms to manage multiple resources efficiently. As part of the initial analysis, several algorithms were reviewed for their suitability to implement into EOMPA to solve the selected use cases and their applicability towards constellations. Ant Colony Optimization (ACO) and Squeaky Wheel Optimization (SWO) were selected and are described in the following subsections. To ascertain the performance of both algorithms and to determine how they compare, the design of the prototype is such that both algorithms are launched on the same planning problem simultaneously. To assess the performance of the optimization algorithms, the following metrics were calculated:

1. The fitness function, which is the fraction of scheduled time out of the total makespan.
2. The measure of the total time that is scheduled.
3. The measure of the fraction of the activities scheduled with respect to the total number of activities to be scheduled

The results of these metrics were issued as part of the output of each schedule so that the operator could visually determine which of the plans has performed the best, depending on the criteria selected, and from this result select the plan to create the output schedule from.

Although only two algorithms were implemented initially, the design of the solver component however means that additional algorithms can be added to the prototype in the future with minimal effort.

2.2.1 Ant Colony Optimization

ACO is a population-based algorithm inspired by the foraging behaviour of an ant colony and searches for the most efficient pathways between resources. The problem can be translated to an algorithm by mapping the problem onto a graph consisting of nodes and connecting edges, which represent aspects of the problem. An artificial ant will start from an initial node and travel along the edges from node to node, creating a path which is analogous to a problem solution, and grade the path with a pheromone. Each ant acts independently by following a basic set of rules and has no knowledge of the behaviour of the overall colony. The levels of pheromone on a path will subsequently influence future ants leaving the initial node, ultimately identifying the optimum path.

This technique is highly scalable and has been adopted previously in several mission planning scenarios including Earth Observation and data relay [4]. This algorithm was developed from scratch within the scope of this study and applied to the planning inputs.

2.2.2 Squeaky Wheel Optimization

SWO is a greedy algorithm that focuses on the problematic elements within a schedule and improves on these elements iteratively, resulting in an optimized solution. To create a schedule, an initial solution is generated and blames are assigned to the problematic elements within this initial solution. Following this, a new schedule is then generated but with the problematic elements either improved upon or removed entirely. This process repeats until an exit criterion is met and an optimized solution is determined.

Rather than implementing this algorithm from scratch, ESA's optimization tool APSI [5] was integrated with the prototype which included an implementation of the SWO algorithm. This generic implementation was modified to align it with the constellation use case which helped to demonstrated that it was possible to integrate pre-existing components into the solver component of the prototype with relative ease.

2.3 Mission Planning Services

Mission Planning Systems need to interface with several existing third-party systems, which in some cases may be geographically distributed. As EOMPA's design aimed to focus on reusability and interoperability, the interfaces were based on international standards to support this effort. The use of these standards supported the selection of the EOMPA study as one of the demonstrators for the CCSDS MPS Service activity [6,7].

The Consultative Committee for Space Data Systems (CCSDS) aim to standardise information exchanged between Mission Planning systems and external entities by specifying the service-based interfaces to increase interoperability between systems to help enable collaborative, international space missions. The adoption of these standards across the space industry is important as it would introduce the possibility of re-use between missions, leading to a decreased cost for mission operations and enable faster times for deployment and innovation. The increased flexibility will also mean a distribution of functions between organisations and improved long-term maintainability as the components can easily be replaced.

To support this endeavour, five initial services have been identified:

- Planning Request Service to allow for the submission of planning requests to a system
- Plan Distribution Service to distribute and access plans generated by the system
- Plan Execution Control Service to control the management and execution of a plan

- Plan Information Management Service to enable users to list and retrieve available definitions for MPS items
- Plan Edit Service to enable users to modify plans after they have been submitted for execution.

These services were implemented within the EOMPA prototype to support the efforts of the CCSDS and to enhance the interoperability of the prototype.

4. Prototype Validation and Evaluation

The objective of the validation phase was to demonstrate that the final prototype developed during this study met operators needs, which was achieved by validating the system against the operational use cases defined with the stakeholder's involvement. This enabled the system to be validated against conditions as close as possible to the real operations system. The data used to validate the scenarios was generated from existing mission data to replicate a small constellation of satellites. Demonstrations of the prototype were carried out to Planet and the stakeholder expert group for their evaluation. These were interactive sessions in which the evaluators could analyse the performance of the prototype, provide feedback and make suggestions on additional capabilities that could be added to future versions of the system.

3.1 Use Cases

The use cases identified by the stakeholder expert group represented scenarios that could be applicable for either Constellations, Earth Observation or Interoperability scenarios and in some cases covered more than one classification. Constellation use cases identified were prioritised and selected based on the enhanced capability their solution would offer to the system overall. From a mission planning viewpoint, both the operations for the individual satellite must be covered as well as the constellation itself, considering higher-level capabilities and services that the constellation aims to deliver. To allow the first iteration of the prototype to be as generic as possible, the use cases selected for the evaluation phase were ones that were realistic, applicable to other mission and possible to model with the dataset available. This included scenarios such as minimizing the idle time on-board the satellite, the management of a new satellite to the constellation and the reassignment of a task in the case of an outage.

3.2 Validation Data

To validate the prototype, payload planning data from a large constellation of satellites needed to be replicated so that the mission planning system could choose the combination of acquisitions to be taken during a given period to satisfy requirements in terms of requested images. To simulate this, data from the ESA-EC Copernicus system was selected to validate the EOMPA prototype. The Copernicus satellites provide accurate, timely and easily accessible Earth Observation data to assist in the decision making for management of the environment, mitigation against the effects of climate change and support disaster response efforts. As such, it is a good representation of an EO constellation mission of heterogenous satellites.

The Sentinel 1 A and B satellites carry a C-Band Synthetic-Aperture Radar (SAR) instrument on-board which has a spatial resolution of 5m and a swatch of 400km. This mission was a particular interest for the EOMPA study as users can make observation requests to the satellite. Stakeholders from the SAR user community can submit requests to the mission planning and this is taken into account when the operational plan is produced. As the management of multiple user requests was identified as both a key requirement and a dedicated use case for the EOMPA study, the data from this mission was used for the validation of the optimization use cases.

To simulate a baseline constellation scenario to validate the prototype, a mini constellation with five satellites was defined. Data from the Sentinel-1 A and B satellites was combined and divided into five streams, one for each satellite in a simulated five-satellite constellation scenario. With this approach, the number of simulated satellites could be increased iteratively as the activity progressed and as the design of the prototype is generic, additional satellites from the Copernicus programme could be added in the future.

3.3 Workflow

As EOMPA used EGOS MPS as its baseline, its operational concept was modelled on the concept of operations in ESOC. Planning inputs are received from multiple entities, such as Flight Dynamics, Payload Data and Ground Segment and user requests. These were then ingested into the prototype as planning inputs.

5. Results and Discussion

As mentioned in the previous section, evaluation demonstrations were carried out to mission planning experts to gather feedback on the prototype and suggestions on future versions. The mission planning experts included Planet, members of the stakeholder user group who collaborated with developers during the initial phase of the activity and experts who previously were not involved in the study. During the evaluating sessions, scenarios were run demonstrating the optimization of the planning by the algorithms, the ability to plan for a single satellite scenario or a multiple satellite scenario and the functionality to add new satellites to the system.

Overall, the feedback received on the prototype's performance and handling of the scenarios was extremely positive. The evaluators confirmed that the prototype could successfully demonstrate the planning of multi-satellites and the use of optimization techniques to generate a plan. While many useful comments were received, two were of particular value for future versions of the prototype.

Firstly, although the approach taken to optimization algorithms was suitable for a first iteration of such a prototype, it was suggested that future versions could expand much further on this and include more complexity both on the constraints of the resources and the types of planning scenarios modelled. This increase in complexity would also necessitate an increase in the number of metrics used to measure the success of the algorithms and to provide transparency to the operator. In addition to adding complexity in the planning problems modelled and given the service architecture implemented, more algorithms could be added to the system with relative ease to provide the operator more choice of solutions. The algorithms selected for this first version were done specifically with sensing request planning in mind, but the definition of new, more complex use cases in the future could mean that other algorithms may be more suitable then the two presented here.

Secondly, evaluators suggested that the Request Editor function could be enhanced by integrating an advanced visualisation component. One example of this could be the implementation of an interactive globe viewer which would enable the user to select an area of interest directly on a globe view along with some additional parameters, which would in turn generate a sensing request in the system for the selected area automatically to be included in the planning process.

The feedback to empower operators to add more complex optimization algorithms to the prototype autonomously and to provide the functionality to select an area of interest from a globe viewer shall be considered in future versions of the prototype.

6. Conclusions

GMV have successfully developed a service-based prototype that combines the traditional ESOC workflows with advanced optimization algorithms to support the mission planning of future Earth Observation Constellations. The prototype is the first to implement advanced optimization algorithms and the recently defined CCSDS MPS service standards in a semi-operational system. The use of service-oriented architecture means that the framework is flexible enough so that new components can be integrated into future versions with ease. As such, this prototype will be used as a baseline for future developments in ESOC for an interactive mission planning system which incorporates all users in an end-to-end mission planning system.

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