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LARGE HETEROGENEOUS EARTH OBSERVATION CONSTELLATIONS EXPLOITATION: ARCHITECTURE OF A PIPELINE FOR AUTOMATED OPERATIONS, FROM USER NEEDS TO ACQUISITIONS DOWNLINK

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The advent of large constellations of agile satellites for Earth observation marks a paradigm shift in Earth Observation: from individual user requests to flexible and optimized acquisition services, based on user needs. A mission may involve dozens of satellites that can ensure increasingly efficient and continuous observation. In addition, upcoming networks of heterogeneous constellations such as the Italian IRIDE will uncover previously inaccessible usage scenarios, allowing for timely flexible and preventive observations, using different types of payloads (i.e. optical or SAR) available on the constellations part of the network. The management of such space assets needs significant innovation in the operations and Ground Segments fields, to fully exploit their potential. In particular, a strong degree of automation is needed, to process user requests and more importantly to schedule the operations of the satellites, in terms of acquisition and then downlink. This paper presents an overview on a possible pipeline for the handling of a network of heterogeneous constellations. The first block of the pipeline processes user needs: it takes as input high level user requests and translates them into acquisition requests in terms of location, acquisition payload, mode and resolution. Then, a closed loop between a network scheduler and a simulator completes the architecture. The scheduler receives the set of acquisition requests and has the task to optimally allocate them on the different satellites. This block considers platform constraints, such as the time needed by the satellites to point the target, or the time needed to recharge the batteries. Uplink of commands and downlink of the acquired observation have also to be scheduled, considering constraints in terms of Ground Stations visibility and needed communication times. The simulator models the dynamical environment and simulates the acquisitions of the satellites, testing the optimal operations sets computed by the scheduler. The closed loop is useful to test the reliability and flexibility of the scheduler: failed acquisitions due to on board failures or unfavourable conditions (such as cloud coverage for optical payloads) can be included in the simulations and fed back to the scheduler, that needs to re-plan the acquisitions finding a new optimal schedule. Possible strategies to implement each block of the pipeline are presented, leveraging on the state of the art and presenting elements of novelty, to exploit to the maximum the potential of distributed and heterogeneous space assets.

Keywords: Constellations, Operations, Earth Observations, Agile Satellites Scheduling, Dynamic Planning,

Abbreviations

ACO	: Ant Colony Optimization
AEOSSP	: Agile Earth Observation Satellite Scheduling Problem
AOI	: Age of Information
DAG	: Directed Acyclic Graph
DTN	: Delay Tolerant Network
EA	: Evolutionary Algorithm
EO	: Earth Observation
GA	: Genetic Algorithm
ISL	: Inter Satellite Link
LNS	: Large Neighborhood Search
MCC	: Mission Control Center
SAR	: Synthetic Aperture Radar
VTW	: Visibility Time Window

1. Introduction

The advent of large constellations of agile satellites for Earth Observation (EO) marks a paradigm shift in the EO field: from individual user requests to flexible and optimized acquisition services, based on user needs. Indeed, the foreseen networks of heterogeneous constellations as the 34-satellite Italian IRIDE [1] will be able to provide more refined and user-tailored services. The possible coordination among heterogeneous space assets will allow combined acquisition campaigns, with multiple payloads. As detailed in [2], for optical multispectral acquisitions, combined services can largely benefit users, for a wide range of applications, from services for agriculture to disaster response to coast and marine monitoring. In addition, including Synthetic Aperture Radar (SAR) constellations into the network can further enhance the services, with possibilities of coordinated acquisitions by optical and radar services. This can prove useful on a variety of applications, as noticeable in table 1. The information reported comes from a literature review on EO services and applications, beyond the scope of this paper. The interested reader can refer to some useful references: [2], [3], [4], [5], [6].

Table 1: Overview of possible applications of EO data, with the needed payload type between SAR, optical in the visible spectrum (VIS) and optical infrared (IR).

Service	SAR	VIS	IR
Fire monitoring		x	x
Coast monitoring	x	x	x
Crop monitoring	x	x	x
Disaster response	x	x	x
Security	x	x	x
Air quality		x	x
Ground motion	x	x	x
Water resources		x	
Ecosystem monitoring		x	x

Furthermore, the large number of satellites will shorten the needed response times from user request to data downlink, thanks to shorter revisit times. In addition, the new Earth Observation (EO) satellite platforms are going in the direction of being agile small satellites with strong 3-axis attitude adjusting capability. This pointing capability adds flexibility to the operations, as can be seen graphically in fig. 1.

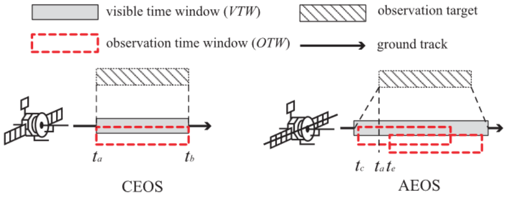

Fig. 1: Comparison between the acquisition capability of a Conventional EO Satellite (CEOS) and an AEOS [7].

This capability allows for higher quality solutions in terms of response time but also adds complexity to the operations, as the selection of the starting and ending time instants of the observation within a Visibility Time Window are not fixed as in the case of traditional EO Satellites, with more limited pointing capability.

A further opportunity offered by the new constellations is the possible minimization of the costs and of the overall response time thanks to the exploitation of the Inter Satellite Link (ISL): satellites will be able to communicate among themselves, dispatching telecommands and, if the data rate is large enough, exchanging acquired data. Data routes can be defined, connecting satellites to ground stations by exploiting cross-links in orbit in addition to direct satellite-to-ground links. This can provide faster services with a short Age of Information (AOI), the time between the acquisition and the downlink. This feature can be game-changing in applications as disaster response or for military purposes. The framework for data exchange on orbit has already been defined and it is presented in [8], with the protocols for data exchange that have been standardized by the (Consultative Committee for Space Data Systems (CCSDS) [9] .

However, heterogeneous satellite networks pose important challenges from a planning and scheduling point of view: there is the need to handle the operations of a vast number of satellites with different characteristics, to satisfy all the acquisition requests. As the number of satellites grows, it is clear that a traditional Mission Control Center (MCC) in which all the decisions are taken by human operators becomes more and more insufficient, overloaded by requests and unable to manage all the satellites of the constellation. This is why EO services providers as SkySat (now part of Planet Labs Inc.) [10], [11], [12] have already started efforts to shift towards an increased level of automation in their operations.

Additionally, academic research on automated satellite constellation scheduling has constantly been growing over the past two decades, moving the necessary steps towards automated satellite operations, at least for nominal activities of payload acquisitions and downlink.

This paper will develop the topic by providing a literature review and then proposing an architecture to address these challenges. The work has the following structure: firstly, the scheduling problem relevant aspects of the state of the art are summarised in a literature review, in section 2 and section 3. Then, a proposed pipeline architecture is presented in section 4, describing a dynamic receding horizon dynamic planner. The single blocks of the pipeline are described, giving hints on the possible techniques best suited for each one. A simulation and validation approach is also presented, as the last block of the pipeline, operating in closed loop with the rest. The paper is then concluded by the conclusions section, presenting the future direction of the work.

2. The satellite scheduling problem

The satellite scheduling problem has been extensively studied in the literature, especially over the past two decades. The problem is a combinatory problem, with the schedule of one or more satellites that has to be filled with acquisitions, selecting the best possible set of VTWs over the targets of interest. The problem can be seen as an optimization problem, often solved as a single-objective problem in which the goal can be the maximization of the number of performed acquisition over a time horizon or a sum of the rewards associated with the performed acquisitions. The targets can be spot targets covered with a single acquisition as in [13], or area targets for whom multiple acquisitions are needed [14], [15]. In this case, the target area has to be decomposed prior to the computation of the schedule, as done for example in [16].

In most of the cases requests are assumed to be satisfied with a single acquisition of the target area, but there are also examples in the literature that consider also repeated acquisitions [17], which model real-world monitoring campaigns of areas of interest.

Multi-objective implementations of the problem can also be found in the literature as in [18], [19], [20]. As an example, Kim et al. [18] used as objectives the maximization of the total number of observations and the minimization of the time between the acquisition of the same target with two different payloads part of a heterogeneous constellation. Starting from first examples of satellite scheduling as [21], [22], the focus has shifted to the Agile EO Satellite Scheduling Problem (AEOSSP). As detailed and formalized in [7], the problem is an optimization problem subject to constraints that regulate the mathematical consistency of the setup. Temporal constraints are added, to ensure the temporal feasibility of the schedule, ensuring that the schedule of a satellite includes a sequence of visibility time windows with no overlapping times. Additionally, operational constraints are frequently included to account for onboard resource limitations. This aspect is crucial for real application scenarios, as the planning of a real satellite must take into account onboard resources to produce a feasible schedule. In particular, power, attitude, and onboard data constraints are relevant. Implementations of the problem taking into account these constraints can be found in [23], [24].

Another important aspect is that the observation scheduling problem is coupled with the downlink scheduling problem in a real scenario: the acquired data needs to be downloaded, exploiting contacts between the satellite and ground stations. Mathematically the downlink scheduling problem is close to the observation scheduling one: visibility windows with targets have to be selected to maximize an objective while satisfying operational constraints, as in [25]. Scheduling and downlink problems are strictly coupled and need to be solved together to optimally exploit the limited onboard data storage resources: a satellite has a finite mass memory storage and can store data corresponding to a limited number of acquisitions. Therefore, contacts with the ground stations need to be scheduled within the operations, to free up the storage for further acquisitions.

3. Satellite Constellation Scheduling

A lot of work has been published in the past two decades on this topic, with a large variety of approaches that have been tried to obtain optimal schedules for groups of satellites, often in simplified scenarios. This section provides a summary of the literature, divided into the most relevant lines of research.

3.1 Centralised Approaches

This class of approaches groups strategies that solve the scheduling problem on ground for the whole constellation considered, providing individual schedules that then need to be uploaded on the single satellites. A variety of methods has been used in this framework.

Interesting results have been obtained by scholars using heuristic methods, in which the problem is stated as a combinatory optimization, with a heuristic rule aimed at maximizing the number of observed on-ground targets. Successful examples can be found in [26] and [14]. In the first reference, Bianchessi and Righini developed a heuristic algorithm for the planning and scheduling of the observations and downlink of the COSMO SkyMed constellation, consisting in 4 SAR satellites, considering simplified attitude constraints. In the second reference Wang et al. developed a similar framework for an analogous scenario (4 SAR satellite constellation) considering also simplified power demand constraints for the satellites. The principal strength of this kind of algorithm is the fact that it can quickly provide satisfactory solutions to the problem, without relying on optimization techniques: a set of target observations, the algorithm simply goes through them trying to build the schedule for the satellites, checking at each step heuristic rules and constraints. However, there is no mathematical guarantee of the optimality of the found solution, and this becomes an issue when the problem scenario is not simple. As an example in [27] a simple greedy search heuristic is compared with an optimization-based approach, that largely outperforms it in terms of observed targets, with a difference that grows with the number of satellites and targets involved in the case study.

Another interesting approach is the one by Eddy and Kochenfender in [16]: they solve only the observations scheduling problem modeling it as a graph with infeasibility edges. The possible acquisitions are modeled as the vertices in a graph, in which edges connect mutually exclusive acquisitions (due to VTW overlap). This way, the optimal schedule represents the maximum independent set of the graph, found by a local search algorithm. Compared to Directed Acyclic Graph (DAG)-based approaches with feasibility edges as [15], the strategy in [16] is computationally lighter because an infeasibility-edges DAG is far less dense than the complementary feasibility-edges DAG for the scheduling problem.

Approaches based on Evolutionary Algorithms such as Ant Colony Optimization [28] or the Genetic Algorithm (GA) [15], [29], have also been published showing promising results in scenarios with a limited number of satellites. However, GA encounters computational issues when applied to the coupled acquisition-downlink scheduling problem [30]. Another relevant reference is [31], in which an Evolutionary Algorithm is used together with Population-Based Incremental Learning to plan the operations of two satellites over a month on 2000 active requests.

Neighborhood search algorithms have also been used. In particular, Squillaci et al. [17] used Large Neighborhood Search (LNS) for the acquisition scheduling problem, showing promising results for a constellation of 16 satellites over a 1-day planning horizon. Another example can be found in [30], solving the coupled acquisition-downlink problem with a Tabu Search algorithm. The strategy is shown to work on a 4 satellite scenario, with some computational load issues, as the computational time is comparable with the scheduling time horizon.

Research applying Machine Learning techniques to the scheduling problem has also been carried out [32], [33], but it is still at a preliminary stage, with simplified scenarios and small-sized constellations.

In addition to heuristic methods, Mixed Integer Linear Programming (MILP) has also been often applied to find optimal solutions. Recent examples of MILP implementations for the scheduling problem can be found in [34], [18], [35]. MILP has shown success in finding optimal solutions in scenarios including hundreds of targets and tens of satellites. Moreover, constraints related to power, attitude, and on-board storage can be incorporated into the formulation, if written in linear form. However, as noted in the literature [27], while MILP can deliver optimal solutions, the computational times are often too long for practical use in real-world mission scenarios and day-to-day mission control operations.

Researchers have thus split the coupled acquisition-download problem into two phases: the first selects the downlink windows, while the second applies MILP to solve the acquisition scheduling problem, thereby completing the satellite planning. This has been developed by Augenstein et al. in [36] and by Cho et al. in [27]. In the first reference the downlink scheduling is solved with MILP, weighting each possible downlink window based on an approximated estimate of the acquired reward by imaging if the downlink window is not used. In the second refrence, the downlink schedule is obtained maximizing the sum of the downlink time for all the satellites.

This strategy allows a significant reduction of the size of the problem fed to the optimizer, without major losses in terms of solution quality, as shown by both references. In particular, the algorithm in [36] is an interesting benchmark as it manages to efficiently schedule the operations of a 13 satellite constellation for a 10h scheduling horizon over 7000 imaging targets with a computational time in the order of 10 seconds, a performance significantly ahead of most approaches in the literature.

3.2 Scheduling with ISL

The exploitation of Inter Satellite Link in Earth Observation is a relatively recent line of research, that is constantly gaining interest. Indeed, the ISL can potentially allow to control and operate a high number of satellites with a limited number of ground stations, relying on the communication windows among the satellites to build data routes. In the case of a radio link between the satellites, the data rate is limited but the communication often happens without strong pointing requirements. On the contrary, an optical communication link grants high data rates that would ease a lot the exchange of imaging data between the satellites, but it requires fine pointing. Here the focus is kept on radio links, as the technology is more mature and has already been used even on small satellites and cubesats, for various applications [37], [38]. The exploited links can be among the satellites of the constellations or with external space assets, that act as a relay.

When applied to the satellite scheduling problem, ISL links build a delayed time-varying communication network [8] on which telecommands or payload data can travel, with a data rate that is limited by the link budget of the communication between the satellites.

Kennedy [39] developed a centralised MILP-based algorithm to handle the operations of a 30 satellite constellation over a small number of targets, with ISL between the satellites. After the computation of data routes, assuming a maximum exchangeable data volume for each link window, the author introduces a pre-pruning step, to cut down suboptimal routes. Then, the whole uplink-acquisition-downlink chain is computed, by a MILP-based algorithm.

Chan [40] instead exploited the Dijkstra path planning algorithm [41] to optimize data routing paths among the satellites of a reconfigurable constellation, considering the communication network as a Delay Tolerant Network (DTN), as done also in [42].

Lowe et al [43] worked considering the constellation a DTN too, using the Contact Graph Routing (CGR) implementation of [8]. Contact Graph Routing is a set of techniques to find the optimal data paths among the assets of a DTN, and it is based on the definition of a Contact Graph. The latter is a way to model a DTN as a DAG in which the Vertices are all the possible link windows among the elements of the network and the Edges connect windows that can be used in sequence. The detailed definition of the Contact Graph and the corresponding Routing techniques are omitted here for brevity, the interested reader can refer to [8]. Lowe et. al exploited CGR to solve the uplink-acquisition-downlink scheduling problem with a task-optimal approach, aiming at the minimization of the delivery time of each single acquisition request, processing them dynamically one after the other as they are fed to the planner.

3.3 Decentralised Approaches

All the strategies reported up to now are centralized, with the ground segment that computes the schedule for all the satellites in the constellation. The literature also presents decentralized approaches, that rely on the autonomy of the single satellites of the constellation to compute the schedule. In addition, the exploitation of ISL allows to coordinate the actions of the satellites, applying multi-agent optimization theory. Viewed in this framework, the problem is a cost-coupled and decision-coupled multi-agent program, with a time-varying communication network. This is the most complex type of multi-agent problem. In addition, the computational resources of satellites are not comparable to the ones of on-ground applications of this framework. Nevertheless, multi-agent optimization approaches have been used for simplified scenarios with strong assumptions, as in [42] and [44], laying down foundations for future works.

3.4 Scheduling Under Uncertainties

In a real scenario, events such as cloud coverage or satellite onboard failures can impact the operations. The literature presents examples of satellite scheduling under uncertainties, to cope with unforeseen operations and make the planning more robust. Poveda et al. [31] included uncertainty in the acquisitions priority value, associated with a probability of success of each observation (in a real scenario this priority index can be a function of the weather conditions on the target area for example). Works such as [45], and [46] included cloud coverage uncertainty directly in the optimization process.

4. Pipeline Architecture

This section provides the overview of the proposed architecture of a pipeline for the scheduling and simulation of a heterogeneous constellation network of satellites. The core of the architecture is a two-step receding horizon dynamic planner, that has to compute the complete uplink-acquisition-downlink chain of the satellites, exploiting isotropic radio ISL to dispatch telecommands and to support the downlink. The objective is to develop an infrastructure to efficiently plan and then realistically simulate the operations of a heterogeneous satellite network, including constellations of optical and SAR payloads, up to a total 50 satellites. With this goal in mind, a trade-off among the alternatives found in literature has been carried out, to select candidate techniques for each block of the architecture.

The proposed architecture is presented in fig. 2. The system works in closed loop: requests are processed and transformed into inputs for the Dynamic Planner, which produces the schedule. The schedule is then validated into the Simulation Environment block, which accurately simulates the operations of the satellites. The output of this block is the batch of failed requests, so all the requests that have not been satisfied by the generated schedule over the planning horizon. In addition, the closed-loop enables the possibility to inject high-priority requests during the simulation, to

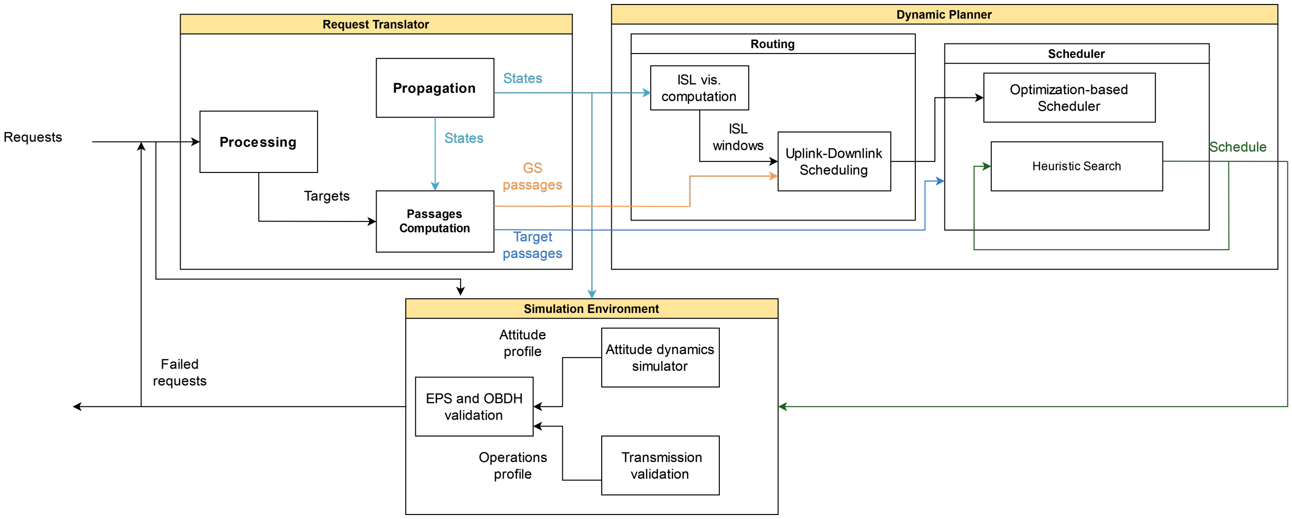

Fig. 2: Overview on the proposed architecture.

be handled by the dynamic planner as it will be detailed in section 4.2 and section 4.3. The following sections provide further details on the single blocks of the architecture.

4.1 User Needs Processing

This block takes as input Requests, formalized as objects that contain an ID and information on the area of interest and the type of acquisition, specifying if it is a single or recurring acquisition and what type of payload is involved (single or combined). Additional information such as priority indexes or a deadline can also be provided.

Requests are fed to the processing block, which translates each one of them into one or more Targets. Targets carry the information of the requests in terms of ID, area, and needed payload. This latter aspect is specified in terms of technology and, if provided, with a resolution threshold and visibility limitations. Targets then go through the Passages Computation block. This block is fed also with the propagation of the satellite of the constellations over a user-selected planning horizon and knows as parameters the characteristics of the satellites present in the network (payload, resolution on ground, acquisition data rate) and information on the ground stations (location, data rate with each satellite).

The output of this block is the set of possible windows to satisfy the requests, obtained computing passages over the targets of all the satellites having compatible payload and resolution characteristics with the target. To have a more comprehensive scenario, this block needs to include an area decomposition algorithm, such as the one in [16], to handle large area acquisitions. Both Target Passages and GS Passages have their visibility time window, satellite ID, initial and final across and along track pointing angles, the electrical energy amount they require to be completed, and the amount of acquired or downloaded data. Target Passages carry also their associated request ID.

4.2 Dynamic Planner

The dynamic planner is a two-step block, building on the successful approaches presented in [36], [39], [27]. A centralized approach is needed, because with a large number of satellites involved and with the consequent large communication DTN, multi-agent strategies would be unpractical, with long times needed to share the information among all the satellites. In the first step, the Routing sub-block solves the data routing problem, computing the ISL windows between the satellites and then computing the uplink-downlink schedule for all the satellites.

The uplink schedule can be computed with a shortest path algorithm such as Dijkstra's algorithm [41], to reach each satellite with commands uplink at the earliest possible time within the planning horizon. Then, the downlink scheduling problem is solved, and this can be done with approaches similar to the ones used in [36] and [27] or performing optimization in the CGR framework [8] to select the best possible data routes. The output of the Routing sub-block is the communication schedule for all the satellites.

This serves as input for the scheduler sub-block, which is made by two separate schedulers: an optimization-based one and a lower-level heuristic search. The optimization-based scheduler is operated once at the beginning of the planning horizon with inputs coming from an initial set of active requests, considering the pre-scheduled communications as fixed and discarding for each satellite all the GS and target passages occurring before it is reached by the uplink chain. The scheduler computes the acquisition schedule taking into account power, attitude and on-board data constraints, formulated in a simplified way such that the problem can be solved with a MILP solver. Alternatively, a Neighborhood Search algorithm can be chosen for this block, implementing an iterative destroy-and-repair procedure to fill the schedule of the whole constellation while checking the compliance with the constraints. Such an approach would be computationally lighter at the expense of a possible drop in solution quality. This strategy can be more suitable than MILP in case of large sized constellations, in which the number of satellites often allows to obtain satisfactory performance even if the schedule is not the mathematical global optimal optimum.

The lower-level heuristic search instead is a much simpler greedy search algorithm, that schedules the requests it receives with a First-in-First-Out (FIFO) logic, trying to add them to one satellite at a time. For each request, the satellites with a payload compatible with it are scanned, computing the earliest delivery time of the acquisition that each satellite can achieve. The earliest delivery time is the earliest possible time instant at which the downlink of a request can be completed. This parameter is computed considering for each satellite only visibility windows that come after the next first possible uplink opportunity. The request is then added to the schedule of the satellite offering the lowest earliest delivery time. This heuristic algorithm has the purpose of supporting the dynamic operations of the planner. The approach relies on the size of the constellation: with an high number of satellites the revisit times over the areas of interest can be in the order of minutes, granting a lot of possible acquisition windows, increasing the chance that there are empty slots in the schedule of the satellites after the generation of the optimization-based schedule. When a new urgent request comes in during the operations, the request translator block obtains the corresponding target passages for all the compatible satellites, then the planner tries to satisfy the request as early as possible. If the process fails, the algorithm can be complemented with a priority scheme, to inject the request into the schedule of the constellation at the expense of pre-scheduled lower-priority ones. The output of the Dynamic planner is in any case a Schedule object, which is fed to the Simulation Environment block.

4.3 Simulation Environment

The Simulation Environment takes as input the schedule and simulates it forward in time over a fixed interval to validate it. The time interval can be longer than the planning horizon of the optimization-based planner, which can in that case work at fixed time instants with a receding horizon strategy. Validation is performed through the use of the Attitude Dynamics Simulator, Transmission Validation, and EPS and OBDH Validation sub-blocks, which model with a high degree of accuracy the behavior of all the satellites, checking the validity of the schedule.

Requests that have not been satisfied during the process are grouped into the output of the whole chain and it is added to the new Requests for the new planning horizon of the scheduler, thus closing the loop.

The environment must also grant the possibility to inject new requests, to test and validate also the dynamic features of the planner, as already implemented for similar purposes [39], [43].

In addition, the simulation environment can be used to inject failed acquisitions into the simulation, removing acquisitions from the schedule and adding the corresponding Requests into the Failed Requests list. Acquisitions can be removed from the schedule based on probability models for onboard failures (of the payloads or of the platforms) and on cloud coverage models for optical acquisitions.

5. Conclusions and Future Work

This paper presented the state of the art on EO satellite constellation operations, through an extensive literature review on the major lines of research on EO satellite constellation scheduling. The foreseen developments on the topic and their challenges have been underlined. A possible modular architecture to efficiently address these challenges has been proposed, centered around a 2-step 2-levels dynamic planner.

After the finalization of the selection of the algorithms, the next steps would be the implementation and extensive use case testing of the structure. Starting from heterogeneous constellation networks of reduced size, the architecture will be refined as testing goes on, progressively scaling up the size of the use case, up to the goal of simulating the automated operations of a fleet of 50 EO satellites. Once satisfactory performance in deterministic scenarios have been obtained, extensive Monte Carlo simulations will also be executed, to assess the performance of the pipeline under weather and failure uncertainties.

Another relevant aspect to be tested is the sensitivity of the performance of the pipeline to the number of ground sta-

tions considered. Indeed, ground station booking costs are one of the major contributors to the cost of EO services. It is therefore useful to evaluate what is the minimum number of ground station windows needed to grant satisfactory performance as function of the number of satellites and requests.
In addition, further trade-offs on the level of autonomy of the satellites will be performed to further increase the robustness of the architecture. On top of the presented architecture, multi-agent onboard planners can be added, for local re-planning of subsets of the constellation network. This would allow to evaluate if an increased level of autonomy can improve the performance in presence of uncertain events.
Another line of research would be to try machine learning techniques to the acquisition scheduling part of the problem, training a neural network with data coming from runs of the presented pipeline.

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