SCUOLA DI INGEGNERIA INDUSTRIALE
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Executive Summary of the Thesis

Synchronous high revisit mixed sensor constellation: architectural design optimisation and trade-offs for emergency response

Laurea Magistrale in Space Engineering - Ingegneria Spaziale

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1. Introduction

In the last decade, the Earth observation (EO) domain has been gaining more and more importance, with many public and private entities increasingly investing in upstream and downstream EO applications. In the future, remote sensing satellites will be of paramount importance, especially considering the growing frequency of extreme weather events due to climate change. In particular, optical and Synthetic Aperture Radar (SAR) sensors can be effectively exploited in emergency response related to extreme events. Moreover, these data can be jointly analysed as fused data to improve the measurements [1]. However, frequent and timely observations are needed for fast and effective emergency response. Therefore, this work aims to design a constellation of optical and SAR small satellites devoted to critical infrastructure monitoring and emergency response in Italy, which is particularly exposed to hydrogeological risk due to floods.
Constellation design is a complex task, and the designer's objective is to find a solution that maximises the performance while minimising the cost [2]. However, performance and cost are expressed by conflicting metrics, and a set of compromise solutions should be found. Thanks to their flexibility, multi-objective evolutionary algorithms are particularly suitable for the complex problem of constellation optimisation, with NSGA-II [3] being one of the most used algorithms. Only recently, new multi-objective algorithms have been explored in literature, such as MOPSO [4] and MOEA/D [5]. Despite the large number of studies investigating constellation design, the problem of hybrid mixed sensor constellations optimised for data fusion has been addressed only in a work of Chiatante [6]. Specifically, Chiatante proposed the design of a synchronous constellation that maximises the optical and SAR revisits within 60 seconds. However, the required time interval between an optical and a SAR acquisition strongly depends on the final application and can be in contrast with other objectives. In this work, the desired time interval between the two acquisitions will be further analysed, and trade-offs between the synchronous performance and cost will be explored. Moreover, two new figures of merit for mixed sensor constellations will be proposed, and new constellation patterns will be explored.

2. Background

During the constellation design process, some performance indices (or figures of merits) are defined, along with cost drivers. An optimisation method is then employed to identify optimal orbital parameters that maximise performance while minimising costs. Two of the most important figures of merit often considered for optimising EO constellations are the coverage and the revisit time. Coverage expresses the percentage of the area of interest that can be sensed by the satellites in a given amount of time, while revisit time measures the gap between two consecutive observation opportunities. These figures of merits are classically defined for constellations carrying a single sensor. Therefore, new figures of merit should be defined for a synchronous optical and SAR constellation, such as the ones presented in section 4.1.

On the contrary, two key cost drivers are the number of satellites and the launch options. The number of satellites is usually proportional to the cost of the constellation, but at the same time, it is the principal determinant of the coverage and the revisit time. Moreover, the number of launches that are required to deploy the full constellation has an essential impact on the price, as well as the launcher that is used.

2.1. Specialised orbits

Repeating ground tracks and Sun-synchronous orbits (SSO) are often adopted for EO missions for characteristics that make them particularly appropriate.

Repeating ground tracks are orbits that retrace their ground track after k revolutions of the satellite and m rotations of the Earth, with k and m integer numbers. This makes them particularly favourable in Earth observation for their consistent viewing angle at each passage and periodic revisits over the same location.

SSOs are instead exploited because they maintain an approximately constant angle between the orbital plane and the Sun's direction. This property is particularly useful for optical satellites because it ensures that any location is sensed with consistent illumination conditions since the satellite will always pass over any given point on the Earth's surface at the same time of day. The constant illumination angle is also beneficial for the consistent exposure of solar panels to the Sun's rays. However, the high inclinations of SSOs generally increase launch costs.

2.2. Optical and SAR sensors

Optical and SAR sensors can be employed in many tasks, including emergency response and critical infrastructure monitoring [1]. The main difference between the two instruments is that while the first requires an external energy source (i.e. usually the Sun or a thermal energy source), the second one provides its own illumination source. Therefore, SAR sensors can operate in any illumination condition, even at night, while optical sensors not. For this reason, SAR instruments are called active sensors, while optical systems are passive sensors. Moreover, optical sensors cannot penetrate clouds, in contrast to SAR. The two instruments also have different acquisition geometries. In fact, SAR sensors have a side-looking geometry, while optical sensors are often nadir-pointing instruments.

2.3. Multi-objective optimisation

Constellation design is often formalised as a multi-objective optimisation problem (MOOP) since the designer's main goal is to identify an optimum orbital pattern that can minimise cost and maximise performance. Since these objectives are in contrast, it is not possible to obtain a single solution that minimises the cost and maximises the performance at the same time, so a set of compromise solutions is found, i.e. the so-called Pareto set. In a MOOP, each objective function f_i can be collected in the objective function vector:

$$\mathbf{F}(\boldsymbol{x}) = [f_1(\boldsymbol{x}),\, f_2(\boldsymbol{x}),\, \ldots,\, f_k(\boldsymbol{x})] \tag{1}$$

in which k is the number of objective functions $f_i : Q \rightarrow \mathbb{R}$, and $\boldsymbol{x} = [x_1, x_2, \ldots, x_n]^T$ is the vector of the decision variables. The set $Q \subset \mathbb{R}^n$ is the domain of $\mathbf{F}$, also called parameter space or decision space. Moreover, the decision variables may be subjected to m inequality, and p equality constraints:

$$g_i(\boldsymbol{x}) \leq 0 \quad i = 1, 2, \ldots, m \tag{2}$$

$$h_i(\boldsymbol{x}) = 0 \quad i = 1, 2, \ldots, p \tag{3}$$

Since the objective functions are often in conflict, in this kind of problem, we look to a set of feasible solutions $\boldsymbol{x}^*$ that are said to be *Pareto*

optimal. A solution is said to be Pareto optimal if there exists no feasible vector of decision variables that would improve at least one objective function without degrading another one.
Several approaches can be adopted for the solution of a multi-objective problem. For example, it is possible to modify the problem in a single-objective one by computing a weighted sum of the objectives or by modifying them in inequality constraints. However, some of the most flexible tools are metaheuristics algorithms, such as multi-objective evolutionary algorithms (MOEAs), which are optimisation algorithms inspired by natural selection mechanisms based on Darwin's principle of the survival of the fittest.
MOEAs are stochastic algorithms since random decisions are made during the process. Therefore, different runs will typically produce different solutions. Moreover, MOEAs need to include also a diversity maintenance mechanism. In fact, because of the stochastic noise, EA can tend to reach a single solution, and some strategies need to be applied to avoid this risk. For this reason, some MOEAs penalise solutions that are too similar in the objective function space, promoting evenly spread solutions along the Pareto front.

3. Constellation requirements

The constellation requirements are derived after analysing two case studies related to extreme weather events in Italy, i.e. the 2017 Abruzzo snowfall and the 2022 Marche flood. During the first event, intense snowstorms affected the Abruzzo region, causing widespread damage to transmission and distribution lines, mainly caused by the formation of ice sleeves on overhead power lines. Almost 12-13% of the Italian surface was marked at risk of ice sleeve formation. In the second event, heavy rains and floods affected the Marche region. A considerable amount of rain was recorded in a short time, with the first floods reported just four hours after the beginning of the rainfall. Moreover, the water level of rivers rapidly increased because of the flood wave, causing inundations in just a few hours.
After the analysis of these events, the main actors involved in the emergency response were identified as possible end-users of the EO services provided by a high-revisit constellation. Therefore, their main activities and needs were characterised by an operational analysis. In particular, the Transmission System Operator (TSO) could exploit EO data to locate the ice sleeves formation on overhead power lines and apply defence strategies such as heating the conductor or sectionalising the affected line. Instead, Civil Protection could exploit EO data to map the flood extent and depth, coordinating the rescue operations by the fire and rescue service (Vigili del Fuoco), the Police Force and the civil protection volunteers. Some of the main system requirements are reported in table 1. These requirements will be partially exploited as optimisation constraints, as reported in section 4.2.

REQ.ID	Requirement
SR-010	The system shall perform measurements with SAR sensors
SR-020	The system shall provide optical remotely sensed data
SR-030	The SAR system shall cover 15% of the Italian territory in 12 hours
SR-050	The 90% of the revisit time gaps shall be below 3 h over the Italian territory
SR-080	The SAR system shall have a resolution of 3 x 3 m (Az. x Rg.) in Stripmap mode
SR-090	The optical system shall provide VNIR images with a GSD = 3 m

Table 1: System requirements.

4. Methods

The optimisation process was carried out starting from a MATLAB modelling code developed during the previous works of Sartoretto [7] and Chiatante [6]. However, the code has been modified to deal with different optical-SAR constellation patterns and investigate trade-offs between the cost and the synchronous performance of the hybrid constellation. The tool is composed of three main parts:

- a function that generates the initial Keplerian elements of each satellite of the constellation, starting from the decision variables vector;

- a numerical orbit propagator that includes J2 perturbation
- a function that evaluates revisit and coverage.

In order to compute coverage and revisit, the Italian territory is discretised in grid points, each representing a specific latitude and longitude.
SAR coverage has been defined assuming a 20 km swath and a fixed look angle of 25° on the right. SAR revisit is instead evaluated assuming an access angle ranging from 20° to 60°, both to the right and left direction. Additionally, SAR duty cycle is considered. Thus, the sensor is assumed to be turned on continuously for 60 seconds when passing over Italy and then turned off for at least one orbit. Optical coverage has been evaluated considering a nadir-pointing instrument with the field of view, $FOV = 1.6°$. Furthermore, the optical revisit is evaluated considering an access angle of +/- 30° with respect to the nadir. Additionally, the illumination constraint is observed for optical sensors. Therefore, a grid point is considered covered or revisited only if the solar zenith angle over the location is between 10° and 80°.
The tool has been validated through a comparison in STK. SAR coverage was overestimated by just 4.4% in MATLAB, while optical coverage was underestimated by -0.5%. Moreover, the obtained revisit instants are bounded within the simulation time step.

4.1. Mixed-sensors constellations figure of merits

The fundamental concept behind a mixed-sensor constellation is that the optical and SAR acquisitions should be taken within a very short time interval to enhance the reliability of the data and reduce temporal decorrelation. For simplicity, we will refer to the required time span between an optical and a SAR acquisition for data fusion as *synchronicity time*. Conceptually, the synchronicity time can either be imposed as an input or can become an objective function to minimise.
If the same location is revisited by both sensors within the synchronicity time, this constitutes a *data fusion opportunity*. Data fusion opportunities are evaluated by comparing the optical and SAR revisits, and every time that a grid point is revisited within the synchronicity time, this is recorded as a data fusion opportunity. *Synchronous revisit time* is the time interval between two consecutive data fusion opportunities. The first figure of merit proposed in this work is the synchronous mean revisit time over the Italian territory, which is computed by averaging the synchronous revisit times for each grid point of the territory of interest and then averaging again among all the grid points. The second figure of merit is the synchronous daily coverage, which is the surface of the territory of interest covered by the two sensors within the synchronicity time in one day.

4.2. Problem modeling and mathematical formulation

The problem of constellation optimisation is rather complex since it involves both discrete and continuous decision variables, nonlinear and non-differentiable objective functions obtained by numerical integration, and nonlinear inequality constraints. Therefore, EAs are particularly suitable for these kinds of problems thanks to their flexibility. In this work, two EAs have been investigated: the NSGA-II variation included in MATLAB (i.e. the MATLAB function `gamultiobj`) and the MOEA/D algorithm. The two algorithms have been tested with a benchmark problem, i.e. the optimisation of a simple SAR constellation. As shown in fig. 1, the NSGA-II gave better results than MOEA/D since it tends to preserve population diversity and returns results distributed uniformly. For this reason, only the MATLAB function `gamultiobj` will be used to optimise the optical-SAR constellation.

4.2.1 Constellation patterns, decision variables and domain

Considering the optical and SAR geometries and the optical illumination constraint, three possible orbital patterns have been proposed:

1. Walker with Sun-synchronous orbits (or Walker SSO)
2. Walker with generally inclined orbits (or Walker inclined)
3. SAR with inclined orbits and optical with Sun-synchronous orbits (or hybrid inclined-SSO)

The first two patterns exploit a RAAN shift, $\Delta\Omega$, and an altitude difference between the

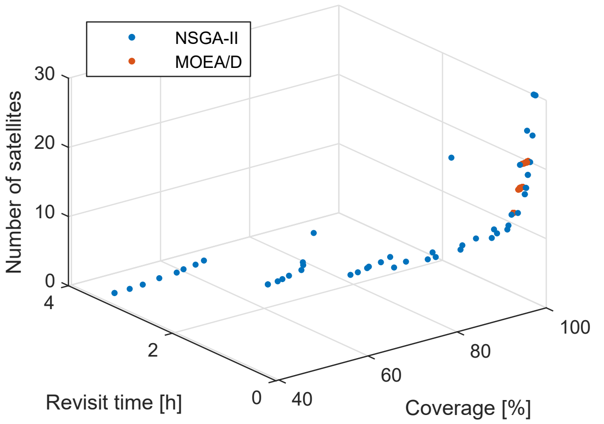


Figure 1: Comparison between the NSGA-II and MOEA/D algorithms in a benchmark problem. MOEA/D tends to converge toward local optima, while NSGA-II gives more uniform results and preserves diversity.

optical and SAR planes, trying to achieve a favourable acquisition geometry between the two sensors. Furthermore, Walker constellation patterns have been employed to simplify the problem and reduce the number of decision variables, thus shrinking the parameter space. The third pattern employs optical satellites on modified Walker in which the planes are evenly spaced in the LTAN ranges 8.30-11.00 and 13.00-15.30, taking advantage of the favourable lighting conditions, while the SAR satellites are on generally inclined orbits to maximise the SAR coverage and revisit. The integer and real decision variables for the three patterns are, respectively:

$$\boldsymbol{x}_{SSO} = [S_{SAR},\ S_{opt},\ P,\ F_{SAR},\ F_{opt}, \dots \\ \text{index SSO}_{SAR},\ \text{index SSO}_{opt},\ \Delta\Omega,\ t_{syn}]^T$$

$$\boldsymbol{x}_{inc} = [S_{SAR},\ S_{opt},\ P,\ F_{SAR},\ F_{opt}, \dots \\ index_{mk},\ i_{SAR},\ a_{opt},\ \Delta\Omega,\ t_{syn}]^T$$

$$\boldsymbol{x}_{hyb} = [S_{SAR},\ P_{SAR},\ F_{SAR},\ S_{opt},\ P_{opt}, \dots \\ F_{opt},\ index_{mk},\ i_{SAR},\ \text{index SSO}_{opt},\ t_{syn}]^T$$

The subscripts SAR and opt are used to distinguish between variables relative to the SAR and optical constellation. The parameters S_{SAR} and S_{opt} are the number of satellites for each of the P planes. F_{SAR} and F_{opt} are the Walker phasing parameters of the two constellations. a and i indicate the semi-major axis and the inclination. t_{syn} is the synchronicity time. The ground track repeat cycle is determined by the variables index SSO and $index_{mk}$. All the Sun-synchronous orbits for $m \in [1, 40]$ and $k \in [1, 613]$ that observe the altitude constraint are computed and stored in a matrix, as in the work of Sartoretto [7] and Chiatante [6]. In fact, there are only a finite number of SSOs with repeating ground tracks with these characteristics. Therefore, index SSO identifies the row of a matrix in which the SSOs with repeating ground tracks are stored. Similarly, $index_{mk}$ is an integer value that selects the row of a matrix containing different combinations of m and k, with $m \in [1, 25]$ and $k \in [1, 383]$. Moreover, in the Walker inclined pattern, the inclination of the optical satellites is imposed in such a way that they experience the same nodal precession as the SAR satellites.

Finally, lower and upper boundaries are defined for the three decision variables:

$$\mathbf{lb}_{SSO} = [2, 2, 3, 1, 1, 1, 1, -15^\circ, 60\,\text{s}]$$
$$\mathbf{ub}_{SSO} = [5, 5, 5, 4, 4, 166, 312, 15^\circ, 900\,\text{s}]$$

$$\mathbf{lb}_{inc} = [2, 2, 3, 1, 1, 1, 40^\circ, 450\,\text{km}, -15^\circ, 60\,\text{s}]$$
$$\mathbf{ub}_{inc} = [5, 5, 5, 4, 4, 108, 89^\circ, 645\,\text{km}, 15^\circ, 900\,\text{s}]$$

$$\mathbf{lb}_{hyb} = [2, 2, 1, 1, 2, 2, 1, 40^\circ, 1, 60\,\text{s}]$$
$$\mathbf{ub}_{hyb} = [9, 4, 3, 9, 4, 3, 108, 89^\circ, 312, 900\,\text{s}]$$

4.2.2 Constraints

For the optimisation process, some constraints are used to reduce the decision space and avoid non-feasible solutions. The first constraint is related to the Walker phasing parameter, F:

$$F \leq P - 1$$

This constraint is expressed as a linear constraint since both F and P are decision variables of the problem.

For the Walker inclined, and Walker SSO configurations, a higher altitude for the optical satellites with respect to the SAR is imposed as a nonlinear constraint:

$$a_{SAR} + 10\,\text{km} \leq a_{opt} \leq 100\,\text{km}$$

The constraint is nonlinear because the semi-major axis must be computed starting from m, k and the inclination. Moreover, the semi-major axis of the satellites is bounded by the constraints:

$$450\,\text{km} \leq a_{SAR} \leq 550\,\text{km}$$
$$450\,\text{km} \leq a_{opt} \leq 645\,\text{km}$$

Additional constraints are related to the coverage in time and the revisit time of the SAR satellites. A 15% coverage of the Italian surface in 12 hours is imposed:

$$cov_{SAR} \geq 15\%$$

The revisit time is constrained such that 90% of the SAR revisits are within 3 hours:

$$rev_{90\%} \leq 3 \text{ h}$$

in which $rev_{90\%}$ is the SAR 90th percentile revisit time. Finally, the SAR mean revisit time is constrained similarly:

$$\overline{rev} \leq 3 \text{ h}$$

Coverage and revisit are computed thanks to the coverage and revisit function. The last three constraints related to SAR coverage and revisit are imposed as nonlinear constraints.

4.3. Objective functions

The first objective function is one of the main cost drivers, i.e. the total number of optical and SAR satellites:

$$f_1(\boldsymbol{x}) = T_{opt} + T_{SAR}$$

The second objective function $f_2(\boldsymbol{x})$ is the launch cost. In this work, the launch cost is computed considering a Vega-C launcher as:

$$f_2(\boldsymbol{x}) = C \cdot N_{lnch}$$

in which N_{lnch} is the total number of launches required for the deployment, and $C = 37$ M\$ is the cost of a single launch, which is considered constant. A maximum capacity of 9 microsatellites per launch and a maximum mass of $m_{max} = 2200$ kg for inclined orbit and $m_{max} = 2000 kg$ for Sun-synchronous orbits are considered. For the Walker Sun-synchronous pattern and Walker inclined pattern, the total number of launches is computed as:

$$N_{lnch} = P \cdot K$$

with $K = 1$ if the launcher capacity is not saturated, and $K > 1$ if saturated. Launcher capacity is considered saturated if more than 9 satellites per plane are needed, or if their combined masses exceed m_{max}. For the hybrid inclined-SSO pattern the number of launches is computed similarly:

$$N_{lnch} = P_{SAR} \cdot K_{SAR} + P_{opt} \cdot K_{opt}$$

Therefore, each optical and SAR plane requires at least one launch. The mass of each satellite m is computed as the sum of the dry mass and the propellant mass:

$$m = m_{dry} + m_{prop}$$

The propellant needed for altitude maintenance and end-of-life disposal is considered. Furthermore, since SAR and optical satellites belonging to adjacent planes are launched together, the propellant needed for the required orbit raising and change of inclination manoeuvre are considered. The change of plane manoeuvre and the orbit phasing are not considered as they depend on the deployment strategy and the desired transfer time.

The last three objective functions are related to the synchronous performance of the hybrid optical-SAR constellation. They are the synchronous mean revisit time, the synchronous daily coverage and the synchronicity time:

$$f_3(\mathbf{x}) = rev_{syn}$$
$$f_4(\mathbf{x}) = (-1)\, cov_{syn}$$
$$f_5(\mathbf{x}) = t_{syn}$$

Since the analysis period is longer than 24 hours, the synchronous daily coverage for each day of the simulation is evaluated, and then the mean among all synchronous daily coverage values of each day is computed.

4.4. Discussion on uncertanties

The problem related to the uncertainties of the optimisation process can be divided into two main categories, including:

- Uncertainties in the modelling tool.
- Uncertainties related to the optimisation algorithm adopted.

The orbit propagator in the modelling tool introduces errors derived from the perturbation model adopted and from the numerical integration error. However, the numerical error can be easily mitigated by imposing a small tolerance of the ordinary differential equation (ODE) solver. In the altitude ranges investigated in this thesis,

the predominant perturbation is the acceleration due to Earth's oblateness J2. Secular effects deriving from other perturbative forces should be considered only for longer analysis periods. Another source of uncertainties derives from the coverage and revisit model that is influenced by the grid spacing, the simulation time step and the time span employed for the analysis. More accurate models are computationally expensive and can significantly slow down the optimisation process. Nevertheless, since the proposed tool should serve at the early stages of the design, an approximated model can be very beneficial to explore a larger number of candidate solutions. Uncertainty can also arise from the adopted optimisation algorithm. Evolutionary algorithms offer a stochastic search approach and do not guarantee convergence to the global optimum. In fact, different runs of the algorithm can lead to different solutions. To face this problem, a greater number of iterations can allow us to explore more solutions and give better results. However, an excessive number of iterations may cause high utilisation of temporal and computational resources. Alternatively, the search space can be reduced thanks to some constraints.
All these uncertainties source contribute to the total optimisation uncertainty. For example, if the coverage is overestimated, this could result in underestimating the required number of satellites. Vice versa, if the coverage is underestimated, the obtained constellation would be oversized.

4.5. Workstation and optimisation time

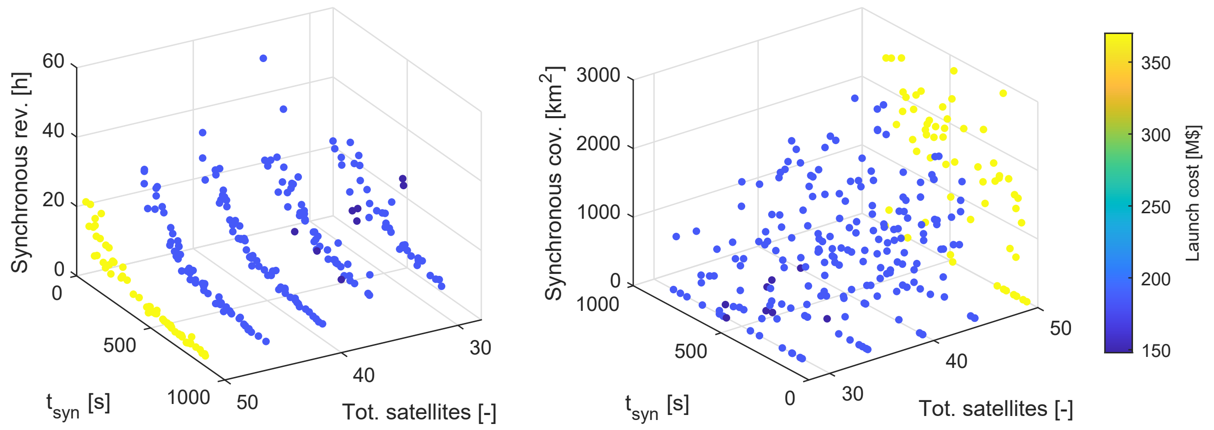
The optimisation has been performed using a 16-core workstation with a clock speed of 3.00 GHz. Regarding the setting of the genetic algorithm, the population size is set to 750 individuals and the maximum number of iterations to 50. The optimisation time is equal to 24 hours for the Sun-synchronous Wlaker pattern, 30 h for the Walker inclined pattern, and 44 h for the hybrid inclined-SSO pattern.

5. Results

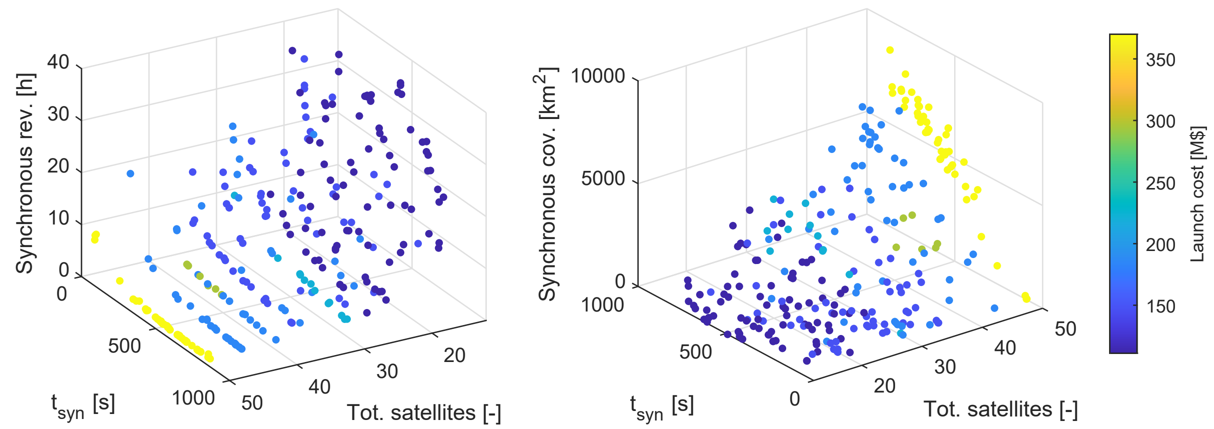
The sets of nondominated solutions (or Pareto fronts) generated by the optimisation process with the three patterns are shown in fig. 2. A total of 263 solutions have been found for each pattern. Both the synchronous mean revisit time and the synchronous daily coverage depend on the number of satellites and the synchronicity time. Specifically, a larger constellation implies more frequent revisits and more extended coverage, resulting in improved performance. On the other hand, a shorter synchronicity time worsens the synchronous revisit and coverage since it is more challenging to achieve SAR and optical acquisitions within a short time interval. Moreover, larger and more performing constellations also require a higher launch cost. In fact, the launch cost is related to the number of planes and the number of satellites, and constellations with a higher number of planes can achieve better performances. For the Walker inclined pattern, most of the solutions have a RAAN shift, $\Delta\Omega$, in the range of -8.5° to -7.5°, with only two solutions between -4° and 4°. Regarding the Walker SSO pattern, the majority of solutions have a RAAN shift between -5° and -4°, and only two solutions are in the range of -2° to 2°. Furthermore, a slightly favourable ratio between the optical and SAR altitude near $H_{opt}/H_{SAR} \approx 1.185$ is observed for the Walker inclined pattern. Most of the SAR inclined orbits have inclinations between 46° and 56°, which is slightly higher than the latitude range of Italy. Finally, two selection methods have been proposed: preference-driven and cost-driven approaches. The performance-driven approach selects the most affordable option that meets the desired performance criteria, while the cost-driven approach chooses the constellation based on the desired cost. The Walker inclined pattern is the most suitable option for regional coverage over Italy because it meets the desired performance with the lowest number of satellites or achieves the best performance at a fixed cost. However, the hybrid inclined-SSO pattern performs more consistently during the year because the optical satellites are placed on orbits with an LTAN range that allows good lighting conditions.

6. Conclusions and future works

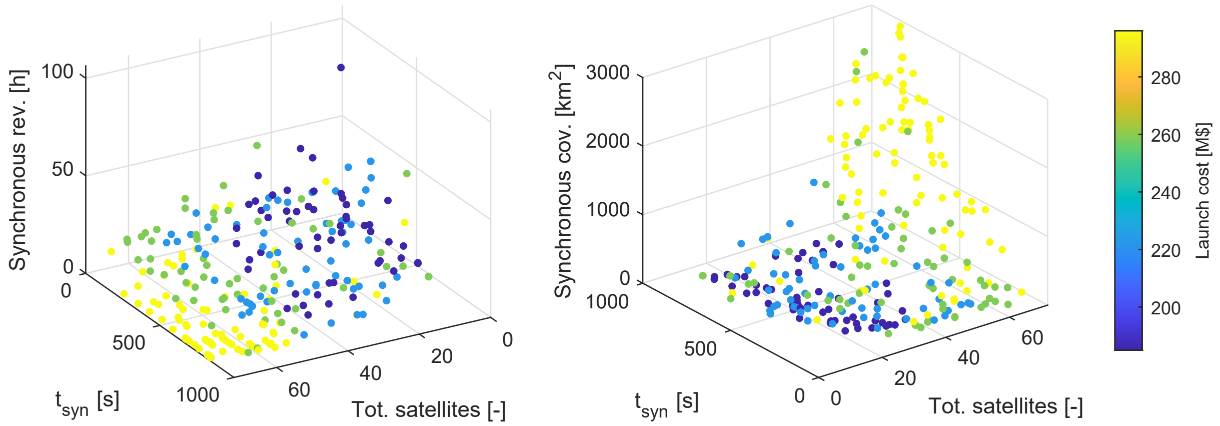
This thesis aimed to address the design problem of a constellation of small optical and SAR satellites to support Italian decision-makers during flood emergency response and monitor crit-



(a) Walker Sun-synchronous pattern.



(b) Walker inclined pattern.



(c) Hybrid inclined-SSO pattern.

Figure 2: Pareto front of the hybrid optical-SAR constellation designs. The left scatter plots illustrate the total number of satellites (f_1), the launch cost (f_2), the synchronous mean revisit time (f_3), and the synchronicity time (f_5). The right scatter plots have on the z-axis the daily synchronous coverage (f_4) in place of the synchronous mean revisit time.

ical infrastructures during fast critical events such as ice sleeves formation on overhead power lines. Additionally, the peculiar problem of synchronous mixed-sensor constellations was investigated. Therefore, new figures of merits have been proposed for this kind of constellation. The constellation design was then formalised as a multi-objective optimisation problem, and two optimisation algorithms were considered: a variation of NSGA-II included in MATLAB and the MOEA/D. The first algorithm was selected for the final optimisation because it better preserves population diversity. However, the uncertainties of the proposed tool should be further investigated in future works to quantify how different optimisation settings can influence the obtained results.
The Pareto set of optimal designs that maximise the synchronous performance and minimise the cost was found. Three different constellation patterns are explored for the design: a constellation with optical and SAR satellites on generally inclined orbits, one with optical and SAR satellites on Sun-synchronous orbits and a final one with optical satellites on Sun-synchronous orbits and SAR satellites on inclined orbits. The first pattern with both sensors on generally inclined orbits gives the best results over Italy. In fact, with this pattern, it is possible to meet the desired performance with the lowest number of satellites or achieve the best performance at a fixed cost. However, placing optical satellites on Sun-synchronous orbits makes it possible to have a more consistent performance during the year. Different configurations or even asymmetric patterns are possible and could be explored in future works.
Additionally, the coverage problem of optical and SAR satellites should be further researched. This work evaluated the coverage by assuming a fixed instrument look-angle and SAR satellites operating in Stripmap mode. This approximation tends to underestimate the actual constellation coverage. In a real-case scenario, satellites operate with a variable line-of-sight optimised based on the available resources. Moreover, SAR satellites can also employ different acquisition modes, such as ScanSAR and Spotlight.
Overall, this work proposes an optimisation tool that could be adopted in a preliminary phase of the design process. It enables the designer to relate the desired performance of a mixed sensor system with a rough cost estimation.

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