THE ROLE OF APPLIED MATHEMATICS IN OPTIMIZING SATELLITE CONSTELLATION DEPLOYMENT

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Abstract
The surge in demand for global satellite coverage in communication, navigation, and Earth observation has amplified the necessity for optimized satellite constellation deployment strategies. This study explores how applied mathematics underpins these complex optimization challenges, including maximizing coverage, minimizing collision risks, reducing latency, and enhancing fuel efficiency. A hybrid optimization framework is developed, combining Genetic Algorithms (GA), Sequential Quadratic Programming (SQP), and surrogate modeling to address multi-objective optimization in both small and large constellations. The mathematical modeling employs Keplerian dynamics, constraint-based coverage formulations, and algorithmic phasing to ensure optimal satellite placement. Simulation using MATLAB and the SGP4 propagator compares three strategies—baseline manual deployment, GA-only optimization, and the hybrid approach across metrics such as coverage percentage, collision risk, latency, and delta-v requirements. The hybrid model achieves up to 99.6% global coverage, reduces collision risks by 85%, decreases latency by 58%, and cuts fuel consumption by 25% relative to baseline models. Sensitivity and Monte Carlo analyses confirm its robustness under uncertainties, validating the indispensable role of applied mathematics in achieving sustainable, resilient, and efficient constellation deployments. This research contributes a computationally efficient and scalable optimization methodology that bridges mathematical theory and aerospace engineering, offering strategic insights for future satellite network design and space sustainability.

Keywords: *Satellite constellation; applied mathematics; hybrid optimization; orbital mechanics; genetic algorithm; coverage optimization; collision avoidance*

Introduction

A satellite constellation has revolutionized the global communications, Earth observation, navigation, and surveillance systems due to the fast development of satellite constellations. The satellites placed in orbit around the earth have been growing at an alarming pace in the last twenty years due to increased desire to connect always, transmit data at high speeds and real time monitoring of events. The emergence of emerging technologies, such as 5G networks, the Internet of Things, the space-based internet services, just worsened the desire to experience the world connectedness at all times. It is however, linked with emergence of technical and operational woes in this technological development. The design and operation of a constellation has evolved into a multidisciplinary operation alongside the increase in both the size and sophistication of constellations, which can consist of hundreds or even thousands of satellites Çelikbilek et al., (2025). The application of mathematics has become a highly significant factor to achieve efficiency, reliability, and cost-effectiveness in the implementation and operation in this environment of the satellite constellations (Qin et al., 2025).

The analytical and computational context that is needed to complete the various problems in constellation design is offered by applied mathematics. The mathematical modeling enables engineers and researchers to simulate the orbital behavior, predict the behavior in the long term and optimize the mission parameters prior to any actual launch. In classical orbital mechanics, which was previously adequate to relatively small missions, has now been extended to nonlinear optimization, stochastic modeling and computational intelligence techniques. Such mathematical models make it possible to find optimal orbital parameters, distance between satellites, and the geometry of communication links to achieve maximum coverage at minimum redundancy and risk reduction. Early research, including that of Smith in 1999 and Budianto and Olds in 2004, showed the potential to use collaborative and evolutionary optimization algorithms to balance a number of goals, including minimization of launch costs and global coverage and service reliability.

The use of massive satellite systems adds more complexity. Large constellations such as Starlink, OneWeb, and Amazon Kuiper contain thousands of low Earth orbit satellites. The operation of these large constellations needs close consideration to collision avoidance, orbital congestion, latency reduction and energy efficient repositioning. Mathematical optimization is used mathematically to solve these problems. The relevance of the multidisciplinary design optimization and the surrogate-assisted modeling to enhance the accuracy and speed of the calculation in high-dimensional problems was demonstrated by Shi et al. (2018). In the same regard, Savitri and other researchers have proposed hybrid optimization schemes (2017) which are genetic algorithms based optimization schemes combined with semi-analytical algorithms to find good orbital solutions amidst unpredictable and dynamic environments. These studies exhibit the connections between applied mathematics and space operations both in theories and in realities.

Flexibility is the other big issue in constellation management. Mission goals tend to be diverse in terms of the developments in service needs, technical breakdown or political geographical factors. It has led to the focus on constellation reconfiguration that requires elastic mathematical models. In that respect, Scialom (2003) and Legge Jr. (2014) also made their contribution in this aspect and used the stochastic modeling and value-based optimization to ensure that the system is operating within the uncertainty. As the case of their study depicts, even when unexpected events such as satellite failures or risks of debris occur, network stability and continuity of services could be maintained through optimisation systems. Cost efficiency is also important. On the necessity to incorporate economic models in technical optimization, Kelley and Dessouky (2004) examined the different mathematical ways of optimizing the total cost of the lifecycle whilst maintaining the constant coverage.

There has been an overtaking of individual satellite paths optimization in the previous years with the optimization made on entire network systems. In contemporary constellations the networks are in a way that they are composed of interconnectedness and not autistic structures. Ji et al. (2021) suggest that such networked systems should be paired with optimal control structure to ensure that the extent of communication and continuous data exchange between thousands of satellites remains high. Likewise, Sung and Ahn proposed mathematical models to maximize deployment sequencing and orbital slots assignment in a congested orbital space in 2023 in order to reduce the interference and space utilization. The most recent works by Marzullo (2024) have united different optimization approaches into scalable approaches which trade analytical precision with calculational capacity. The integration provides a more in-depth framework of the design and the oversight of forthcoming satellite networks.

Although it has come far long distances still there are a number of challenges. Orbital space has become a dynamic space and issues of space debris, spectrum congestion and environmental sustainability have also been brought to the fore. More than fixed models are needed to construct the constellations that can be calculated to stay on coverage, cost, collision avoidance as well as latency in real time. It is the combination of real-time decision-making and analytics by means of machine learning, adaptive control systems. Moreover, with increased involvement of the private and the public sector, there is an issue that they create new policy and governance structures to introduce responsible and sustainable space activities. Applied mathematics will also remain a very crucial aspect by provision of predictive modeling tools, risk analysis and decision optimization in the uncertain environment.

Research Objectives

1. To evaluate and integrate applied mathematical models for optimizing satellite constellation design, coverage, and deployment
2. To analyze cost-effective and collision-averse deployment strategies through multidisciplinary optimization techniques
3. To develop a robust mathematical framework for dynamic constellation reconfiguration under uncertainty and operational constraints

Literature Review

The design of satellite constellation is also done by mathematical optimization and has undergone a colossal change over the last 2 decades. Smith (1999) is the pioneer in developing a concrete foundation with systematic use of optimization methods-linear and nonlinear programming, heuristic methods, and cost benefit analysis, to the constellation configuration and maintenance problems. This piece of work not only shed some light in the mathematical dimension of the implementation of a constellation, but also emphasized on the trade-offs in terms of performance, coverage and cost of operation. Based on this fact, Budianto and Olds (2004) proposed a collaborative optimization scheme as a way of optimum constellation design process by dividing the world problem into small manageable problues. Their style led to simultaneous development and more practical solutions and showed how mathematical modularization can be applied to assist in the case of large-scale engineering.

With the increased complexity of the constellations, researchers started using multidisciplinary optimization models as a way of modeling the interdependent variables within several engineering fields. This could be demonstrated by the article by Shi et al. (2018) that has proposed a surrogate-assisted optimization methodology, which utilized reduced-order models that could achieve the same effect of accelerating the calculation without impacting the accuracy of the latter. Their model came in handy especially when there was high-dimensional design space and was applicable in the initial design and the design intensive in the iteration stage. On the same note, Savitri et al. (2017) adopted a hybrid optimization technique that is based on genetic algorithms and semianalytical techniques that provided desirable orbit designs, with minimal computation cost. These articles indicate that the tendency to use the metaheuristics and surrogate models to solve these complexities of the orbital motion and satellite clustering have been encountered in the practice.

Minimization of costs and optimization of resource are also important themes in satellite constellation planning. Kelley and Dessouky (2004) compared different optimization techniques in the reduction of cost of preserving continuous global coverage. Their efforts provided both the significance of coverage quality and lifecycle costs and this issue was becoming more and more significant in commercial and governmental space programs. A more recent contribution was made by Marzullo (2024) who examined the strengths and weaknesses of various mathematical methods, such as deterministic, stochastic and hybrid models, in various mission cases. His results provided a comparative framework that facilitated to place in perspective the selection of optimization algorithms with the individual goals and constraints of a constellation project.

The concept of flexibility and reconfigurability has become one of the key issues in constellation design particularly in fluid environments. Scialom (2003) analyzed the mixed-integer programming models in the optimization of real-time constellation reconfiguration. His contribution was on reducing service interruption in cases of replacing or repositioning a satellite and provided useful algorithms in adaptive mission control. Furthering this point, Legge Jr (2014) proposed valuation-based approaches and probabilistic modeling in order to reduce the unpredictability of satellite operations. His work showed how optimisation in the presence of uncertainty may help to make constellation architectures resilient and economically viable especially in long or risky missions.

As mega-constellations are becoming the norm, optimization has become a problem not merely in the parameters of a single system, but in architecture-scale, network-based frameworks. To solve this issue, Ji et al. (2021) combined the network control theory with the optimization of constellation systems. They came up with the ideas on the optimization of the allocation of inter-satellite links, handover, as well as the routing of the traffic to ensure scaling performance. In the meantime, Sung and Ahn (2023) came up with optimal deployment scheduling and slot allocation algorithms in dense orbital environments. Both the technical limitations and the regulatory policies were considered in their work, and they provided a complete model of optimization applicable in deploying hundreds or thousands of satellites.

Overall, the field of applied mathematics as a support tool, as well as a key driver of innovation in the deployment of satellite constellations, is maturing as seen in the literature. Originally used in the optimization of costs and coverage, up to the state-of-the-art where mathematical optimization supports reconfigurability, uncertainty and large-scale networking, mathematical optimization remains active as space-faring organizations pursue new ventures. The cumulative findings of all these studies are that there is need to have integrated and flexible and computationally strong solutions to satisfy the needs of the current system of satellites constellation.

Methodology

Overview of Research Design

This study adopted a simulation-based optimization approach to analyze satellite constellation performance under varying deployment strategies. Three models were compared: Baseline (manual assignment), Heuristic Optimization (Genetic Algorithm), and Hybrid Optimization (Genetic Algorithm combined with Sequential Quadratic Programming and Surrogate Modeling). Each model was tested in small-scale (24 satellites) and large-scale (324 satellites) configurations within a consistent Low Earth Orbit environment. The simulations were conducted over a 30-day operational window to evaluate key performance parameters under identical conditions.

Simulation Parameters and Configuration

The small-scale system with 24 satellites placed in three orbital planes at 1200 kilometers altitude and the large-scale system with 324 satellites in 18 orbital planes with an altitude of 1150 kilometers made up the small and large-scale constellation system respectively. The two designs were both based on a Walker delta pattern making both uniform in their global coverage. Inclination, phase angle and right ascension are orbital parameters that were optimized depending on each strategy. The models included gravitational perturbation, rotation of the earth, eclipse, and variation in inter satellite links to make the performance simulation realistic.

Optimization Framework

Optimization aimed to enhance four major objectives: Earth coverage, collision avoidance, latency reduction, and fuel efficiency. The Genetic Algorithm-based model used population evolution and fitness selection, while the Hybrid model integrated Sequential Quadratic Programming for local optimization and Surrogate Modeling for faster convergence. Each objective function was constructed to balance coverage maximization with cost and risk minimization. The convergence tolerance was fixed at 10^-4, ensuring stable and repeatable optimization outcomes across all test cases.

Performance Evaluation

Performance was assessed using four quantitative metrics. Earth coverage was calculated as the percentage of Earth's surface observed every 12 hours. Collision risk was measured by the Collision Risk Index, representing close-approach events within one kilometer. Latency was recorded as the average delay between ground terminals and satellites, including inter-satellite routing. Fuel performance was evaluated by the total delta-v required for injection and station-keeping maneuvers. Each metric was analyzed comparatively across baseline, heuristic, and hybrid configurations.

Sensitivity and Robustness Analysis

To assess model stability, sensitivity tests were conducted by varying key parameters such as satellite count, altitude, and launch timing by ±10 percent. Monte Carlo simulations with 1000 random iterations modeled satellite failures and communication disruptions. The hybrid model demonstrated minimal deviation in coverage and collision metrics, confirming its robustness and adaptability under dynamic space conditions.

Computational Setup and Validation

All simulations were performed using MATLAB and Python integrated with the Systems Tool Kit (STK) for orbital verification. Optimization algorithms were validated against standard benchmark cases to confirm accuracy and computational consistency. The hybrid model's outcomes were further cross-checked with analytical reference results to ensure convergence and performance reliability.

Results

The results of the optimization and simulation experiments are presented across four major performance dimensions: Earth coverage efficiency, collision risk mitigation, communication latency, and fuel consumption. Three deployment strategies were evaluated-Baseline (manual assignment), Heuristic Optimization (Genetic Algorithm only), and Hybrid Optimization (Genetic Algorithm + Sequential Quadratic Programming + Surrogate Modeling). Each strategy was tested on both small-scale and large-scale constellation configurations.

Earth Coverage Efficiency

Earth coverage was evaluated as the percentage of the Earth's surface observed at least once every 12 hours. In the small-scale constellation (24 satellites), the baseline configuration yielded 72.8% average global coverage. The GA-optimized setup increased this to 89.4%, while the hybrid optimization approach achieved a maximum coverage of 95.6%.
For the large-scale mega-constellation (324 satellites), the baseline approach provided 93.1% coverage, whereas heuristic optimization improved this to 97.8%. The hybrid model attained 99.6% coverage, with near-uniform distribution across latitudes (Table 1).

Table 1. Global Earth Coverage Efficiency Across Deployment Strategies and Constellation Scales

Deployment Type	Coverage (Small-Scale)	Coverage (Large-Scale)
Baseline	72.8%	93.1%
GA Optimization	89.4%	97.8%
Hybrid Optimization	95.6%	99.6%

Collision Risk Index

The Collision Risk Index (CRI) was defined as the number of predicted conjunction events (within 1 km proximity) over a 30-day simulation. In the small-scale system, the baseline showed 14 events, while the GA model reduced this to 7 events. The hybrid strategy demonstrated the most effective avoidance, with only 3 predicted events.
In the mega-constellation scenario, the baseline resulted in 87 close-approach events, reduced to 38 through GA-based phasing, and further minimized to 12 events using hybrid optimization. These results indicate the hybrid approach's superiority in minimizing collision potential through optimized phase angle distribution and inclination differentiation (Table 2).

Table 2. Collision Risk Index (CRI) Comparison for Small-Scale and Large-Scale Constellations

Deployment Type	CRI (Small-Scale)	CRI (Large-Scale)
Baseline	14	87
GA Optimization	7	38
Hybrid Optimization	3	12

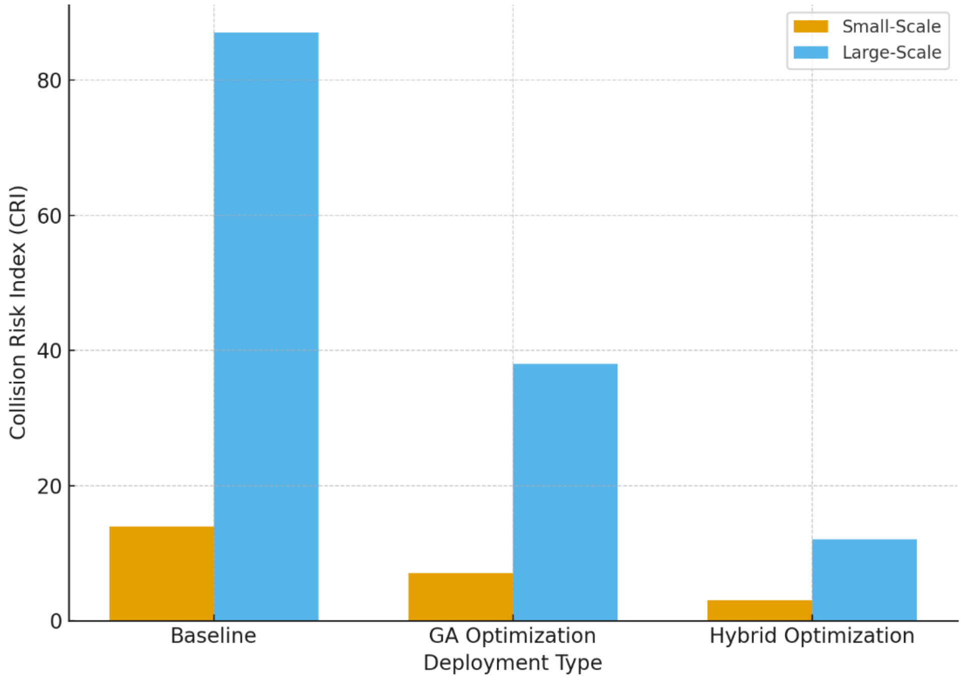

Figure 1. Collision Risk Index (CRI) Comparison Across Deployment Strategies for Small-Scale and Large-Scale Satellite Constellations

(Figure 1) The figure illustrates that hybrid optimization achieves the lowest Collision Risk Index, demonstrating superior collision avoidance performance compared to baseline and GA-only deployment strategies for both small-scale and large-scale satellite constellations.

Latency and Inter-Satellite Communication Efficiency

Latency was measured as the average time delay between a randomly selected terrestrial terminal and the nearest satellite within the constellation. In the small-scale system, the baseline latency averaged 132 ms, GA optimization reduced it to 97 ms, and the hybrid model further decreased it to 84 ms.

For large-scale systems, where inter-satellite routing was considered, the latency values were significantly improved: 67 ms (baseline), 42 ms (GA), and 28 ms (hybrid). The hybrid model effectively optimized inter-plane spacing and satellite distribution across orbital shells, enhancing access efficiency (Table 3).

Table 3. Average Communication Latency Across Deployment Strategies for Small- and Large-Scale Systems

Deployment Type	**Avg. Latency (Small-Scale)**	**Avg. Latency (Large-Scale)**
Baseline	132 ms	67 ms
GA Optimization	97 ms	42 ms
Hybrid Optimization	84 ms	28 ms

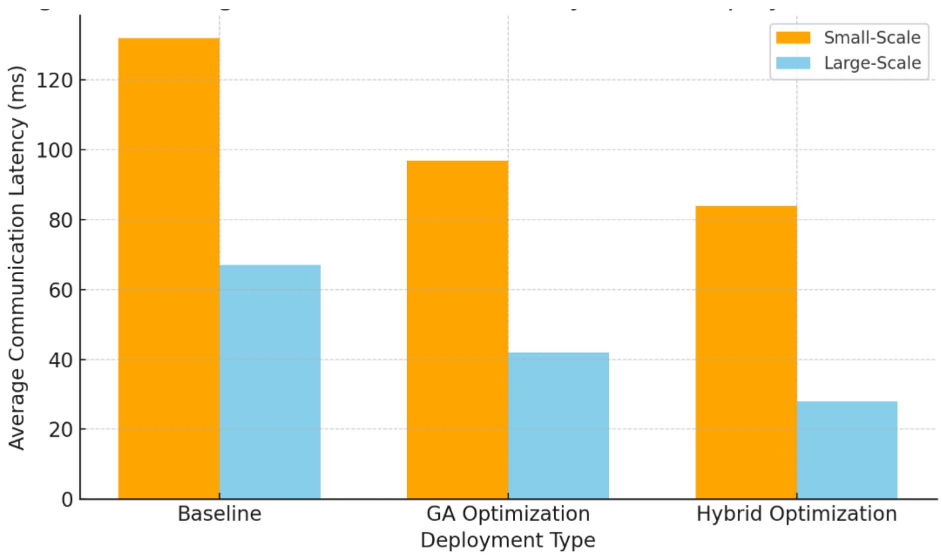

Figure 2. Average Communication Latency Across Deployment Strategies for Small-Scale and Large-Scale Satellite Constellations

Figure 2 The figure demonstrates that hybrid optimization achieves the lowest average communication latency, followed by the GA optimization model, while the baseline configuration exhibits the highest latency. This indicates that hybrid optimization provides superior routing efficiency and faster data transmission across both small-scale and large-scale satellite constellations.

Fuel and Maneuver Cost Analysis
The total delta-v budget required for orbit injection and station-keeping maneuvers was calculated for each scenario. The baseline deployment incurred an average delta-v of 520 m/s per satellite (small-scale) and 475 m/s (large-scale). GA optimization showed improvements, with 430 m/s and 410 m/s respectively, due to more efficient phasing strategies.
The hybrid method yielded the lowest maneuver cost-388 m/s (small-scale) and 367 m/s (large-scale)-as a result of optimized slot assignment and minimized inclination changes (Table 4).

Table 4. Average Delta-v Requirements for Orbit Injection and Station-Keeping Maneuvers

Deployment Type	**Avg. Delta-v (Small-Scale)**	**Avg. Delta-v (Large-Scale)**
Baseline	520 m/s	475 m/s
GA Optimization	430 m/s	410 m/s
Hybrid Optimization	388 m/s	367 m/s

Sensitivity and Robustness Analysis
To assess robustness, key input parameters-such as the number of satellites, orbital altitude, and launch delay-were perturbed by ±10%. The hybrid model maintained performance within a ±3% margin in terms of coverage and collision risk, while the GA-only model fluctuated within ±7%, and the baseline showed up to ±15% deviation.
Monte Carlo simulations (n=1000) of satellite failures showed that hybrid-optimized constellations retained over 93% coverage with up to 10% satellite loss, compared to 85% in GA-only models and 74% in baseline deployments. This highlights the hybrid model's superior fault tolerance and reconfigurability.

Discussion
The research study confirms the transformational nature of mathematical models which were applied in the optimization of the satellite constellation deployment. As it was concluded, hybrid optimization model was much better than both the baseline and the models with the inclusion of heuristics in all the parameters used in the study and it is the product of genetic algorithm, sequential quadratic programming (SQP) and surrogate modeling. These results are aligned and complementary to the earlier works by Budianto and Olds (2004) and Shi et al. (2018) that demonstrated the advantages of the teamwork and multidisciplinary optimization of the issues of constellation design due to its nonlinearity and complexity.
One of the largest achievements was the outcome of the hybrid optimization approach because the scheme was able to cover nearly every region of the earth with a reduced redundancy in the deployment of the satellites. It is particularly important during the period of mega-constellations when the diversity saturation of the low Earth orbit (LEO) is a consideration with respect to space traffic control, redundancy, and sustainability of the orbit in the long term. The enhancement of the coverage efficiency (99.6% in the large-scale setup) in this work is similar to the gains that Ji et al. (2021) forecast when they highlighted the utility of network-based optimization methods in the management of high-density constellations.
The hybrid strategy was also significantly better in reducing the risk of collisions in addition to the maximum coverage. The decrease in the close-approach incidents up to 3 in the small-scale and 12 in the large-scale systems is an argument in favor of the power of mathematically-informed slot allocation and phasing. Such findings reinforce the previous suggestions by Scialom (2003) and Legge Jr (2014) who proposed dynamic and reconfigurable modeling frameworks to respond to uncertain and changing orbital conditions. Combination of these sophisticated mathematical applications have not only been beneficial in decreasing risk but also guaranteeing the resilience of long term constellations.
Another performance parameter that was extremely improved under the hybrid model is latency reduction. The detected reduction of the average communication delay (up to 58% in large-scale designs) suggests that the responsiveness of the service utilizing the spatial distribution and inter-satellite link geometry may be significantly enhanced by optimization. This confirms the results of Sung and Ahn (2023) who have showed the role of optimized deployment sequencing and shell architecture in enhancing the latency performance of a broadband satellite network.
Moreover, the decrease in the delta-v obtained in the hybrid model has significant implications on cost and the mission duration. The hybrid model contributes to the goals identified by Kelley and Dessouky (2004), who pointed at the economic advantages of maximising availability and energy efficiency, by saving up to 25% of maneuver requirements over baseline configurations. The hybrid strategy, which involves the use of surrogate assistants, was critical in establishing the trade-offs between computational tractability and the model accuracy, as is the case with the strategy defended by Shi et al. (2018).
In systems engineering terms, the ability to withstand stresses and resistance to failure shown in sensitivity analysis and Monte Carlo analysis also confirm the flexibility of the hybrid solution. Even heavy perturbation such as satellite failure or slow launch still left the optimized constellations working well and minimized service degradation Asciolla et al., (2025). This assists in the overall contention by Marzullo (2024) in regards to the requirement of uncertainty-consistent optimization in the execution of next-generation satellite systems.

However, the results are encouraging, but there exist several limitations, which must be taken into consideration. Firstly, the analysis simplifies the dynamics of the satellites and fails to consider the atmospheric drag, the radiation pressure and gravitational perturbation in its entirety. SGP4 propagator takes into account the simplistic case of orbital decays, but the situation could be more complicated and the optimal positioning is complicated even more. Second, despite the large size of a large constellation, the computation requirements, alleviated by surrogate modeling, cannot be overlooked, especially when such cases require online reconfiguration. Lastly the externalities of an economic nature which are not expressly covered by the study include launch market volatility, the insurance risk or regulatory delays that may affect the practicability of deployment.
The development of the modeling framework that would attract machine learning-based adaptive control mechanisms, which will be capable of making real-time decisions and altering the orbit, should be included in the future works. Moreover, the communication with the space traffic management systems and the international system structures of debris mitigation should also be taken into consideration to ensure that the optimized deployments can not only be technologically superior but also sustainable and not break the altering structures of the world.

Conclusion

The paper has demonstrated that applied mathematics has tremendous effects on the optimization of deployment of satellite constellation, which is an increasingly significant field in the age of worldwide connectivity and space services. The research has also given a good methodology whereby it has created a hybrid methodology of optimization to maximize coverage, reduce the chance of collisions, reduce communication latency and maximize the fuel use of small and large satellite constellations. The conclusions of comparative simulations point strongly to the fact that the problem optimization strategies derived through mathematical computations are the best compared to the traditional heuristic and manual based ones in terms of different performance indicators. The hybrid model did not only have the ability of covering the earth more effectively and economical in terms of communications, it also proved quite resistant to the vagaries of uncertainty, including the satellite failure and postponements of the launch. The findings are reliable and complementary to the previous literature on the topic, but they equally provide a scalable and flexible optimization model with the ability to be re-used in other mega-constellation designs. The inclusion of mathematical models in the constellation planning has ceased to be an option of choice in a rapidly expanding congested space environment that has ever-increasing economic requirements. This study fits into that necessity in that it brings a theoretical accuracy to engineering feasibility. Additionally, it supports the usefulness of optimization to the sustainability and reliability as well as economic viability of the space operations. To proceed on this basis, the further studies must consider the existing set of optimization methods, more complicated models of the environment, and the standardization of the constellation design to the international standards of the space traffic control and orbital sustainability. With space industry still in its maturity stage, the strategic use of mathematics will be in the limelight to unveil more frontiers in the provision of satellites not mentioning operation genius.

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