

Original Research Paper

Crafting a LEO Satellite Constellation for the Tehran Region Using an Innovative Hybrid GA-PSO Optimization Algorithm

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ABSTRACT

This study investigates the essential role of satellite constellations within the rapidly expanding space economy, emphasizing their increasing contribution to global connectivity, navigation, and economic development. As the demand for reliable space-based infrastructure accelerates, the design and optimization of efficient satellite constellations have become a critical engineering challenge. This research focuses on determining key orbital design parameters for satellite constellations, with particular emphasis on developing an optimized configuration specifically for the Tehran metropolitan region. To address the inherent complexity and high-dimensional nature of the constellation design problem, a hybrid optimization approach is introduced that combines the strengths of Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) techniques. The problem is formulated as a thirty-variable optimization task that incorporates both global and local search strategies. Initially, the GA explores the broad solution space to identify high-quality global optima. These solutions subsequently serve as initial conditions for a refined optimization process using the GA-PSO hybrid algorithm, which further improves solution quality and enhances computational efficiency. Through this two-stage optimization process, the objective function was improved by 610 seconds compared to the GA-only approach, demonstrating the effectiveness and superiority of the proposed hybrid method. The final outcome is the design of a ten-satellite LEO constellation optimized to provide maximum coverage over Tehran, achieving 17 hours of daily coverage within a 24-hour period. The findings underscore the significant potential of advanced computational optimization techniques for improving satellite constellation design and contribute to the development of more efficient, reliable, and cost-effective space-based telecommunication solutions.


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NOMENCLATURE

| | |
|-----------------|--|
| ECEF | Earth-Centered, Earth-Fixed |
| GA | Genetic Algorithm |
| GA-PSO | Hybrid Genetic Algorithm – Particle Swarm Optimization |
| PSO | Particle Swarm Optimization |
| Ω (RAAN) | Right Ascension of the Ascending Node |
| ω | Argument of perigee |
| ν (nu) | True anomaly |
| μ | Gravitational parameter ($\mu = G \cdot M$) |
| P_i | Selection probability (GA) |
| r | Position vector |

1. INTRODUCTION

Satellite constellations, particularly those in Low Earth Orbit (LEO), are rapidly becoming indispensable for a wide array of applications, including global communication, Earth observation, and precise navigation. The design of these complex systems poses a significant optimization challenge, requiring the fine-tuning of numerous interdependent parameters to meet specific performance criteria within defined constraints [1]. Traditional optimization methods often prove insufficient due to the high-dimensional, non-convex nature of the design space, making it difficult to achieve optimal solutions. Consequently, hybrid optimization algorithms, such as the Genetic Algorithm-Particle Swarm Optimization (GA-PSO) approach, have emerged as highly effective tools for tackling these intricate design problems [2]. The GA-PSO algorithm

leverages the strengths of both Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO) [3]. GAs, inspired by natural selection, excel in exploring broad solution spaces, identifying promising areas, but often exhibit slow convergence. PSO, on the other hand, excels at rapid local refinement, fine-tuning solutions within a limited neighborhood, but may become trapped in local optima [4]. GA-PSO combines the global search capabilities of GAs with the local search precision of PSO to effectively mitigate their individual drawbacks. In GA-PSO, the initial

population is generated with GA, and then each solution of this population is optimized using PSO algorithm. This will result in optimum result for each solution. Then, the next generation is created using GA operator and again is optimized using PSO. This iterative method will converge to optimum solution very faster. This synergistic combination provides a more robust and efficient optimization strategy compared to either method alone [5].

Several factors highlight the suitability of the GA-PSO algorithm for satellite constellation design:

- **Multi-Parameter Optimization:** Satellite constellation design involves the simultaneous optimization of numerous parameters, including orbital altitude, inclination, eccentricity, the number of satellites, the distribution of satellites, inter-satellite link architecture, and payload specifications. GA-PSO is capable of handling this multi-faceted optimization, delivering a comprehensive design [6].
- **Non-Convex Solution Space:** The objective functions for satellite constellation design are typically highly non-convex, with numerous local optima. The hybrid nature of GA-PSO, with its explorative and exploitative phases, allows the algorithm to escape local optima and converge to a global or near-global optimum [1, 3].
- **Constraint Handling:** Practical satellite constellation designs must adhere to several constraints related to coverage area, communication performance, orbital stability, and cost. GA-PSO can incorporate these constraints through penalty function techniques, ensuring that the designs fulfill the specific requirements [7].
- **Computational Efficiency:** GA-PSO has demonstrated faster convergence rates compared to purely GA or PSO methods, thereby reducing the computational time and resources needed for finding near-optimal designs. This enhanced efficiency is crucial for tackling the computationally demanding problem of satellite constellation design [2, 5].
- **Adaptability:** GA-PSO can be adapted to various optimization objectives in satellite

constellation design, such as minimizing mission cost, maximizing coverage area, minimizing revisit time, or increasing communication throughput [8].

In the context of satellite constellation design, GA-PSO has applications in:

- Coverage Optimization: The algorithm can optimize orbital parameters to achieve maximal coverage of the Earth or specific geographic regions, which is crucial for earth observation, global internet service, and telecommunication [6, 8].
- Cost Reduction: GA-PSO can be used to identify constellation configurations that minimize overall mission costs by optimally distributing the satellites and selecting the optimal design parameters without compromising performance [9].
- Enhanced Communication: GA-PSO can optimize the inter-satellite link architecture and orbital parameters to achieve high throughput, minimal latency, and reliable communication, which are essential for real-time data transfer, navigation, and other communication-dependent applications [7, 9].
- Orbital Stability: The algorithm can help design constellations with improved orbital stability, reducing the need for frequent station-keeping maneuvers, and prolonging the operational lifetime of satellites [10].

the traditional design paradigms for satellite constellations, which predominantly rely on symmetric patterns such as the Walker and Star configurations. It is clarified that while these symmetric models are highly effective for Medium Earth Orbit (MEO) constellations or those designed for global coverage, their inherent constraints can be suboptimal for regional coverage missions in Low Earth Orbit (LEO). For a dedicated local coverage scenario, enforcing a rigid symmetric structure is not only unnecessary but may also limit the constellation's performance potential. Therefore, this research intentionally departs from these traditional models. The paper now more clearly articulates that by employing a hybrid GA-PSO optimization algorithm, the design problem is approached without the constraints of symmetry. The algorithm is given the freedom to independently

optimize the orbital elements for each satellite, thereby discovering the most effective asymmetric configuration tailored specifically to maximize coverage for the target region. This approach ensures that the final design is truly optimized for its specific mission, rather than being confined by a pre-determined symmetric pattern.

In summary, the GA-PSO algorithm provides a powerful and efficient means to address the highly complex optimization challenges in satellite constellation design. Its ability to tackle multi-parameter optimization, navigate non-convex landscapes, accommodate various constraints, adapt to different design objectives, and demonstrate enhanced computational efficiency makes it a valuable tool in the development of next-generation satellite constellations. Further research and application of hybrid algorithms such as GA-PSO are vital for the advancement of satellite technology and its potential to support societal needs.

2. GA-PSO OPTIMIZATION ALGORITHM

The Genetic Algorithm-Particle Swarm Optimization (GA-PSO) hybrid algorithm represents a powerful paradigm shift in the realm of optimization, ingeniously blending the explorative prowess of Genetic Algorithms (GAs) with the exploitative efficiency of Particle Swarm Optimization (PSO). This synergistic approach offers a compelling solution to the complexities inherent in high-dimensional, non-convex optimization landscapes, often encountered in engineering and scientific disciplines. In essence, GA-PSO transcends the limitations of its constituent algorithms, providing a robust framework for navigating intricate optimization challenges with enhanced efficacy and adaptability.

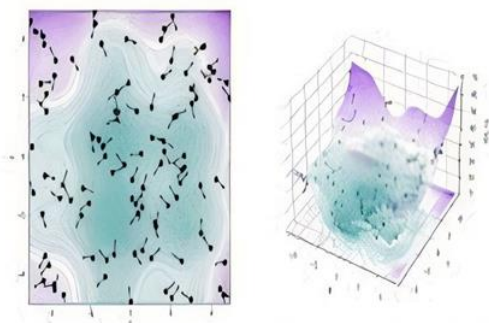


Fig. 1. Searching for birds in the function space.

At its core, GA-PSO employs a phased methodology, beginning with a population-based global search using GAs, followed by localized refinement through PSO. This two-tiered approach is predicated on the notion that global exploration followed by meticulous local tuning is often superior to approaches that rely on either method in isolation. The process unfolds as follows:

- Initialization (GA Phase): The algorithm initiates with a randomly generated population of candidate solutions. Each solution, or “chromosome,” represents a potential configuration for the optimization problem, such as a satellite constellation design or a parameter set for a complex system.
- Genetic Operations (GA Phase): Standard genetic operations, including selection, crossover, and mutation, are applied to this initial population. Selection favors individuals with higher fitness, thus mimicking the principles of natural selection. Crossover blends genetic material from selected parents, creating offspring with traits inherited from both. Mutation introduces random changes to individual chromosomes, promoting genetic diversity within the population. This iterative process facilitates global exploration, enabling the algorithm to navigate the search space and locate promising regions.
- Local Refinement (PSO Phase): Once a population of promising solutions has been identified via the GA phase, the PSO algorithm is applied to each individual, treating them as particles in a swarm. Each particle adjusts its position based on its own best-known position and the best-known position of its neighbors. This local refinement process allows the algorithm to hone in on optimal or near-optimal solutions within the identified promising regions.

g is the Iterative Convergence: The GA and PSO phases are iteratively alternated. The enhanced local convergence by PSO in each generation provides improved quality input for GA, and hence results better solution in the next

GA generation. This cyclic process continues until the algorithm achieves a predefined level of convergence, indicating a satisfactory solution has been identified.

Genetic Algorithm: The genetic operations can be represented mathematically as follows:

Selection: A selection probability P_i is associated with the fitness of each individual in the population:

$$P_i = f(x_i) / \sum f(x_j) \quad (1)$$

where $f(x_i)$ is the fitness of i -th individual.

Particle Swarm Optimization: Each particle's position $x_i(t)$ and velocity $v_i(t)$ are updated as follows:

$$v_i(t+1) = w * v_i(t) + c1 * r1 * (p_i - x_i(t)) + c2 * r2 * (g - x_i(t)) \quad (2)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (3)$$

The convergence of GA-PSO is not always guaranteed due to its stochastic nature, but careful parameter selection (e.g., population size, crossover rate, mutation rate, inertia weight, and acceleration coefficients) and proper integration of GA and PSO can significantly enhance the algorithm's convergence rate and probability. The iterative exchange of information between GA and PSO enables a dynamic balance between global exploration and local exploitation, contributing to its efficient convergence towards optimal solutions. The convergence criteria are often based on the change in the fitness of the best solutions, and iterations are continued until the change goes below a certain threshold. Beyond the equations and computational mechanics, the GA-PSO algorithm embodies a powerful analogy to human problem-solving. Just as we explore a vast range of possibilities and then focus on refining the most promising ideas, GA-PSO mimics this dual approach, demonstrating how hybrid strategies can lead to more effective solutions. The algorithm, in a way, mirrors the evolution of ideas, starting from a diverse set of options and gradually converging toward optimality.

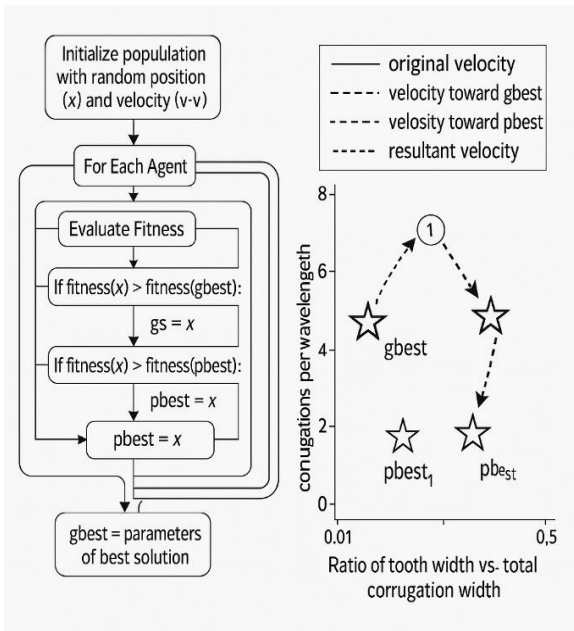


Fig. 2. Genetic algorithm (GA) and particle swarm optimization (PSO).

The algorithm can be seen as a collaboration of two different methods to result in a superior solution. In this sense it is a reflection of how humans collaborate, each with different skills, together achieve better results. The interplay between global exploration (GA) and local exploitation (PSO) is a metaphor for the creative process, highlighting the importance of both breadth of perspective and focused attention. GA-PSO is not merely a tool for optimization; it is a testament to the power of combining seemingly disparate approaches to achieve greater goals. Its success highlights the potential in diverse and collaborative efforts, whether in algorithms or in human endeavors. As we continue to push the boundaries of what is achievable, algorithms such as GA-PSO are not just mechanisms for calculations, they are mirrors reflecting our own ingenuity and the possibilities that emerge when distinct perspectives converge.

3. SATELLITE ORBITAL PARAMETER

Orbital parameters are highly influential factors governing the initial design of satellite constellations. Their deterministic role becomes especially pronounced in the context of designing constellations for operation within Low Earth Orbit (LEO). This is attributable to the

comparatively reduced angular visibility (or field of view) from LEO relative to orbits like Medium Earth Orbit (MEO) and Geostationary Orbit (GEO) [11].

Satellite orbits are defined by a set of parameters that describe the shape, size, and orientation of the orbit in space. These parameters are crucial for determining satellite visibility, access time, and coverage area. Here are the most essential orbital parameters:

- **Semi-Major Axis (a):** Definition: Half the longest diameter of the elliptical orbit. It essentially determines the size of the orbit. Impact: Primarily affects the orbital period. (how long it takes the satellite to complete one orbit). A larger semi-major axis results in a longer orbital period. It also dictates the altitude of the orbit.
- **Eccentricity (e):** Definition: Describes the shape of the orbit, ranging from 0 (a perfect circle) to a value less than 1 (an ellipse).

Impact: Affects the distance of the satellite from the Earth at different points in its orbit. An eccentricity of 0 gives a circle and an eccentricity close to 1 leads to an elongated ellipse.

- **Inclination (i):** Definition: The angle between the orbital plane and the Earth's equatorial plane. Impact: Determines the latitude range over which the satellite passes. An inclination of 0 degrees is an orbit over the equator, while an inclination of 90 degrees means the satellite is in a polar orbit.
- **Right Ascension of the Ascending Node (Ω):** Definition: The angle in the equatorial plane, measured eastward from the vernal equinox to the point where the orbit crosses the equator from south to north. This defines the orientation of the orbital plane in space. Impact: Affects the longitudinal location of the orbit and its orientation with respect to the Earth's rotation.
- **Argument of Perigee (ω):** Definition: The angle in the orbital plane between the ascending node and the perigee (the point of closest approach to Earth). Impact: Determines the orientation of the orbit within its orbital plane. It also dictates the location of the closest point to the Earth in case of elliptical orbit.

- True Anomaly (v): Definition: The angular position of the satellite within its orbit, measured from the perigee. Impact: Specifies the satellite's position at any given time within its orbit.
- Orbital Period (T): Definition: The time it takes for a satellite to complete one full orbit. Impact: Depends on the semi-major axis and the gravitational force.

Other Important Factors:

- ❖ Altitude: The height of the satellite above the Earth's surface. It is closely related to the semi-major axis but is commonly used as a practical measure.
 - ❖ Ground Track: The path traced by the satellite on the Earth's surface. It is affected by the satellite's orbital parameters and the Earth's rotation.
- Number of Satellites: The number of satellites in a constellation will have a major impact on coverage and access time.

Optimization Goals in Satellite Constellation Design is a key goal in satellite constellation design is to maximize access time to ground stations while minimizing the number of satellites.

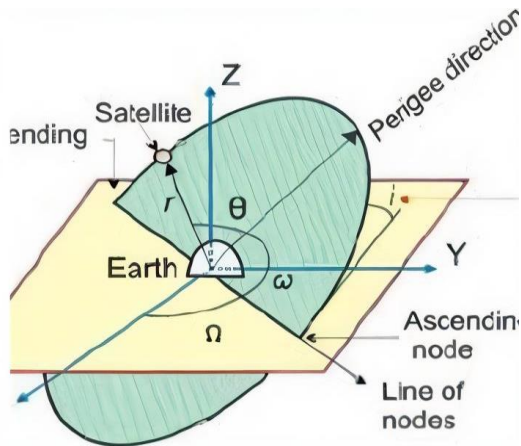


Fig. 3. Satellite orbital parameters.

Orbital Reference Frame (Perifocal Frame)

The orbital reference frame, also known as the perifocal frame, is a coordinate system that's convenient for describing a satellite's motion within its orbit. It's defined as follows:

X-axis: Points from the center of the Earth to the perigee (the point of closest approach to the Earth) of the orbit.

Z-axis: Points perpendicular to the orbital plane (defined by the right-hand rule).

Y-axis: Completes the right-handed coordinate system, being perpendicular to both the X and Z axes.

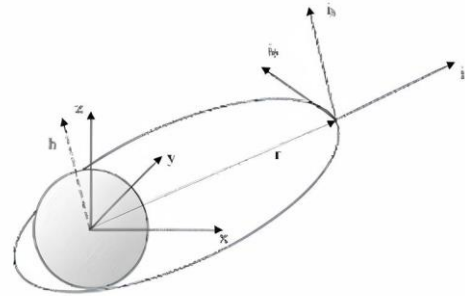


Fig. 4. Orbital reference frame.

In this frame, the satellite's position and velocity are relatively simple to calculate using the orbital parameters:

Position in Perifocal Frame:

The position vector r can be calculated using the semi-major axis (a), eccentricity (e), and the true anomaly (v).

$$r = [r_x, r_y, 0] \tag{4}$$

$$r_x = r \cos(v) \tag{5}$$

$$r_y = r \sin(v) \tag{6}$$

$$r = a(1-e^2)/(1+e\cos(v)) \tag{7}$$

Velocity (v) in Perifocal Frame:

The velocity vector v can also be calculated based on semi-major axis (a), eccentricity (e), the true anomaly (v), and the gravitational parameter (μ).

$$v = [v_x, v_y, 0] \tag{8}$$

$$v_x = -\sqrt{\mu/a} \sin(v) / \sqrt{1-e^2} \tag{9}$$

$$v_y = \sqrt{\mu/a} (e + \cos(v)) / \sqrt{1-e^2} \tag{10}$$

Where $\mu = G * M$, G is gravitational constant and M is mass of the Earth.

Geographical (ECEF) Reference Frame:

The ECEF (Earth-Centered, Earth-Fixed) frame is a coordinate system that rotates with the Earth. It's defined as follows:

X-axis: Points from the Earth's center towards the intersection of the equator and the prime meridian (0 degrees longitude).

Y-axis: Points from the Earth's center towards 90 degrees east longitude on the equator.

Z-axis: Points from the Earth's center towards the North Pole.

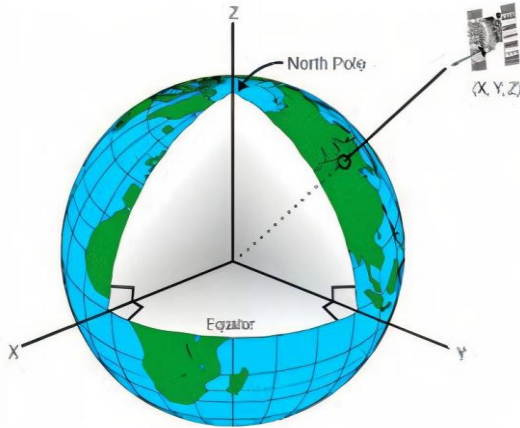


Fig. 5. The ECEF (Earth-Centered, Earth-Fixed) frame.

To get from the orbital reference frame to the ECEF frame, we need to perform a series of rotations using the following parameters:

- Right Ascension of the Ascending Node (Ω): Rotation around the Z-axis
- Inclination (i): Rotation around the X-axis
- Argument of Perigee (ω): Rotation around the Z-axis

True Anomaly (v): Rotation around Z-axis

The transformation can be represented by a series of rotation matrices:

$R_z(\theta)$: A rotation by an angle θ around the Z axis.

$$R_z(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (11)$$

$R_x(\theta)$: A rotation by an angle θ around the X axis.

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \quad (12)$$

Transform Matrix (Q):

The overall transformation matrix, Q is obtained by multiplying these rotation matrices in the following order:

$$Q = R_z(\Omega) R_x(i) R_z(\omega) \quad (13)$$

$$r_{ecf} = Q * r \quad (14)$$

$$v_{ecf} = Q * v \quad (15)$$

Where, r and v are position and velocity vectors in the orbital frame * r_{ecf} and v_{ecf} are position and velocity vectors in ECEF frame.

Relationship Explanation

Orbital Parameters Define the Orbit: The orbital parameters (a, e, i, Ω, ω) dictate the shape, size, and orientation of the satellite's orbit in space. These

parameters are time-independent (for ideal orbits), or are very slowly varying due to perturbations.

Perifocal Frame Calculation: Using the orbital parameters and time (t), we can calculate the true anomaly (v) and then the satellite's position and velocity in the perifocal frame which moves with the satellite's orbit.

Transformation to ECEF: Then the transformation matrix (Q) is used to transform both position and velocity vectors from orbital frame into the ECEF reference frame.

ECEF Coordinates and Velocity: Once in the ECEF frame, the satellite's position is given in terms of X, Y, and Z coordinates that are fixed to the rotating Earth, and velocity vector is the velocity in ECEF frame.

4. SIMULATION

Having established the necessary mathematical framework, the ensuing step in this research is the design of a telecommunications satellite constellation via a hybrid GA-PSO optimization algorithm. Initially, the Genetic Algorithm (GA), through its mutation and crossover operations, performs a broad exploration of the solution space to identify a region of global convergence. Subsequently, the Particle Swarm Optimization (PSO) algorithm, informed by the global convergence point identified by the GA, undertakes a focused search within this region to determine the most optimal configuration. This strategic combination leverages the extensive search capability of the GA and the precise local optimization power of the PSO.

the optimization problem ultimately involves thirty variables. Each of the ten satellites has Thirty optimization variables, and the satellites must be placed in an optimal configuration to achieve maximized access time. Additionally, a constraint determined by the satellite communication antenna range and the Earth's curvature is considered, wherein a wide field of view is assumed, thus satellite access is interrupted exclusively during periods of sunset.

$$Max(F(X)) = \text{time access}(X(e, I, \omega, \Omega, h, \theta)) \quad (16)$$

Table 1. Range of variation of design variables.

| | e | i | Ω | ω | H | θ |
|------|---|-----|----------|----------|------|----------|
| max | 0 | 180 | 0 | 0 | 1200 | 0 |
| min | 0 | 0 | 0 | 360 | 1200 | 360 |
| unit | | deg | deg | deg | Km | deg |

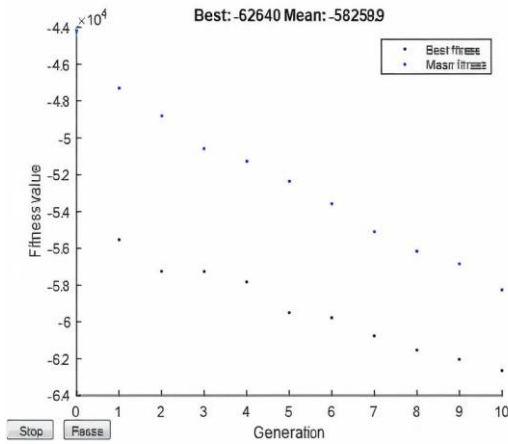


Fig 6: Genetic algorithm optimization.

The Genetic Algorithm (GA) converged within ten generations to produce a satellite constellation design that achieved 62,640 seconds of coverage for the target area within a 24-hour timeframe. This highlights the optimization efficiency in achieving extensive target coverage over one daily period.

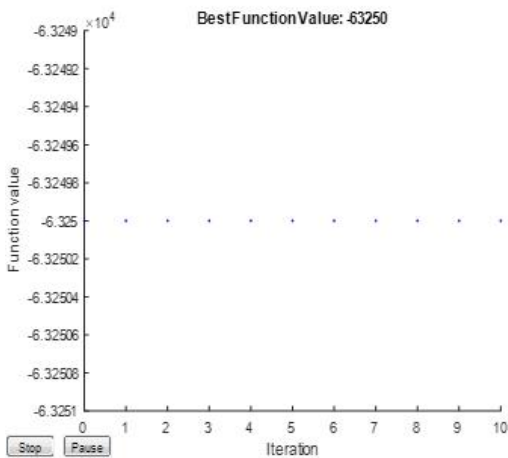


Fig. 7. PSO algorithm optimization.

Subsequently, the optimal solutions identified by the Genetic Algorithm (GA) are passed as inputs to the Particle Swarm Optimization (PSO) algorithm. The PSO algorithm then initiates a local search within the neighborhood of these globally optimized solutions, aiming to identify a refined local optimum. The results of this process demonstrate that the PSO algorithm was able to further increase the coverage time by 610 seconds, highlighting its effectiveness in enhancing local solutions

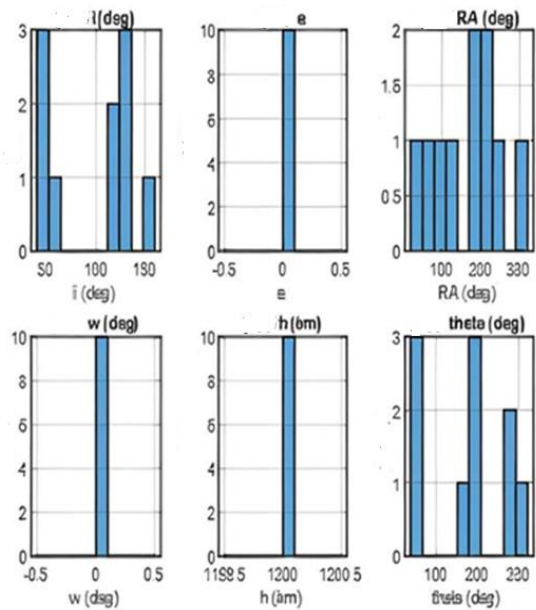


Fig. 8. Numerical distribution chart of variables.

The spatial distribution of the satellite constellation is achieved through optimized placement at appropriate orbital inclinations. Specifically, the optimization algorithm sought to deploy satellites at constant inclination angles across various distinct orbital planes. This particular configuration was intentionally pursued to fine-tune the satellite rise and set events relative to the target, ensuring maximal temporal coverage.

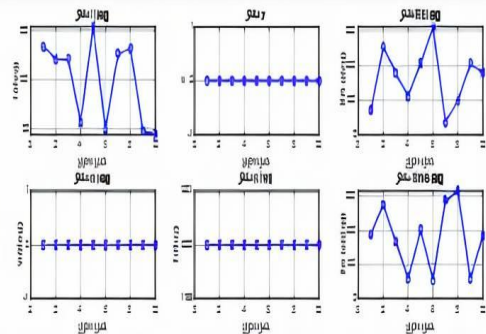


Fig. 9. Numerical value of satellite orbital parameters.

As previously stated and visually corroborated in Fig. 10, the hybrid GA-PSO optimization algorithm demonstrably enhanced the performance of the standalone GA by an additional 610 seconds. This increase in the optimal solution time highlights the synergistic effect of the combined approach.

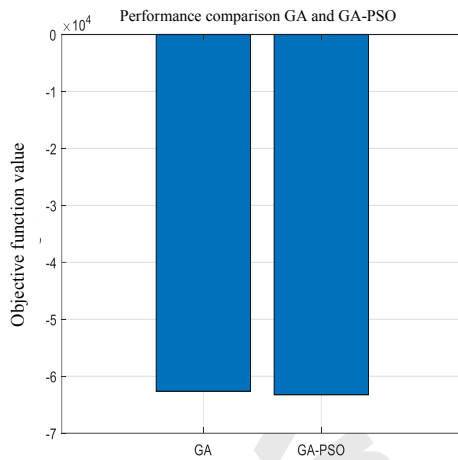


Fig. 10. Difference in performance of genetic and hybrid optimization algorithm GA-PSO.

In Table 2, the optimized variables can also be examined.

Table 2. Orbital Parameters of the Communication Satellite System Hybrid Optimization Algorithm GA-PSO.

| Number | E | I(Deg) | Ω (Deg) | ω (Deg) | H(Km) | Θ (Deg) |
|--------|---|--------|----------------|----------------|-------|----------------|
| 1 | 0 | 134.31 | 71.94 | 0.00 | 1200 | 189.67 |
| 2 | 0 | 121.09 | 254.63 | 0.00 | 1200 | 275.58 |
| 3 | 0 | 121.40 | 179.96 | 0.00 | 1200 | 167.68 |
| 4 | 0 | 56.32 | 111.61 | 0.00 | 1200 | 57.65 |
| 5 | 0 | 154.20 | 208.04 | 0.00 | 1200 | 200.57 |
| 6 | 0 | 48.40 | 313.15 | 0.00 | 1200 | 54.51 |
| 7 | 0 | 126.54 | 36.70 | 0.0000 | 1200 | 289.28 |
| 8 | 0 | 132.53 | 98.39 | 0.00 | 1200 | 316.02 |
| 9 | 0 | 47.91 | 206.05 | 0.00 | 1200 | 60.30 |
| 10 | 0 | 43.33 | 180.68 | 0.00 | 1200 | 182.76 |

However, a pertinent question arises regarding the extent to which the Particle Swarm Optimization (PSO) algorithm, in isolation, can enhance satellite access time. To investigate this specific contribution, the optimization problem was subsequently addressed using solely the PSO algorithm.

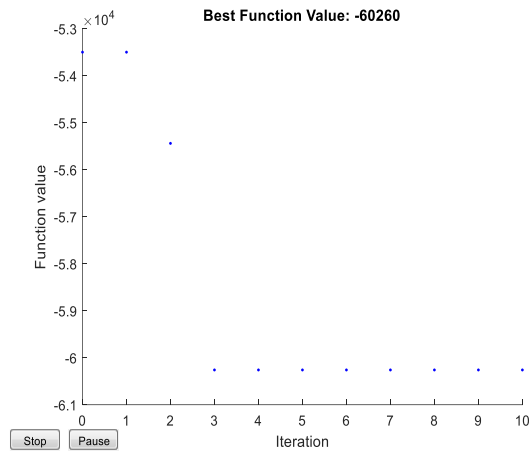


Fig. 11. PSO algorithm optimization.

Results demonstrate that the Particle Swarm Optimization (PSO) algorithm performed effectively, yielding a satellite constellation access time of 60,260 seconds. Nevertheless, notwithstanding this favorable result, the PSO algorithm was observed to converge rapidly. This is a consequence of the particles' swift convergence dynamics. This outcome highlights the potential of the Genetic Algorithm (GA), which utilizes a richer set of operators including crossover and mutation, to prevent premature convergence. The GA could potentially establish an initial optimization space, enabling the PSO algorithm to then perform a fine-grained exploration within this defined space to reach final convergence.

Table 3. Comparison between the optimization algorithms used

| Algorithm type | Best access time(s) | Coverage(%) |
|----------------|---------------------|-------------|
| GA | 62640 | 72.5% |
| PSO | 60260 | 69.75% |
| GA-PSO | 63250 | 73.21% |

5. CONCLUSION

This paper investigates the critical role of optimization algorithms in maximizing the coverage duration of a designated target location, acknowledging the paramount importance of satellite constellations for humanity's future. Initially, an optimization problem encompassing thirty variables was formulated by defining the orbital parameters for each satellite within the

constellation. The methodology employed a sequential approach: first, a Genetic Algorithm (GA) was utilized to identify a global optimum solution. Subsequently, a hybrid GA-PSO algorithm took the resultant GA-derived optimal points as input and further refined the satellite constellation optimization problem. The results demonstrate that the hybrid GA-PSO algorithm achieves a substantial 610-second performance improvement over the standalone GA. This optimized configuration yields a telecommunication satellite constellation capable of providing 17 hours of coverage per 24-hour cycle over Tehran, with a 73% coverage footprint of the defined target area. This 0.7% improvement (Between GA and GA-PSO) in coverage translates to approximately 10 additional minutes of coverage per day. Cumulatively, this amounts to over 60 hours per year, and more than 25 days of extra coverage over a typical 10-year operational lifespan of the constellation. Such a cumulative gain can have a direct impact on reducing operational costs and significantly increasing the service value, especially for critical and commercial applications.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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