Optimal Deployment Strategies for Cislunar PNT+C Architectures

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Cislunar operations are expected to rise dramatically within the next decade, requiring a comparable increase in PNT and communications services. However, current PNT systems are at capacity and need to be augmented to serve a cislunar space domain, specifically in the form of novel cislunar PNT architectures. This paper studies the problem of the deployment of PNT and communications satellites, specifically, the problem of deployment strategies spanning multiple stages over extended periods of time. A set of stage definitions will be determined along with areas of potential user activity. A novel application of the hidden gene genetic algorithm to the constellation optimization problem is presented. A design space exploration is presented with comparisons of circular and elliptical constellations. Optimization results from the first stage are also provided. It is shown that acceptable performance can be achieved with a low number of deployed satellites and that strong trade-offs exist between performance and stability.

I. Introduction and Motivation

The lunar sphere of influence is of vital interest to the military, government, and private sectors. As such, human activity in cislunar space is expected to rise dramatically within the next decade. These major missions include AFRL's cislunar space domain awareness initiative [1] and NASA's Lunar Gateway project [2]. Private space companies such as Lockheed Martin have also expressed interest in cislunar space [3].

A key enabler for these missions is Positioning, Navigation, and Timing (PNT) services, as well as communications services. Currently these needs are being met by the Deep Space Network, where all communication is relayed directly from a singular point in cislunar space to a corresponding receiver on Earth [4]. This service is limited to groundstation contact and Moon occultation [5]. Some capability to utilize signals from the Global Navigation Satellite Systems is available in cislunar space; however, there are no guarantees of performance at the Moon [5].

Many architectures designed with the specific goal of meeting increased Positioning, Navigation, Timing, and Communication (PNT+C) support needs on and around the Moon have been proposed. In order to support full coverage of cislunar space, particularly the lunar surface, most proposed architectures consist of multiple satellites in preset orbits around the Moon to directly provide service [4–11]. Other work proposes a relay structure which still requires satellites and orbital design [12–16]. An example of such a relay-based structure can be seen in Fig. 1 from Giordano et al. [15]. The PNT+C service is primarily provided by a 5G tower, but it is supplemented and sent to Earth by orbital assets.

For satisfactory coverage of the full lunar surface, upwards of twenty satellites may be required [5, 17]. Further, the service degrades as you reach the polar regions [5], which are of significant interest for early exploration [10]. However, targeted polar coverage similarly degrades towards the equator and opposite hemisphere [11]. This indicates that alternative constellation design or positioning technologies will be needed at different stages of development on the Moon.

In addition to the difficulties of strong trade-offs between the coverage of areas of interest, the orbits around the Moon pose special challenges in the physics of their orbits. Orbits around the Moon must take the third body effects of Earth into account, which increases the instability of orbits as their altitude increases [5]. Further, the mass distribution of the Moon is much less uniform than Earth. Mascons, or areas of high density, contribute similarly to oblateness to perturb orbits from stable states [18]. This leads the orbits having varying levels of stability dependent on their path. The corrective maneuvers to maintain a set of orbits increase their operational cost and must be considered alongside the quality of a provided service.

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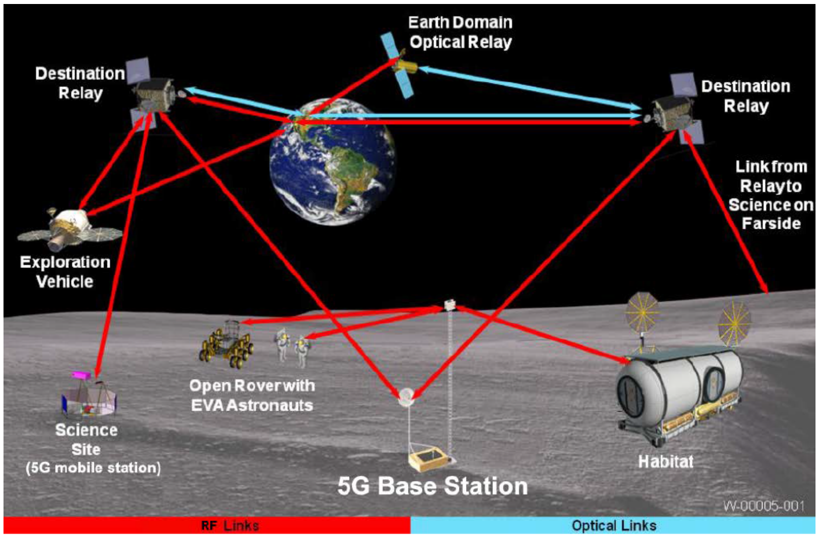

Fig. 1 Relay-based PNT+C Architecture (Image Source: Giordano et al. [15])

For these reasons and others, full lunar surface service is not yet a necessary or reasonable mission goal for cislunar architectures. This leads to a need to gradually build capability from the near-term targeted localized service to the final full surface ecosystem. The increased challenges of performance and cost trade-offs require effective optimization and design space evaluation techniques capable of considering key architecture decisions. Examples of such decisions include the use of frozen and near-frozen orbits or having increased maintenance maneuvers and whether to augment existing constellations or deploying new ones when expanding service regions.

This study seeks to develop an approach to identify optimal strategies for deploying large-scale architectures for cislunar PNT+C. The deployment strategy will define the stages of deployment, where each stage consists of one or more satellites being positioned to support expected PNT+C needs during its corresponding service period. The two main objectives of this work are to optimize the parameters of the satellites deployed in each stage and identify the deployment strategy's effect on PNT+C performance across the analysis period. The following sections outline the technical approach, experimental setup, results of this effort to date, and the path forward.

II. Background

A. Satellite Constellation Optimization

Since orbital system support is the most prevalent alternative for PNT+C service delivery, the processes behind optimizing the orbits and number of orbital systems has been investigated extensively. The problem is inherently a variable size design space problem where the number of decision variables is set by the number of satellites being considered. This effect can be mitigated by developing a specific constellation definition. One example of this approach is a Walker constellation, where the number of orbital planes and satellites per plane are tied to the orbital parameters of the satellites [19].

Once a specific definition is determined, the problem becomes a multi-objective optimization problem over a space with both discrete and continuous variables. Multi-objective heuristic optimization algorithms have been applied to this constellation optimization problem including the following classes: evolutionary algorithms [5, 20–26] and ant colony optimization [27]. Evolutionary algorithms have several well studied algorithms with simple implementations for multi-objective optimizaton [28]. The evolutionary algorithm class can further be broken down into generic evolutionary algorithms [5, 20, 25] and genetic algorithms [20, 22–24, 26]. Genetic algorithms provide the benefit of directly handling mixed variable types [20], yet they do not necessarily handle constraints well. Some evolutionary algorithms can handle constraints directly [25]. However, with significant uncertainty in the performance needs and cost limitations for the lunar PNT+C problem, the constraint space is ill-defined, so no constraints aside from planetary collison are currently needed. Both of these classes cannot directly handle a variable size design space problem. Recently, Hidden Gene Genetic Algorithms (HGGA) have been applied to the constellation optimization problem [23]. This gene definition scheme allows for direct handling of the variable size design space problem by turning sections of the gene off or on [29]. This could provide significant benefit over the algorithm having to select design variables which remove orbits from the problem. Therefore, a genetic algorithm with a hidden gene definition scheme is a good candidate for solving the constellation optimization problem.

B. Staged Deployment

As mentioned, different phases of lunar development will call for different levels of PNT+C service and different primary areas of service. However, it is not always economical to deploy all of the satellites required for a final architecture at first [22, 30]. There are two primary methods of staging the deployment of an architecture. de Weck et al. [30] presents a method wherein each stage is a wholly new constellation. This provides the benefit of targeting coverage to the current areas of interest, yet previous areas could receive a lower level of coverage when included with the aggregate. Alternatively, Lee et al. [22] presents an additive method where the previous stage is used as the foundation for the following stage. This provides the benefits of maintaining targeted coverage of previous areas and reducing the number of launches. One potential detraction is that with more satellites in orbit sufficient service quality might be able to be provided with more stable orbits than were required for the previous stage. This work follows the additive process put forward in Lee et al. [22].

III. Technical Approach

A. Simulation Environment

The modeling for this effort was conducted in System ToolKit (STK) version 12. Primarily the STK Python API was used to containerize the operation for integration with the optimization implementation. All metrics were calculated using the coverage and figure of merit tools in STK. The areas of interest for each stage were modeled as rectangular area targets defined by latitude and longitude pairs. These areas are discretized by STK at a user specified granularity. For this work, a step of 0.1° of latitude or longitude was used. The high precision orbit propagator was used to quantify orbital degradation. Additionally, the third body gravity effects of the Sun and Earth were used for the orbital modeling. Solar radiation pressure was not included for orbit degradation. The GRAIL660 Lunar gravity model was used to capture perturbations, as it has been shown to be more accurate than other models [31].

B. Performance and Cost Metrics

To judge performance, Geometric Dilution of Precision (GDOP), coverage, revisit time, and visibility will be utilized. GDOP is a measure of the added positioning error due to non-ideal satellite orientations. This metric requires a minimum of four satellites to be in view for its calculation [32]. This leads areas of poor coverage to result in non-number values for some time-steps. Coverage is defined as the amount of time that at least one satellite is within view. This was implemented within the STK as the percent of the area of interest with access to a satellite at any given time. Revist time is the amount of time between accesses to a satellite. The maximum revisit time was defined for each location and average over locations. Visibility has been defined for the purposes of this effort as the number of satellites in view at any given time for a location. This was tracked by using the "number of assets in view" figure of merit in STK. The minimum value was tracked over the area at each evaluation time step. The average over the evaluation time of two days was taken at sample of 100 seconds to obtain the overall objective value.

Cost will be represented by the number of satellites launched and a measure of the station-keeping requirements for the satellite orbits. Since only architecture level design is being considered, the cost in dollars of deploying a satellite and orbit maintenance propellant cannot be determined. This would required specific satellite designs including propulsion systems and maneuver schedules. Initially, the station keeping requirements will be represented by a relative measure of the degradation of each orbit as a function of orbital parameters. This is done by quantifying the deviation of radius of periapsis, eccentricity, and inclination over the two day evaluation period for each orbital plane. The root sum squared value was defined across all of the defined orbital planes to obtain a final value for each tracked parameter. More stable orbits will have less degradation, while unstable orbits will experience more degradation. Representing the station-keeping needs this way should aid in setting propulsion system requirements in the future. It is also possible that the optimization algorithm attempts an infeasible orbit. In this case, there is no contribution to the cost or performance metrics. This objective space definition results in seven objectives.

C. Dimensional Variable HGGA Optimization

Hidden Gene Genetic Algorithm's were originally defined to design interplanetary trajectories [29, 33, 34]. In this problem, the order of the sections being used matters. Therefore, a binary tag is defined for each variable. This creates a gene of significant length. For problems like constellation design where the order of the included variables does not matter, Gamot et al. [35] presented a method of implementing an HGGA where the set of active variables in a gene is set by a single dimensional variable. This allows for the usage of standard operations inside the genetic algorithm. Additionally, it was shown to have more favorable convergence compared to the tag method when applied to an optimal layout problem [35]. From literature, it appears that this dimensional variable approach has yet to be applied to the constellation optimization problem.

The dimensional variable for this work is the number of orbital planes. Then, n copies of number of satellites per plane, semi-major axis, eccentricity, inclination, argument of periapsis, and Right Ascension of the Ascending Node (RAAN) are defined for each gene where n is maximum value of the number of orbital planes. This resulted in a gene of size thirty-one. In general, this scheme should allow for hybridized constellations with significant variation between the constituent orbits.

D. Optimization Approach

Beginning with an original location of interest and accounting for the growth of requirements with the advancement of stages, a set of near optimal constellation configurations is desired. To obtain this, a Pareto Front on the basis of both performance and cost for the first stage will be defined. The Pareto Front was generated by wrapping a multi-objective optimization routine around the modeling environment developed with STK12. Particularly, the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) was implemented with the dimensional variable gene definition discussed previously [36]. The NSGA-II implementation in the pymoo Python package was used [28].

To evaluate the second stage, an optimization will be performed for each of the Pareto-optimal points identified in the analysis of the first stage. This process will generate a set of near-optimal additions for each of the potential constellations for the first stage. For the third stage, the associated combinations between the first and second stage constellations will be similarly used as a base for the optimization of a third addition. This process could be continued for as many stages as needed. Transition between stages may be defined as combinations of varying areas of operation, changes to the objectives of interest, and constraints applied on objectives.This optimization process will result in a mapping between performance at each stage and the satellites needed at each stage. From this mapping, a staging structure can be selected with a multi-attribute decision making method. This general process will result in a large number of alternatives if the desired objective weightings are not known *a priori*.

IV. Experimental Setup

To test the effects of a staged deployment on a fully integrated PNT+C lunar architecture, three stages are defined. In stage one, surface operations are limited to an area around the South Pole. For the purposes of this paper a square area of operation with legs of 100 km has been selected. This area was discretized into sets of latitude and longitude pairs for the calculation of specific metrics [5, 22, 24, 37]. In stage two, there are multiple bases across the surface with each base having a 100 km square area of operation. In the final stage, surface operations are dispersed across the entire Moon. We will evaluate the following potential base locations: the South Pole, Aristarchus Crater, and Mare Smythii. It will be assumed that each stage operates for 10 years before the deployment of the next stage. In the first stage, GDOP will not be used for the optimization as it will be assumed that other positioning technologies are being used to supplement any orbital service.

Table 1 Monte Carlo Variable Ranges

Variable	Min	Max
Num. Planes	1	4
Num. Sats. per Plane	2	4
Inclination	45°	135°
Eccentricity	0	0.5
Semi-Major Axis	2500 km	5000 km

To determine reasonable ranges for the design variables used in the optimization, an initial design space exploration was conducted using the Monte Carlo tool in STK. The initial design space exploration looked at circular and elliptical orbits over three areas of services: the South Pole, the Southern Hemisphere, and the full lunar surface. Standard Walker constellations were used defined by number of orbital planes, number of satellites per plane, inclination, and semi-major axis. For the elliptical orbits, eccentricity was added. The ranges used for variables are given in Table 1. The argument of periapsis was held constant at 90° for the first two areas of service and 270° for the full surface case. The maximum revisit time, minimum number of assets in view, total number of satellites, and coverage were collected. For the latter two areas of service the average GDOP was calculated as well.

V. Results

A. Design Space Exploration

In analyzing the results from the Monte Carlo design space search, no direct relationships were seen between the design variables and performance. The design variables primarily operated as a limiter. Essentially, better performance required at least a certain value of a design variable, but that did not preclude poor performance. This is a similar result to previous work on circular Walker constellations [17]. Another interest is the variance in performance between orbit types. Little to no variance in coverage was quantified, so the results presented will focus on the other objectives. Figure 2 presents the objective space for the South Pole case where the label and color on each bin represent the average number of satellites in the constellations comprising the bin. It is seen the the highest maximum revisit time is much higher for the circular only constellations than for the elliptical ones. Additionally, the middle performance of lower revisit time and high minimum number of assets in view requires an average of 1.65 less satellites to achieve the same performance. The satellite requirements at the extremes of performance are similar.

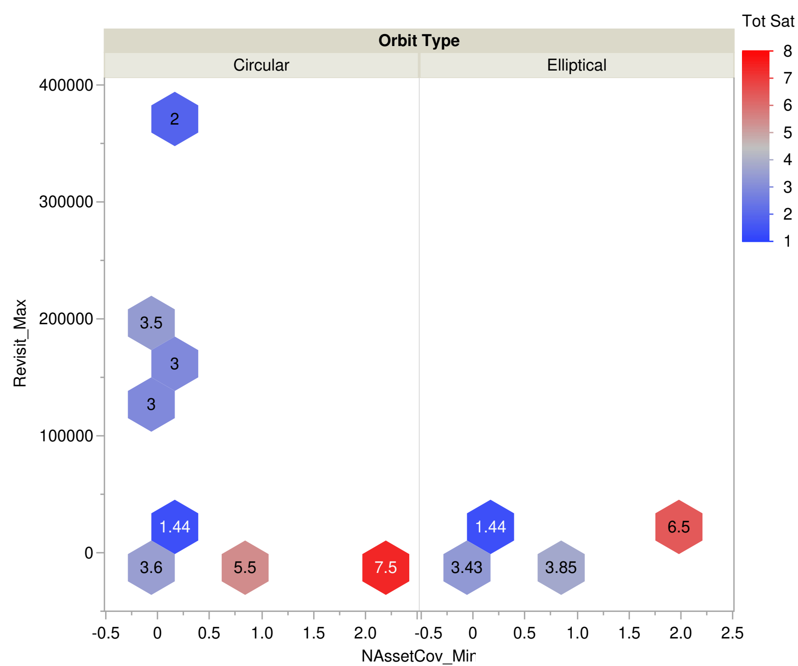

Fig. 2 South Pole Monte Carlo Objective Space

For the southern hemisphere case, the GDOP could be consistently calculated. Figure 3 gives a comparison of the distribution of GDOP performance between the two orbit types. Again it is seen that the elliptical orbits perform better; however, the average GDOP values are still very high with a median of 30. It is also worth noting that the average GDOP can only sometimes be calculated leading to the potential for low values when on average there are a low number of assets in view.

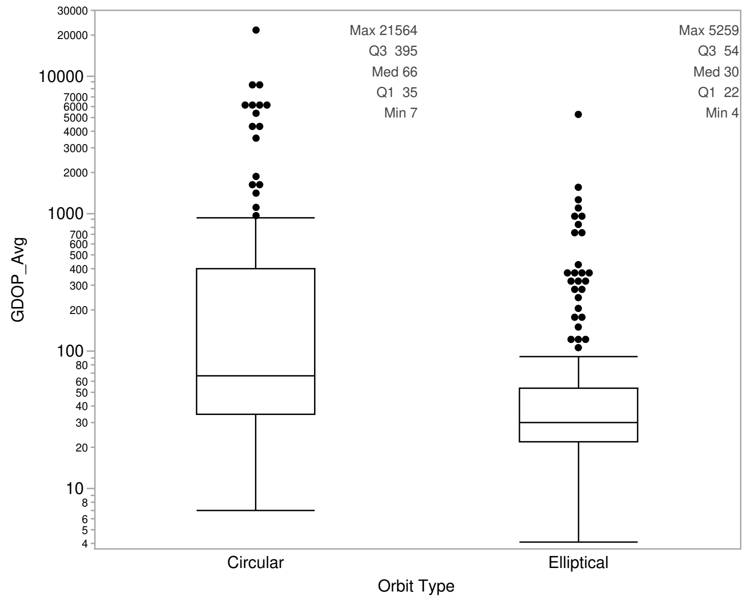

Fig. 3 Southern Hemisphere GDOP Performance

The overall objective space for the southern hemisphere case is given in Fig. 4. Average GDOP is on the y-axis with a logarithmic scale. The same general trends as Fig. 2 are seen. The elliptical orbits can achieve better performance and, in other cases, similar performance with fewer assets. The relationship were the minimum achieved GDOP increases with minimum number of assets in view is indicative that some of the low GDOP cases are due to a smaller set of positions were it is calculated.

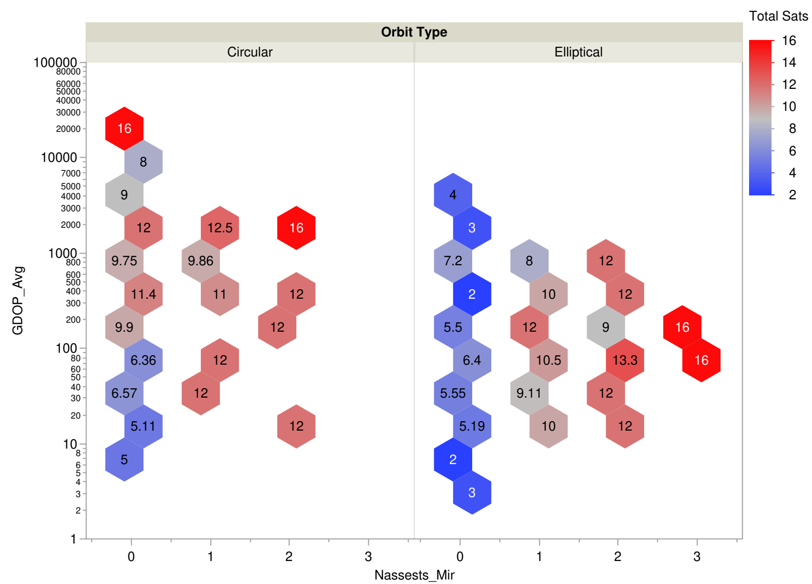

Fig. 4 Southern Hemisphere Monte Carlo Objective Space

For the full surface case, the circular and elliptical performance begins to converge, as seen in Fig. 5. While the elliptical orbits do require fewer assets, the difference is less than for the previous cases. The overall performance achieved is more similar as well.

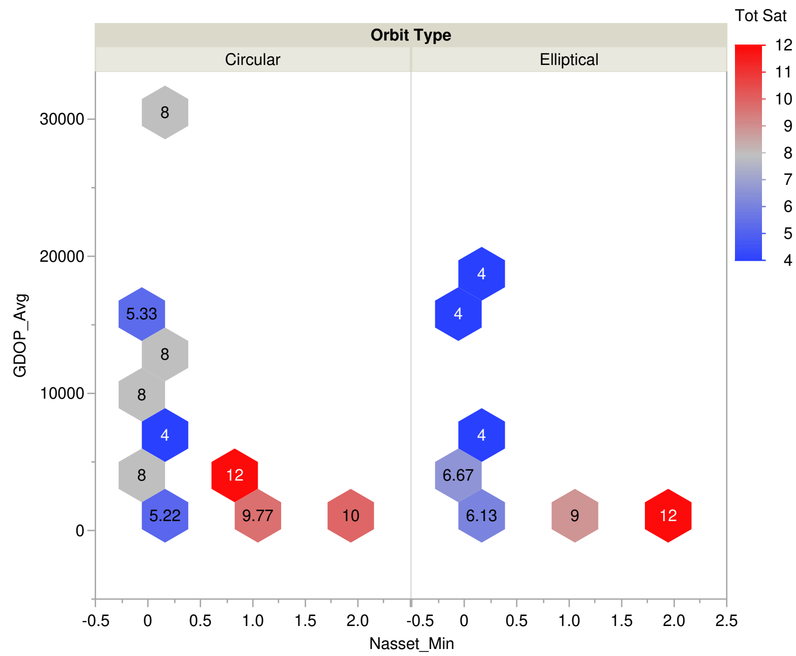

Fig. 5 Full Surface Monte Carlo Objective Space

B. Initial Optimization Results

The optimization algorithm was implemented without the direct formulation for the mixed variable case. Instead, the discrete variables were rounded. Additionally, a satellite was taken to be infeasible if the radius of periapsis was calculated to be less than 1750 km. As mentioned previously, this plane would be skipped and not included in any objective calculations. The upper and lower limits for the design variables are given in Table 2. With the high eccentricity allowed and the relatively low semi-major axis upper limit, large portions of this search space are infeasible. Therefore, larger orbits should be explored even if they will be less stable. The optimization was run with a population size of twenty-five and terminated after 100 generations.

Table 2 Optimization Variable Ranges

Variable	Lower	Upper
Num. Planes	1	5
Num. Sats. per Plane	1	6
Inclination (INC)	0°	180°
Eccentricity (ECC)	0	0.98
Semi-Major Axis	2500 km	5000 km
Argument of Periapsis	0°	360°
RAAN	0°	360°

The primary result from the optimization was that the optimization algorithm did not seem to exploit the dimensional variable. Of the resulting non-dominated set, all of the alternatives had three or four planes. However, many of the designs had only 1 or 2 feasible orbital planes. The optimization algorithm exploited the feasibility check rather than the dimensional variable to keep the total number of satellites low. This could be that this mechanism is just more efficient, or it could be a result of the such a large quantity of search space being infeasible. All of the feasible orbits selected by the optimizer had a semi-major axis greater than 4000 km.

The objective space resulting from the optimization shows the clear trade offs between performance and cost. The objective space is given in Fig. 6. The performance objectives are aligned, or the best performing case for one performance objective is also the best performing case for the other objectives. This can be seen in the second and third rows of Fig. 6. While there is a frontier of performance between coverage, minimum number of assets in view, and maximum revisit time, it does not occur in the bottom left corner of the plots were the objectives are at their minimum. The negative of the coverage and minimum number of assets in view were used to consistently minimize across all objectives. Alternatively, coverage and change in radius of periapsis (Delta_RoP) have a clear adversarial relationship where 100% coverage is only achieved with high level of change in radius of periapsis. It is also worth noting that one design was able to achieve 100% coverage with only three satellites.

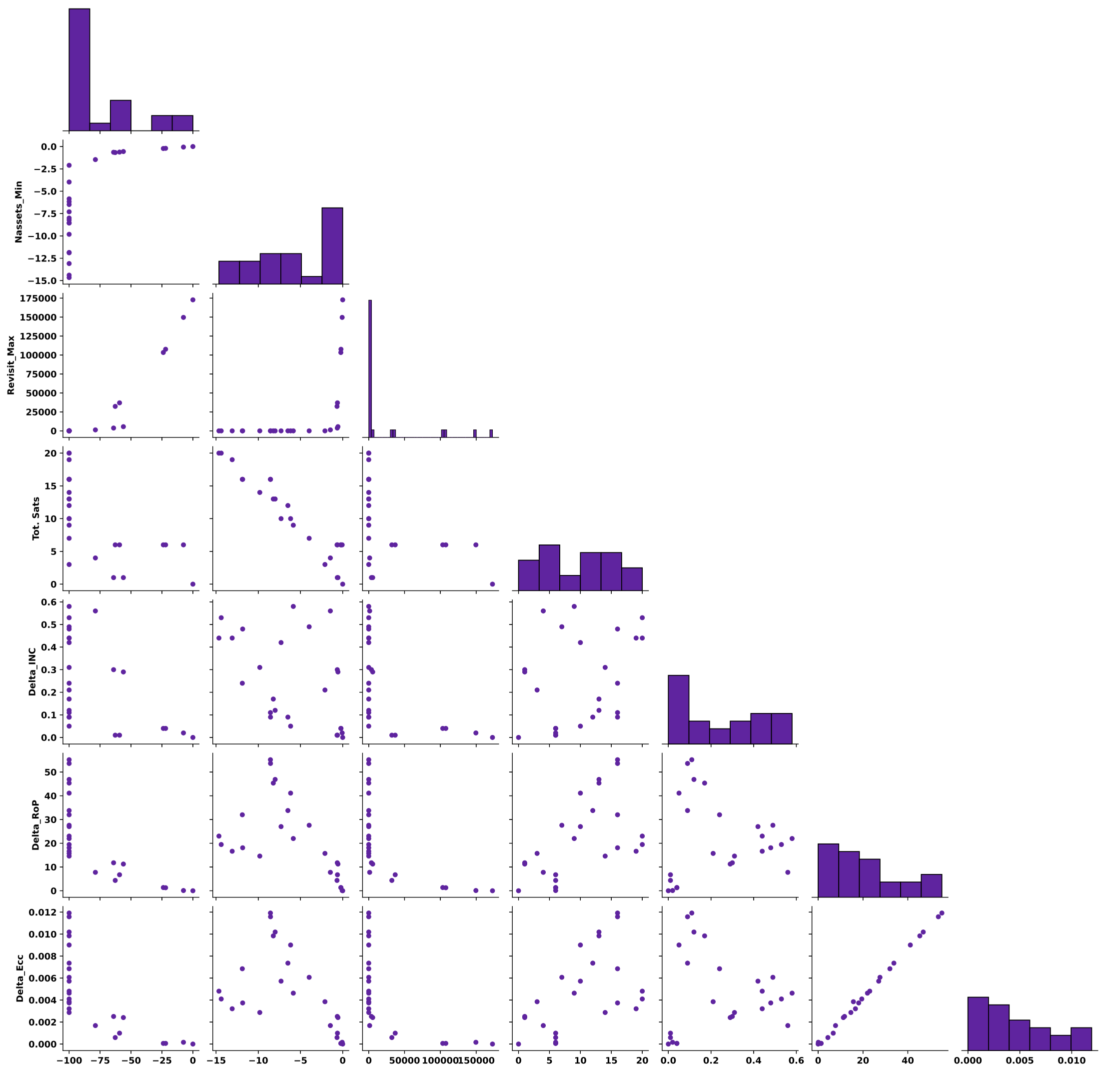

Fig. 6 Stage 1 Pareto Optimal Set

VI. Conclusion and Future Work

This paper presents a method for finding optimal staged deployment strategies for PNT+C architectures in cislunar space. A novel application of a dimensional variable Hidden Gene Genetic Algorithm to the constellation optimization problem is presented with initial results. Elliptical Walker constellations were shown to outperform purely circular constellations across a number of metrics and areas of service. The results of the optimization for the first stage of lunar development around the south pole are provided. It was seen that the optimizer did not utilize the dimensional variable mechanism preferring the feasibility check. These results also confirmed that high performance relies on larger values of semi-major axis, which increases the level of orbit degradation. Strong trade-offs between orbit stability and performance were seen confirming the need for high fidelity orbit propagation and multi-objective optimization.

Going forward, the behavior of the optimization scheme with an expanded search area will be investigated. Additionally, a convergence comparison to a standard NSGA-II algorithm without dimensional variables will be conducted. Finally, the optimization for the later stages will be conducted and analyzed as set forward. An implementation of various propulsion systems to trade specific ΔV costs could provide useful insight into the feasibility of the architectures and the likely lifespan of the deployed assets.

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References

[1] Perkins, J., "AFRL's Cislunar Highway Patrol System seeks industry collaboration," , March 2022. URL `https://www.afrl.af.mil/News/Article/2972971/afrls-cislunar-highway-patrol-system-seeks-industry-collaboration/`.

[2] Fuller, S., Lehnhardt, E., Zaid, C., and Halloran, K., "Gateway program status and overview," *Journal of Space Safety Engineering*, Vol. 9, No. 4, 2022, pp. 625–628. https://doi.org/https://doi.org/10.1016/j.jsse.2022.07.008.

[3] Lockheed Martin, "Crescent Space To Deliver Critical Services To A Growing Lunar Economy," , March 2023. URL https://news.lockheedmartin.com/2023-03-28-Crescent-Space-to-Deliver-Critical-Services-to-a-Growing-Lunar-Economy.

[4] Reinhart, R. C., Schier, J. S., Israel, D. J., Tai, W., Liebrecht, P. E., and Townes, S. A., "Enabling future science and human exploration with NASA's next generation near earth and deep space communications and navigation architecture," *Proceedings of the 68th International Astronautical Congress*, IAC-17-B2.1.1.41830, 2017, pp. 4716–4725. URL https://ntrs.nasa.gov/api/citations/20170009462/downloads/20170009462.pdf.

[5] Pereira, F., and Selva, D., "Exploring the Design Space of Lunar GNSS in Frozen Orbit Conditions," *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, IEEE, 2020, pp. 444–451. https://doi.org/10.1109/PLANS46316.2020.9110202.

[6] Jun, W. W., Cheung, K.-M., Lightsey, E. G., and Lee, C., "A Minimal Architecture for Real-Time Lunar Surface Positioning Using Joint Doppler and Ranging," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 58, No. 2, 2022, pp. 1367–1376. https://doi.org/10.1109/TAES.2021.3122876.

[7] Israel, D. J., Mauldin, K. D., Roberts, C. J., Mitchell, J. W., Pulkkinen, A. A., Cooper, L. V. D., Johnson, M. A., Christe, S. D., and Gramling, C. J., "LunaNet: a Flexible and Extensible Lunar Exploration Communications and Navigation Infrastructure," *2020 IEEE Aerospace Conference*, IEEE, 2020, pp. 1–14. https://doi.org/10.1109/AERO47225.2020.9172509.

[8] Israel, D. J., Schier, J. S., Petro, A., Tai, W., Anzalone, E., and Sharma, A., "LunaNet Architecture and Concept of Operations," *16th International Conference on Space Operations*, SpaceOps–2021,8,x1327, 2021.

[9] Bhamidipati, S., Mina, T., and Gao, G., "A Case Study Analysis for Designing a Lunar Navigation Satellite System with Time-Transfer from Earth-GPS," *Proceedings of the International Technical Meeting of The Institute of Navigation, ITM*, Vol. 2022-Janua, 2022, pp. 407–419. https://doi.org/10.33012/2022.18202.

[10] Thompson, J. R., Haygood, H. G., and Kezirian, M. T., "Design and Analysis of Lunar Communication and Navigation Satellite Constellation Architectures," *AIAA SPACE 2010 Conference & Exposition*, AIAA 2010-8644, AIAA, 2010. https://doi.org/10.2514/6.2010-8644.

[11] Hartigan, M., Smith, D., and Lightsey, E. G., "OPTIMIZATION OF EARLY-PHASE CISLUNAR NAVIGATION CONSTELLATIONS FOR USERS NEAR THE LUNAR SOUTH POLE," *2023 AAS/AIAA Astrodynamics Specialist Conference*, AAS 23-442, American Astronautical Society, 2023. Preprint.

[12] Mitch, R., Weaver, G., Bruzzi, J., Millard, W., Summers, B., and Bradfield, J., "Lighthouses: An Extensible Cislunar Positioning, Navigation, and Timing Architecture," *Proceedings of the 2022 International Technical Meeting of The Institute of Navigation*, 2022, pp. 438–452. https://doi.org/10.33012/2022.18203.

[13] Johnson, S. K., Mortensen, D. J., Chavez, M. A., and Woodland, C. L., "Gateway – a communications platform for lunar exploration," *38th International Communications Satellite Systems Conference (ICSSC 2021)*, Institution of Engineering and Technology, 2021, pp. 9–16. https://doi.org/10.1049/icp.2022.0544.

[14] Offord Harle, N., Oates, C., Bywater, S., Cranstoun, C., Friend, J., Lay, G., Schwarz, B., Stevens, P., Hufenbach, B., Liuicci, F., Cosby, M., and Saunders, C., "Lunar comms and nav infrastructure – first data relay orbiter Lunar Pathfinder, operational in 2024, paves the way for full constellation by 2030s," *ASCEND 2021*, AIAA 2021-4132, AIAA, 2021. https://doi.org/10.2514/6.2021-4132.

[15] Giordano, P., Lisi, M., and Modenini, A., "5G technologies for a communications and navigation integrated infrastructure on moon and mars," *Advances in Communications Satellite Systems Proceedings of The 36th International Communications Satellite Systems Conference (ICSSC-2018)*, IET TELECOMMUNICATIONS SERIES 86, The Institution of Engineering and Technology, 2019, pp. 269–278. https://doi.org/10.1049/PBTE086E.

[16] Bhasin, K., Warner, J., and Anderson, L., "Lunar Communication Terminals for NASA Exploration Missions: Needs, Operations Cocepts and Architectures," *26th International Communications Satellite Systems Conference (ICSSC)*, AIAA 2008-5479, AIAA, 2008. https://doi.org/10.2514/6.2008-5479.

[17] Bender, T. E., Gabhart, A. S., Steffens, M. J., and Mavris, D. N., "Defining and Parameterizing the Design Space for Cislunar PNT Architectures," *AIAA SCITECH 2023 Forum*, AIAA 2023-1504, AIAA, 2023. https://doi.org/10.2514/6.2023-1504.

[18] Varoqui, M., Steffens, M. J., and Mavris, D. N., "Surrogate Modeling of Orbital Decay of Lunar Orbits," *AIAA SCITECH 2023 Forum*, AIAA 2023-1419, AIAA, 2023. https://doi.org/10.2514/6.2023-1419.

[19] Walker, J. G., "Continuous whole-earth coverage by circular-orbit satellite patterns," Tech. rep., Royal Aircraft Establishment Farnborough (United Kingdom), 1977. URL https://apps.dtic.mil/sti/pdfs/ADA044593.pdf, [cited: April 2023].

[20] Ferringer, M. P., Clifton, R. S., and Thompson, T. G., "Efficient and Accurate Evolutionary Multi-Objective Optimization Paradigms for Satellite Constellation Design," *Journal of Spacecraft and Rockets*, Vol. 44, No. 3, 2007, pp. 682–691. https://doi.org/10.2514/1.26747.

[21] Frayssinhes, E., "Investigating new satellite constellation geometries with genetic algorithms," *Astrodynamics Conference*, American Institute of Aeronautics and Astronautics, Reston, Virigina, 1996, pp. 582–588. https://doi.org/10.2514/6.1996-3636.

[22] Lee, H. W., Jakob, P. C., Ho, K., Shimizu, S., and Yoshikawa, S., "Optimization of satellite constellation deployment strategy considering uncertain areas of interest," *Acta Astronautica*, Vol. 153, 2018, pp. 213–228. https://doi.org/10.1016/j.actaastro.2018.03.054.

[23] Visonneau, L., Shimane, Y., and Ho, K., "Optimizing Multi-Spacecraft Cislunar Space Domain Awareness Systems via Hidden-Genes Genetic Algorithm," *The Journal of the Astronautical Sciences*, Vol. 20, No. 22, 2023. https://doi.org/10.1007/s40295-023-00386-8.

[24] Savitri, T., Kim, Y., Jo, S., and Bang, H., "Satellite Constellation Orbit Design Optimization with Combined Genetic Algorithm and Semianalytical Approach," *International Journal of Aerospace Engineering*, 2017, pp. 1–17. https://doi.org/10.1155/2017/1235692.

[25] Arcia Gil, A. D., Renwick, D., Cappelletti, C., and Blunt, P., "Methodology for optimizing a Constellation of a Lunar Global Navigation System with a multi-objective optimization algorithm," *Acta Astronautica*, Vol. 204, 2023, pp. 348–357. https://doi.org/https://doi.org/10.1016/j.actaastro.2023.01.003.

[26] Bender, T., McNabb, J., Birbasov, N., Bowne, M., Robertson, B. E., Sudol, A., Mavris, D. N., and Lourenco, N., "Satellite Formation Design to Enhance Passive Millimeter Wave Imaging Mission Performance," *AIAA SCITECH 2022 Forum*, AIAA 2022-1881, AIAA, 2022. https://doi.org/10.2514/6.2022-1881.

[27] Zanotti, G., Ceresoli, M., Pasquale, A., Prinetto, J., and Lavagna, M., "High performance lunar constellation for navigation services to Moon orbiting users," *Advances in Space Research*, 2023. https://doi.org/10.1016/j.asr.2023.03.032.

[28] Blank, J., and Deb, K., "pymoo: Multi-Objective Optimization in Python," *IEEE Access*, Vol. 8, 2020, pp. 89497–89509. https://doi.org/10.1109/ACCESS.2020.2990567.

[29] Abdelkhalik, O., "Hidden genes genetic optimization for variable-size design space problems," *Journal of Optimization Theory and Applications*, Vol. 156, No. 2, 2013, p. 450–468. https://doi.org/10.1007/s10957-012-0122-6.

[30] de Weck, O. L., de Neufville, R., and Chaize, M., "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit," *Journal of Aerospace Computing, Information, and Communication*, Vol. 1, No. 3, 2004, pp. 119–136. https://doi.org/10.2514/1.6346.

[31] Kim, Y.-R., Song, Y.-J., Bae, J., and Kim, B.-Y., "Influence of the Choice of Lunar Gravity Model on Orbit Determination for Lunar Orbiters," *Mathematical Problems in Engineering*, Vol. 2018, 2018. https://doi.org/10.1155/2018/5145419.

[32] Drosendahl, M., Bender, T. E., Steffens, M. J., and Mavris, D. N., "A Methodology for Evaluating Cislunar PNT Architectures during Initial Design Space Exploration," *AIAA SCITECH 2023 Forum*, AIAA 2023-1418, AIAA, 2023. https://doi.org/10.2514/6.2023-1418.

[33] Abdelkhalik, O., and Darani, S., "Evolving Hidden Genes in Genetic Algorithms for Systems Architecture Optimization," *Journal of Dynamic Systems, Measurement, and Control*, Vol. 140, No. 10, 2018, p. 101015. https://doi.org/10.1115/1.4040207.

[34] Ellithy, A., Abdelkhalik, O., and Englander, J., "Multi-Objective Hidden Genes Genetic Algorithm for Multigravity-Assist Trajectory Optimization," *Journal of Guidance, Control, and Dynamics*, Vol. 45, No. 7, 2022, pp. 1269–1285. https://doi.org/10.2514/1.G006415.

[35] Gamot, J., Balesdent, M., Tremolet, A., Wuilbercq, R., Melab, N., and Talbi, E.-G., "Hidden-variables genetic algorithm for variable-size design space optimal layout problems with application to aerospace vehicles," *Engineering Applications of Artificial Intelligence*, Vol. 121, 2023, p. 105941. https://doi.org/10.1016/j.engappai.2023.105941.

[36] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T., "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation*, Vol. 6, No. 2, 2002, pp. 182–197. https://doi.org/10.1109/4235.996017.

[37] Hagenau, B., Peters, B., Burton, R., Hashemi, K., and Cramer, N., "Introducing The Lunar Autonomous PNT System (LAPS) Simulator," *2021 IEEE Aerospace Conference (50100)*, IEEE, 2021, pp. 1–11. https://doi.org/10.1109/AERO50100.2021.9438538.