Design of Optimal Satellite Constellation for Indonesian Regional Navigation System based on GEO and GSO Satellites

Astriany Noer[1], Farid Armin[2], Kamirul[3], Janne Anna Christa Wejay[4]
LAPAN Biak Office
Indonesian National Institute of Aeronautics and Space
Biak, Indonesia
astriany.noer@lapan.go.id[1], farid.armin@lapan.go.id[2], kamirul@lapan.go.id[3], janne.anna@lapan.go.id[4]

***Abstract*—Autonomous regional navigation system provides independent and accurate positioning services continuously to a selected region. This paper presents the space segment's design algorithm for the Indonesian regional navigation system, which will provide real-time self-reliance positioning, velocity, and timing services to the civilians and more accurate positional service to military personnel. The purpose of this research is to find the optimal satellite constellation of combined Geostationary (GEO) and Geosynchronous (GSO) satellites with 100% coverage throughout Indonesia territory and better positioning service to the user using a minimum number of satellites. The Genetic Algorithm (GA) has been used for finding optimal satellite constellation, which gives the least mean Geometric Dilution of Precision (GDOP) over the selected places in Indonesia. Then the optimal constellation is simulated in System Tool Kit (STK) to verify the performance of the Genetic Algorithm results. The design algorithm's output depicts that the optimized satellite constellation for the Indonesian regional navigation system consists of 3 GEO and 4 GSO satellites. The simulation results in STK indicate that the proposed satellite constellation provides accurate position and navigation services to entire Indonesia with the mean GDOP of less than 4 value.**

Keywords—Regional Navigation System, Optimal Satellite Constellation, Satellite, GDOP, Genetic Algorithm, Indonesia, GEO, GSO

I. INTRODUCTION

Radio navigation provides accurate position finding and navigation services by using radio waves. It started with the Ground-based navigation using non-directional Radio beacons, and hyperbolic navigation system in which the radio waves are broadcasted from multiple ground stations [1].

Ground-based navigation was the earliest human-made navigation system that used radio waves broadcasted from a Master Station and a Slave Station. It has limited area coverage, which is later covered by Satellite-based Navigation. It is started with Sputnik I and Transit Satellites in the early 1960s based on the Doppler effect. With a few changes, the US launched the Global Positioning System (GPS) that works on Trilateration. The Global Navigation Satellite System (GNSS) is the satellite navigation system that provides navigation services to the entire globe. Today, the GNSS includes GPS from USA, Global Navigation Satellite System (GLONASS) from Russia, Galileo from Europe, and BeiDou-3 from China. GPS consists of 30 satellites in 6 Medium Earth Orbit (MEO) orbital planes, which are continuously transmitting radio navigation signals to the entire globe. GLONASS consists of 24 operational satellites in 3 MEO orbits. Galileo consists of 22 operational and 2 testing Satellites. Beidou-3 consists of 49 satellites in MEO, Geostationary (GEO), and Geosynchronous (GSO) Orbits. All these satellite constellations independently provide position, velocity, and timing services globally.

Satellite-Based Augmented System (SBAS) and Ground-Based Augmented System (GBAS) are GNSS augmented systems that improve the accuracy of the users' position. The augmented system sends information about corrections of GNSS system errors, which are processed by users to achieve better positional service [2].

Though GNSS is available over the entire globe, many countries began developing their own regional navigation satellite constellation. Indian Space Research Organization (ISRO) developed the Indian Regional Navigation Satellite System (IRNSS), which is a Regional Navigation System. Currently, IRNSS is operational and provides navigation services primarily to India and also covers the region extending 1200 km around India. IRNSS satellite constellation comprises of 3 GEO Satellites and 4 GSO Satellites [3].

Quasi-Zenith Satellite System (QZSS) is also a satellite-based navigation program with regional service coverage. Currently, QZSS works as a regional time transfer system and also as a GPS augmented system. QZSS comprises of 1 GEO satellite and 3 satellites in a Quasi-Zenith Orbits (QZO) orbit. Japan is planning to make QZSS as an independent regional navigation satellite system by adding 3 more satellites to QZSS [4].

The satellite constellation is a network of satellites that accomplishes the mission requirements collectively. Traditional satellite constellation design methods have main objective of providing continuous coverage with less number of satellites. Walker [5] and Ballard [6] have proposed constellation theories with symmetric inclined circular orbits, while Luders [7] and Rider [8] proposed the Street-of-coverage method with polar orbital planes. However, these conventional constellation design methods are not optimal as they lead to redundant coverage by satellites. Another method introduced by Mortari et al, a flower-constellation method for global or zonal coverage with elliptical or circular orbits [9] but this technique also has limitation of repeatable ground tracks.

Genetic Algorithm (GA) is one of methods for designing satellite constellation [10]. GA is a generic optimization tool and provides a set of optimal solutions for the given objective. GA known for its global optimization performance, is now widely used as satellite constellation design tool.

The novelty of this research is finding an optimal navigation satellite constellation for Indonesia by using an efficient approach to GA, pre-computing partially optimized result set and using GA to find the best solution from the

978-1-7281-8404-3/20/PRINT ©2020 IEEE

partial optimized result set. The initial step in this proposed method is using semi-analytical methods to compute a nearly optimized solution that fulfills certain objectives. GA finds the best solution from the partial optimized result set computed in the first step. With this approach, computational time for finding an optimal solution will be reduced. In this paper, a partial optimized set of orbital elements are calculated initially based on the mission purpose, coverage area coordinates, and mission constraints and then GA is used to find the optimum satellite constellation for Indonesian Regional Navigation System.

Indonesia requires an independent and accurate navigation system for better position, navigation and timing services in surveying, military purpose and disaster management. In this research, the authors will briefly present an outline of their research on finding the optimal satellite constellation of combined GEO and GSO satellites which can cover throughout Indonesia territory and provide better positioning service to the user using a minimum number of satellites.

The necessity of regional navigation satellite system arrives from the uncertainty in the availability of accurate positioning services from GNSS during hostile situations. To achieve the nation's security and obtain accurate positional services without depending on GNSS signals, one must need a regional navigation satellite system.

After the introduction in Section I, the remaining of this paper is written as follows: Section II describes the regional navigation satellite system, which are related to architecture, design of space segment, and Geometric Dilution of Precision (GDOP); Section III describe the Design algorithm implementation; Simulation and results are outlined in section IV; Section V presents the conclusion with future work; and acknowledgment in the last section, Section VI.

II. Regional Navigation Satellite System

A. Architecture

Every satellite-based navigation system consists of three segments.

1) Space Segment

Space segment comprises the constellation of satellites, which are arranged in a specific manner to provide global coverage, zonal coverage, or certain regional coverage. They transmit navigation radio signals continuously to the ground.

2) Ground Segment

The ground segment consists of a control center, tracking and commanding ground stations, ranging stations, and monitoring stations. The master control center controls the satellite constellation, monitors the health status of the satellite's, determines the satellite's orbit ephemeris, and synchronizes the satellite's clock at regular intervals.

3) User Segment

The user segment consists of civilians and military personnel who receive the navigation signals from the space segment and calculates the user's position, velocity, and time. Users need specially designed GPS receivers that can receive the signals from regional navigation satellites and also compatible with other GNSS constellations.

B. Design of Space Segment

In this paper, the design of the space segment for the self-reliant Indonesian regional navigation system is presented. The objective of this paper is to find an optimal satellite constellation for providing better navigation service to the entire Indonesia. There are many methods to design a constellation like Walker's method, the Streets of coverage. Walker's method is a symmetrical and inclined design algorithm used to find an optimized satellite constellation for global or zonal coverage. In Walker's method, satellites are arranged uniformly at an equal altitude and inclination. Streets-of-Coverage is a polar satellite constellation design algorithm [11]. Besides traditional constellation methods, the Genetic Algorithm also provides an optimum solution with multiple constraints. However, there is no specific unified approach for a zonal coverage satellite constellation.

Steps taken in the design algorithm for finding the optimized satellite constellation are:

1) Define the latitude and longitude range of an interested area that requires navigation.
2) Define the number of visible satellites and coverage percentage throughout the day.
3) Select the type of orbit for satellites and compute their orbital parameters.
4) Define upper and lower bounds of unknown orbital parameters.
5) Select the specific locations in the area of interest that are located at extreme ends.
6) Compute the optimal satellite constellation using a GA with the objective of least GDOP for those locations within the range of unknown orbital parameters.
7) Simulate the optimized satellite constellation in System Tool Kit (STK) and verify the GDOP at selected locations.

C. Geometric Dilution of Precision (GDOP)

The sole purpose of a navigation system is to provide an accurate position and time to the user. But the estimated position and time always differ from the actual position and time of the user due to various factors, that includes selection of satellites, algorithm to calculate the range, atmospheric errors, and the geometry of the satellites and the receiver. Based on the source for errors generation, errors are classified as statistical errors that arise in the range measurement process and errors due to geometric distribution of navigation satellites. The overall position error is the product of these two errors as shown in (1).

$$Position\ Error\ =\ GDOP\ x\ UERE \qquad (1)$$

Where GDOP is the error due to geometrical relationship between the user and the navigation satellites and User Equivalent Range Error (UERE) represents measurement errors. Mathematically, GDOP is the ratio of the standard deviation of a parameter and pseudo-range. It dilutes the precision of the position and time calculated at the receiver end whereas UERE includes errors due to satellites and receiver clock biases, atmospheric propagation, and Multipath.

Errors due to satellite-reciever geometry are minimized by maintaining good geometric distribution between navigation satellites and the user whereas range measurement errors are minimized by implementing efficient algorithms at the user end. Since, GDOP represents impact of satellite-receiver geometry on positional error, it became an essential parameter in determining the optimal satellite constellation [12]. It determines how good the constellation is for providing accurate position and time services to the user.

Position Dilution of Precision (PDOP) is a measure of the uncertainty in three-dimensional positions. It is the uncertainty in horizontal (latitude & longitude) and vertical (altitude) positions. Time Dilution of Precision (TDOP) is a measure of the uncertainty in the User clock. GDOP is the sum of the squares of PDOP and TDOP. GDOP Ratings are given in Table I [13].

TABLE I. DOP RATINGS

GDOP Value	Ratings
1	Ideal
2-4	Excellent
4-6	Good
6-8	Moderate
8-20	Fair
20-25	Poor

From the Table I, a navigation system with GDOP less than 4 can provide better position and time accuracy. The first step in calculating GDOP is computing coordinates of user receiver and satellite in Earth-Centered Earth-Fixed (ECEF) coordinates using the WGS-84 geodetic datum and then calculates unit vectors from user receiver to i^{th} satellite [14] using (2) below.

$$\left(\frac{x_i-x}{R_i}, \frac{y_i-y}{R_i}, \frac{z_i-z}{R_i}\right) \tag{2}$$

Where

$$R_i = \sqrt{(x_i-x)^2+(y_i-y)^2+(z_i-z)^2} \tag{3}$$

x, y, and z are ECEF coordinates of the user receiver,

x_i, y_i, and z_i are ECEF coordinates of an i^{th} satellite.

Formulate the matrix A with unit vectors from user to each satellite using (4) as follow.

$$A = \begin{pmatrix} \frac{x_1-x}{R_1} & \frac{y_1-y}{R_1} & \frac{z_1-z}{R_1} & -1 \\ \frac{x_2-x}{R_2} & \frac{y_2-y}{R_2} & \frac{z_2-z}{R_2} & -1 \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix} \tag{4}$$

If the elements in the fourth column are -1 then TDOP is appropriately calculated. Formulate the matrix Q using (5).

$$Q = (ATA)^{-1} \tag{5}$$

Q matrix acts as a covariance matrix and can be used to determine GDOP, PDOP, and TDOP as given by

$$Q = \begin{pmatrix} {\sigma_x}^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{xy} & {\sigma_y}^2 & \sigma_{yz} & \sigma_{yt} \\ \sigma_{xz} & \sigma_{yz} & {\sigma_z}^2 & \sigma_{zt} \\ \sigma_{xt} & \sigma_{yt} & \sigma_{zt} & \sigma_t \end{pmatrix} \tag{6}$$

$$TDOP = \sqrt{{\sigma_t}^2} \tag{7}$$

$$PDOP = \sqrt{{\sigma_x}^2 + {\sigma_y}^2 + {\sigma_z}^2} \tag{8}$$

$$GDOP = \sqrt{PDOP^2 + TDOP^2} \tag{9}$$

GDOP is the comprehensive uncertainty of position and time due to satellite geometry as shown in (9) and it is widely used as the performance metric of space segment design in a navigation system. When the value of GDOP is small, the uncertainty in the user position and time becomes small. The value of GDOP will vary for any location as the satellite position changes with respect to the ground location. So, mean of the GDOP over a day is considered as the fitness function in GA for finding the optimal satellite constellation.

D. Genetic Algorithm (GA)

Holland introduced a new optimization tool called Genetic Algorithm (GA). Its approach in finding optimal solution is different from conventional optimization methods like classical calculus-based and enumerative techniques. This iterative optimization tool uses "survival of the fittest" and "evolutionary" processes of the nature in finding the optimized solution for the given task [15]. In each iteration, GA finds the chromosomes (input parameters) that fits the objective and performs crossover of these fitting chromosomes which results in new generation chromosomes that are used for next iteration. So, after every iteration, more efficient chromosomes will evolve and these iterations continue till the optimized solution is found for the given task [16]. GA is used in finding optimal solutions in different applications due to its global optimization performance.

III. DESIGN ALGORITHM IMPLEMENTATION

The territory of the Republic of Indonesia country is spread across the Equator from 95^0 East to 145^0 East in longitude and from 6^0 North to 11^0 South latitude shown in Fig. 1.

Fig. 1. Indonesia geography

Three extreme locations are selected from this territory, and optimal constellation has to be found that gives minimum GDOP over these 3 selected locations.

1) Rondo Island: 6^0N 95^0E as northernmost point

2) Pamana Island: 11^0S 122^0E as southernmost point

3) Torai Estuary: 9^0S 141.5^0E as easternmost point

Requires visibility of at least 4 satellites to calculate the user's position. The optimum solution for regional navigation can't be Low Earth Orbit (LEO) or MEO satellites as more number of LEO or MEO satellites are required to cover a certain region. Therefore, GEO or GSO satellites are best for a regional navigation satellite system since they are visible continuously over a region. Generally, regional navigation satellite system consists of 6 or 7 GEO or GSO satellites to get a more accurate position [17]. With 6 satellites, least mean GDOP at the three selected locations was above 4, exceeding the GDOP limit for an accurate navigation system. So, the 6 satellite constellation is not preferred for the Indonesian Regional Navigation System. Therefore, 7 satellites have been chosen to be in the constellation and carried out the design implementation.

The satellite cutoff angle is the minimum acceptable angle of satellite and elevation below 15^0 is considered as low elevation for navigation satellites [18]. Angle 15^0 is the minimum visible angle to avoid tall building blockages and hill obstructions. With 15^0 cutoff angle, the GEO belt range is given below for the above selected 3 areas.

1) Rondo Island: 29^0E to 161^0E

2) Pamana Island: 56^0E to 188^0E

3) Torai Estuary: 75.5^0 E to 207.5^0 E

So the longitude of all satellites' ascending node has a lower bound of 75.5^0 E and upper bound of 161^0 E. Other Orbital parameters and their ranges are given in following Tabel II.

TABLE II. ORBITAL PARAMETERS AND ALLOWED VALUES

Orbital Parameter	Values	Status
Semi Major Axis	42,167 km	Fixed
Eccentricity	0	Fixed
Longitude of Ascending Node	75. 5^0E to 161^0E	Unknown
Inclination	0^0 - 90^0	Unknown
Argument of Perigee	0^0	Fixed
True Anomaly	0^0	Fixed

Satellite propagation is modeled by considering effects of inclination and other perturbing forces on satellite's position [19]. Over the three selected locations, GDOP is calculated iteratively with the range of different orbital parameters, and the constellation with the lowest mean GDOP is considered as an optimal solution.

IV. SIMULATION AND RESULTS

GA is a search-based optimization technique inspired by Charles Darwin's natural evolution theory. This algorithm reflects the process of natural selection where the fittest individuals are selected for reproduction to produce offspring of the next generation. In this research, GA is used with MATLAB software to find unknown orbital parameters for Navigation Constellation.

GA is used to determine the optimized constellation with 7 satellites that give the least mean GDOP at selected points by iterating over the range values of different orbital parameters. Fitness function is the mathematical representation of the problem. It is the figure of merit for which GA calculates the optimum solution.

In the simulation, mean GDOP at 3 selected locations is used as fitness function. The constraints for the GA are as follow:

1) All 7 satellites should be visible to the entire indonesia region throughout the day.

2) Elevation to all satellites > 15^0.

3) Range of Orbital parameters' values as mentioned in Table II.

The result show that the optimal constellation solution of 7 Satellites consists of 3 GEOs and 4 GSOs and is shown in Fig. 2.

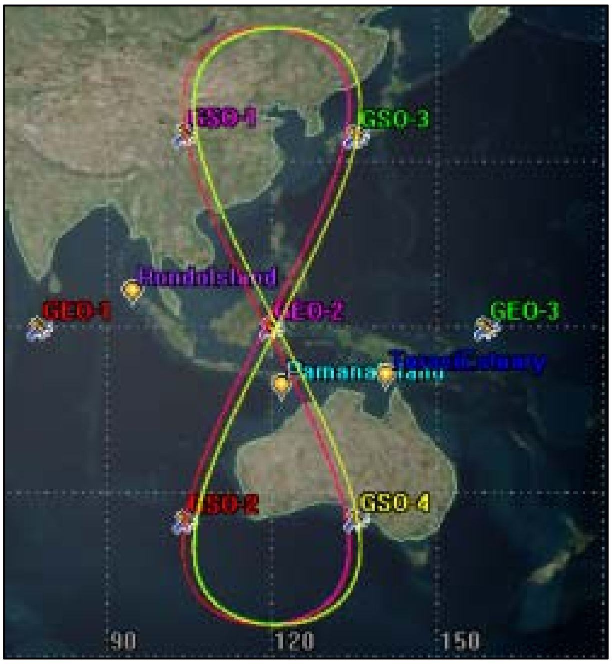

Fig. 2. The layout of the 7-satellite optimal constellation

The two unknown orbital parameters are calculated by GA for obtaining the optimized satellite constellation. Orbital parameters and Equatorial crossing time of GEO and GSO satellites that give the least mean GDOP at selected locations are given in Table III.

TABLE III. ORBITAL PARAMETERS OF GEO AND GSO SATELLITES

Satellite	Inclination	Long. Of Ascending Node	Equatorial Crossing Time
GEO-1	0^0	78^0 E	-
GEO-2	0^0	120^0 E	-
GEO-3	0^0	159^0 E	-
GSO-1	54^0	119^0 E	3 UT
GSO-2	-54^0	119^0 E	15 UT
GSO-3	54^0	121^0 E	9 UT
GSO-4	-54^0	121^0 E	21 UT

This optimal constellation is simulated in STK and verified the coverage and GDOP values at the three locations. Mean GDOP, mean PDOP, and mean TDOP values calculated from the optimal satellite constellation in Table IV.

TABLE IV. MEAN DOP AT THE SELECTED LOCATIONS

Location	Mean GDOP
Rondo Island	3.4535
Pamana Island	3.3740
Torai Estuary	3.4424

Fig. 3, Fig. 4 and Fig. 5 show the GDOP value graphs calculated at the three locations with the above optimized 7-satellite constellation over a day.

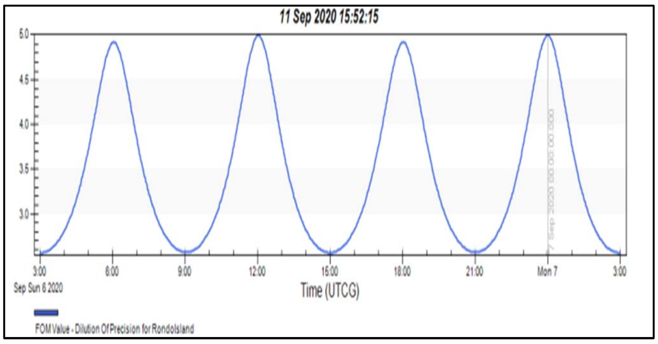

Fig. 3. GDOP at Rondo Island

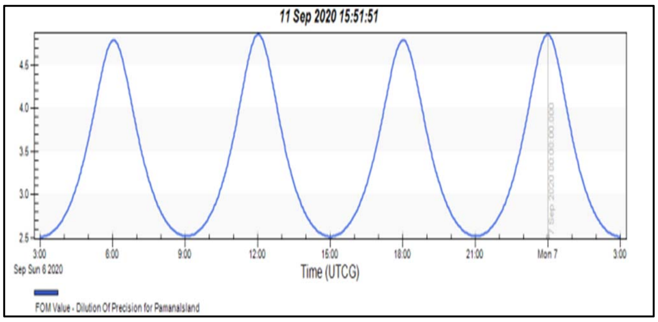

Fig. 4. GDOP at Pamana Island

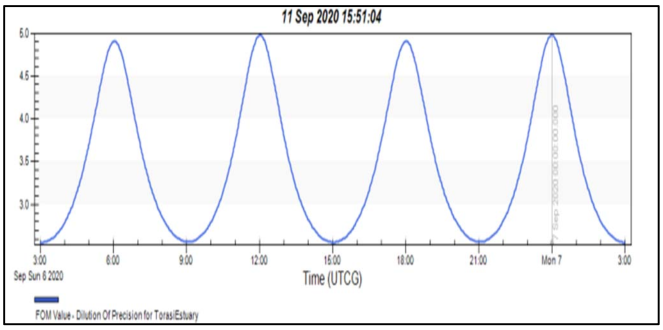

Fig. 5. GDOP at Torai Estuary

In the above Fig. 3, Fig. 4, and Fig. 5, the GDOP value varies from minimum of 2.5 to maximum value of 5 at all the three locations. At any particular time, GDOP is nearly same at all three locations. GDOP is least when all the satellites are widely separated, which occurs at 3 UT, 9 UT, 15 UT, and 21 UT and is maximum when all the satellites are close to each other, which occurs at 6 UT, 12 UT, 18 UT, and 00 UT.

V. CONCLUSION

This research aims to find the optimal satellite constellation for providing self-reliant positioning and timing services to the Indonesia country. In this paper, the design of an optimal navigational satellite constellation is presented and an optimal satellite constellation is found to serve Indonesia with satellites above 15^0 elevation and 7 visible satellites at all the time. This design is based on GA with the mean GDOP parameter as a fitness function. Results are simulated in STK to verify the optimized solution. The 4GSO and 3GEO is the optimal 7 satellites constellation that has the least mean GDOP of less than 4 over the Indonesia Region.

Future work of this research is to find an optimal network of Ground Stations to monitor navigation satellites and develop an efficient Position-computing receivers to make Indonesian Regional Navigation System fully operational. Further research on optimal satellite constellation design can be explored using different optimization techniques.

VI. ACKNOWLEDGMENT

The authors would like to thank Biak Satellite Control Center, Space and Atmospheric Observation, and Remote Sensing, Indonesian National Institute of Aeronautics and Space for providing software tools and supporting documents required for this research

REFERENCES

[1] C. Specht, A. Weintrit, and M. Specht, "*A History of MaritimeRadio-Navigation Positioning Systems Used in Poland,*" Journal of Navigation, Vol. 69(3), 2016.

[2] International Committee on Global Navigation Satellite Systems Provider's Forum, "Current and Planned Global and Regional Navigation Satellite Systems and Satellite-based Augmentations Systems," United Nation: New York, 2010.

[3] Indian Space Research Organization, "Indian Regional Navigation Satellite System Signal-in-Space ICD for Standard Positioning Service," Satellite Navigation Programme , 2017.

[4] QSZ System Service Inc., "Project Overview of the Quasi-Zenith Satellite System," PNT (Positioning Navigation and Timing) Advisory Board, Oct. 31, 2015.

[5] J.G. Walker, "Satellite constellations," Journal of the British Interplanetary Society, 37:559–572, December 1984

[6] A. H. Ballard, "Rosette constellations of earth satellites," Aerospace and Electronic Systems, IEEE Transactions on, AES-16(5):656–673, 1980.

[7] R. D. Luders, "Satellite networks for continuous zonal coverage," ARS Journal, 31(2):179–184, 1961.

[8] L. Rider. Analytic design of satellite constellations for zonal earth coverage using inclined circular orbits. Journal of the Astronautical Sciences, 34:31–64, Mar 1986.

[9] D. Mortari, M. P. Wilkins, and C. Bruccoleri, "The flower constellations," Journal of Astronautical Sciences, Vol. 52, No. 1, 2004, pp. 107–127.

[10] E. Frayssinhes, "Investigating new satellite constellation geometries with genetic algorithms," AIAA/AAS Astrodynamics Conference, pages 582–588, 1996.

[11] T. W. Beech, S. Cornara, M. B. Mora, and G. Dutruel-Lecohier, "A Study of three satellite constellation design algorithms," 14th International Symposium on Space Flight Dynamics, Foz do Ignaqu, February 1999.

[12] I. Sharp, “GDOP Analysis for Positioning System Design”, IEEE Transactions on Vehicular Technology, 2009.

[13] R .B. Langley, “Dilution of Precision,” GPS World, May 1999.

[14] F. Keyvani, and S. Torabi, “Design and Simulation of Regional Navigation Constellation with Optimized Mean DOP based on Hybrid GEO and IGSO Satellites,” International Journal of Aviation, Aeronautics, and Aerospace, 2019.

[15] A. Ghasempour and M. B. Menhaj, “A new genetic based algorithm for channel assignment problem,” in Computational Intelligence, Theory and Applications, Ed. B. Reusch, Berlin: Springer, 2006, pp. 85-92.

[16] A. Ghasempour, “Using a Genetic-Based Algorithm to solve the Scheduling Optimization Problem for Long-Range Molecular Communications in Nanonetworks,” IEEE Int. Symp. On Pers., Indoor and Mobile Radio Commun., Hong Kong, 2015, pp. 1825-9.

[17] H. Renault, “Mission Design & Implementation of Satellite Constellations,” Constellation studies for future navigation system, Dordrecht, Netherlands: Springer, 1998, pp.163-168.

[18] M. Yue, and S. Fu-Ping, “Global Navigaton satellite constellation design using Walker constellation,” Journal of Zhengzhou Institute of Surveying and Mapping, 2006.

[19] M. Richharia, “Satellite Communication Systems: Design Principles”, McGraw-Hill Professional; 2nd Edition, 1999, pp. 429-484.