Utilization of genetic algorithms in orbit optimization for maximum time over target: past and present research

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1. Background

1.1 Past scientific knowledge and utility of research

In the field of spaceflight, the degree of success often depends on the extent to which one can optimize the mission parameters. Modern computation has allowed better and better optimization techniques to be used, particularly in the case of the spacecraft trajectory. There are some famous examples of trajectory optimization being used to bolster mission success. The *Voyager* spacecraft famously used multiple gravity assists to reach as many as four separate planets. ("Basics of Space Flight," n.d.) This was an incredible example of the optimization of orbits for minimum fuel expenditure. However, orbits can be optimized for more than just minimum fuel expenditure. Satellites that perform tasks such as communications or remote sensing may only be useful when they have a ground target within their field-of-view. This presents a dilemma: satellites are only over ground targets for a small percentage of their time in orbit. This is the nature of orbits. Spacecraft moving so fast can only hold a ground target in their field-of-view for so long. Classical solutions to this problem have been prevalent. Geostationary orbits are useful in this regard, as a satellite in one of these orbits can hold a ground target in view for as long as it can stay in that orbit. However, these orbits also present some disadvantages. They can only view a certain section of the Earth during their lifetime, so multiple satellites are needed for complete coverage of the Earth's surface. They also have the disadvantage of being a long distance from the surface of the Earth, which means that sensors onboard are less accurate and communications are worse, both because of the decreased signal strength and the light speed delay. This solution works fine for weather satellites or large-scale communications satellites. NOAA uses these orbits for their weather satellites, the

Geostationary Operational Environmental Satellites, as they don't need high resolution sensing data or high-speed communications. ("NOAA GOES Geostationary Satellite Server," 2015)

There are other solutions to this problem besides geostationary orbits. Large amounts of satellites in low-orbits can form constellations that simultaneously cover much of the Earth's surface while also providing high-speed communications. Iridium famously uses a 66-satellite constellation orbiting at under 500 miles to offer its satellite phone service. ("Iridium Global Network," n.d.) This method allows for faster communication, but is expensive, as far more satellites must be launched, although this is partly offset by the fact that they can be launched into lower orbits on smaller rockets.

The middle-ground between high altitude orbits with few satellites (geostationary orbits) and low altitude orbits with many satellites is the utilization of medium altitude orbits with medium numbers of satellites. Currently, medium Earth orbit (MEO) is used by constellations of GPS and communications satellites. The United State's GPS network utilizes 24 satellites at an altitude of 12,550 miles.

("GPS Space Segment," n.d.) Note that the methods used in these types of orbits are very similar to the methods used in low-altitude constellations, with the sole difference being that the higher altitude means a larger field-of-view and thus fewer satellites. This compromise is useful for situations where high-speed communication is not incredibly important, but lower altitudes are still necessary for a variety of reasons, notably a need for higher sensor resolution or a need for higher communication speed/bandwidth.

Some systems of satellites need to cover only certain ground targets at relatively low-medium altitudes (due to a need for better communication or better sensor resolution), but don't have the resources necessary to support a large constellation. In these cases, lower numbers of satellites can be used at low-medium altitudes. In this case, the system would not provide constant coverage to all ground targets. The exact amount of time the ground targets spend in the field-of-view of the system depends on the orbits of the individual satellites in the system. Therefore, certain sets of orbits would provide better coverage than others, and a certain set of orbits for given ground targets and number of satellites could be considered

the best if it provided the most amount of time with the target in its field-of-view at the lowest altitude. Finding this optimum set of orbits could mean more efficient use of ground or space resources.

1.2 Present research

The optimization of orbits has been highly studied recently, although never as proposed here. In general, evolutionary algorithms have been an interesting way to study such optimization problems. A study on interplanetary trajectory design recently used evolutionary algorithms to reduce time and fuel expenditure. (Izzo, Sprague, & Tailor, 2018) One study that worked in this area was a look at optimizing the orbit for a single satellite in a way that minimized the time necessary to visit all of a set of ground targets. (Abdelkhalik & Gad, 2010) This research was able to develop a method for optimizing this orbit for minimum time necessary to visit all ground targets. They used genetic algorithms, a subset of evolutionary algorithms, to optimize the defining parameters of the orbit against the parameter optimized, which in this case was the time required to fly over all ground targets. However, this study was limited in the fact that it only dealt with a single satellite, did not examine factors such as

communications strength that would affect the altitude of the orbit, and didn't optimize for variables such as maximum time over the ground target.

Some similar research took place more recently. Savitri, Kim, Jo, and Bang researched optimizing the coverage of a specific area on Earth, specifically Korea, using a low-altitude constellation with genetic algorithms. Their research was limited by the fact that they used a large-scale constellation and a small, single target area. (2017) Other research also looked at optimizing constellations, such as the work of Paeck, Kim, and Weck, who investigated the optimization of a reconfigurable satellite network which tries to cover the surface of Earth evenly under normal conditions and then modify the orbits of the individual satellites to cover a single target area. Their research used genetic algorithms to improve satellite coverage, and thus occurred generally within the field of this research, but it is really outside of the scope of this research.

One of the best pieces of published research that relates to this subject comes from the master's thesis of Pegher and Parish. This thesis investigated the method of genetic algorithms for optimization

against other, more traditional techniques that created "Walker constellations," with percent coverage and revisit time being the primary variables optimized. The paper compared these techniques for constellations of 9-24 satellites. They found that the genetic algorithm outperformed the traditional method in every case except the 24-satellite constellation, with the genetic algorithm performing better and better in comparison as the number of satellites decreased. (2004) This means that in the case of this research, where the number of satellites is relatively low, genetic algorithms would be a useful technique for optimization.

2. Discussion of Proposed Research

This research, as proposed, chooses to investigate the utilization of genetic algorithms to optimize orbits of satellite networks for the maximum time over target where the number of satellites is relatively low. Genetic algorithms have been shown to be much better than other orbit design techniques in the case of satellites networks with a low number of satellites. (Pegher & Parish, 2004)

The research that has happened so far is different from that of the research proposed here. Most research has looked at large constellations of satellites, while the remaining research has looked at the case of single satellites. This leaves a gap in research with networks of about 2-8 satellites, which is the area where this research will take place. Most research has also looked at minimum revisit time or percent coverage, with none looking at maximum time with specific targets in the field of view of the satellite network.

This research may seem like an extremely specific niche, but there are real world examples where finding these optimum orbits would greatly help. The Mars Science Laboratory (MSL, better known as the Curiosity rover) could benefit from the solution to this optimization problem. The rover carries antennae that allow it to communicate with Earth directly at a rate of about 500 bits per second. However, by relaying data through one of the satellites orbiting Mars, it can transfer up to 2 million bits per second. Unfortunately, these relay spacecraft are only overhead for about 8 minutes out of every day. This limits the amount of data that the rover can send back to Earth each day. ("Data Rates/Returns," n.d.) Optimizing the orbits of the two spacecraft acting as relay satellites could potentially significantly increase the amount of scientific data

yielded from the rover, which would be useful.

Overall, it can be seen that this research is 1) unique and different from previous research, 2) important for study, and 3) doable, as evidenced by similar studies having taken place.

References

Abdelkhalik, O., & Ahmed, G. (2010). Optimization of space orbits design for Earth orbiting missions. *Acta Astronautica, 68*(7-8), 1307-1317. https://doi.org/10.1016/j.actaastro.2010.09.029

Basics of Space Flight. (n.d.). Retrieved May 12, 2019, from https://solarsystem.nasa.gov/basics/primer/

Data Rates/Returns. (n.d.). Retrieved May 12, 2019, from https://mars.nasa.gov/msl/mission/communicationwithearth/data/

GPS Space Segment. (n.d.). Retrieved May 12, 2019, from https://www.gps.gov/systems/gps/space/

Iridium Global Network. (n.d.). Retrieved May 12, 2019, from https://www.iridium.com/network/globalnetwork/

Izzo, D., Sprague, C. I., & Tailor, D. V. (2018). Machine Learning and Evolutionary Techniques in Interplanetary Trajectory Design. *(Almost) Impossible Integrals, Sums, and Series Problem Books in Mathematics,* 191-210. https://doi.org/10.1007/978-3-030-10501-3_8

NOAA GOES Geostationary Satellite Server. (2015, July 07). Retrieved from https://www.goes.noaa.gov/

Paek, S., Kim, S., & Weck, O. (2019). Optimization of Reconfigurable Satellite Constellations Using Simulated Annealing and Genetic Algorithm. *Sensors, 19*(765), 1-29. https://doi.org/10.3390s19040765

Pegher, D., & Parish, J. (2004). *Optimizing Coverage and Revisit Time in Sparse Military Satellite Constellations: A Comparison of Traditional Approaches and Genetic Algorithms*. Monterey, CA: Naval postgraduate school

Savitri, T., Kim, Y., Jo, S., & Bang, H. (2017). Satellite Constellation Orbit Design Optimization with Combined Genetic Algorithm and Semianalytical Approach. *International Journal of Aerospace Engineering, 2017*, 1-17 https://doi.org/10.1155/2017/1235692