Orbit Design and Optimization Based on Global Telecommunication Performance Metrics

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Abstract—The orbit selection of telecommunications orbiters is one of the critical design processes and should be guided by global telecom performance metrics and mission-specific constraints. In order to aid the orbit selection, we have coupled the Telecom Orbit Analysis and Simulation Tool (TOAST) with genetic optimization algorithms. As a demonstration, we have applied the developed tool to select an optimal orbit for general Mars telecommunications orbiters with the constraint of being a frozen orbit. While a typical optimization goal is to minimize tele-communications down time, several relevant performance metrics are examined: 1) area-weighted average gap time, 2) global maximum of local maximum gap time, 3) global maximum of local minimum gap time. Optimal solutions are found with each of the metrics. Common and different features among the optimal solutions as well as the advantage and disadvantage of each metric are presented. The optimal solutions are compared with several candidate orbits that were considered during the development of Mars Telecommunications Orbiter.

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1. INTRODUCTION

Observational orbiters such as Mars Global Surveyor, Mars Odyssey, and Mars Express not only have advanced human understanding of Mars through detailed observations but also have served as a communications replay station for other missions [1]. For such a multifunctional orbiter, telecommunication performance is one of the metrics to consider in the process of orbit selection. In order to aid the orbit selection process, we have coupled the Telecom Orbit Analysis and Simulation Tool (TOAST) with genetic optimization algorithms.

In a previous study, Lee *et al* showed that TOAST provide global telecom performance metrics of an orbiter with a variety of central planetary bodies and a range of orbiter design parameters such as orbit elements, transmitter power, antenna gain, and frequency band [2]. In the current study, genetic optimization algorithms are coupled to TOAST in order to efficiently explore the design space and to solve the optimization problems.

2. TELECOM METRICS AND CONSTRAINTS

For the orbit selection problem based on telecommunication performance, typical optimization goals are 1) to maximize data volume and 2) to minimize down time. Within one of the two goals, several relevant performance metrics can be constructed. For the goal of maximizing data volume, possible metrics are 1) maximum instantaneous data rates, 2) average data volumes over all communications opportunities. In the spirit of minimizing down time, reasonable metrics are 1) global maximum of local maximum gap time, 2) global maximum of local minimum gap time, 3) area-weighted gap time. It is not obvious whether each performance metric yields a common optimal orbit or a different one. Some of the metrics may compete in a way that improving one metric is accompanied by degrading other metrics.

In addition to the telecom metrics, the orbit selection problem involves constraints such as being a sun-synchronous, ground-track repeating, and frozen orbit. Each constraint results in the reduction of the feasible orbit design space. The sun-synchronous constraint means that the change rate of the ascending node should be equal to the orbital rate of the planet around the Sun. This requirement yields an equality condition given by a function of eccentricity and inclination. The ground-track repeating constraint requires the orbiter's orbit period to be commensurable to the planet's inertial rotation period, when a simple point-mass gravity model is used. The frozen-orbit constraint restricts the inclination angle to be either 63.4 or 116.6 degrees if an orbit is elliptical. When perturbation forces such as third-body gravitational forces, planet oblateness effect, or atmospheric drag are included, the constraint becomes more complicated and may require occasional propulsive maneuvers to adjust the orbit. Meeting all the constraints may be impossible in some cases (i.e. over-conditioned problem) or may result in degrading performance metrics. Therefore, one should consider the cost of adding new constraints to the performance metrics.

3. WHY GENETIC OPTIMIZATION ALGORITHMS

Genetic optimization algorithms are chosen for this optimization due to its simplicity and flexibility over

traditional mathematical programming techniques such as gradient-descent methods, conjugate direction methods, and nonlinear programming. The genetic algorithm is inspired by natural selection and the sexual reproduction process of living organisms. The algorithm implements abstracted biological processes including mutation (random variation), recombination (mixing partial solutions) to explore a design space and is shown to be efficient in finding a global optimal solution in a high-dimensional, multi-modal, rugged, constrained search space.

The reason why the genetic algorithm is more suitable for the orbit selection problem than traditional methods is three-fold. First, the objective function (fitness landscape) given by telecom metrics is often rugged, where gradient-based methods are inoperable. An abrupt change of the gradient misguides the search direction in the traditional gradient-based algorithms. The genetic algorithm does not depend on the gradient and is hence more robust in the rugged search space.

Second, the variables to optimize in the orbit selection problem can be a collection of various types such as integer values, real values, and options rather than one type of variables. A traditional method is typically designed to handle one type of variables. For example, the integer programming is for integer variables while the nonlinear programming is for real variables. The genetic algorithm is flexible to handle various types directly or indirectly by encoding them to binary genes.

Third, the objective function in the orbit selection process is complicated and typically ill-defined. The objective function can be a combination of various telecom metrics with different constraints associated to each metric. The overall optimization goal can involve multiple completing objectives rather than one single one. The optimization priority order of the multiple objectives is often unknown until later mission design phases. When the objective function is ill-defined, the traditional method is either inoperable or yields a solution that becomes meaningless when the objective function is redefined. The genetic algorithm is vulnerable to ill-defined objective functions. It has a mechanism to take into account the error and noise in the objective function and to generate k-best solutions rather than a single point solution if needed. Furthermore, the genetic algorithm can optimize multiple objectives simultaneously without introducing an arbitrary priority order or weighting factors.

4. OPTIMAL ORBIT SELECTION

As an initial study, we have applied the developed tool to select an optimal orbit for general Mars telecommunications orbiters with the constraint of being a frozen orbit. A list of variables in this optimization includes semimajor axis, eccentricity, inclination, and argument of perigee. Since only one orbiter is considered, the time of perigee and the argument of the ascending node are irrelevant variables for the single orbiter's telecommunications performance. Due to the frozen-orbit constraint, the inclination angles for elliptical orbits (non-zero eccentricity) are restricted to two values (63.4 and 116.6 degrees). Note that any inclination angle is allowed for a circular orbit. Three metrics relevant to the down-time measurement are considered in this orbit selection: 1) area-weighted gap time (Area-Average), 2) global maximum of local maximum gap time (Max-Max), 3) global maximum of local minimum gap time (Max-Min).

For the genetic algorithm, the following parameters are used. The population size is 100, the crossover probability is 0.8, the mutation probability per gene/variable is 1/4, the elitist fraction in the population is 0.2 (meaning that the best 20% solutions are passed to the next generation/iteration without mutation and crossover), and the maximum number of generations is 40. The variables are encoded into real genes except for the inclination angle. In order to take into account the frozen-orbit constraint, the inclination angle is treated as an option. If the orbit is circular, the angle can vary between 0 and 180. Otherwise, the angle is chosen between two values (63.4 and 116.6 degrees). The bound of the semimajor axis is between 4000 and 10000 km. The upper bound of the eccentricity is given by the condition that the orbit's periapsis is larger than 3500 km, which gives about 100 km altitude margin to the Mars radius (3396 km).

When the orbit period is incommensurable to the planet's internal rotation period, a ground-track repeating time is very long or even infinite. Therefore, a simulation time should be long enough for the telecommunication performance metrics to converge. We check the metric convergence with respect to the simulation time. Figure 1 shows the convergence of the metrics for various semimajor axes. Except for the semimajor axis of 4000 km, the Area-Average gap converges gradually, the Max-Max gap converges quickly after a few Sols, and the Max-Min gap jumps abruptly once and converges thereafter. The orbit with the semimajor axis of 4000 km has a ground area that is consistently missed which leads to the increase of the down time as the simulation time increases. Overall, the simulation time of 15 Martian Sols is long enough to obtain an approximate gap time if the gap time converges. If the gap time increases linearly with the simulation time, it indicates that the orbit has a ground area that is consistently missed. Since their gap time either diverges or converges to a much larger gap time than other converged solutions, the simulation time of 15 Martian Sols is still reasonable to approximately estimate the gap times.

The three performance metrics are based on the global map of the telecommunication gap times and thus depends on the resolution for the global maps of the planet's surface. The convergence of the gap times with respect to the resolution of the global map is monitored. As the granularity of the longitude and latitude of the global map improves from 30 degrees to 1 degree, the gap times converges. We choose 5 degrees as the resolution of the global map for the optimization process, as it properly represents the telecommunication metrics.

The optimal orbit solutions found by the genetic algorithm within TOAST tool are listed in Table 1. A different performance metric leads to a different solution. Common features among the three optimal solutions are that they are all circular orbits and highly inclined. The performance of the optimal solutions is compared with that of four candidate orbits of Mars Telecommunications Orbiter (MTO) [3]. The found optimal solutions are better than the candidate solutions in terms of the three metrics considered.

The MTO candidate solutions have been identified by considering several aspects that are not included in our optimization process. For example, all of the MTO candidate solutions are sun-synchronous to save spacecraft power and simplify spacecraft thermal control. Three of the candidate solutions (MACCI4N, CCS4N, ESS4N) daily repeat ground track to have their contacts with every point on the surface at the same local time each Sol. Finally, all the MTO candidate solutions have high altitudes to obtain long pass durations and large footprints. In our optimization process, we did not impose the constraints for sun-synchronous, ground-track repeating, or a high altitude.

With the optimal solutions, their global maps of the telecommunication gaps are plotted in Figure 3. Although the daily ground-track repeating constraint is not imposed, two of the optimal solutions (Area-Average and Max-Min) show the daily ground-track repeating feature. The orbit period is close to one fifth of a Martian Sol. The global maps were obtained with the simulation time of 15 Sols, and it shows that the local gap time is repeating during the 15 Sols. The Max-Max solution is a polar orbit and thus the gap time is uniform across the longitude axis.

We further investigate why all the optimal solutions found are circular and highly inclined and to what extent the optimal solutions are better than other solutions. The dependence of the metric value on orbit variables is explored. A parametric study is set up by incrementally changing the semimajor axis and inclination angles while the eccentricity is set to zero for a circular orbit. Another parametric study is set up by gradually changing the semimajor axis and eccentricity while choosing the inclination angle between 63.4 and 116.6 for an elliptical orbit. Note that a circular orbit does not have a restriction in choosing the inclination angle while an elliptical orbit does due to the frozen orbit requirement.

4. CONCLUSIONS

We have developed a method to select an optimal orbit solution for orbiters based on the telecommunications performance metrics. The method uses the TOAST tool to estimate the performance metrics and uses a genetic algorithm to optimize the metrics. The developed method is applied to an orbit selection for general Mars telecommunication orbiters with the frozen orbit constraint in order to reduce a station-keeping cost. The optimization goal is to reduce the telecommunication down time, and three relevant performance metrics are constructed: 1) area-weighted average down time, 2) global maximum of local maximum gap time, 3) global maximum of local minimum gap time. In order to ensure the reliable measurement of the performance metric, the convergence of the metric value is monitored with respect to the resolution of the planet surface and the simulation time. With the proper resolution and simulation time, an optimal solution for each metric is found. The common features among the optimal solutions are that they are all circular and highly inclined. The reason why circular orbits are optimal is that a circular orbit does not have a restriction in choosing the inclination angle while an elliptical orbit does due to the frozen orbit requirement. The found solutions are compared with several candidate orbits for Mars Telecommunication Orbiters (MTO). The MTO candidates are identified after considering different metrics/criteria and constraints. As a result, the MTO solutions are different from our solutions. This reveals complexity and trade-off in the orbit selection process as there are many relevant metrics and constraints to consider and there are no direct way to compare and prioritize the multiple metrics and constraints. Future work includes the assessment of a trade-off between different metrics and constraint/requirements.

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BIOGRAPHY

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