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14. ABSTRACT
Satellite constellations around Earth can be used for observing and/or communicating with targets on the surface. This research mainly addressed maneuvering existing satellite constellations in order to improve coverage of multiple targets over a timespan of 30 to 120 days. However, designing new satellite constellations can also be addressed by using a portion of this research regarding coverage estimation. This research identified a direct relationship between a satellite's orbital geometry and the coverage provided by that satellite. This is accomplished by (1) identifying the view of the satellite orbit from an inertial sphere centered on the Earth, and (2) utilizing information from all the orbital views across the target's inertial latitude on order to arrive at lower and upper bounds on coverage. Altering a satellite orbit also alters the coverage that it provides. Gauss' variational equations were used to find maneuvering strategies that effect maximal changes in orbital geometry. These distinct maneuvering strategies were then complied into a list that will be used in the subsequent optimization.

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IMPROVING THE COVERAGE OF EARTH TARGETS BY MANEUVERING SATELLITE CONSTELLATIONS

BY

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AUGUST 23, 2007

Abstract

Satellite constellations around Earth can be used for observing and/or communicating with targets on the surface. This research mainly addressed maneuvering existing satellite constellations in order to improve coverage of multiple targets over a timespan of 30 to 120 days. However, designing new satellite constellations can also be addressed by using a portion of this research regarding coverage estimation.

This research identified a direct relationship between a satellite's orbital geometry and the coverage provided by that satellite. This is accomplished by (1) identifying the view of the satellite orbit from an inertial sphere centered on the Earth, and (2) utilizing information from all the orbital views across the target's inertial latitude in order to arrive at lower and upper bounds on coverage.

Altering a satellite orbit also alters the coverage that it provides. Gauss' variational equations were used to find maneuvering strategies that effect maximal changes in orbital geometry. These distinct maneuvering strategies were then compiled into a list that will be used in the subsequent optimization.

Executive Summary

This research was performed by Michel Santos and Benjamin Shapiro. During this research effort, Michel Santos completed his dissertation which is available at http://michel.filabs.com/Dissertation.pdf.

Comprehensive Technical Summary

This research has focused on reconfiguring existing satellite constellations in order to improve coverage of multiple targets on the surface of the Earth. The research effort investigated how the focus of this work differs from other work on satellite constellations. The constellation reconfiguration problem was then described as a multiobjective optimization problem.

Table 1: Qualitative description of the coverage optimization problem

Optimize	· Coverage of Target 1 · Coverage of Target 2 ⋮ · Coverage of Target n
By varying	· Time-varying thrust-vector for Satellite 1 · Time-varying thrust-vector for Satellite 2 ⋮ · Time-varying thrust-vector for Satellite m
Subject to	· Timespan of interest · Initial conditions of Targets and Earth · Targets and Earth equations-of-motion · Initial conditions of satellite · Satellite equations-of-motion · Line-of-sight constraints · Limits on satellite propulsion · Finite thrust limits · Finite propellant

The research effort then identified models used to describe the physical elements essential to calculating coverage. This included the model for the satellite motion, description of the Earth's surface, planetary rotation, line-of-sight between a target and a satellite, visibility schedules, and figures-of-merit.

The research effort identified the relationship between orbital geometry and the coverage that a satellite provides. This was done by inspecting the line-of-sight cones emanating from locations on Earth-centered virtual spheres and identifying what portions of a satellite orbit were visible. These orbital views were then displayed as color-coded visibility maps on a virtual inertial sphere. The rotation of the Earth through/underneath these visibility maps illustrated patterns of coverage provided by a satellite over the course of a sidereal day. Finally, estimates of coverage provided by a single satellite were shown to be obtainable by aggregating this geometrical information from across a target's inertial latitude.

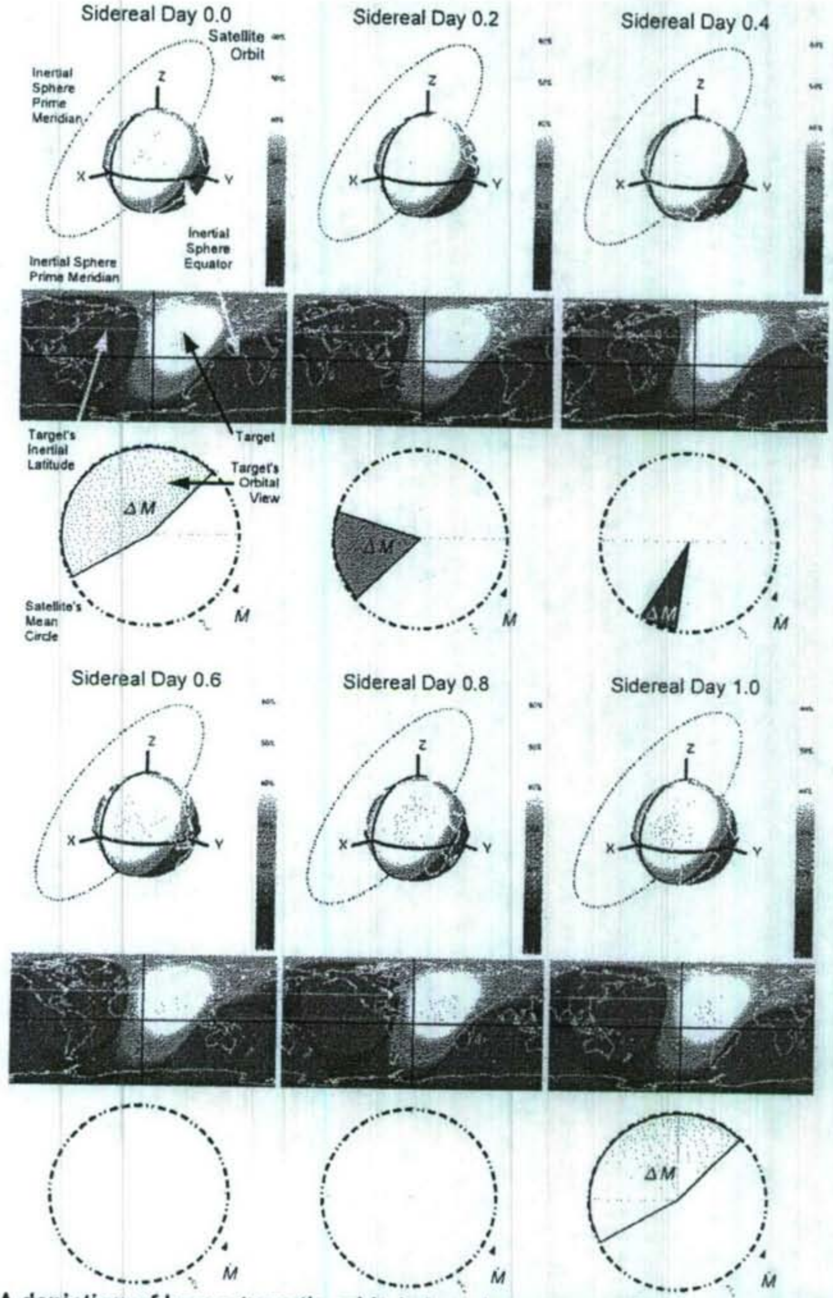

Figure 1: A depiction of how a target's orbital view changes over the course of a sidereal day. By definition, the Earth completes one revolution relative to an Earth-centered inertial-frame during a sidereal day. A target on the Earth's surface will rotate with it. A target's view of a satellite orbit will change during the sidereal day. At some points in time (i.e. inertial longitude) the satellite's orbit will be visible to one degree or another (e.g. Sidereal Day 0.0, 0.2, 0.4, and 1.0). At other points in time, the satellite's orbit will not be visible (e.g. Sidereal Day 0.6 and 0.8).

Gauss' variational equations were then used to arrive at a set of maneuvering strategies that effect maximal changes to different properties of a satellite orbit's geometry. This was done by maximizing the rate-of-change of the various orbital properties as a function of radial, a_R, tangential, a_θ, and cross-track, a_{CT}, thrusting employed by the satellite. The general approach for optimizing these rates-of-change are as follows:

1. Formulate the rate-of-change equation as a function of the satellite's control inputs (a_R, a_θ, and a_{CT}) and the true anomaly, ν, which is the independent variable.
2. Take the derivative with respect to the control input.
3. By the necessary condition for optimality, set the derivative equal to zero, and solve for an expression of the control input as a function of the independent variable, ν.
4. Plug the control back into the rate-of-change equation.
5. Confirm that the solution found is a maximal solution.

The original optimization problem was then rephrased as a new multiobjective optimization problem to take advantage of the conclusions from the coverage estimation. In it, discrete maneuvering strategies and continuous propellant allotments for each satellite became the parameters to be varied within the optimization problem.

Table 2: Qualitative description of the rephrased coverage optimization problem

Optimize	• Coverage of Target 1 • Coverage of Target 2 ⋮ • Coverage of Target n • Total propellant allocated for maneuvering

By varying	• Satellite 1
	  • Discrete maneuvering strategy
	  • Disambiguation angle for the discrete maneuvering strategy
	  • Propellant allocated for maneuver
	• Satellite 2
	  • Discrete maneuvering strategy
	  • Disambiguation angle for the discrete maneuvering strategy
	  • Propellant allocated for maneuver
	⋮
	• Satellite m
	  • Discrete maneuvering strategy
	  • Disambiguation angle for the discrete maneuvering strategy
	  • Propellant allocated for maneuver

Subject to (implicit by formulation)	• Timespan of interest
	• Initial conditions of Targets and Earth
	• Targets and Earth equations-of-motion
	• Initial conditions of satellite
	• Satellite equations-of-motion
	• Line-of-sight constraints
	• Limits on satellite propulsion
	  • Finite thrust limits
	  • Finite propellant

Despite the rephrasing, the optimization problem still bears certain difficulties:

(a) The optimization parameters are discrete and continuous

For each satellite, there is one discrete variable and two continuous variables.

(b) Nonlinear objectives

The objective functions, being coverage metrics, tend to be discontinuous with respect to changes in the orbit due to coverage windows popping in and out of the visibility schedule.

(c) Multiple objectives

The optimization problem seeks to improve coverage of multiple targets. However, depending on the targets and the satellite constellation, improving the coverage over one target may actually worsen the coverage over another. Therefore, there will not likely be a single solution that optimizes all of the objectives.

To address these difficulties, a novel multiobjective evolutionary algorithm was used to address this problem by adopting features from other similar algorithms.

Finally, a set of examples were investigated to demonstrate the utility of satellite reconfiguration on improving coverage over multiple targets on the surface of the Earth. The examples were optimized using the described evolutionary algorithm, and several nondominated surfaces were obtained. These nondominated surfaces showed how coverage over all targets were improved with orbital maneuvering.