Application of Scheduling Theory to Spacecraft Constellations

by

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We the undersigned committee hereby recommend that the attached document be accepted as fulfilling in part the requirements for the degree of Master of Science in Computer Science.

"Application of Scheduling Theory to Spacecraft Constellations" a thesis by Christopher John Graham

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Abstract

Title: Application of Scheduling Theory to Spacecraft Constellations
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In this thesis we advance the state-of the practice in the Space Mission Operations domain by leveraging single spacecraft technologies along with classical scheduling frameworks and notation to create a scheduler for a constellation of spacecraft. We define a scheduling product that is focused on the problem of scheduling networked groups of spacecraft, called constellations. Within this thesis we show that the constellation schedule problem is a very complex problem, and the application of heuristics is one approach that allow us to schedule successfully. Our first objective, comprising chapters 1, 2, and 3, is to describe the spacecraft constellation domain and the objectives of the thesis. This background provides a foundation for understanding the constellation scheduling problem domain. Our second objective, comprising chapters 4, 5 and 6, is to provide a representation and description of the components of a constellation system, and a formal definition of the constellation schedule problem via existing formal scheduling frameworks and notation. Our third objective, comprising chapter 7, is to use these frameworks to allow us to deduce the complexity of the problem. Our fourth objective, comprising chapter 8, is to present techniques that allow us to leverage single spacecraft scheduling techniques to construct a constellation scheduler. Our final objective, comprising chapter 9, is to propose a scheduler architecture that satisfies a typical constellation scheduling problem.

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Acknowledgement

"Imagination is more important than knowledge. Knowledge is limited; imagination encircles the world."

Albert Einstein [1]

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Dedication

"…it was Your light that raised me."

Dante Alighieri, Paradiso, Canto I, 73-75 [2]

for Sandra, my mother, and my father

1 Introduction

Historically, space missions have been based upon technologies that utilize single spacecraft to achieve a single overall scientific mission. In the past, owners and operators of these spacecraft have been mostly government agencies. The new paradigm is commercial. The objective is to make money. Communication companies drive this commercial mission. To achieve their mission objectives, these companies are shifting away from using single spacecraft to utilizing groups of spacecraft.

1.1 Evolving Space Operation Trends

Communication companies are now offering subscriber services, supporting instantaneous contact between globally distributed points. It is now possible to contact any person, located anywhere on earth, at anytime of day. The spectrum of services available currently include digital television, digital radio, paging, mobile phone, and computer networking, to name just a few. What make all these services possible, are advanced networks of orbiting spacecraft. These networks are comprised of spacecraft primarily in four types of orbits: Low Earth Orbit[1] (LEO), Medium Earth Orbit[2]

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[1] Low earth orbit (LEO) spacecraft typically orbit the earth at a distance of between 500 to 1000 miles above the earth. The transmission delay of a communication signal between a LEO spacecraft and the earth is only.05 seconds. [3]

[2] Medium earth orbit (MEO) spacecraft typically orbit the earth at a distance of approximately 8000 miles. The transmission delay of a communication signal between a MEO spacecraft and the earth is less than.1 seconds. [3]

(MEO), Geosynchronous Orbit[3] (GEO), and Geostationary Orbit[4] (GSO). Which particular orbit a spacecraft follows depends largely on the mission objective. Roaming subscriber services such as telephones typically use LEO and MEO satellites. Fixed services such as television broadcasts and weather sensing typically use satellites in GEO and GSO orbits. Missions that provide both roaming and fixed services typically use a combination of LEO, MEO, GEO, or GSO spacecraft.

Since the commercial endeavors have been so successful, network based mission objectives soon will not just be limited to commercial satellite services. Government agencies are now looking to leverage the evolving technologies to provide services of their own. On the horizon, future NASA missions will consist of constellations in support of scientific objectives. One such example is the Constellation-X Observatory [4] that will be comprised of a network of space based telescopes used to perform advanced x-ray observing. We also see an evolving trend in the development of NASA spacecraft that contain different payloads and different mission objectives, but share a common set of ground support services in an effort to bring down the cost of operations. NASA envisions a fleet of spacecraft that share common terrestrial based facilities, but perform widely varying mission objectives ranging from earth sensing to planetary exploration to deep space exploration. The

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[3] Geosynchronous (GEO) spacecraft typically orbit the earth at a distance of approximately 22,300 miles. The have a orbital period of 24 hours. The transmission delay of a communication signal between a GEO spacecraft and the earth is approximately.25 seconds [3]

[4] Geostationary (GSO) spacecraft are in a GEO orbit and are always located above the same spot above the equator (at zero inclination). A spacecraft that is in a GSO orbit is often said to be in a Clarke orbit, in honor of Arthur C. Clarke. Clarke first suggested in 1945 that satellites in geosynchronous orbits could be used for communications purposes. [3]

NASA Earth Observing System (EOS) is an effort underway to evolve spacecraft that fly with shared resources on the ground. The spacecraft of the EOS project will be small spacecraft that contain one or two instruments. This is a departure from previous missions that were based upon medium and large spacecraft that contained many experiments. NASA is gearing up to run spacecraft that are smaller, cheaper and faster, and using the shared resources in a spacecraft network is one way they will achieve their goal.

In both the commercial and governmental domains, support for constellation of spacecraft will require a new set of tools and technologies to schedule[5], command, control, and operate spacecraft, as well as to distribute and process the plethora of data these networks will provide. This thesis will focus on a segment of this problem, the scheduling of spacecraft networks.

1.2 Migration From Single Spacecraft to Spacecraft Constellations

Advanced spacecraft networks called constellations consist of spacecraft that are able to network between the ground and other spacecraft to share and route information needed to solve mission objectives. Constellations provide new mission capabilities such as creating large distributed telescopes or providing the ability to bounce data between global point to point services.

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[5] "Scheduling can be defined as the process of designing a procedure for sequencing a set of desired activities that take place over a set of objectives. This sequencing is based on the time constraints for the delivery of the results, or availability of the resources necessary for performing an action" [5]

The largest constellation is the Iridium[6] project. It provides the ability to receive a phone call or use computer services anywhere, for example the North Pole, the South Pole, the deepest parts of the Amazon, the middle of any ocean, or any location in between. Within the Iridium constellation, 66 satellites are in mission orbit, with a set of over 14 spare satellites ready to replace any mission satellite that becomes obsolete. The Iridium constellation provides global paging and telephone service. Another project of similar design now being developed is the Teledesic[7] constellation of global, broadband "Internet-in-the-Sky" satellites. Numbering over 160 satellites, Teledesic will serve the data throughput needs of an evolving global society. Business models to solve communication needs are now focused globally, not regionally or nationally as in the past. Currently, there are over 14 major commercial spacecraft constellations being deployed [8] with many government systems also being developed.

1.3 Seeking a Solution to the Spacecraft Constellation Problem

Scheduling for a constellation is difficult, since with an increasing number of spacecraft to be scheduled, the problem quickly leads to a high degree of complexity. As experience has shown us from the Iridium program, you cannot directly use the "tried and true" techniques of single spacecraft operations to support a constellation. Since all spacecraft within a constellation have to share ground resources such as relay stations, control center resources, and the most precious resource of all, human operators, there is a need for new solutions to be developed.

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[6] Iridium is a trademark of Iridium LLC, [6]

[7] Teledesic is a trademark of Teledesic LLC, [7]

This problem is compounded with the inability to go off-line with a spacecraft since it is often providing mission critical payload needs. Customers and system users simply will not accept disruption in services or precious research time for activities such as system maintenance and spacecraft failure.

1.4 A Spacecraft Constellation Scheduling Solution

This thesis will advance the state of the art in the scheduling domain by integrating current areas of single spacecraft scheduling research and migrating them to the spacecraft constellation scheduling problem. Technologies such as constraint based scheduling, schedule efficiency, and schedule goal requirements will be merged with the unique requirements of spacecraft constellations. Specific research areas that will be merged into the solution of the constellation scheduling problem are as follows.

- Constraint based scheduling - The ability to schedule with diverse constraints such as time, resource utilization, or manpower.
- Schedule Goal Requirements: The ability to generate schedules with the constellation goal as an objective.
- Spacecraft Constellation Requirements: The ability to share resources that are constrained between spacecraft.

This thesis will outline a new type of scheduling product for the problem of the scheduling constellations.

2 Technical Objectives

The primary objective of this thesis is to lay the groundwork for creation of an actual constellation scheduler. First, we provide an overview of the constellation domain. Second, we provide a formal definition of a constellation schedule. Third we present technologies that support the creation of a constellation scheduler. Lastly, we propose a constellation scheduler architecture that can be used as the basis to build an actual working solution.

2.1 Objective 1: Domain Overview and Representation

The first objective of this thesis is to provide the reader with an understanding of spacecraft and constellations. We will present three operating modes that are utilized during the lifecycle of a constellation. The constellation operating modes are single spacecraft, island networks, and the full constellation. We will also present a detailed description of how we will represent a constellation schedule, along with the definition of the components of the domain.

2.2 Objective 2: Schedule Classification

The second objective of this thesis is the definition of a constellation schedule via an established formal schedule notation and framework. This problem definition will allow us to classify what type of schedule problem that we are attempting to solve, and to provide a concise schedule model that objectives 4 and 5 will be based upon.

2.3 Objective 3: Schedule Complexity

The third objective and major thrust of this thesis is to determine the complexity of the constellation schedule problem. We use a classical approach of schedule complexity classification to determine what type of schedule problem is utilized in the scheduling of constellations. The complexity classification will allow us top leverage techniques that have solved problems of similar complexity.

2.4 Objective 4: Scheduling Solution

The fourth objective of this thesis is the application of existing technologies to solve the spacecraft constellation scheduling problem. We propose to leverage powerful single spacecraft scheduling technologies that support a new constellation scheduler solution. Heuristics and constraint directed searching are two technologies that are detailed.

2.5 Objective 5: Scheduler Architecture

The last objective of this thesis is the presentation of an architecture to solve the constellation problem. The proposed architecture will allow the creation of a scheduler to support schedule generation.

3 Constellation Schedule Problem Domain

3.1 Overview of the domain

As we migrate from existing single contact scheduling to constellation scheduling, we will progress through three modes in which we view the spacecraft. First we see spacecraft as single entities able to function autonomously. Next during the lifecycle of the project, we will start to schedule spacecraft in what we will call islands. An island is the networking of two or more spacecraft that occurs as we progress towards one fully networked group of spacecraft. We are able to have multiple islands, and they are able to fully function as an island. Finally, we will see one group or network that is called a constellation. It is desirable (and often utilized) to maintain the capability to schedule in respect to each of the three operating modes at any one time. That is, even though we have a constellation, we still want the ability to schedule a single spacecraft at any time or even break the constellation into islands when desired. This scheduling capability can support constellation breakup, should spacecraft fail or planned maintenance is needed. Within the constellation scheduling domain, constraints of a prototypical system are described in section 4.1. One constraint to note at this time is that the domain will be viewed on a daily basis. That is, when we talk about a schedule, it only will span one day, called a planning day. Also, the set of spacecraft can be viewed as a set of single spacecraft, a set of islands, or one entity called a constellation. When the set of island spacecraft has the cardinality one, we will call it the constellation.