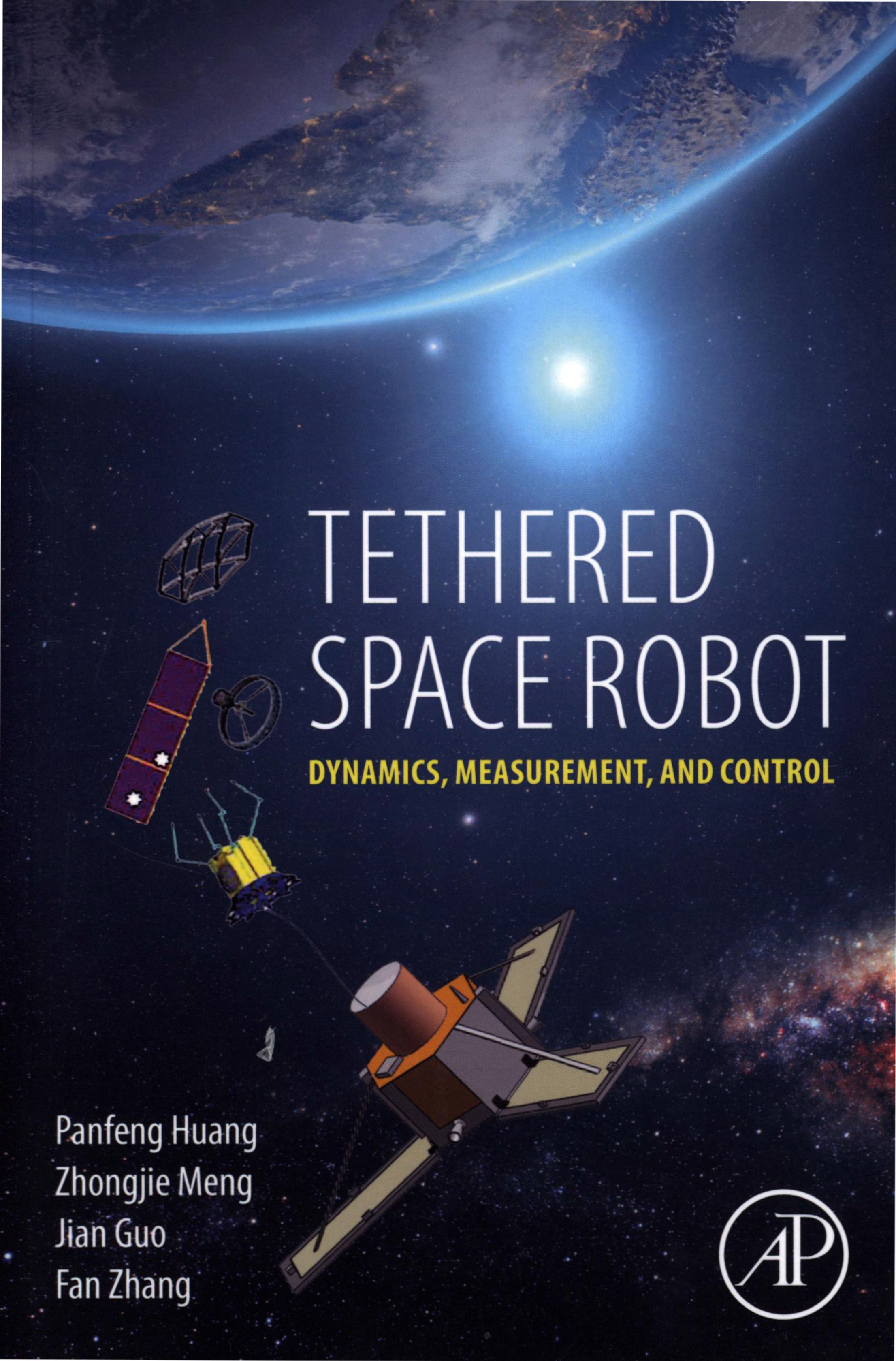

TETHERED SPACE ROBOT

DYNAMICS, MEASUREMENT, AND CONTROL

Panfeng Huang
Zhongjie Meng
Jian Guo
Fan Zhang

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The first book to describe a tethered space robot (TSR) system, from fundamental principles to system and mission design specs

- Provides for the first time comprehensive coverage of various aspects of tethered space robots
- Presents both fundamental principles and application technologies including pose measurement, dynamics and control
- Describes some new control techniques, including a coordinated control method for tracking optimal trajectory, coordinated coupling control and coordinated approaching control using mobile tether attachment points

Tethered Space Robot: Dynamics, Measurement, and Control discusses a novel tethered space robot (TSR) system that contains the space platform, flexible tether and gripper. TSR can capture and remove non-cooperative targets such as space debris. It is the first time the concept has been described in a book, which describes the system and mission design of TSR and then introduces the latest research on pose measurement, dynamics and control. The book covers the TSR system, from principle to applications, including a complete implementing scheme. A useful reference for researchers, engineers and students interested in space robots, OOS and debris removal.

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TETHERED SPACE ROBOT

Dynamics, Measurement, and Control

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TETHERED SPACE ROBOT

CONTENTS

CHAPTER 1

Introduction

In recent years, there has been a growing interest in active debris removal (ADR) due to the treatment of space debris in the orbital environment. Different kinds of robotic devices have been developed for various space targets. In this chapter, a brief review of the ADR missions and technologies is given first to help readers have an "intuitionistic" cognition on ADR. Background information, including the brief history of space tentacles, space manipulators, space tethers, and tethered space robots (TSR), is provided. Then, the design of the TSR and a classical mission scenario are described, which form the foundations of the subsequent chapters of this book.

1.1 BACKGROUND

Since the realization that space debris poses a threat for space activities, many capture and removal techniques have been investigated to clean the Earth's orbit. The solution to this space debris problem will consist of multiple methods, as no single capturing method can deal with the different kinds of space debris. Due to their relative maturity, space tentacles [1–4] and space manipulators (including single [5–7] and multiple arms [8]) are among the first methods that have been proposed for the capture of space debris.

However, rigid manipulators only work for short-range targets and point-to-point capture is difficult and risky, especially for an uncooperative target. Therefore, the space tether is considered to be the most promising approach for capturing debris. Most traditional applications of the space tether (e.g., orbit transfer or artificial gravity) are impossible or excessively costly with the existing space technology and engineering capacity. With the maturity of space tether technology and the high demand for new space tasks, research on the design, dynamics, control, and testing of various space tethers are motivated by their potential in space applications. TSR is precisely a new application of space tether for ADR.

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1.1.1 Brief History of the Space Tentacles

In ESAs e.Deorbit project [1], tentacles are used for capturing debris, either with or without a robotic arm. If a robotic arm is used, tentacle capturing embraces the space debris with a clamping mechanism after holding a point on the target with the robotic arm. Finally, a velocity increment by the chaser will deorbit the combined object. A trade-off shows that tentacle capturing with a robotic arm leads to a higher cost, mass, volume, hazardousness, and complexity of design compared to one without a robotic arm. Although the simulation of the target grabbing without a robotic arm performs successfully, practical missions require more stringent grabbing conditions because of high precision requirements. Aviospace is also a tentacles capture device working on the project CADET [2], which is in a closed configuration made by belts to soften the contact between tentacles and target. Finite element simulation and ground-based testing have been conducted for the capturing process and dynamics behavior, and the detailed design has been in progress since June 2014. Yoshida and his team proposed another type of tentacle that is inspired by biology and is named the Target Collaborativize (TAKO) Flyer [3]. TAKO is composed of a main service satellite and a TAKO Gripper. This gripper is composed of several fingers driven by the gas pressure in a pneumatic bellows. The TAKO Flyer can also use several thrusters installed on the TAKO Gripper in order to work on nonoperational targets that may be tumbling or that have failed to provide information. OctArm is a variant tentacle capturing device proposed by McMahan in Ref. [4] that contains three sections connected by the endplates. Each section is constructed with air muscle actuators and it is capable of two axis bending and extension with nine degrees of freedom.

According to the aforementioned four kinds of tentacles, the advantages of the tentacles are clear, including the stiff composite, easy ground test, and higher Technology Readiness Level (TRL). However, the drawbacks are also distinct, such as complicated rendezvous, possible bouncing, and the requirement of accurate information of relative positioning and velocity.

1.1.2 Brief History of the Space Manipulator

On-orbit service (OOS) comprises all aspects of on-orbit assembly of parts into systems, maintenance of equipment (preventative and corrective), replenishment of consumables, upgrade, repair, and of course, target capture and removal [8–10]. Most malfunctioning spacecraft have to be replaced due to the lack of OOS opportunities. The accomplishment of OOS missions

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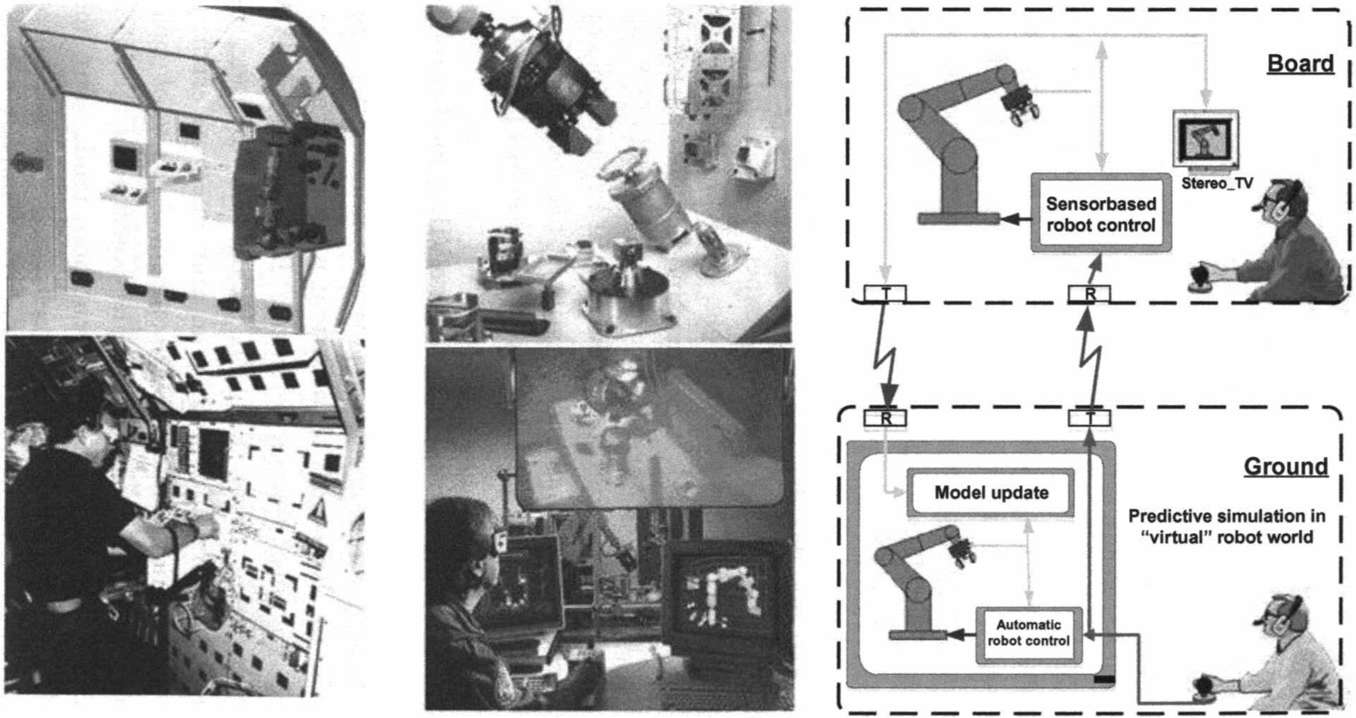
would be of great benefits, such as spacecraft assembly, orbit transfer, maintenance and repair, resupply, or even safe deorbiting. Over more than a decade, numerous projects around the world have dealt with OOS of spacecraft supported by space robotics. A major subset of OOS consists of unmanned OOS missions that use a space robot.

Most manned OOS missions are critical for astronauts and are extremely expensive. In contrast to manned OOS missions, unmanned robotic OOS missions play a more important role in the development of OOS. As early as the 1980s, the National Aeronautics and Space Administration (NASA) realized the importance of robotics on-orbit servicing operations to protect their assets in space. Space robotics is considered one of the most promising approaches for unmanned on-orbit servicing (OOS) missions, such as docking, berthing, refueling, repairing, upgrading, transporting, rescuing, and orbital debris removal [11]. Many enabling space robotics techniques have been developed, and several OOS experimental demonstration missions, including both manned and unmanned missions, have been successfully accomplished in the past two decades.

The German ROTEX (Robot Technology Experiment) is one of the milestones of space robot technology, shown in Fig. 1.1. ROTEX was conducted in May 1993 in the space shuttle experiment module and operated by an onboard astronaut and an operator on the ground [12]. ROTEX was the first remotely controlled robot in space, and several key technologies were successfully tested, such as a multisensory gripper, teleoperation from the ground, shared autonomy, and time-delay compensation by a predictive 3D-stereo-graphic display.

The Japanese ETS-VII (Engineering Test Satellite VII) is another milestone in the development of space robot technology and is considered to be the first robotic OOS demonstration mission [13], shown in Fig. 1.2. Different from ROTEX, the ETS-VII's robot system is a satellite mounted EVA (extra-vehicular-activity) type robot while ROTEX is an IVA (intra-vehicular-activity) type robot. ETS-VII includes a 2-m long, 6-degrees-of-freedom robotic arm mounted on an unmanned spacecraft. It was developed by the National Space Development Agency of Japan (NASDA) and launched in November 1997. The objective of the ETS-VII mission was to verify technologies for autonomous rendezvous, and docking and robotic servicing in space. These technologies include teleoperation from the ground with a time-delay, robotic servicing task demonstrations such as ORU exchange and deployment of a space structure, dynamically coordinated control between the manipulator's reaction


Board
Stereo_TV
Sensorbased robot control
T
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R
T
Ground
Model update
Predictive simulation in "virtual" robot world
Automatic robot control

Fig. 1.1 ROTEX.

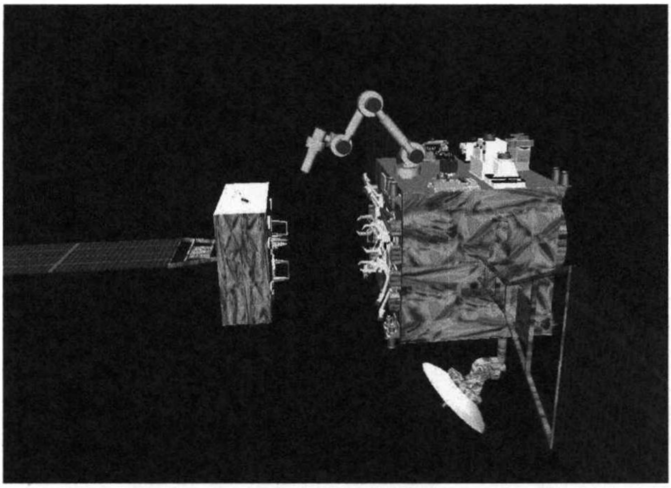

Fig. 1.2 ETS-VII.

and the satellite's response, and capture and berthing of a target satellite [14–16].

The Defense Advanced Research Projects Agency's (DARPA) Orbital Express program was successfully launched and accomplished in 2007 [17]. The Orbital Express system comprises two satellites, the ASTRO (Autonomous Space Transfer & Robotic Orbital Servicer) servicing vehicle that included a 6-DOF rotary joint robotic arm, and the NextSat demonstration client vehicle [18]. As an advanced OOS technology demonstration mission, it demonstrated the technologies of one spacecraft servicing another one, such as short-range and long-range autonomous rendezvous and docking, capture and berthing, robotic ORU replacements, on-orbit refueling, and autonomous fly-around visual inspection [19, 20].

The SUMO (Spacecraft for the Universal Modification of Orbits) was another risk reduction program for an advanced servicing spacecraft sponsored by DARPA and executed by the NRL (Naval Research Laboratory) in 2002, shown in Fig. 1.3. The purpose of this program was to demonstrate the integration of machine vision, robotics, mechanisms, and autonomous control algorithms to accomplish autonomously rendezvous and capture customer satellites at geosynchronous orbits for future spacecraft servicing operations [21]. In 2005, the program was renamed to FREND (Front-end Robotics Enabling Near-term Demonstration), which included a 7-DOF flight robotic arm system with the objective of performing autonomous rendezvous and docking with satellites not pre-designed for servicing [22]. This capability allowed nearly any satellite to be repositioned on-orbit

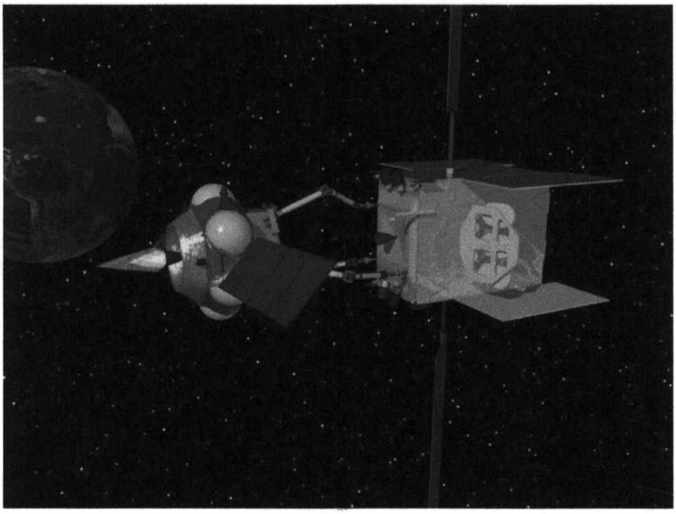

Fig. 1.3 SUMO.

and, therefore, provided many benefits including satellite life extension and disposal of derelict spacecraft [7].

The FREND robotic arm was utilized in a new DARPA's Phoenix program in 2012. The goal of the Phoenix program was to develop technologies to cooperatively harvest and reuse valuable components from retired nonoperating satellites in geosynchronous orbit (GEO). By physically separating these components from the host nonworking satellite using on-orbit grappling tools, the Phoenix program aimed to demonstrate the ability to create new space systems at a greatly reduced cost [23]. In the first case study for this concept, Phoenix sought to demonstrate around-the-clock, globally persistent communication capability for warfighters that were more economical due to robotically removing and reusing GEO-based space apertures and antennas from decommissioned satellites in the graveyard or disposal orbit [24].

In 2009, another OOS mission, known as DEOS was proposed. The German's DEOS (Deutsche Orbital Servicing Mission) was a robotic technology demonstration mission that consisted of a servicing satellite equipped with a robotic arm, and a target microsatellite to be captured and serviced in orbit [25]. The main purpose was to capture a tumbling noncooperative client satellite with a servicing spacecraft using a robotic arm, and to deorbit the coupled configuration within a predefined orbit corridor at the end of mission [5]. After capture, the servicer would dock to the client using a grapple inserted into the main propulsion unit and perform several practice manipulation tasks like placing cameras and inserting a refueling adapter as well as orbit maneuvers with the mated configuration.

Most of the above robotic manipulators are designed and built in a manner that maximizes stiffness in an attempt to minimize the vibration of the end-effector to achieve good position accuracy. Compared to the conventional heavy rigid manipulator in OOS, flexible manipulators have the potential advantage of lower cost, greater payload-to-manipulator-weight ratio, better maneuverability, better transportability, and safer operation. Because the reduction in weight lowers the launching cost to space and softness improves safety at the moment of contact with the object, the flexible manipulators are also used for space applications in OOS.

The Japan's Aerospace Dual-Arm Manipulator (ADAM) was a dual-flexible-arm robot used for capturing a spinning object [26]. ADAM has two flexible links and seven joints in each arm. Research on space robotic technologies such as flexible arm control, control of coupling vibration, control of cooperating dual arms, and teleoperation of robots with multiple arms were examined with the ADAM [27, 28].

A space debris micro-remover (SDMR) was studied by the Japan Aerospace Exploration Agency (JAXA) in 2009 for active space debris removal [29]. SDMR consists of a micro satellite, an electro-dynamic tether (EDT) and an extensible, flexible folder arm. It aimed at capturing a tumbling non-cooperative target satellite using this flexible folder arm. EDT technology was investigated as a highly efficient orbital transfer approach for deorbiting. A small EDT package provided a possible means for lowering the orbits of objects without the need for propellant, and the flexible folder arm was used to capture and remove large space debris.

Similar as the tentacles, the space manipulator is also a stiff composite, which possesses both advantages and drawbacks. The rigid structure is easy to establish ground-based test before launch, and has a higher TRL. On the other hand, the probability of collision is higher due to the limited maximum length of the arm. Besides, the grappling point must be precise during the rendezvous and docking.

1.1.3 Brief History of the Space Tether

Tethers are commonly considered to have rather good performance in becoming as useful in space as they have always been on Earth. This problem has been studied for over one hundred years with application scenarios proposed by many researchers. In this section, we would like to recapitulate several basic applications of space tethers, without pretending to cover the full list, and name various excellent contributions to the development of space tether ideas, which is also the theoretical and engineering foundation of the DTSR.

1.1.3.1 Single Space Tether

Artificial Gravity

It is a well-known fact that artificial gravity is highly desirable for long manned space flights since even small fractions of g-force will improve living conditions aboard a space station. It was exactly for this task that the use of a space tether was first proposed. Nowadays, we know that the centrifugal force of inertia can be used to create artificial gravity on Earth or in space. This idea was first presented by Tsiolkovsky in 1895 [30]. For this application, two spacecraft were connected by a tether chain, and then the whole system was rotated to create artificial gravity. The length of the chain is a key factor in determining the magnitude of force created, as well as the square of angular velocity of the mechanical system's rotation. Chobotov [31] was the first researcher to render a detailed dynamic analysis of this mode of motion in orbit in 1963. Gemini-11 tethered to the rocket stage Agena was the first spacecraft to demonstrate the feasibility of this concept during its flight in 1966 [32]. Even a created artificial gravity of 10^{-4} g can be very useful in space. For example, when transferring supplies from one spacecraft to another, such as the transmission of fuel, microgravity can be useful to speed up these missions [33].

In the past, designers of space stations did not want to complicate things with artificial gravity, but in the future, generations of space tourist and travelers may find it much more comfortable and desirable.

Orbital Transfer

Advantageous and far-reaching tether applications are associated with space transportation. Traditionally, thrusters are mounted on the spacecraft as a reactive mass for maneuvering in orbit. However, when the working medium is exhausted, this process will fail. For tethered satellites on separate sides, the use of a space tether system characterizes a pure exchange of energy and angular momentum between them. Since there is no working medium consumed, this kind of orbit transfer system promises sizable saving in fuel. Hence, it can be used as a viable alternative to the traditional approach.

Colombo et al. [34], Bekey [35], Bekey and Penzo [36], and Carroll [37] have studied this problem at length. Their research shows that the use of a

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