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.

Tethered Space Robot
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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.

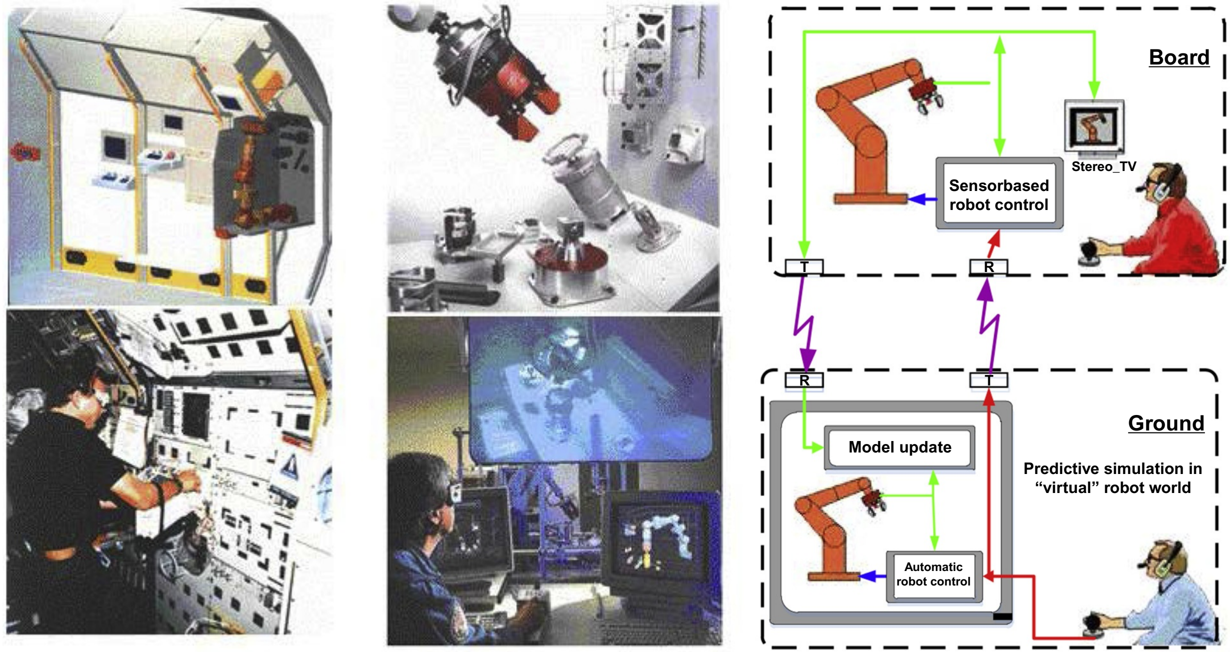
1.1.2 Brief History of the Space Manipulator

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 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
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Automatic robot control

Fig. 1.1 ROTEX.

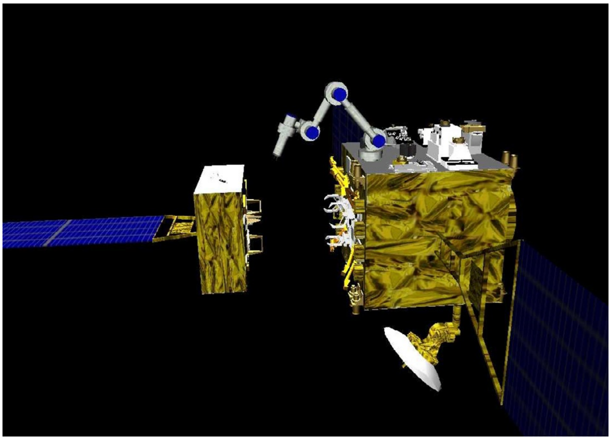

Fig. 1.2 ETS-VII.

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

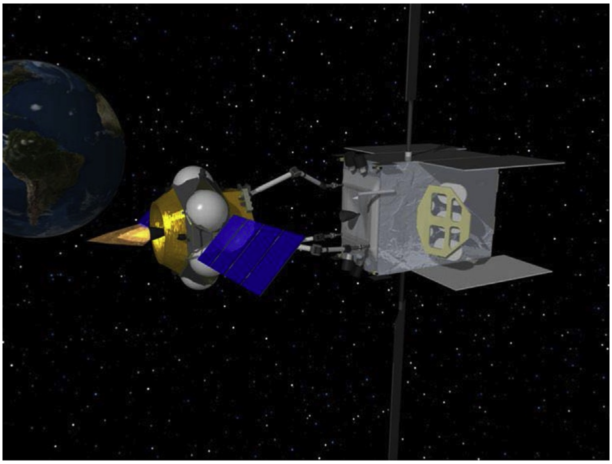

Fig. 1.3 SUMO.

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 space tether system can provide a sizable saving in fuel for transfer missions in circular orbits. Kyroudis and Conway [38] further studied a tethered dumbbell system used in an elliptically orbit and stated its' advantages for satellite transfer to geosynchronous altitude. In Ref. [39], Kumar et al. studied different kinds of tether deployment systems for orbit raising, and they also discuss the out-of-plane libration on the payload. Yasaka [40] studied the problems of orbit transfer for exhausted tumbling satellites. Bekey [41] and Kumar [42] stated the advantages of using a tethered reusable satellite for payload deployment. Lorenzini et al. [43], Ziegler [44] both studied the spinning tethered system by releasing the tether by using spindle dynamics is studied to achieve altitude gains of the SV/payload, which is the earlier investigations by Ziegler and Cartmell. Kumar et al. [45] studied the tether retrieval system used for the SV/payload deployment. And they propose a system model including a payload and a connection tether.

Bonnal et al. [46] introduced the principle and modeling for the "MAILMAN" process. They put forward the idea of an optimization with variable weighting factors that can be applied to the deorbitation of debris with passive tethers. In their plan, a passive tether is used to lower the orbital lifetime of the debris N. Simultaneously, the chaser maneuvers from N to the adjacent one $N+1$ benefiting from the momentum ΔV saved. Hyslop et al. [47] presented details of a micro-launcher with a tethered upper stage. They designed two typical missions, including how to deliver the payload into target orbit and deorbit the exhausted solid stage to the Earth. They also proposed a preliminary design of the tether system.

Attitude Stabilization

According to the mission of a spacecraft, its orientation in the Earth's direction is usually designed specially. When in space, it is usually required to keep the orientation for a long time. To satisfy this requirement, the systems of active stabilization are designed. Traditionally, these systems use jet engines with a small thrust and gyros for attitude adjustment. However, this kind of system has a disadvantage, which is that the requirement for expenditure of a propellant is great. Hence, another kind of systems has developed since the middle of the last century, which is defined as passive stabilization systems. A long flexible tether with the load is one kind of passive stabilization system.

In the 1960s, Chobotov [48] and Robe [49] both proposed and improved the idea of using a tether for the satellite's gravity-gradient stabilization. The tether can be applied for an increased distance as long as there are several kilometers between the spacecraft and the stabilizing target. It resulted into an increase of the recovering moment of gravity-gradient. And this value is proportional to the distance in its first approximation. Misra and Diamond [50] presented a TSS model for attitude stabilization. The model consisted of a main satellite and a sub satellite that were linked by two extensible massless tethers. The motion of the TSS was assumed in a circular Keplerian orbit, including out-of-plane and in-plane motions. In addition, the longitudinal oscillations of the tether are also involved. Ciardo and Bergamaschi [51] researched the motion discipline of the two-tether system. They studied three dimensional attitude motion of the tether, including in-plane and out-of-plane angles. Ignoring tether tension variations, motion disciplines were described by linearized equations and simulations were demonstrated. Banerjee and Kane [52] studied how to use the pull force of the tethers for controlling the stability of a space platform that was connected to a space station by two tethers. Kumar [53] studied how to use two tethers for the attitude stabilization of a satellite, which moved in a circular orbit. Furthermore, Kumar [54, 55] studied the case of a satellite that moved in elliptic orbits. Their works demonstrated that it was feasible to use two tethers for passive satellite pointing stability. Kumar [56] also analyzed the attitude dynamics of a two-tether system, which used a kite-like tether configuration.

1.1.3.2 Multi-Space Tethers

The application of using multi-tethers, namely the tethered formation flying, has been identified as a means of reducing cost and adding flexibility to space-based programs. A single, large spacecraft would be replaced by many smaller, less complicated satellites that make up a particular spatial configuration. Compared with a single large spacecraft, satellite formations have higher flexibility and system reliability. Therefore it has become one of the most promising technologies for future space missions. Currently, the satellite formation has been proposed for various applications, such as synthetic aperture, radar satellite formation, distributed meteorological satellite stereoscopic imaging, high-resolution synthetic aperture optical interferometry, and electronic surveillance. However, spatial formation flying is facing multiple challenges, especially space environmental disturbance, such as interference of gravity, air resistance, sunlight pressure, electromagnetism, and modeled force, which make spatial formations difficult in the long run. The satellites have to consume large quantities of fuel to keep the stable configuration. Therefore the service life of the satellite formation is significantly reduced. When the tethers are applied to the satellites, the relative distances between spacecraft can be maintained accurately because the satellite is connected to the spacecraft via tethers, making the tethers remain taut. The satellite formation connected by a tether is called tethered satellite formation. The system rotates along an axis, or utilizes thrusters, gravity gradient, or air resistance to keep the tethers in tension and to maintain the shape of the formation. The main advantages of using tethers for satellite flight formation have been summarized by Fedi Casas, Manrico in Ref. [57]. However, the tether also has many disadvantages to the satellite formation, such as increasing the complexity of deploying the satellite cluster; the risk of collisions; the complexity of tether dynamics; the possibility of environmental deterioration and micrometeoroid damage; and complexities regarding optics and controls for tethered satellites [58]. The investigation of tethered satellite formations has become a hot topic.

Dynamics and Control

There have been many investigations on the dynamics and control of tethered satellite formation flying. Misra and Modi [59] and Kumar [60] have made an extensive literature survey about the dynamics and control of tethered satellite systems. Avanzini and Fedi investigated the dynamics of multi-tethered satellite formations, where tethers are modeled by means of a sequence of point-masses and massless springs. The results showed that the massless tether model is sufficiently accurate for capturing the most relevant aspects of the behavior of the formation, whereas tether mass affects formation dynamics for closed configurations featuring external tethers [61]. Liu et al. proposed a nonlinear output tracking control scheme based on the θ-D technique to fulfill the station—keep control of the rotating TSS along halo orbits. The obtained nonlinear suboptimal controller is in a closed form and is easy to implement [62]. Cai et al. investigated the nonlinear coupled dynamics of a rotating triangular tethered satellite formation near libration points, developed the dynamical formulation, and analyzed the dynamic characteristics [63]. Zhao and Cai presented the nonlinear coupling (not linearized) dynamics of multi-tethered satellite formations, in which the parent satellite follows three-dimensional larger Halo orbits centered about the second libration point of the Sun-Earth system. They developed a dynamic system model and demonstrated that both the orbit motion and tether librations have better stability characteristics in a relatively long-term as a result of the increased initial spin rate and length of tethers [64]. Pizarro-Chong and Misra examined the dynamics of certain multi-tethered satellite formations containing a parent (or central) body [65]. Literature [66] presented the dynamics of multi-tethered satellite formations that consists of a parent satellite and subsatellites connected in a hub-spoke configuration via variable-length tethers near libration points. Chung et al. established the nonlinear equations of motions of multi-vehicle tethered spacecraft. By using the diagonalization technique, decentralization was realized. The controllability analysis indicated that both array resizing and spin-up are fully controllable only by the reaction wheels and the tether motor, thereby eliminating the need for thrusters [67].

Attitude Control

It is necessary for the satellite formation to change the spin axis direction in many missions, such as interferometry observation missions [68]. Nakaya and Matsunaga discussed attitude maneuvers of spinning a tethered formation flying system and proposed a feedback maneuver control based on the virtual structure approach [69]. Mori and Matsunaga proposed a tethered satellite cluster system, which consists of a cluster of satellites connected by tethers. This cluster system can maintain and change formation via active control of the tether's tension and length to save thruster fuel and improve control accuracy. The equilibrium conditions that the tether tension imposes on the rotational motion were given, and a coordinated control method for the thrusters, the reaction wheels, and the tether tension/torque was proposed [70]. Menon and Bombardelli considered a tethered formation system that consists of two platforms linked by a flexible tether at a few hundred meters long. This system constitutes the building block of more complex tethered architectures utilized in proposed space interferometry missions, and the tethered units are modeled as extended rigid bodies [71]. Liang et al. proposed a class of decentralized coordinated attitude control laws using a behavior-based control approach, where the choice of behavior weights defines the coordination connections. In the presence of model uncertainties and external disturbances, the presented class of controllers can guarantee globally asymptotical reachability of a given desired trajectory [72].

Structure and Configuration

Since initially the proposed applications involved only two bodies, the interest of the investigators was on two-body systems. Sarychev investigated the equilibria of two connected rigid bodies in a circular orbit with respect to the orbital reference frame [73]. Lorenzini investigated a satellite system that consists of three platforms: the Space Station, an end mass anchored at the end of a 10-km-long Kevlar tether, and a micro-g/variable-g laboratory with the capability of crawling along the tether [74]. Pizarro-Chong and Misra investigated the dynamics of possible configurations for multi-tethered satellite formation and studied two main possibilities. In the first one, there is a central body (hub) that contains stem tethers (spokes) with a satellite at the end of each tether. The other was the closed-hub-and-spoke configuration, where tethers connecting one peripheral satellite to the next are added to the configuration described in the first one. The configurations were nominally in two-dimensions, but three-dimensional motion was studied. The relative motion of the satellites was examined for both configurations and for varying number of bodies. When the configuration spins in the orbital plane, the hub-and-spoke configuration is stable for up to four bodies. Above that number, outer tethers are necessary [75]. Kumar and Yasaka investigated the feasibility of rotating satellite formation using flexible tethers. The system was composed of three satellites connected through tethers and located at the vertices of a triangle-like configuration. Open-loop tether deployment and retrieval laws were developed. In the case when three satellites had equal masses, the critical minimum value of spin rate for system steady-spin motion in the orbital plane was found to be 0.58 times the orbital rate [76]. Literature [61, 65] investigated the dynamics of multi-tethered satellite formations. Guerman studied tetrahedral equilibrium configurations of a chain consisting of four satellites connected by three rigid weightless rods [77]. Cai et al. investigated the dynamic stability of a rotating triangular tethered satellite formation near libration points during the deployment and retrieval stages [78].

Although many investigations about tethered spacecraft formation have been made in recent years, there have also been many problems. The majority of researchers assumed the tethers to be massless and inextensible. Few individuals took the tether mass and elasticity into account in their studies. The folding and releasing control and the reconfiguration of the tethered spacecraft formation are two critical problems that deserve more close attention. Another challenge for this topic is the ground test design, which is necessary in addition to numerical analysis and simulations.

1.1.4 Brief History of the TSR

A tethered space robot is a novel kind of space robot, which consists of a gripper, a space tether, and a space platform (Fig. 1.4). Owing to its

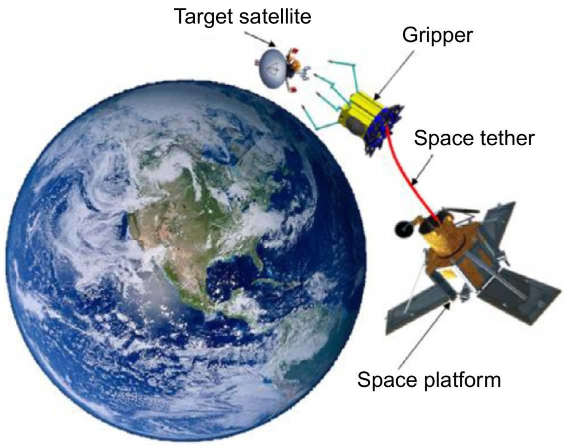

Fig. 1.4 TSR.

flexibility and great workspace, a TSR has wide applications in future on-orbit services including on-orbit maintenance, on-orbit refueling, auxiliary orbit transfer, and space debris removal [79–81]. Many problems may arise during different phases of a TSR capture mission, which is typically separated into the deployment, approach, capture and post-capture phase, and retrieval or deorbiting phase.

1.1.4.1 Releasing/Retrieving Phase

The dynamic characteristics of the TSR during the release and retrieval phase are quite complicated. Mantri [82] investigated the system parameters that affect the length to which a tethered satellite system will deploy [83]. Yu [56] presented the effect of J2 perturbation on the deployment and retrieval of tethered satellite and showed the new dynamics with the heating effect taken into account. Some particular laws of deployment retrieval leading to analytical solutions for the small in-plane and out-of-plane motions of the system are obtained in Ref. [84]. The retrieval dynamics of the tethered satellite system is simulated using Galerkin's method with and without the contribution of the lateral vibration to the strain and the bead model approach, where the tether is assumed to be a series of point-masses connected to each other by massless springs and revolute joints in Ref. [85].

The orbit and attitude controls during the approaching and retrieving target phase are the key missions for TSR and have been studied by many researchers. Pradeep [86] proposed a new method to determine the tension control law, which is designed using theorems in analytical mechanics.

Modi [87] designed an off-set control strategy, which is implemented using a manipulator mounted on the platform to regulate the tether swing. The corresponding state feedback controller is designed using a graph theoretic approach, and the controller successfully regulates the tethered system. The particular laws of deployment/retrieval obtained in Ref. [57] are extended to massive tether in Ref. [84]. The dynamics of a tethered satellite system during deployment and retrieval in orbit was considered and an intermediate scheme, generalizing the previously proposed conventional scheme and the crawler scheme, is presented in Ref. [88]. Pradeep [86] suggested a new method to determine the tension control law by using theorems in analytical mechanics. In Ref. [89], the dynamic behavior of a tether connected satellite system during the deployment and retrieval process was considered, and fast retrieval laws for tethered satellite systems were obtained. He [90] studied the stability of the system equilibrium state for tethered satellite system and developed a range-rate control algorithm to achieve the stable control of a tether's deploying, keeping, and retrieving. In Ref. [91], the dynamics of variable-length tethers was studied, and a control strategy was proposed to avoid slackness of the tethers during deployment. Fujii [92] studied the optimal trajectory for the deployment and retrieval of a tethered subsatellite. To prevent tether slackness and/or angle buildup, thrusters are employed for control augmentation during tethered satellite retrieval in Ref. [93]. From control theory, Fujii [94] presented a new control algorithm applied to the problem of deployment and retrieval of tethered satellite systems. An idea of the "mission function" was introduced and the deployment and retrieval process was thus controlled to decrease the mission function. Vadali [95] applied the Lyapunov approach to the tethered subsatellite deployment and retrieval problem and developed a nonlinear feedback tension control law to guarantee the stability of the closed-loop system, which was used in combination with out-of-plane thrusting during retrieval. The effects of various deployment schemes, as well as out-of-plane vibrations on a tethered payload, were studied in Ref. [39]. Netzer [96] described the optimization analysis results of deployment and retrieval of a tethered satellite system. Fujii [97] developed a feedback control law to follow an optimal path for the deployment/retrieval phase of a subsatellite connected to the shuttle through a tether. The deployment/retrieval control of a tethered subsatellite connected through an elastic tether to the main body was studied in Ref. [98]. Lakso [99] presented an approach to determine optimal tether deployment/retrieval trajectories using direct collocation and nonlinear programming. Wen [100] presented the nonlinear optimal control for the deployment process of an elastically tethered subsatellite model, which involved not only the usually addressed in-plane motion but also the out-of-plane motion. Besides, given the uncertainties in the mass parameter, the perturbations in initial states, and the external disturbance forces, a non-linear optimal feedback control for the deployment process of a tethered subsatellite model was presented in Ref. [101]. A methodology for deployment/retrieval optimization of tethered satellite systems was presented with the space tether composed of lumped masses connected via inelastic links in Ref. [102]. Barkow [103] considered two slightly different approaches called pendulum control and targeting, which are efficient concerning the necessary energy input and less energy expense. Moreover, Barkow [104] also introduced an optimal control strategy to simulate the force controlled deployment of a tethered satellite from a spaceship.

The attitude control of the TSR has received extensive attentions in recent years. Nohmi [105] investigated the arm link to control the TSR's attitude during the deployment phase, and a microgravity experiment was conducted to validate the feasibility of this scheme. Beda [106] investigated how the attitude dynamics of a tethered satellite can be controlled for eccentric orbits by simply using the feedback of the pitch angle. Bergamaschi [107] studied the coupling between the tether taut string vibrations and the satellite attitude motion. A fault-tolerant nonlinear control design was presented by Godard [108] to control the attitude of a satellite using the movement of the tether attachment points in cases where tether deployment suddenly stops and tether breakage occurs. In addition, Godard [109] also investigated a corresponding adaptive fault-tolerant control method in the presence of unknown slow-varying satellite mass distribution and tether rigidity parameters.

To save on fuel consumption during the target releasing phase is quite significant and meaningful for the TSR, Nakamura [110] discussed the collaborative control of tension (controlled by the servicing satellite) and thruster (controlled by the tethered robot) when approaching the target of the tethered retriever. Wang [111] presented a control scheme of a TSR using a mobile tether attachment point in the approaching phase, which can realize the coordinated control of the tether tension and thruster force. Considering the increased mass of the tether and the distributed force acting on the tether, Huang et al. [112] designed an optimal coordinated controller which can minimize the fuel consumption by using the hp-adaptive pseudospectral method and the classical PD controller. Nohmi [113] proposed a cooperative control scheme for a TSR to reach a destination point. By using the translation and link motion of the TSR, Nohmi [114] found that the angular momentum of the tethered robot can be controlled by proper motion of the tether attachment point. Xu et al. [115] investigated the coordinated position and attitude control method of a TSR, where the traditional position control force is obtained using the linear quadratic regulator, and then the control force is distributed to space tether and thrusters by optimization.

The oscillations of the space tether must be considered for the TSR. Steiner [116] showed that with the aid of center manifold theory for the nonlinear system the out-of-plane oscillations of tethered satellite systems can be stabilized by tension control. Vestroni et al. [117] studied the oscillations of tethered satellite systems caused by internal resonance and presented a control method to reduce the primary and secondary instability regions of oscillations perturbed by internally resonant disturbance components. In Ref. [118], a method of damping structural vibrations using optimization techniques is presented and applied to a tethered satellite system. Misra [119] considered control of the rotational motion as well as longitudinal and transverse vibrations of a tethered subsatellite system during its retrieval to the shuttle.

1.1.4.2 Capture and Post-Capture Phase

Due to the presence of the tether, the dynamic characteristics of the TSR differ from those of a traditional space robot during the capture and post-capture phase. Zhang et al. [120] presented a new methodology for the on-line inertial parameters estimation of rigid space debris captured by a tethered system. Huang et al. [121] presented a novel scheme for achieving attitude control of a tumbling TSR in the post-capture phase, which coordinates the controller of the tether force and thruster force with the controller of single thruster force. To realize the stabilization of a TSR-target combination system after a capturing phase, Wang et al. [122] proposed a coordinated optimal control scheme of the tether tension, thruster control torque of the gripper, and the manipulator, which is solved by Gauss pseudospectral method.

1.1.4.3 Deorbiting Phase

The TSR has many advantages on target deorbiting. Sun et al. [123] investigated the effects of propulsive coefficients on librational stability during maneuvering and presented a hierarchical sliding-mode tension control method to track the expected in-plane angle Liu [124] conducted an in-depth investigation on tether-tugging deorbit issues of defunct geostationary satellites.

1.2 SYSTEM AND MISSION DESIGN OF TSR

1.2.1 System Architecture

Since space debris is uncooperative for the capture device, a TSR is promising for ADR. The three-finger operational robot hand of the TSR proposed in this book can properly catch space debris with a good trade-off between the operating efficiency and cost efficiency.

The space platform has the capability of autonomous orbit transfer, and can execute multiple space tasks using several capture device payloads (one kind or several kinds) mounted on it. Various sensors, such as stereo cameras, laser rangers, and microwave radars are used to inspect, track, and measure the targets (cooperative and noncooperative). The space tether used here is nonconductive and very strong. It is not available to transport information or supply power. We designed it to provide tension for coordinated control and to deorbit the debris, which may reduce the propulsion fuel consumption and the size of designed Operational Robot accordingly.

The designed operational robot of the TSR, with a total mass of 10 kg and a length of 480 mm and a diameter of 260 mm, is a free-flying element that is connected to spacecraft platform by a space tether. To meet these requirements, we designed the configuration and selected the sensors delicately.

As shown in Fig. 1.5, the operational robot of the TSR is designed to be a hexahedron and is principally composed of seven subsystems, including a

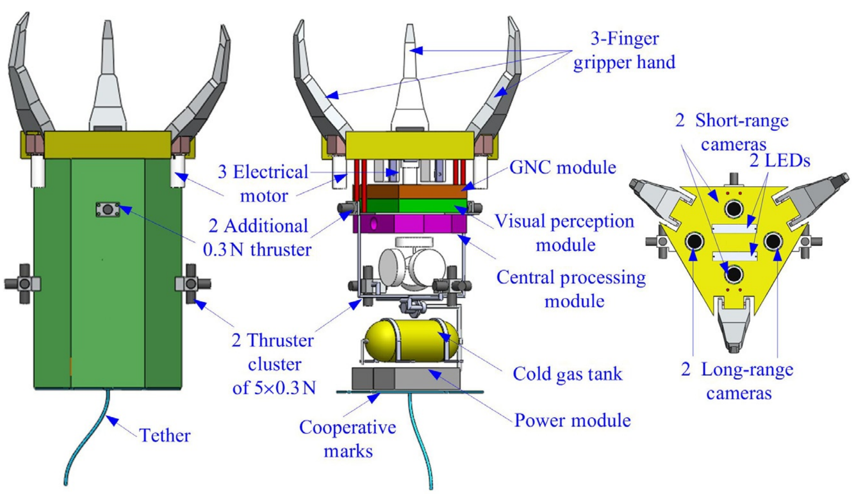

Fig. 1.5 Architecture of the operational robot.

structure subsystem; a thermal control subsystem; a power supply subsystem; a propulsion subsystem; a guide, navigation, control (GNC) subsystem; a visual perception subsystem; and a central processing subsystem. On the upper panel are mounted two stereo cameras, two light emitting diodes (LEDs), and a 3-finger gripping element. The motion to the target and rotations will be performed by a cold gas propulsion system using 12 thrusters of 0.3 N thrust each, using a tank containing approximately 1 kg liquid nitrogen. Inertial measurement unit (IMU) is also used for pose measurement [125–127]. Moreover, the cooperative visual markers used for relative pose measurement is fixed on the lower panel.

1.2.2 Mission Scenarios

Similar to Zhai's description in Ref. [128], the TSR's mission scenario is shown in Fig. 1.6.

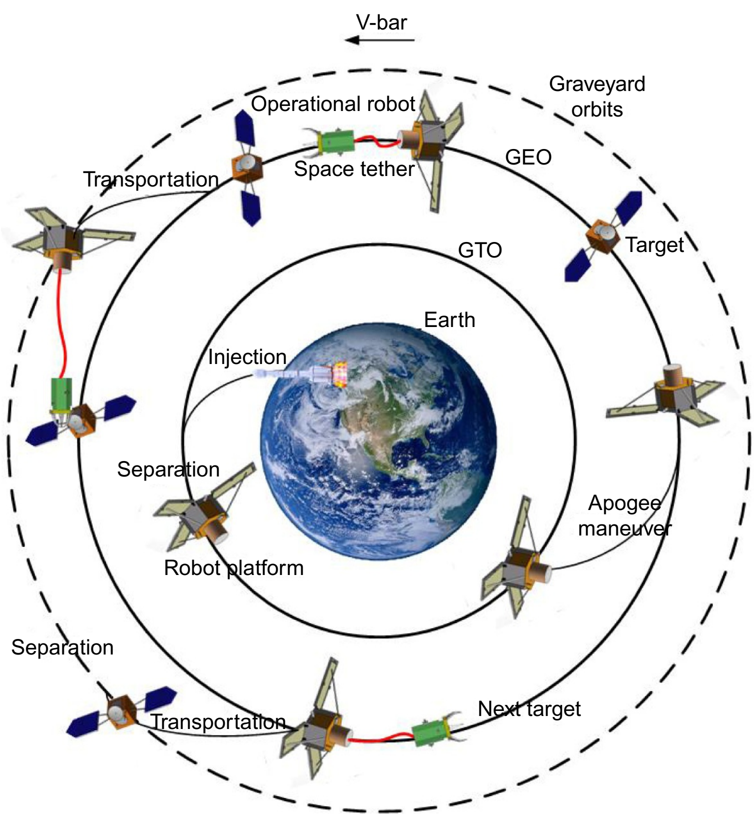

Fig. 1.6 Orbit maneuvers designed for TSR.

It begins with the launch of large launchers, such as CZ-3, capable of transporting a 3.8-ton spacecraft into a geostationary orbit. When TSR reaches the GTO and is separated from the launcher, it will perform the injection maneuver (apogee maneuver) by using its propulsion system to go into a nearby GEO, allowing for phasing to an orbit position, where the rendezvous maneuver to the first target satellite can start.

The whole rendezvous is divided into four sub-maneuvers, particularly orbital inclination sub-maneuver (point S1), homing sub-maneuver (point S2), closing sub-maneuver (point S3), and in-plane inspection sub-maneuver (point S4), to minimize the effects of uncertainties, as shown in Fig. 1.7. Once the relative pose is in line with capture condition, the 3-fingers point to the region of interest (ROI) of the target, capture the solar panel, manipulation, and lock. After the complete capture, the thruster will work against the direction of the velocity, and target debris will be de-orbited to the graveyard orbit, where the debris will be set free by stretching the 3-fingers.

The TSR features high flexibility and greater workspace and is promising in future OSS missions such as auxiliary orbit transfer and space debris removal. In recent years, many researchers have worked on the TSR, especially the dynamics and controls of releasing and retrieving phase, resulting in many achievements. However, the TSR is a rather complex multi-body with its dynamics highly coupled and requires more investigations. Dynamic modeling is one of the most important problems for the TSR, especially the modeling of the space tether, which has been studied by many researchers. Moreover, the dynamic behavior of a space tether is quite complicated,

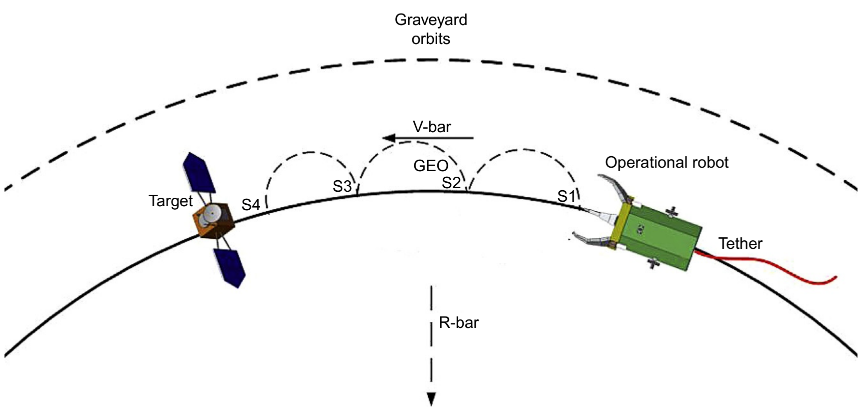

Fig. 1.7 Orbit maneuvers designed for TSR.

which leads to highly coupled dynamic characteristics of TSR during the employment, capture, retrieval, and deorbiting phases. Therefore, more efforts are required to study the dynamic modeling and behavior of the TSR deeply. Besides, the nonlinear dynamic model of the TSR is quite complicated due to the existence of space tether and the control during the mission is challenging but very meaningful. The investigations of control during employment and retrieval have been drawn much attention. However, the problems of target capture and post-capture have not been fully addressed, which will be the topics of the subsequent chapters.

REFERENCES

[1] R. Biesbroek, The e.Deorbit study in the concurrent design facility, in: Presentation Handouts, Workshop on Active Space Debris Removal, vol. 17, Darmstadt, Germany, 2012.

[2] A. Chiesa, F. Alberto, Enabling technologies for active space debris removal: the cadet project, in: 3rd European Workshop on Space Debris Modeling and Remediation, Paris, France, 2014.

[3] K. Yoshida, H. Nakanishi, The TAKO (target collaborativize) flyer: a new concept for future satellite servicing, in: i-SAIRAS: International Symposium on Artificial Intelligence, Robotics and Automation in Space, Montreal, Canada, 2001, pp. 18–22.

[4] W. McMahan, et al., Field trials and testing of the OctArm continuum manipulator, in: Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006, ICRA2006, IEEE, Orlando, FL, USA, 2006, pp. 2336–2341.

[5] D. Reintsema, et al., DEOS—the German robotics approach to secure and de-orbit malfunctioned satellites from low earth orbits, in: Proceedings of the i-SAIRAS, Sapporo, Japan, 2010.

[6] T. Boge, et al., EPOS—a robotics-based hard ware-in-the-loop simulator for simulating satellite RvD operations, in: Proceedings of the 10th International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS), vol. 29, Sapporo, Japan, 2010.

[7] T.J. Debus, S.P. Dougherty, Overview and performance of the front-end robotics enabling near-term demonstration (FREND) robotic arm, in: AIAA Aerospace Conference, Reston, VA, USA, 2009.

[8] A. Ellery, A robotics perspective on human spaceflight, Earth Moon Planets 87 (3) (1999) 173–190.

[9] A. Ellery, et al., The case for robotic on-orbit servicing of spacecraft: spacecraft reliability is a myth, Acta Astronaut. 63 (5) (2008) 632–648.

[10] A. Flores-Abad, et al., A review of space robotics technologies for on-orbit servicing, Prog. Aerosp. Sci. 68 (2014) 1–26.

[11] M. Shan, et al., Review and comparison of active space debris capturing and removal methods, Prog. Aerosp. Sci. 80 (2016) 18–32.

[12] G. Hirzinger, et al., ROTEX—the first remotely controlled robot in space, in: IEEE International Conference on Robotics and Automation, IEEE, 1994.

[13] M. Oda, Space robot experiments on NASDA's ETS-VII satellite-preliminary overview of the experiment results, in: IEEE International Conference on Robotics and Automation, vol. 2. IEEE, 1999.

[14] N. Inaba, M. Oda, Autonomous satellite capture by a space robot: world first on-orbit experiment on a Japanese robot satellite ETS-VII, in: IEEE International Conference on Robotics and Automation, 2000, ICRA'00, vol. 2, IEEE, 2000.
[15] K. Yoshida, Engineering test satellite VII flight experiments for space robot dynamics and control: theories on laboratory test beds ten years ago, now in orbit, Int. J. Robot. Res. 22 (5) (2003) 321–335.
[16] Y. Ohkami, I. Kawano, Autonomous rendezvous and docking by engineering test satellite VII: a challenge of Japan in guidance, navigation and control—Breakwell memorial lecture, Acta Astronaut. 53 (1) (2003) 1–8.
[17] David A. Whelan, et al., DARPA orbital express program: effecting a revolution in space-based systems, in: International Symposium on Optical Science and Technology, International Society for Optics and Photonics, 2000.
[18] J. Shoemaker, M. Wright, Orbital express space operations architecture program, in: Defense and Security, International Society for Optics and Photonics, 2004.
[19] S. Stamm, P. Motaghedi, Orbital express capture system: concept to reality, in: Defense and Security, International Society for Optics and Photonics, 2004.
[20] R.B. Friend, Orbital Express program summary and mission overview, in: SPIE Defense and Security Symposium, International Society for Optics and Photonics, 2008.
[21] A.B. Bosse, et al., SUMO: spacecraft for the universal modification of orbits, in: Defense and Security, International Society for Optics and Photonics, 2004.
[22] J. Obermark, et al., SUMO/FREND: vision system for autonomous satellite grapple, in: Defense and Security Symposium, International Society for Optics and Photonics, 2007.
[23] B. Sullivan, et al., Phoenix project status 2013, 2013.
[24] A. Krolikowski, E. David, Commercial on-orbit satellite servicing: national and international policy considerations raised by industry proposals, New Space 1 (1) (2013) 29–41.
[25] T. Rupp, et al., Flight dynamics challenges of the German on-orbit servicing mission DEOS, in: 21st International Symposium on Space Flight Dynamics, 2009.
[26] Masaru Uchiyama, et al., Development of a flexible dual-arm manipulator testbed for space robotics, in: IEEE International Workshop on Intelligent Robots and Systems' 90'. Towards a New Frontier of Applications', Proceedings, IROS'90, IEEE, 1990.
[27] M. Yamano, et al., Capturing a spinning object by two flexible manipulators, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2000 (IROS 2000). Proceedings, vol. 3, IEEE, 2000.
[28] T. Miyabe, et al., An approach toward an automated object retrieval operation with a two-arm flexible manipulator, Int. J. Robot. Res. 23 (3) (2004) 275–291.
[29] S.-I. Nishida, et al., Space debris removal system using a small satellite, Acta Astronaut. 65 (1) (2009) 95–102.
[30] J. Pearson, Konstantin Tsiolkovski and the origin of the space elevator, AAS Hist. Ser. 26 (2005) 17–24.
[31] V. Chobotov, Gravity-gradient excitation of a rotating cable-counterweight space station in orbit, J. Appl. Mech. 30 (4) (1963) 547–554.
[32] C.R. O'dell, et al., Structure of the Barnard loop nebula as determined from Gemini 11 photographs, Astrophys. J. 150 (1967) 835.
[33] D.D. Lang, R.K. Nolting, Operations with tethered space vehicles, NASA Specl. Publ. 138 (1967) 55.
[34] G. Colombo, et al., The use of tethers for payload orbit transfer, NASA Rep. 82 (1982) 26705.
[35] I. Bekey, Tethers open new space options, Astronaut. Aeronaut. 21 (4) (1983) 32–40.
[36] I. Bekey, P.A. Penzo, Tether propulsion, Aerosp. Am. 24 (7) (1998) 40–43.

[37] J.A. Carroll, Tether applications in space transportation, Acta Astronaut. 13 (4) (1986) 165–174.
[38] G.A. Kyroudis, B.A. Conway, Advantages of tether release of satellites from elliptic orbits, J. Guid. Control. Dyn. 11 (5) (1988) 441–448.
[39] K. Kumar, et al., Effects of deployment rates and librations on tethered payload raising, J. Guid. Control. Dyn. 15 (5) (1992) 1230–1235.
[40] T. Yasaka, Tumble orbit transfer of spent satellites, J. Spacecr. Rocket. 27 (3) (1990) 348–350.
[41] I. Bekey, Tethering a new technique for payload deployment, Aerosp. Am. 35 (3) (1997) 36–40.
[42] K.D. Kumar, Payload deployment by reusable launch vehicle using tether, J. Spacecr. Rocket. 38 (2) (2001) 291–294.
[43] E.C. Lorenzini, et al., Mission analysis of spinning systems for transfers from low orbits to geostationary, J. Spacecr. Rocket. 37 (2) (2000) 165–172.
[44] S.W. Ziegler, M.P. Cartmell, Using motorized tethers for payload orbital transfer, J. Spacecr. Rocket. 38 (6) (2001) 904–913.
[45] K.D. Kumar, et al., Orbit transfer of service vehicle/payload through tether retrieval, Acta Astronaut. 54 (9) (2004) 687–698.
[46] C. Bonnal, et al., Optimization of tethered de-orbitation of spent upper stages, in: Proceedings of 4th European Conference on Space Debris, 2005, ESA-SP-587, 2005, pp. 361–366.
[47] A. Hyslop, et al., Designed a micro-launcher with tethered upper stage, in: Proceedings of 57th International Astronautical Conference, IAC; 2006, IAC-06-D2.3.03, 2006, pp. 1–15.
[48] V. Chobotov, Gravitational excitation of an extensible dumbbell satellite, J. Spacecr. Rocket. 4 (10) (1967) 1295–1300.
[49] R.Q. Robe, Salt flux in and classification of the Columbia River Estuary during high and low discharge, MS report, University of Washington, 1968.
[50] A.K. Misra, G.S. Diamond, Dynamics of a subsatellite system supported by two tethers, J. Guid. Control. Dyn. 9 (1) (1986) 12–16.
[51] S. Ciardo, S. Bergamaschi, A new method for a tethered system aided space station assembly, in: Proceedings of AGARD, Space Vehicle Flight Mechanics, 1990. p(SEE N 90-27741 22-18).
[52] A.K. Banerjee, T.R. Kane, Pointing control, with tethers as actuators, of a Space Station supported platform, J. Guid. Control Dynam. 16 (2) (1993) 396–399.
[53] K. Kumar, Satellite attitude stabilization through tether, Acta Astronaut. 35 (6) (1995) 385–390.
[54] K. Kumar, K.D. Kumar, Open-loop satellite librational control in elliptic orbits through tether, Acta Astronaut. 41 (1) (1997) 15–21.
[55] K. Kurnar, K.D. Kumar, Satellite attitude maneuver through tether: a novel concept, Acta Astronaut. 40 (2) (1997) 247–256.
[56] K.D. Kumar, T. Yasaka, Satellite attitude stabilization through kite-like tether configuration, J. Spacecr. Rocket. 39 (5) (2002) 755–760.
[57] M. Fedi Casas, Dynamics and control of tethered satellite formations in low-Earth orbits, Materia (s) 24 (2015). 04-2015.
[58] T. Williams, K. Moore, Dynamics of tethered satellite formations, Adv. Astronaut. Sci. 112 (2002) 1219–1235.
[59] A.K. Misra, V.J. Modi, A survey on the dynamics and control of tethered satellite systems, in: Tethers in Space, vol. 1, 1986.
[60] K.D. Kumar, Review on dynamics and control of nonelectrodynamic tethered satellite systems, J. Spacecr. Rocket. 43 (4) (2006) 705–720.

[61] G. Avanzini, M. Fedi, Refined dynamical analysis of multi-tethered satellite formations, Acta Astronaut. 84 (2013) 36–48.
[62] G. Liu, et al., Nonlinear dynamics and station-keeping control of a rotating tethered satellite system in halo orbits, Chin. J. Aeronaut. 26 (5) (2013) 1227–1237.
[63] Z. Cai, X. Li, H. Zhou, Nonlinear dynamics of a rotating triangular tethered satellite formation near libration points, Aerosp. Sci. Technol. 42 (2015) 384–391.
[64] J. Zhao, Z. Cai, Nonlinear dynamics and simulation of multi-tethered satellite formations in Halo orbits, Acta Astronaut. 63 (5) (2008) 673–681.
[65] A. Pizarro-Chong, A.K. Misra, Dynamics of multi-tethered satellite formations containing a parent body, Acta Astronaut. 63 (11) (2008) 1188–1202.
[66] J. Zhao, Z. Cai, Z. Qi, Dynamics of variable-length tethered formations near libration points, J. Guid. Control. Dyn. 33 (4) (2010) 1172–1183.
[67] S.-J. Chung, E.M. Kong, D.W. Miller, Dynamics and control of tethered formation flight spacecraft using the SPHERES testbed, in: 2005 AIAA Guidance, Navigation and Control Conference, 2005.
[68] M. Quadrelli, Modeling and dynamics analysis of tethered formations for space interferometry, in: AAS/AIAA Spaceflight Mechanics Meeting, Santa Barbara, CA, 2001, 2001.
[69] K. Nakaya, S. Matunaga, On attitude maneuver of spinning tethered formation flying based on virtual structure method, in: AIAA Guidance, Navigation, and Control Conference, 2005.
[70] O. Mori, S. Matunaga, Formation and attitude control for rotational tethered satellite clusters, J. Spacecr. Rocket. 44 (1) (2007) 211–220.
[71] C. Menon, C. Bombardelli, Self-stabilising attitude control for spinning tethered formations, Acta Astronaut. 60 (10) (2007) 828–833.
[72] H. Liang, J. Wang, Z. Sun, Robust decentralized coordinated attitude control of spacecraft formation, Acta Astronaut. 69 (5) (2011) 280–288.
[73] V.A. Sarychev, Positions of relative equilibrium for two bodies connected by a spherical hinge in a circular orbit, Cosm. Res. 5 (1967) 314.
[74] E.C. Lorenzini, A three-mass tethered system for micro-g/variable-g applications, J. Guid. Control. Dyn. 10 (3) (1987) 242–249.
[75] A. Pizarro-Chong, A.K. Misra, Dynamics of a multi-tethered satellite formation, in: AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Providence, 2004.
[76] K.D. Kumar, T. Yasaka, Rotation formation flying of three satellites using tethers, J. Spacecr. Rocket. 41 (6) (2004) 973–985.
[77] A.D. Guerman, et al., Stationary configurations of a tetrahedral tethered satellite formation, J. Guid. Control. Dyn. 31 (2) (2008) 424–428.
[78] Z. Cai, X. Li, W. Zhigang, Deployment and retrieval of a rotating triangular tethered satellite formation near libration points, Acta Astronaut. 98 (2014) 37–49.
[79] M.P. Cartmell, D.J. McKenzie, A review of space tether research, Prog. Aerosp. Sci. 44 (2008) 1–21.
[80] E.M. Levin, Dynamic analysis of space tether missions, Adv. Astronaut. Sci. (2007) 126.
[81] K.D. Kumar, Review of dynamics and control of nonelectrodynamic tethered satellite systems, J. Spacecr. Rocket. 43 (4) (2006) 705–720.
[82] P. Mantri, A.P. Mazzoleni, D.A. Padgett, Parametric study of deployment of tethered satellite systems, J. Spacecr. Rocket. 44 (2) (2007) 412–423.
[83] B.S. Yu, D.P. Jin, Deployment and retrieval of tethered satellite system under J 2 perturbation and heating effect, Acta Astronaut. 67 (7) (2010) 845–853.
[84] A. Djebli, M. Pascal, L. El Bakkali, Laws of deployment/retrieval in tether connected satellites systems, Acta Astronaut. 45 (2) (1999) 61–73.
[85] E. Kim, S.R. Vadali, Modeling issues related to retrieval of flexible tethered satellite systems, J. Guid. Control. Dyn. 18 (5) (1995) 1169–1176.

[86] S. Pradeep, A new tension control law for deployment of tethered satellites, Mech. Res. Commun. 24 (3) (1997) 247–254.
[87] V.J. Modi, S. Pradhan, A.K. Misra, Off-set control of the tethered systems using a graph theoretic approach, Acta Astronaut. 35 (6) (1995) 373–384.
[88] M. Pascal, A. Djebli, L. El Bakkali, A new deployment/retrieval scheme for a tethered satellite system, intermediate between the conventional scheme and the crawler scheme, J. Appl. Math. Mech. 65 (4) (2001) 689–696.
[89] A. Djebli, L. El Bakkali, M. Pascal, On fast retrieval laws for tethered satellite systems, Acta Astronaut. 50 (8) (2002) 461–470.
[90] Y. He, B. Liang, W. Xu, Study on the stability of tethered satellite system, Acta Astronaut. 11 (2011) 1964–1972.
[91] J.L. Tang, et al., Dynamics of variable-length tethers with application to tethered satellite deployment, Commun. Nonlinear Sci. Numer. Simul. 16 (8) (2011) 3411–3424.
[92] H.A. Fujii, H. Kojima, Optimal trajectory analysis for deployment/retrieval of tethered subsatellite using metric, J. Guid. Control. Dyn. 26 (1) (2003) 177–179.
[93] A.K. Banerjee, T.R. Kane, Tethered satellite retrieval with thruster augmented control, J. Guid. Control. Dyn. 7 (1) (1984) 45–50.
[94] H. Fujii, S. Ishijima, Mission function control for deployment and retrieval of a subsatellite, J. Guid. Control. Dyn. 12 (2) (1989) 243–247.
[95] S.R. Vadali, E. Kim, Nonlinear feedback deployment and retrieval of tethered satellite systems, J. Guid. Control. Dyn. 15 (1) (1992) 28–34.
[96] E. Netzer, T.R. Kane, Deployment and retrieval optimization of a tethered satellite system, J. Guid. Control. Dyn. 16 (6) (1993) 1085–1091.
[97] H.A. Fujii, S. Anazawa, Deployment/retrieval control of tethered subsatellite through an optimal path, J. Guid. Control. Dyn. 17 (6) (1994) 1292–1298.
[98] K. Kokubun, H.A. Fujii, Deployment/retrieval control of a tethered subsatellite under effect of tether elasticity, J. Guid. Control. Dyn. 19 (1) (1996) 84–90.
[99] J.J. Lakso, V.L. Coverstone, Optimal tether deployment/retrieval trajectories using direct collocation, Urbana 51 (2000) 61801.
[100] H. Wen, D. Jin, H. Hu, Three-dimensional optimal deployment of a tethered subsatellite with an elastic tether, Int. J. Comput. Math. 85 (6) (2008) 915–923.
[101] H. Wen, D.P. Jin, H.Y. Hu, Optimal feedback control of the deployment of a tethered subsatellite subject to perturbations, Nonlinear Dyn. 51 (4) (2008) 501–514.
[102] P. Williams, Deployment/retrieval optimization for flexible tethered satellite systems, Nonlinear Dyn. 52 (1–2) (2008) 159–179.
[103] B. Barkow, A. Steindl, H. Troger, A targeting strategy for the deployment of a tethered satellite system, IMA J. Appl. Math. 70 (5) (2005) 626–644.
[104] B. Barkow, et al., Various methods of controlling the deployment of a tethered satellite, J. Vib. Control. 9 (1–2) (2003) 187–208.
[105] M. Nohmi, Mission design of a tethered robot satellite stars for orbital experiment, in: 18th IEEE International Conference on Control Applications Part of 2009 IEEE Multi-Conference on Systems and Control Saint Petersburg, Russia, July 8–10, 2009, 2009.
[106] P.B. Beda, On requirements for attitude dynamics and stability control for tethered satellite systems, JSME Int. J., Ser. C 43 (3) (2000) 678–683.
[107] S. Bergamaschi, F. Bonon, Coupling of tether lateral vibration and subsatellite attitude motion, J. Guid. Control. Dyn. 15 (5) (1992) 1284–1286.
[108] K. Godard, D. Kumar, B. Tan, Nonlinear optimal control of tethered satellite systems using tether offset in the presence of tether failure, Acta Astronaut. (2010) 1434–1448.
[109] K. Godard, D. Kumar, B. Tan, Fault-tolerant stabilization of a tethered satellite system using offset control, J. Spacecr. Rocket. 45 (5) (2008) 1070–1084.

[110] N. Yuya, S. Fumiki, N. Shinichi, Guidance and control of "Tethered Retriever" with collaborative tension-thruster control for future on-orbit service missions, European Space Agency, ESA SP, 2005.

[111] D. Wang, et al., Coordinated control of tethered space robot using mobile tether attachment point in approaching phase, Adv. Space Res. 54 (6) (2014) 1077–1091.

[112] P. Huang, Z. Hu, Z. Meng, Coupling dynamics modelling and optimal coordinated control of tethered space robot, Aerosp. Sci. Technol. 41 (2015) 36–46.

[113] M. Nohmi, D.N. Nenchev, M. Uchiyama, Tethered robot casting using a spacecraft-mounted manipulator, J. Guid. Control. Dyn. 24 (4) (2001) 827–833.

[114] M. Nohmi, D.N. Nenchev, M. Uchiyama, Momentum control of a tethered space robot through tether tension control, in: IEEE International Conference on Robotics and Automation, 1998, Proceedings, vol. 1, IEEE, 1998.

[115] X. Xu, P. Huang, J. Ma, Coordinated position and attitude control method of Tethered Space Robo, in: IEEE International Conference on Robotics and Biomimetics (ROBIO), 2013, IEEE, 2013.

[116] W. Steiner, A. Steindl, H. Troger, Center manifold approach to the control of a tethered satellite system, Appl. Math. Comput. 70 (2) (1995) 15–327.

[117] F. Vestroni, A. Luongo, M. Pasca, Stability and control of transversal oscillations of a tethered satellite system, Appl. Math. Comput. 70 (2) (1995) 343–360.

[118] F. Dignath, W. Schiehlen, Control of the vibrations of a tethered satellite system, J. Appl. Math. Mech. 64 (5) (2000) 715–722.

[119] A.K. Misra, V.J. Modi, D.M. Xu, Thruster-augmented active control of a tethered subsatellite system during its retrieval, J. Guid. Control. Dyn. 9 (6) (1986) 663–672.

[120] F. Zhang, et al., On-line estimation of inertia parameters of space debris for its tether-assisted removal, Acta Astronaut. 107 (2015) 150–162.

[121] P. Huang, et al., Post-capture attitude control for a tethered space robot–target combination system, Robotica (2014) 1–22.

[122] D. Wang, P. Huang, J. Cai, Detumbling a tethered space robot-target combination using optimal control, in: 4th IEEE International Conference on Information Science and Technology (ICIST), 2014, IEEE, 2014.

[123] L. Sun, G. Zhao, H. Huang, Stability and control of tethered satellite with chemical propulsion in orbital plane, Nonlinear Dyn. 74 (4) (2013) 1113–1131.

[124] H.T. Liu, et al., An investigation on tether-tugging de-orbit of defunct geostationary satellites, Sci. China Technol. Sci. 55 (7) (2012) 2019–2027.

[125] S.H.P. Won, F. Golnaraghi, W.W. Melek, A fastening tool tracking system using an IMU and a position sensor with Kalman filters and a fuzzy expert system, IEEE Trans. Ind. Electron. 56 (5) (2009) 1782–1792. May.

[126] Y.M. Zhao, Y. Lin, F.F. Xi, S. Guo, Calibration-based iterative learning control for path tracking of industrial robots. IEEE Trans. Ind. Electron. 62 (5) (2015) 2921–2929, https://doi.org/10.1109/TIE.2014.2364800.

[127] G.L. Du, P. Zhang, Online serial manipulator calibration based on multisensory process via extended Kalman and particle filters, IEEE Trans. Ind. Electron. 61 (12) (2014) 6852–6859.

[128] G. Zhai, J.R. Zhang, Space tether net system for debris capture and removal, in: 4th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC), 2012, vol. 1, IEEE, 2012.

FURTHER READING

[1] Z. Guang, Z. Jing-rui, Space tether net system for debris capture and removal, in: 4th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC), 2012, vol. 1, IEEE, 2012.