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REVIEW

Advances in dynamics and control of tethered satellite systems

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Abstract The concept of tethered satellite system (TSS) promises to revolutionize many aspects of space exploration and exploitation. It provides not only numerous possible and valuable applications, but also challenging and interesting problems related to their dynamics, control, and physical implementation. Over the past decades, this exciting topic has attracted significant attention from many researchers and gained a vast number of analytical, numerical and experimental achievements with a focus on the two essential aspects of both dynamics and control. This review article presents the historic background and recent hot topics for the space tethers, and introduces the dynamics and control of TSSs in a progressive manner, from basic operating principles to the state-of-the-art achievements.

Keywords Tethered satellite system · Space tether · Dynamics · Control

1 Introduction

Space tethers are long cables, made of long strands of high-strength fibers or conducting wires used to connect two or more end-bodies in the space environment [1,2]. A rudimentary example is the life-lines for astronauts carrying out spacewalks during manned orbital missions. Many applications proposed for space tethers can be encapsulated under the concept of tethered satellite system (TSS), namely, two or more satellites (spacecrafts) connected by tethers [3]. There are, in general, three dynamic phases of a typical TSS mission: deployment, station-keeping, and retrieval phases [1]. The TSS for either a non-conductive tether application or a conductive tether application is often referred to as a momentum exchange tether (MET) system or an electro-dynamic tether (EDT) systems, respectively [4]. The later can interact with the Earth's magnetic field and ionospheric plasma so as to generate thrust or drag forces without expending propellant [5]. Recent years have witnessed much attention paid to the TSS for formation flying, that is, a cluster of tether-connected satellites is coordinated to perform various advanced missions, for example, variable-baseline interferometric observations [6,7].

Strictly speaking, space tether is not a new concept. The idea goes back to 1895 when Tsiolkovsky, the Russian pioneer in space technology, conceived an "orbital tower" that would reach to synchronous heights from the Earth's surface [8]. An object after climbing such a structure, without the use of costly rockets, would theoretically have enough orbital velocity to remain in a geosynchronous orbit. However, there was little further studies after Tsiolkovsky for many years until the concept reemerged in the form of a space elevator [9,10], namely, a tether structure deployed from a geostationary satellite to the Earth. The concept seemed futuristic in 1960s because no material available had the required mechanical properties to build such a space elevator. Noticeably, interest on the space elevator has been recently revived [11–15] due to the discovery of super mechanical properties of carbon nanotubes [16].

In 1960s, the NASA Gemini VI and VII manned space missions first realized the space tether system and supported its possible use in generating artificial gravity. The proposal of "Shuttle-borne Skyhook" concept marked the beginning of practical studies on the TSS technology [17,18]. Since then,

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numerous scientists have performed unceasing researches, striving to transfer TSS from a rather wild concept to a technically feasible system. Several missions have been launched to verify the concept of space tethers, including Charge-1 in 1983 and Charge-2 in 1985 [19], OEDIPUS-A (Observations of Electric-Field Distribution in the Ionospheric Plasma—a Unique Strategy) in 1989 and OEDIPUS-C in 1995 [1], TSS-1 in 1992 and TSS-1R in 1996 [1], SEDS-1 (Small Expendable Deployer System) in 1993 and SEDS-2 in 1994 [1], PMG (Plasma Motor Generator) in 1993 [1], TiPS (Tether Physics and Survivability) in 1996 [1], YES (Young Engineers Satellite) in 1997 [20] and YES2 in 2007 [21], ATEx (Advanced Tether Experiment) in 1998 [22], MAST (Multi-Application Survivable Tether) in 2007 [23]. Those missions, albeit in the experimental stages only, have demonstrated several important aspects of tether technology, including tether deployment and spin stabilization (OEDIPUS-C), gravity-gradient stabilization and tether retrieval (TSS-1), electric current generation (TSS-1R), long tether deployment (SEDS-1) and feedback control with brake (SEDS-2), long-term survivability (TiPS), and electro-dynamic orbital boost (PMG).

With significant innovations for years, the concept of TSS has evolved into rather complex forms, such as a double-pyramid tethered satellite formation [24]. Numerous important applications have been identified for the potential use of the TSS, such as artificial gravity generation [25–27], satellite stabilization [28,29], aero-assisted maneuvering [30,31], tether-assisted re-entry [21,32], payload rendezvous and capture [33–37], propellantless launch and orbital transfer [38–42], debris mitigation [43–47], Earth observation and deep space exploration [6,7,48,49], etc. Despite the conceptual richness of TSS, the development of TSS technology may follow a step-wise road map with a logical evolution from the concepts realizable by using current or near-future technologies, towards more complex and highly beneficial applications [50]. Many lowest-cost, high-payoff systems have been suggested for immediate or near-term implementation [51].

Over the past decades, numerous attempts have been made to gain an insight into the complex dynamics and control of the TSS by using a variety of models, many of which have been summarized in several excellent review articles [2–4] and the handbook [1]. A detailed dynamic analysis of tether systems can also be found in the monograph [52]. What presented in the subsequent section is a short summary of basic operating principles of space tether systems. The aspects of dynamics and control are discussed in Sect. 3 with a focus on some recent advances.

2 Fundamental principles and applications

Tethered satellite systems are quite diverse in applications, but share some operating principles in common. This section summarizes three common principles, that is, the concepts of gravity gradient, momentum exchange and electro-dynamic interaction [1]. For brevity, the basic principles are introduced through a simple model, namely, two massive end-bodies coupled together via a low-mass tether moving on an equatorial circular orbit.

2.1 Effect of gravity gradient

The effect of gravity gradient plays a fundamental role in many tether applications. The forces of gravity gradient arise from the fact that, when two connected satellites are moving on different orbit heights, each of the satellites are subject to different gravitational and centrifugal forces. As shown in Fig. 1, for example, two massive end-bodies M and m orbiting at different heights share a common orbital angular rate Ω. Upon the assumption for a massless tether, the equation of motion of this system can be expressed as

$$\begin{aligned} \mu m/r_1^2 - T &= m\Omega^2 r_1, \\ \mu M/r_2^2 + T &= M\Omega^2 r_2, \end{aligned} \tag{1}$$

where T is the tensional force along the tether. Solving Eq. (1) for T and Ω yields

$$\begin{aligned} \Omega^2 &= \frac{\mu}{r_1^2 r_2^2}\frac{mr_2^2 + Mr_1^2}{mr_1 + Mr_2}, \\ T &= \frac{\mu mM}{r_1^2 r_2^2}\frac{r_2^3 - r_1^3}{mr_1 + Mr_2}, \end{aligned} \tag{2}$$

where μ is the gravitational constant of the Earth. The resulting force is directed outward for the end-body on the higher orbit and inward for the lower one. The gravity-gradient force on an end-body increases as its distance from the center of gravity increases and as the orbital radius decreases. The effect of gravity gradient causes the end-bodies to be "pulled" apart and keeps the tether under tension, and makes the system self-stabilized in a stable relative equilibrium position

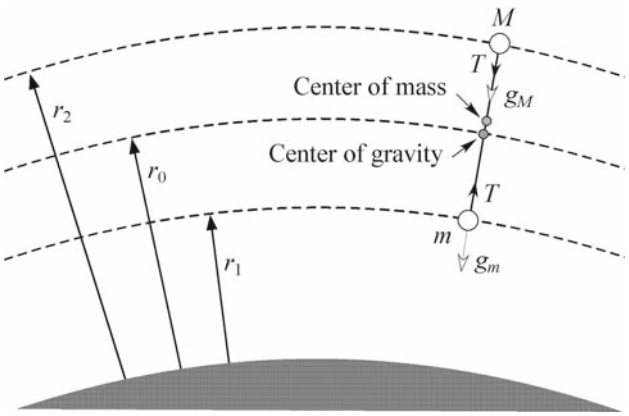


Fig. 1 The forces due to gravity gradient at different heights

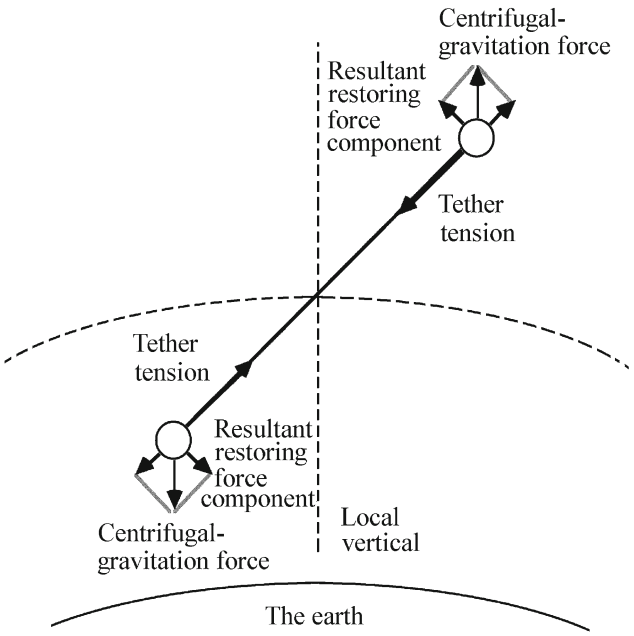


Fig. 2 The restoring forces on tethered end-bodies [1]

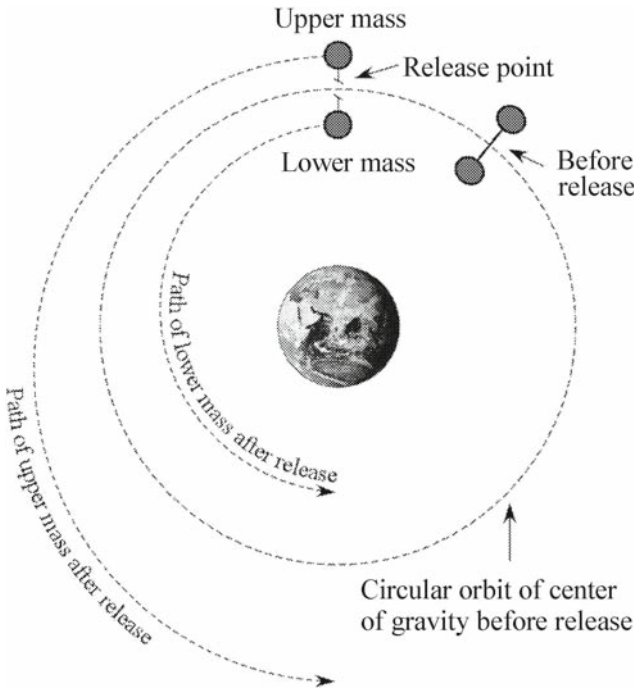


Fig. 3 The orbits of tethered satellites after hanging release

along local vertical. As shown in Fig. 2, displacing the system from the equilibrium position produces restoring forces at each end-body, which trend to return the tether back to the radial direction [1].

The principle of gravity gradient has found many important applications, such as the microgravity experiment, the artificial gravity generation and the stabilization of TSSs [1]. Two ambitious examples in case are gravity-gradient-stabilized space elevators [14], and three-dimensional tethered formations for Earth observation application, which may use the gravity-gradient forces to stabilize the spin axis along nadir [24].

2.2 Momentum exchange

The concept of momentum exchange, supporting numerous applications of mechanical tethers, promises a cheaper way of space transportation over traditional chemical propulsion method [4,50]. The basic idea of MET is to boost one end-body into a higher orbit at the cost of deboosting the other through the momentum exchange between them. A good example is the scenario of a tether-assisted payload re-entry from the International Space Station (ISS). The momentum exchange plays a bi-beneficial role which achieves free altitude gain of the ISS while deorbitting the payload back to the Earth [1]. In its basic form, the MET system involves a hanging tether aligned along the gravity vector, with one end-body on an upper orbit and the other on a lower orbit [53]. Two end-bodies initially move at the same orbital angular velocity as the overall center of gravity. Severing the tether releases the two end-bodies into their new orbits. As shown in Fig. 3, the upper end-body is boosted into an elliptical orbit with the release point as its orbit perigee because it moves at higher angular velocity than the local circular velocity when released. The situation is exactly reversed for the lower end-body, which is at its apogee at the release point and then goes into a different elliptical orbit [54].

The hanging MET can also swing or spin to improve the performance of the momentum exchange. This is because a prograde swing or spin will increase the velocity of the upper payload and decrease that of the lower one [39]. MET systems may be best-suited for the applications involving orbit transfer, such as tether-assisted re-entry, propellantless space transportation and debris deorbit. In addition, both swing-up and spin-up processes critical for many TSSs have exploited the principle of momentum exchange in one way or another, with a good example of spinning artificial gravity generation system [26]. Tethered momentum transfer has successfully demonstrated itself in the TSS1-R, SEDS-1 and SEDS-2, and YES2 missions.

2.3 Electro-dynamic interaction

A long conductive tether, namely an EDT, is able to generate large electro-motive force (EMF) along the length of the tether when it is orbiting around a planet with a magnetic field, as shown in Fig. 4.

The induced EMF may amount to several kilovolts for an EDT (of length order of 10–20 km) moving on a Low Earth

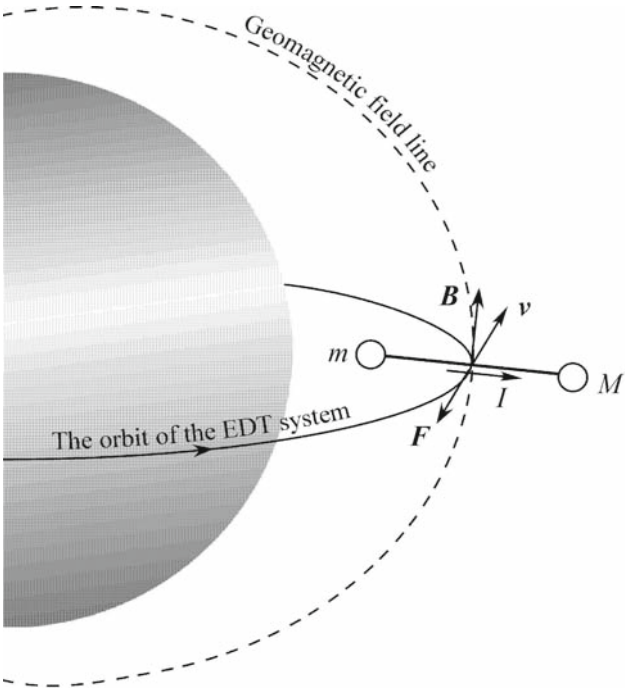


Fig. 4 The schematic view of an EDT system

orbit (LEO). On the basis of a rectilinear tether assumption, the underlying equation for the EMF can be written as follows [1]

$$V = L(\boldsymbol{v} \times \boldsymbol{B}) \cdot \boldsymbol{i}, \tag{3}$$

where V, $\boldsymbol{v}$, L, $\boldsymbol{B}$, and $\boldsymbol{i}$ are induced EMF, the tether velocity (relative to the geomagnetic field), the tether length, the strength of magnetic field and a unit vector aligned along the tether, respectively. The large EMF is of little practical use if the EDT completely insulated from the ambient plasma, since it only results in an internal redistribution of charges [55]. One feasible way to sustain an electric current flow has been demonstrated in TSS-1R mission, in which electric contacts were established between the EDT and the ionosphere. Electrons can be collected passively by the large exposed conductive surface of a spherical collector and then emitted at the other end of the tether via an electronic gun or hollow cathode emitter. The efficiency of electric contacts has a significant influence on the magnitude of the current drawn from the ionosphere. In recent years, more effective ways of electric contact have been suggested for future applications, for instance, the field-emission cathodes (FEC) for electron emission [56] and the bare tether for electron collection [5].

The electric current flowing in an EDT will, in turn, interact with the Earth's magnetic field to cause a Lorentz force. In the case of an insulated tether with two ends exposed for charge transfer, the electric current is uniform along the tether and the underlying equation for the Lorentz force can be written as follows [1]

$$\boldsymbol{F} = I L \boldsymbol{i} \times \boldsymbol{B}, \tag{4}$$

where I is the current strength and its direction is the same as $\boldsymbol{i}$. If not actively controlled by any external power, the Lorentz force $\boldsymbol{F}$ always has a component opposite to the direction of tether motion relative to geomagnetic field [5]. As shown in Fig. 5a, the Lorentz force acts as a drag for an EDT system on a prograde LEO orbit because the orbital velocity of the EDT is larger than the velocity of the magnetic field lines. The situation is exactly reversed for an EDT orbiting beyond the geosyncronous earth orbit (GEO) since the EDT now lags behind the geomagnetic field and experiences the Lorentz force as a thrust [55]. On the other hand, as shown in Fig. 5b, if powered by solar panels or other power supplies, an EDT could carry the current opposite to the direction of the induced electric field, whereby the Lorentz force could be actively controlled via the voltage applied on the tether [55].

Most of the technological interest of EDT arises from their possible utilization for providing propellantless propulsion and emergency power. EDT systems are of particular potentials for reboosting the orbit of the ISS or spacecrafts, and deorbiting defunct satellite or space debris [5]. Recently, a combined concept of both Momentum eXchange and Electro-dynamic Reboost, named MXER for short, was proposed for propellantless orbital transfer [42]. The concept of MXER is of great value because the MET system without reboost could only perform a very limited number of times of momentum exchanges due to the energy loss during its use for boosting payloads. Furthermore, de-orbiting devices based on bare-tether have received great attention for mitigating the growth of orbital debris [57], with cross-references to the concept of Terminator Tether [43] and the proposed Propulsive Small Expendable Deployer System (ProSEDS) mission [58].

3 Dynamics and control of TSSs

Generally speaking, the dynamics and control of any TSS are quite complex. Because of their overall flexibility, the tethers are strongly susceptible to undergoing a complicated set of librations and vibrations when they are placed into a space environment and coupled with flexible satellites. In particular, the EDT system working in an inclined orbit deserves special attention paid to stability because of the continuous pumping of energy from electro-magnetic forces into the tether attitude motion [59]. The problem becomes even more challenging when the deployment and retrieval parts of a TSS mission are taken into consideration because the liberations and vibrations of tether can grow dramatically due to the effect of the Coriolis accelerations [60]. The oscillatory motions of a tether can be exploited for swing-up or spin-up in some scenarios, for example, for rotating tethered formation flying. However, if not carefully controlled, the

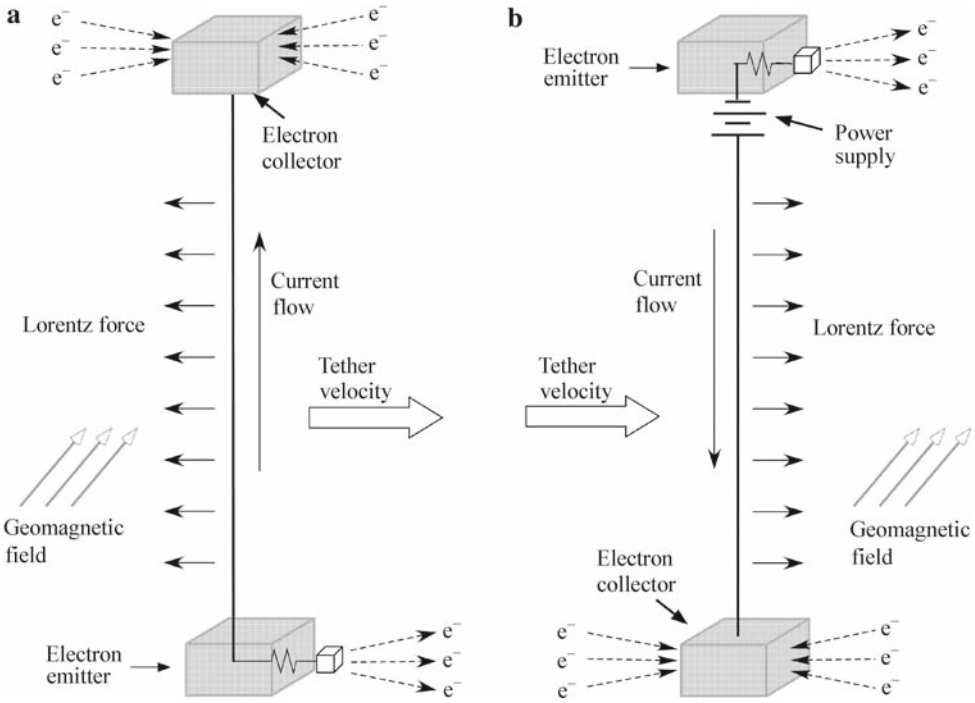


Fig. 5 Two EDT systems on LEO **a** without power supply, and **b** with power supply

motions with large amplitudes may result in an excessively high tensional stress beyond the strength of tether material and may lead to the failure of a whole TSS.

In addition to the considerations for safety, the performance requirements in TSS missions are often quite demanding from a viewpoint of control. For example, in the case of space interferometry applications, the tethered satellites must act as a single unit with precise relative position, and need to be accurately pointed towards the same inertial target while keeping a precise relative attitude for the purpose of optical beam transmission [29]. Furthermore, the establishment of engineering feasibility is usually only the baseline requirement for the control of a TSS, in which high performance is essential to ensure the mission success. However, it is a fundamental, but open problem in control theory to synthesize the nonlinear optimal control for such a complex system. It is also necessary to notice that one peculiarity of controlling a TSS is how to apply the control action to the system. Even though the control action can be realized through thrusters, a simple but effective way is to realize the control by adequately adjusting the tether tension, the tether length, the attachment position (offset) or the combinations of those parameters. These approaches are permitted by the TSS configuration but not feasible with other satellites [3,4].

3.1 Tether models

Over the past decades, numerous studies have been made to gain an insight into the complex dynamics and control of TSSs based on a great variety of models. The simplest, but reasonable model for a TSS is composed of a group of massive bodies connected by massless tethers, with the attitude dynamics of satellites and tether flexibility neglected, and often referred to as a "dumbbell" system when only two massive bodies are involved [61].

Figure 6 shows an idealized dumbbell system consisting of a spaceship of mass M and a subsatellite of mass m connected by a straight massless tether of variable length l. The spaceship and subsatellite are modeled by a point-mass approximation. The attitude of the tether is given by the in-plane pitch angle θ and the out-of-plane roll angle ϕ. In the case of a circular orbit, the equation of motion in dimensionless variables reads

$$\begin{aligned}
&\ddot{\theta} + 2(\dot{\theta} - 1)(\dot{\xi}/\xi - \dot{\phi}\tan\phi) + 3\sin\theta\cos\theta \\
&\quad = Q_\theta/(m_e\Omega^2 l_c^2 \xi^2 \cos^2\varphi), \\
&\ddot{\phi} + 2\dot{\phi}\dot{\xi}/\xi + ((\dot{\theta} - 1)^2 + 3\cos^2\theta)\sin\phi\cos\phi \\
&\quad = Q_\phi/(m_e\Omega^2 l_c^2 \xi^2), \\
&\ddot{\xi} - \xi(\dot{\phi}^2 + (\dot{\theta} - 1)^2\cos^2\phi + 3\cos^2\phi\cos^2\theta - 1) \\
&\quad = -T/(m_e\Omega^2 l_c),
\end{aligned} \tag{5}$$

where the dot represents the derivative with respect to the true anomaly, $\xi = l/l_c$ is the dimensionless length of the tether with l_c being a reference length, Ω is the orbital angular velocity, m_e is defined as $m_e = Mm/(M + m)$, T is the tensional force along the tether, Q_θ and Q_ϕ are the generalized forces in the pitch and roll generalized coordinates, respectively. The dumbbell model can be extended to the case when the longitudinal flexibility (elasticity) of the tether is taken in account [62]. To this end, substituting $\xi = (1+\varepsilon)\xi_0$ and $T = EA\varepsilon$ into Eq. (5) yields the following dynamic equation

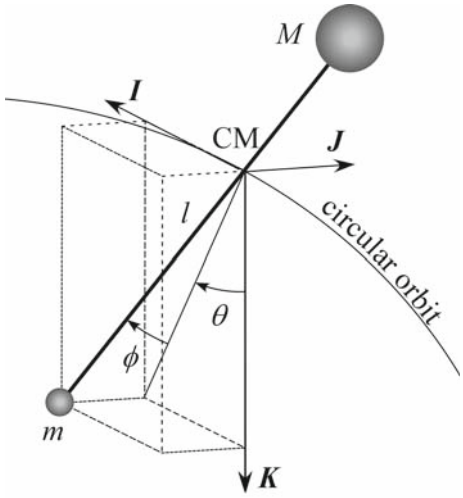


Fig. 6 The schematic view of a TSS on a circular orbit at angular rate Ω. The center of mass of the TSS is denoted by CM, the ***I*** coordinate points in flight direction, the ***J*** coordinate is perpendicular to the orbit plane, and the ***K*** coordinate points to the center of the earth

$$
\begin{aligned}
&\ddot{\theta} + 2(\dot{\theta} - 1)(\dot{\varepsilon}/(1+\varepsilon) + \dot{\xi}_0/\xi_0 - \dot{\phi}\tan\phi) \\
&\quad +3\sin\theta\cos\theta = \frac{Q_\theta}{m_e\Omega^2 l_c^2(1+\varepsilon)^2\xi_0^2\cos^2\phi}, \\
&\ddot{\phi} + 2\dot{\phi}(\dot{\varepsilon}/(1+\varepsilon) + \dot{\xi}_0/\xi_0) + ((\dot{\theta}-1)^2 + 3\cos^2\theta) \\
&\quad \times \sin\phi\cos\phi = \frac{Q_\phi}{m_e\Omega^2 l_c^2(1+\varepsilon)^2\xi_0^2}, \\
&(1+\varepsilon)\ddot{\xi}_0 + 2\dot{\xi}_0\dot{\varepsilon} + \xi_0\ddot{\varepsilon} - (1+\varepsilon)\xi_0(\dot{\phi}^2 \\
&\quad +((\dot{\theta}-1)^2 + 3\cos^2\theta)\cos^2\phi - 1) = \frac{-EA\varepsilon}{m_e\Omega^2 l_c},
\end{aligned}
\tag{6}
$$

where ξ_0 is the dimensionless unstrained tether length, and the strain ε characterizes the longitudinal elongation of the tether with stiffness EA. Such a kind of basic models has gained a wide popularity because of their simplicity in mathematics and their feasibility in controller design. If higher accuracy is required, the basic models can be extended to include the flexible modes of the tether, the attitude dynamics of satellites, and the effect of external forces, such as gravitational perturbation, aerodynamic drag, solar radiation pressure, and electro-dynamic force as well. The models of much higher fidelity have been actively pursued as numerical tools to simulate the dynamics of TSSs and verify the performance of control algorithms although they are usually not suitable for analytical analysis [3].

At least, two kinds of approaches have been proposed to simulate fully flexible tethers. The first kind of approaches is based on a continuum model and a modal approximation of the tether displacements [63]. The modal functions used for approximation are usually taken as the functions in time because of the time dependence of the tether length during the tether deployment and retrieval. In the second kind of approaches, the tether is discretized physically into a collection of interconnected elements, either based on the finite element method (FEM) [64] or in the form of a series of beads (point masses) connected by massless rigid rods [65], springs [66,67], or combinations of springs and dashpots [46,68]. An interesting problem is how to use the discrete models for the simulation of the tether deployment and retrieval. In the case of discrete model, there are two kinds of schemes usually used to deal with the tether with variable length [64]. In the first scheme, the tether is represented as a fixed number of elements and the deployment (or retrieval) process is simulated by simultaneously changing the physical properties of all elements. The other scheme involves a variable number of elements, and simulates the deployment (or retrieval) process by only varying the length and mass of the first element, namely the one nearest to the towing point on the deployer side. Additionally, an element will be added to (or removed from) the start of the chain of the elements when certain criterion is met, for instance, the length of the first element exceeding (or reducing below) a predetermined amount.

Generally speaking, each of the approaches has its merits for simulating flexible tethers. Detailed comparisons of those approaches have been made [64,66,69] and can be taken as references for selecting an appropriate approach and making it work best when a specific problem is regarded. As may be expected, furthermore, those models will become even more sophisticated when they are coupled with the flexible satellites in diverse formations and subject to a variety of external perturbations and control inputs. The problems of great complexity are usually solved by using general-purpose software based on the principles of multibody dynamic system [70] or FEM [64].

3.2 Dynamics and control of two-body TSSs

Much of the early work focused on the dynamics and control of two-body TSSs, which not only promise a great variety of applications but also provide a fundamental basis for the research on more complicated TSSs. This subsection attempts to present a brief survey on this fundamental subject, with a focus on recent advances.

Krupa et al. [60] made a systematic discussion on the modeling, dynamics and control of two-body TSSs. They began with the derivation of the dynamic equations from both balance principles and variational principles, and then moved on to address the numerical solution based on FEM, the control of deployment, the stability of relative equilibria and the chaotic dynamics, and finally suggested a few open problems for future investigation. Yu [71] presented a range-rate control scheme for the TSS model with a mass-distributed and flexible tether, and investigated the stability of the stationary (quasi-stationary) configurations during the station-keeping phase (deployment and retrieval phases). Takeichi et al. [72] studied the periodic solution of the librational

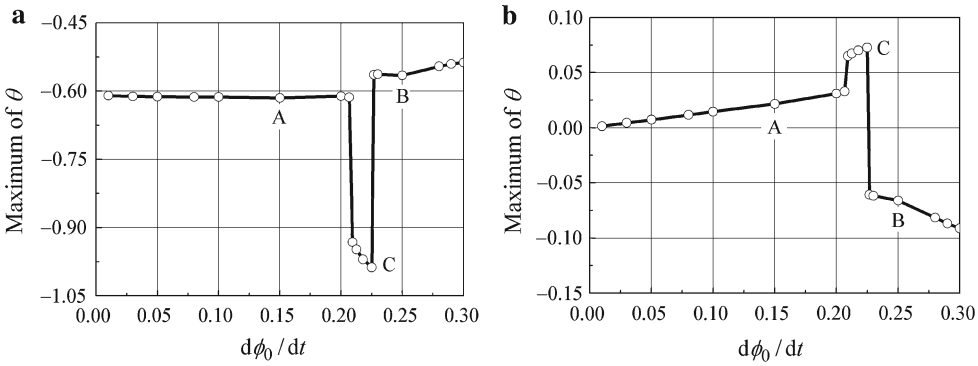


Fig. 7 The maximal pitch and the maximal roll of a tethered satellite system of three degrees of freedom versus initial roll velocity, respectively

motion of the TSS in an elliptic orbit and devised a periodic on-off controller to drive the system to periodic libration trajectories through a thruster installed on the subsatellite. In a series of studies on EDT systems, Peláez et al. [74] identified a new kind of instability due to the pumping of energy from electro-magnetic forces [59] and presented an in-depth analysis of the periodic motion by using asymptotic and numeric techniques [73] along with an evaluation of the performance of two feedback control laws aimed to convert an unstable periodic orbit into an asymptotically stable one. Williams et al. [75] developed a hybrid control scheme for a flexible EDT system to control the libration motion by using electromagnetic forces and suppress unstable high-order modes by proper movement of the tether attachment point. Mankala and Agrawal [76,77] suggested a feedback control law for implementation of the in-plane maneuvers of TSS from one equilibrium configuration to another by using a rigid or a flexible EDT. Afterwards, Zhou et al. [78] extended this approach for the planar TSS motion to include an out-of-plane tether motion. Lanoix et al. [79] investigated the long-term effect of electro-dynamic forces on the equinoctial orbital elements of a TSS by using a detailed model including the Earth's magnetic field, the tether dynamics, the gravity and the aerodynamic effects.

Much of the recent work focused on the control problems concerning tether deployment and retrieval, which may be the most important but also delicate part of a tether mission. Barkow et al. made an in-depth study on the controlled deployment through a comparison of the six different strategies, with in-plane motions taken into account, as follows: (1) free deployment only due to the gravity gradient vector, (2) force braked deployment, (3) Kissel's law using a linear PD controller, (4) open-loop time-optimal control, (5) pendulum control, and (6) targeting and stabilization following the controlling chaos strategy [80]. Steindl et al. [81,82] designed optimal controllers to achieve force controlled deployment and retrieval of a TSS based on the multiple shooting method. Williams [83] proposed a receding horizon controller for a TSS in orbital plane, which exhibits relatively higher computational efficiency. Williams and Trivailo [84] also made a comparison of various cost functions for the optimal control of a TSS in a planar case. The investigation was later extended for controlling the librations of a TSS in elliptic orbits by tracking periodic libration trajectories [85]. Jin and Hu [86] proposed a strategy based on the combination of quasi-linearization and truncated Chebyshev series to solve the constrained nonlinear optimal control problem of the TSS with three degrees of freedom. They studied the effect of the initial roll velocity on the pitch motion and the roll motion, as shown in Fig. 7a and b. Obviously, the maximal pitch motion jumps twice with the variation of the initial roll velocity. If the initial roll velocity is less than approximately 0.2067, the maximal pitch motion remains almost unchanged. Figure 7b shows that the maximal roll motion increases monotonously with an increase in the initial roll velocity. This tendency is reasonable. The peak values of the pitch motion and the roll motion are −0.9873 and 0.0727, respectively.

Okazaki and Ohtsuka [87] presented a switching control algorithm for a satellite deployment and retrieval so that the subsatellite will not collide with the mother ship even if the tether becomes slack or broken. Wen et al. designed the optimal control for the deployment process of a TSS based on real-time trajectory generation with online grid adaptation [61] and differential inclusion of the second order with fixed [62] and free [88] end-time, respectively. They successfully introduced two infinite-horizon control schemes to stabilize the three-dimensional retrieval process of a elastically tethered subsatellite [89]. The first approach involved direct transcription and nonlinear programming whereas the second one was based on the method of quasi-linearization and matrix algebra. As shown in Fig. 8, they further gave a comparison of the initial control inputs $\boldsymbol{u}(\tau_0)$ solved by using different algorithms and different number of nodes. They revealed that the direct solutions were more sensitive to the decrease of the number of nodes and the indirect method was extremely competitive in terms of precision as the number of nodes became less than 50 [89].

Padgett and Mazzoleni [90] investigated a planar dumbbell system under an exponential length control, and found that the tether can be retrieved without causing the TSS to

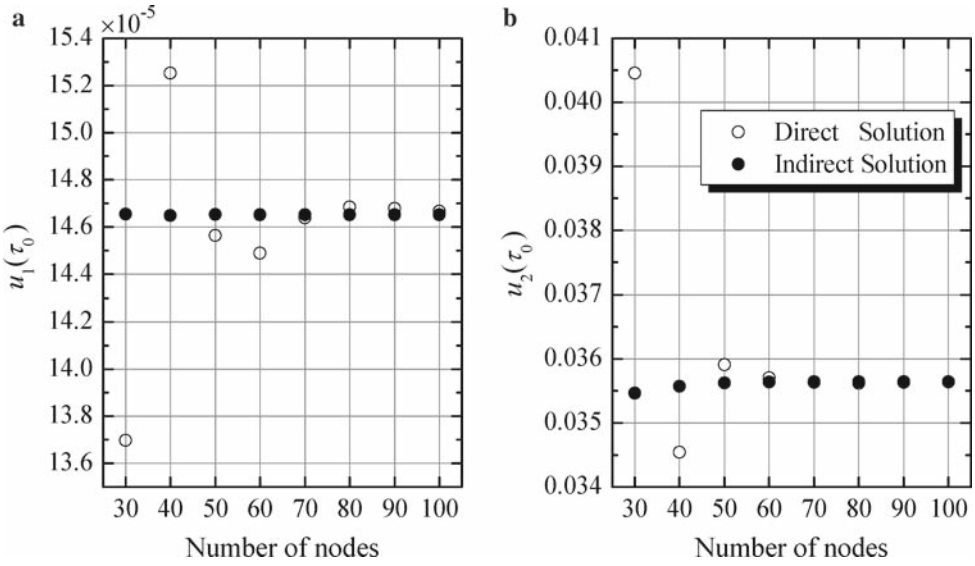


Fig. 8 Comparison of the initial control inputs $\boldsymbol{u}(\tau_0)$ from the first (direct) and the second (indirect) solutions by using different number of nodes [89]

spin, in the case that the initial conditions is located in the neighborhood of the spiral equilibrium. Mantri et al. [91] conducted a detailed study on the deployment dynamics of a TSS with five dimensional and two dimensionless parameters taken into account. Recently, Williams [65] presented a novel methodology for deployment and retrieval optimization of a multibody model of two-body TSS, where the tether was modeled as an inelastic but flexible element.

Great efforts have also been made on the TSS from an application-oriented point of view. For example, Padgett and Mazzoleni [27] presented a nullcline analysis for the proposed tethered artificial gravity (TAG) system [26] to gain an insight into the dynamics arising during a TAG mission and recommended operating parameters for some specific missions. Kumar and Yasaka [28] suggested a kite-like tether configuration for the attitude stabilization of a tethered spacecraft, and investigated its attitude dynamics through linearized stability analysis and numerical simulation. Menon and Bombardelli [29] analyzed the dynamics of a spinning TSS with two platforms linked by a flexible tether based on space interferometry requirements, and proposed to passively control the attitude of the platforms and damp out residual tether oscillations by placing a two-dimensional damper at the tether attachment location. Williams et al. [30] examined the influence of the effects of thermo-mechanical property and tether flexibility on the tethered aerocapture missions based on two temperature-dependent dynamic models of the tether. Jokic et al. [31] presented two ambitious mission concepts to produce significant changes in velocity, without the use of propellant, for the aerogravity-assist maneuver of a TSS during a planetary flyby, and identified important challenges for future investigation. Williams et al. [21] determined the open-loop optimal trajectories for both phases involved in the YES2 mission after comparing the effect of different cost functions on the deployment dynamics, and devised an efficient feedback controller to track the open-loop trajectory. Gläβel et al. [32] proposed the adaptive neural control for the deployment process of a tether-assisted re-entry mission. Lorenzini [33] proposed an error-tolerant design for a tether-mediated payload capture via a spinning tether loop, not only allowing a soft capture of the payload but also accommodating some position and velocity errors during capture. In a series of researches on tether-mediated rendezvous and capture, Williams et al. presented some control schemes for extending the rendezvous time by using rigid tethers and an actuator mass [34], rendezvous on small relative inclination orbits via rigid tethers [35], in-plane capture on circular orbits via elastic tethers [36] and in-plane rendezvous on elliptical orbits via spinning rigid tethers [37]. Lorenzini et al. [38] presented an analysis of the use of spinning tethers for a reusable two-stage system to transfer payloads from an LEO to a GEO, and demonstrated the performance of the system via a comparison with a chemical upper stage. Ziegler and Cartmell [39] investigated three fundamental tether motions for a payload orbital transfer and indicated that the symmetrical motorized spinning tethers worked best in performance. Williams presented an optimal control scheme for the orbital transfer of librating EDT systems [40] with the tether librations explicitly accounted for, and later extended the investigation by considering a spinning EDT with higher performance [41]. Yamaigiwa et al. [44] presented the parametric analyses on the dynamic behavior of EDT deorbit system, and proposed to regulate the tether current for stabilizing the tether dynamics and expanding the limit of orbital eccentricity, within which the deorbit mission can be performed. Takeichi [45] proposed a simple but robust operation strategy for deorbit of an EDT system by employing electric

current switching to stabilize both in-plane and out-of-plane librations.

3.3 Dynamics and control of tethered satellite formations

The studies on the dynamics and control of tethered satellite formations are relatively fewer, but have identified the great potential of tethered formation and drawn increasing attention from the scientific and technical community in recent years. The greatest benefit of such a formation system is that it can maintain and change formation via active control of tether tension only. The traditional free-flying satellite formation, however, requires significant thruster fuel for coordinated work in orbit. This subsection gives a brief overview of some recent studies on this subject.

From the viewpoint of stability, Tragesser [92] studied a spinning planar tethered configuration for the application of Earth sensing and surveillance, and discussed three classes of equilibria of an axially-symmetric spinning rigid body in a circular orbit, but found no stable Earth-oriented configuration in the presence of tether flexibility. Later, Tragesser and Tuncay [49] extended the original in-plane study to a three-dimensional double tetrahedron configuration placed in the off-nadir, earth-facing orientation, and investigated the stability of such a formation, but still failed to find any stable configuration in the Lyapunov sense. Williams and Moore [24] investigated the dynamics of two Earth-facing tethered configurations, including a planar ring of satellites connected through conductive tethers and a three-dimensional double-pyramid formation, and proposed to stabilize the spin axes of them along nadir by exploiting geomagnetic interaction and gravity-gradient forces, respectively. Pizarro-Chong and Misra [93] examined the dynamics and stability of multi-tethered satellite formations in open or close hub-and-spoke configuration spinning either in the orbital plane or normal to orbit plane, and found that the open hub-and-spoke configuration was stable for up to four bodies, and further extended the analysis to the three-dimensional motion of double-pyramid formations [94]. Kumar and Yasaka [95] presented an equilibrium analysis for a spinning triangular tethered formation on an elliptic orbit to determine the design limits on system parameters, along with an investigation of the effects of tether deployment/retrieval on the system response, and found that the spin rate required for system steady-spin motion in the orbital plane was greater than 0.58 or less than -2.581 times the orbital rate. Afterwards, they investigated a rotating linear array TSS on an elliptic orbit modeled by considering straight massless tethers and satellites of finite mass, and also identified the criteria to guarantee the steady-spin motion of the TSS [96]. Corrêa and Gómez [97] numerically determined the equilibrium configurations of a four-body TSS in the plane of a circular orbit through the use of a continuation method, with the solutions of the four-body system obtained by using a parameterization to trace the solutions of the three-body tethered configuration. Recently, Guerman et al. [98] studied two classes of tetrahedral equilibrium configurations of a chain consisting of four satellites connected by three rigid weightless rods, and found that all tetrahedral equilibrium configurations should contain one unloaded link and at least one compressed rod that cannot be replaced with tethers.

Great efforts have also been made on the tethered formations from a viewpoint of control. For instance, Bombardelli et al. [48] investigated the attitude dynamics of a linear tethered formation based on perturbation methods, and presented an open-loop control strategy for smoothly changing the plane of rotation of the formation by using a pair of electric thrusters in an optimized way. Kim and Hall [6] studied the dynamics of a triangular tethered interferometer as applied to the SPECS mission, and developed a nonlinear feedback controller based on input-state feedback linearization for asymptotically tracking desired trajectories, for which the required thrust levels can be significantly decreased through the use of additional tether length control. Kim and Hall [7] further investigated a TetraStar configuration with three more uncontrolled counterweights with respect to the triangular formation, and found that the TetraStar formation showed significant benefits for reducing control efforts, but the uncontrollability of the outer counterweights made it less controllable than the basic triangular configuration, especially for retargeting maneuvers. Kojima et al. [99] proposed to control the librational motion of a three-mass TSS in an elliptic orbit by using the existing delayed feedback control, and designed an innovative control scheme, combining the delayed feedback control with model-following and decoupling-control method, to improve the control performance. Kojima and Sugimoto [100] later extended the investigation to the double pendulum EDT system, and used a decoupling control method and a model-following-decoupling control method to stabilize the chaotic, librational motion of the EDTs by changing the current along the tethers. Williams [101] applied optimal control methods to the deployment and retrieval of a three-mass tethered formation spinning in the orbital plane, and used direct transcription methods to find the optimal trajectories for three kinds of tension-controlled maneuvers, including minimum-time reorientation, deployment and retrieval. He also made a systematic discussion on the dynamics and control of a triangular tethered formation spinning in the orbital plane and a double-pyramid Earth-pointing formation. A modal analysis to these formations was also applied by linearizing the dynamic equations of lumped mass models, and the nonlinear optimal control method was used to determine the periodic trajectories, as well as reconfiguration and retrieval trajectories for the complex double-pyramid configuration, whereas receding horizon control was applied to stabilize

the station-keeping mode of the Earth-pointing formation in a circular orbit [102]. Mori and Matunaga [103] presented the equilibrium conditions and coordinated control laws for rotating tethered satellite clusters when performing circular motions or similar transformations, where the proposed control schemes were implemented through the use of the reel, arm, thruster, and reaction wheel installed on the satellites. Chung et al. [104] proposed a decentralized nonlinear control law for spinning tether formations by reducing the original dynamics to simpler closed-loop dynamics based on oscillation synchronization, and used the contraction theory to prove that a nonlinear control law stabilizing a single-tethered spacecraft can also stabilize arbitrarily large circular arrays of tethered spacecraft.

3.4 Ground-based experiments

Ground-based experiments serve as an important kind of tools to verify the initial results of theoretical studies on the dynamics and control of TSSs before any costly and time consuming spaceflight experiments. For example, Higuchi and Natori [105] presented an experimental set-up where a piece of dry ice was placed on a slope on a rotating table to simulate the in-plane dynamics of TSS, and demonstrated that the unstable motion of a tether retrieval process could be stabilized by employing a simple exponential change of tether length and adding a small control deviation to the basic motion control. Modi et al. [106] designed an experiment to demonstrate an offset control scheme to stabilize the attitude dynamics of a tether based on the feedback linearization technique (FLT). The experimental setup includes a spherical mass representing the subsatellite and a horizontally moving carriage representing the tether attachment involved in the offset control [106]. Schultz et al. [107] recommended an experimental setup involving a horizontally suspended tether, as shown in Fig. 9a, to resemble the effects of the gravity gradient, and used it during the design of the Bi-static Observations with Low-Altitude Satellites (BOLAS) rotating TSS.

Test facilities supported by air bearings have recently proposed for ground-based experiments of TSS, where pressurized air passing through small holes in the ground sections of the bearings was used to establish a thin film to support the payloads [108]. For example, as shown in Fig. 9b, Mori and Matunaga [103] presented a two-dimensional ground experiment system consisting of a ground station and three satellite simulators floated on a flat floor by air-bearings, and used on-board thrusters to control the position and attitude of the simulator based on the attitude measured by gyros and position acquired via computer vision. Chung et al. [104] demonstrated the decentralized nonlinear control of tethered formations via ground experiments conducted at the Synchronized Position Hold, Engage, and Reorient Experimental Satellites (SPHERES) test-bed.

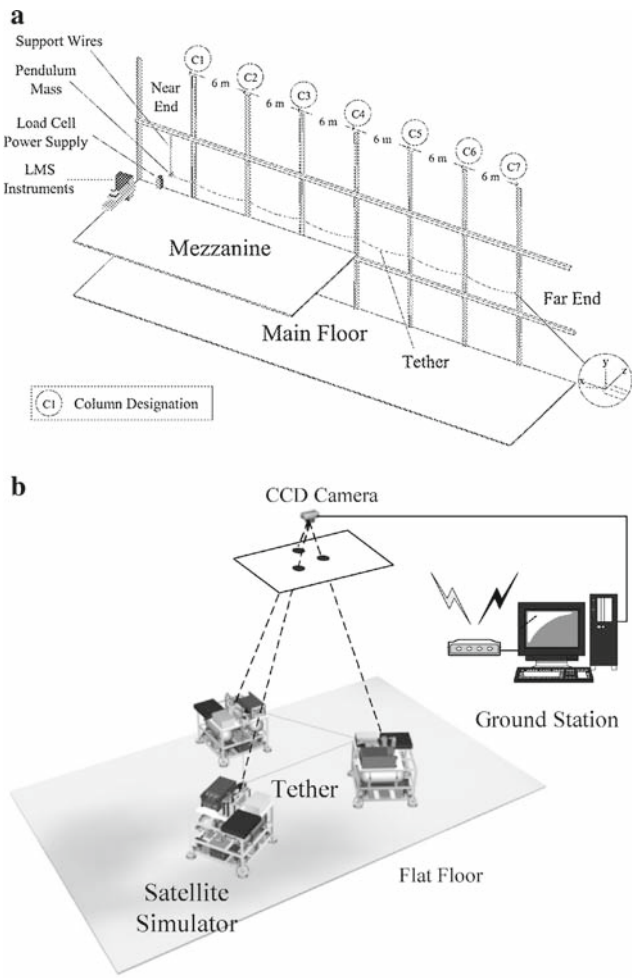


Fig. 9 Configurations of two ground-based experiments reported in references. **a** [107], **b** [103]

Jin et al. established two different experimental facilities, as shown in Fig. 10, for TSS research at Nanjing University of Aeronautics and Astronautics (NUAA). The first facility shown in Fig. 10a enables one to demonstrate the offset control of the tethered-payload system via a horizontally moving slider [109], whereas the second one shown in Fig. 10b can simulate the microgravity field experienced by a TSS by using a planar air-bearing test-bed and Coriolis forces by using on-board thrusts under feedback control. The state information of the TSS model can be obtained on-line from the encoder of angular displacement in the first facility or the subsystem of computer vision in the second facility.

4 Concluding remarks

The concept of TSS not only presents promising potentials in diverse applications, but also gives rise to many challenging problems from a scientific point of view. This review

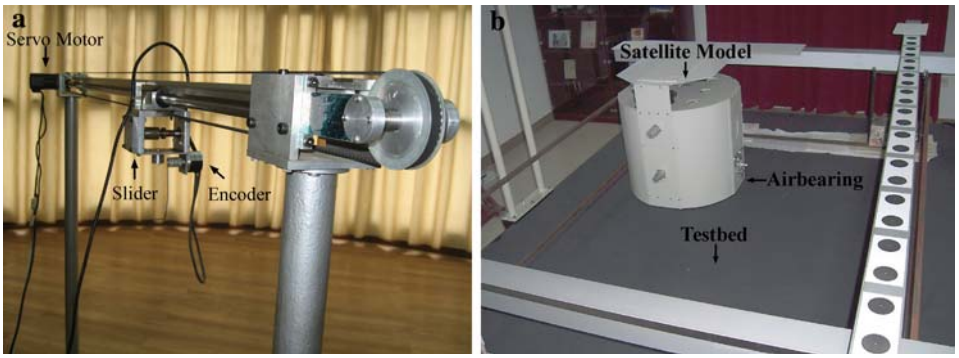


Fig. 10 Configurations of two ground-based experiments at NUAA

article starts with a brief introduction to the historical background and operating principles of TSSs, which may be of special interest to readers. The main focus of the review is then placed on the dynamics and control aspects essential for all TSSs. The discussions, not intended to be exhaustive, focus on recent advances in those two aspects. As reviewed above, recent years have seen considerable developments in this exciting research field, particularly in the tethered formation flying, orbital transfer, debris mitigation, nonlinear control of TSSs and ground-based experiments. Despite of the significant achievements, there are still many open problems of theoretical and practical importance to realize a reliable and efficient TSS. For instance, high-strength survivable tethers, efficient plasma contactors, reliable flight hardware and software, complex dynamics and real-time control of tethered formations are a few in a long list. However, the intensive international efforts on TSS studies have offered a great expectation to achieve some low-risk TSSs by using current or near-future technologies. The realization of more complex and highly beneficial applications should be long-term projects, but enable one to revolutionize the future space exploration and exploitation.

References

1. Cosmo, M.L., Lorenzini, E.C.: Tethers in Space Handbook, 3rd edn. NASA, Washington DC (1997)
2. Modi, V.J., Lakshmanan, P.K., Misra, A.K.: Dynamics and control of tethered spacecraft: a brief overview. In: AIAA Dynamics Specialist Conference. Long Beach, California, 5–6 April (1990)
3. Kumar, K.D.: Review of dynamics and control of nonelectrodynamic tethered satellite systems. J. Spacecr. Rockets **43**(4), 705–720 (2006)
4. Cartmell, M.P., Mckenzie, D.J.: A review of space tether research. Prog. Aerosp. Sci. **44**(1), 1–21 (2008)
5. Estes, R.D., Lorenzini, E.C., Santangelo, A.: An overview of electrodynamic tethers. In: The 38th Aerospace Sciences Meeting and Exhibit. Reno, NV, January 10–13 (2000)
6. Kim, M., Hall, C.D.: Control of a rotating variable-length tethered system. J. Guidance Control Dyn. **27**(5), 849–858 (2004)
7. Kim, M., Hall, C.D.: Dynamics and control of rotating tethered satellite systems. J. Spacecr. Rockets **44**(3), 649–659 (2007)
8. Pearson, J.: The real history of the space elevator. In: The 57th International Astronautical Congress, Valencia, 2–6 October (2006)
9. Artsutanov, Y.: To the cosmos by electric train. Komsomolskaya Pravda, 31 July (1960)
10. Pearson, J.: The orbital tower: a spacecraft launcher using the Earth's rotational energy. Acta Astronaut. **2**(9–10), 785–799 (1975)
11. Iannotta, B.: Nanotubes lift hopes for space elevator. Aerosp. Am. **44**(3), 30–35 (2006)
12. Edwards, B.C.: Design and deployment of a space elevator. Acta Astronaut. **47**(10), 735–744 (2000)
13. Aravind, P.K.: The physics of the space elevator. Am. J. Phys. **75**(2), 125–130 (2007)
14. Steindl, A., Troger, H.: Is the sky-hook configuration stable? Nonlinear Dyn. **40**(4), 419–431 (2005)
15. Cohen, S.S., Misra, A.K.: Elastic oscillations of the space elevator ribbon. J. Guidance Control Dyn. **30**(6), 1711–1717 (2007)
16. Iijima, S.: Helical microtubules of graphitic carbon. Nature **354**(6348), 56–58 (1991)
17. Colombo, G., Gaposchkin, E.M., Grossi, M.D., et al.: The sky-hook: a shuttle-borne tool for low-orbital-altitude research. Meccanica **10**(1), 3–20 (1975)
18. Bilén, S.G.: Space-borne tethers. IEEE Potentials **13**(3), 47–50 (1994)
19. Sasaki, S., Oyama, K.I., Kawashima, N., et al.: Results from a series of tethered rocket experiments. J. Spacecr. Rockets **24**(5), 444–453 (1987)
20. Kruijff, M.: The Young Engineers' satellite: flight results and critical analysis of a super-fast hands-on satellite project. In: The 50th International Astronautical Congress, Amsterdam, 4–8 October (1999)
21. Williams, P., Hyslop, A., Stelzer, M., et al.: YES2 optimal trajectories in presence of eccentricity and aerodynamic drag. In: The 57th International Astronautical Congress, Valencia, 2–6 October (2006)
22. Gates, S.S., Koss, S.M., Zedd, M.F.: Advanced tether experiment deployment failure. J. Spacecr. Rockets **38**(1), 60–68 (2001)
23. Hoyt, R., Slostad, J., Mazzoleni, A.P.: The multi-application survivable tether (MAST) experiment. In: The 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, 20–23 July (2003)
24. Williams, T., Moore, K.: Dynamics of tethered satellite formations. In: AAS/AIAA Spaceflight Mechanics Meeting, San Antonio, 27–30 January (2002)
25. Lorenzini, E.C.: Three-mass tethered system for micro-g/variable-g applications. J. Guidance Control Dyn. **10**(3), 242–249 (1987)
26. Hoffman, J.H., Mazzoleni, A.P.: Investigation of a tethered satellite system for generating artificial gravity. In: The 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, 20–23 July (2003)
27. Padgett, D.A., Mazzoleni, A.P.: Nullcline analysis as an analytical tethered satellite mission design tool. J. Guidance. Control Dyn. **30**(3), 741–752 (2007)

28. Kumar, K.D., Yasaka, T.: Satellite attitude stabilization through kite-like tether configuration. J. Spacecr. Rockets **39**(5), 755–760 (2002)
29. Menon, C., Bombardelli, C.: Self-stabilising attitude control for spinning tethered formations. Acta Astronaut. **60**(10–11), 828–833 (2007)
30. Williams, P., Yeo, S., Blanksby, C.: Heating and modeling effects in tethered aerocapture missions. J. Guidance Control Dyn. **26**(4), 643–654 (2003)
31. Jokic, M.D., Daniel, W.J.T.: Aerogravity-assist maneuvering of a tethered satellite system. J. Spacecr. Rockets **41**(4), 614–621 (2004)
32. Gläβel, H., Zimmermann, F., Brückner, S., Schöttle, U.M.: Adaptive neural control of the deployment procedure for tether-assisted re-entry. Aerosp. Sci. Technol. **8**(1), 73–81 (2004)
33. Lorenzini, E.C.: Error-tolerant technique for catching a spacecraft with a spinning tether. J. Vib. Control **10**(10), 1473–1491 (2004)
34. Williams, P., Blanksby, C.: Prolonged payload rendezvous using a tether actuator mass. J. Spacecr. Rockets **41**(5), 889–893 (2004)
35. Williams, P.: Spacecraft rendezvous on small relative inclination orbits using tethers. J. Spacecr. Rockets **42**(6), 1047–1060 (2005)
36. Williams, P.: In-plane payload capture with an elastic tether. J. Guidance Control Dyn. **29**(4), 810–821 (2006)
37. Williams, P.: Dynamics and control of spinning tethers for rendezvous in elliptic orbits. J. Vib. Control **12**(7), 737–771 (2006)
38. Lorenzini, E.C., Cosmo, M.L., Kaiser, M., et al.: Mission analysis of spinning systems for transfers from low orbits to geostationary. J. Spacecr. Rockets **37**(2), 165–172 (2000)
39. Ziegler, S.W., Cartmell, M.P.: Using motorized tethers for payload orbital transfer. J. Spacecr. Rockets **38**(6), 904–913 (2001)
40. Williams, P.: Optimal orbital transfer with electrodynamic tether. J. Guidance Control Dyn. **28**(2), 369–372 (2005)
41. Williams, P.: Simple approach to orbital control using spinning electrodynamic tethers. J. Spacecr. Rockets **43**(1), 253–256 (2006)
42. Bonometti, J.A., Sorensen, K.F., Dankanich, J.W., et al.: 2006 status of the Momentum eXchange Electrodynamic Re-boost (MXER) tether development. In: The 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Sacramento, 9–12 July (2006)
43. Forward, R.L., Hoyt, R.P., Uphoff, C.W.: Terminator tether: a spacecraft deorbit device. J. Spacecr. Rockets **37**(2), 187–196 (2000)
44. Yamaigiwa, Y., Hiragi, E., Kishimoto, T.: Dynamic behavior of electrodynamic tether deorbit system on elliptical orbit and its control by Lorentz force. Aerosp. Sci. Technol. **9**(4), 366–373 (2005)
45. Takeichi, N.: Practical operation strategy for deorbit of an electrodynamic tethered system. J. Spacecr. Rockets **43**(6), 1283–1288 (2006)
46. Kawamoto, S., Makida, T., Sasaki, F., et al.: Precise numerical simulations of electrodynamic tethers for an active debris removal system. Acta Astronaut. **59**(1–5), 139–148 (2006)
47. Pardini, C., Hanada, T., Krisko, P.H., et al.: Are de-orbiting missions possible using electrodynamic tethers? Task review from the space debris perspective. Acta Astronaut. **60**(10–11), 916–929 (2007)
48. Bombardelli, C., Lorenzini, E.C., Quadrelli, M.B.: Retargeting dynamics of a linear tethered interferometer. J. Guidance Control Dyn. **27**(6), 1061–1067 (2004)
49. Tragesser, S.G., Tuncay, A.: Orbital design of Earth-oriented tethered satellite formations. J. Astronaut. Sci. **53**(1), 51–64 (2005)
50. Eiden, M.J., Cartmell, M.P.: Overcoming the challenges: tether systems roadmap for space transportation applications. In: AIAA International Air and Space Symposium and Exposition, Dayton, 14–17 July (2003)
51. Pearson, J.: High-payoff space tethers. In: The 57th International Astronautical Congress, Valencia, 2–6 October (2006)
52. Beletsky, V.V., Levin, E.M.: Dynamics of space tether systems. Adv. Astronaut. Sci. **83** (1993)
53. Carroll, J.A.: Tether applications in space transportation. Acta Astronaut. **13**(4), 165–174 (1986)
54. Cui, N.G., Qi, N.M., Cheng, J.R.: Calculation of the orbital parameters of a tethered satellite system after tether deployment and cut-off. J. Harbin Inst. Technol. **27**(1), 97–100 (1995) (in Chinese)
55. Iess, L.: Space tethers: an overview. In: The 7th Spacecraft Charging Technology Conference, Noordwijk, 23–27 April (2001)
56. Okawa, Y., Kitamura, S., Kawamoto, S., et al.: An experimental study on carbon nanotube cathodes for electrodynamic tether propulsion. Acta Astronaut. **61**(11–12), 989–994 (2007)
57. Peláez, J., Sanjurjo, M.: Generator regime of self-balanced electrodynamic bare tethers. J. Spacecr. Rockets **43**(6), 1359–1369 (2006)
58. Johnson, L., Estes, R.D., Lorenzini, E., et al.: Propulsive small expendable deployer system experiment. J. Spacecr. Rockets **37**(2), 173–176 (2000)
59. Peláez, J., Lorenzini, E.C., Lopez-rebollal, O., et al.: A new kind of dynamic instability in electrodynamic tethers. J. Astronaut. Sci. **48**(4), 449–476 (2000)
60. Krupa, M., Poth, W., Schagerl, M., et al.: Modelling, dynamics and control of tethered satellite systems. Nonlinear Dyn. **43**(1–2), 73–96 (2006)
61. Wen, H., Jin, D.P., Hu, H.Y.: Optimal feedback control of the deployment of a tethered subsatellite subject to perturbations. Nonlinear Dyn. **51**(4), 501–514 (2008)
62. Wen, H., Jin, D.P., Hu, H.Y.: Three-dimensional optimal deployment of a tethered subsatellite with an elastic tether. Int. J. Comput. Math. (2008), (in press)
63. Mankala, K.K., Agrawal, S.K.: Dynamic modeling and simulation of satellite tethered systems. J. Vib. Acoust. **127**(2), 144–156 (2005)
64. Leamy, M.J., Noor, A.K., Wasfy, T.M.: Dynamic simulation of a tethered satellite system using finite elements and fuzzy sets. Comput. Methods Appl. Mech. Eng. **190**(37–38), 4847–4870 (2001)
65. Williams, P.: Deployment/retrieval optimization for flexible tethered satellite systems. Nonlinear Dyn. **52**(1–2), 159–179 (2008)
66. Kim, E., Vadali, S.R.: Modeling issues related to retrieval of flexible tethered satellite systems. J. Guidance Control Dyn. **18**(5), 1169–1176 (1995)
67. Zhu, R.Z., Lei, D., Lin, H.B.: Sophisticated dynamical model of tethered satellite systems. J. Astronaut. **20**(3), 7–12 (1999) (in Chinese)
68. Carter, J.T., Greene, M.: Simulation of single tether systems. Simulation **58**(1), 42–48 (1992)
69. Steiner, W., Zemann, J., Steindl, A., et al.: Numerical study of large amplitude oscillations of a two-satellite continuous tether system with a varying length. Acta Astronaut. **35**(9–11), 607–621 (1995)
70. Elliott, A.S.: Efficient modeling of extensible cables and pulley systems in ADAMS. In: The 1st MSC. ADAMS European User Conference, London, 13–14 November (2002)
71. Yu, S.H.: Dynamic model and control of mass-distributed tether satellite system. J. Spacecr. Rockets **39**(2), 213–218 (2002)
72. Takeichi, N., Natori, M.C., Okuizumi, N., et al.: Periodic solutions and controls of tethered systems in elliptic orbits. J. Vib. Control **10**(10), 1393–1413 (2004)
73. Peláez, J., Andrés, Y.N.: Dynamic stability of electrodynamic tethers in inclined elliptical orbits. J. Guidance Control Dyn. **28**(4), 611–622 (2005)
74. Peláez, J., Lorenzini, E.C.: Libration control of electrodynamic tethers in inclined orbit. J. Guidance Control Dyn. **28**(2), 269–279 (2005)

75. Williams, P., Watanabe, T., Blanksby, C., et al.: Libration control of flexible tethers using electromagnetic forces and movable attachment. J. Guidance Control Dyn. **27**(5), 882–897 (2004)
76. Mankala, K.K., Agrawal, S.K.: Equilibrium-to-equilibrium maneuvers of rigid electrodynamic tethers. J. Guidance Control Dyn. **28**(3), 541–545 (2005)
77. Mankala, K.K., Agrawal, S.K.: Equilibrium-to-equilibrium maneuvers of flexible electrodynamic tethers in equatorial orbits. J. Spacecr. Rockets **43**(3), 651–658 (2006)
78. Zhou, X., Li, J.F., Baoyin, H., et al.: Equilibrium control of electrodynamic tethered satellite systems in inclined orbits. J. Guidance Control Dyn. **29**(6), 1451–1454 (2006)
79. Lanoix, E.L.M., Misra, A.K., Modi, V.J., et al.: Effect of electrodynamic forces on the orbital dynamics of tethered satellites. J. Guidance Control Dyn. **28**(6), 1309–1315 (2005)
80. Barkow, B., Steindl, A., Troger, H.: A targeting strategy for the deployment of a tethered satellite system. IMA J. Appl. Math. **70**(5), 626–644 (2005)
81. Steindl, A., Troger, H.: Optimal control of deployment of a tethered subsatellite. Nonlinear Dyn. **31**(3), 257–274 (2003)
82. Steindl, A., Steiner, W., Troger, H.: Optimal control of retrieval of a tethered subsatellite. Solid Mech. Appl. **122**, 441–450 (2005)
83. Williams, P.: Application of pseudospectral methods for receding horizon control. J. Guidance Control Dyn. **27**(2), 310–314 (2004)
84. Williams, P., Trivailo, P.: On the optimal deployment and retrieval of tethered satellites. In: The 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Tucson, 10–13 July (2005)
85. Williams, P.: Libration control of tethered satellites in elliptical orbits. J. Spacecr. Rockets **43**(2), 476–479 (2006)
86. Jin, D.P., Hu, H.Y.: Optimal control of a tethered subsatellite of three degrees of freedom. Nonlinear Dyn. **46**(1–2), 161–178 (2006)
87. Okazaki, M., Ohtsuka, T.: Switching control for guaranteeing the safety of a tethered satellite. J. Guidance Control Dyn. **29**(4), 822–830 (2006)
88. Wen, H., Jin, D.P., Hu, H.Y.: Time-optimal deployment of a tethered subsatellite based on differential inclusion. Chin. J. Theor. Appl. Mech. **40**(1), 135–140 (2008) (in Chinese)
89. Wen, H., Jin, D.P., Hu, H.Y.: Infinite-horizon control for retrieving a tethered subsatellite via an elastic tether. J. Guidance Control Dyn. (in press)
90. Padgett, D.A., Mazzoleni, A.P.: Analysis and design for no-spin tethered satellite retrieval. J. Guidance Control Dyn. **30**(5), 1516–1519 (2007)
91. Mantri, P., Mazzoleni, A.P., Padgett, D.A.: Parametric study of deployment of tethered satellite systems. J. Spacecr. Rockets **44**(2), 412–424 (2007)
92. Tragesser, S.G.: Formation flying with tethered spacecraft. In: AIAA/AAS Astrodynamics Specialist Conference, Denver, 14–17 August (2000)
93. Pizarro-chong, A., Misra, A.K.: Dynamics of a multi-tethered satellite formation. In: AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Providence, 16–19 August (2004)
94. Pizarro-chong, A., Misra, A.K.: Dynamics of multi-tethered satellite formations. In: The 56th International Astronautical Congress, Fukuoka, 17–21 October (2005)
95. Kumar, K.D., Yasaka, T.: Rotating formation flying of three satellites using tethers. J. Spacecr. Rockets **41**(6), 973–985 (2004)
96. Kumar, K.D., Yasaka, T.: Dynamics of rotating linear array tethered satellite system. J. Spacecr. Rockets **42**(2), 373–378 (2005)
97. Corrêa, A.A., Gómez, G.: Equilibrium configurations of a four-body tethered system. J. Guidance Control Dyn. **29**(6), 1430–1435 (2006)
98. Guerman, A.D., Smirnov, G., Paglione, P., et al.: Stationary configurations of a tetrahedral tethered satellite formation. J. Guidance Control Dyn. **31**(2), 424–428 (2008)
99. Kojima, H., Iwasaki, M., Fujii, H.A., et al.: Nonlinear control of librational motion of tethered satellites in elliptic orbits. J. Guidance Control Dyn. **27**(2), 229–239 (2004)
100. Kojima, H., Sugimoto, T.: Nonlinear control of a double pendulum electrodynamic tether system. J. Spacecr. Rockets **44**(1), 280–284 (2007)
101. Williams, P.: Optimal deployment/retrieval of a tethered formation spinning in the orbital plane. J. Spacecr. Rockets **43**(3), 638–650 (2006)
102. Williams, P.: Optimal control of a spinning double-pyramid earth-pointing tether formation. In: The 57th International Astronautical Congress, Valencia, 2–6 October (2006)
103. Mori, O., Matunaga, S.: Formation and attitude control for rotational tethered satellite clusters. J. Spacecr. Rockets **44**(1), 211–220 (2007)
104. Chung, S.J., Slotine, J.J.E., Miller, D.W.: Nonlinear model reduction and decentralized control of tethered formation flight. J. Guidance Control Dyn. **30**(2), 390–400 (2007)
105. Higuchi, K., Natori, M.C.: Ground experiment of motion control of retrieving space tether. In: AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference and Exhibit, Kissimmee, 7–10 April (1997)
106. Modi, V.J., Pradhan, S., Misra, A.K.: Controlled dynamics of flexible orbiting tethered systems: analysis and experiments. J. Vib. Control **3**(4), 459–497 (1997)
107. Schultz, F.W., Vigneron, F.R., Jablonski, A.M.: Horizontally-configured ground-test method for tethered satellites. Can. Aeronaut. Space J. **48**(1), 97–106 (2002)
108. Schwartz, J.L., Peck, M.A., Hall, C.D.: Historical review of air-bearing spacecraft simulators. J. Guidance Control Dyn. **26**(4), 513–522 (2003)
109. Jin, D.P., Ding, F.: Positioning control of in-plane motion of the tethered-payload system. J. Vib. Eng. **21**(1), 1–6 (2008) (in Chinese)