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REVIEW PAPER

Review of deployment technology for tethered satellite systems

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Abstract

Tethered satellite systems (TSSs) have attracted significant attention due to their potential and valuable applications for scientific research. With the development of various launched on-orbit missions, the deployment of tethers is considered a crucial technology for operation of a TSS. Both past orbiting experiments and numerical results have shown that oscillations of the deployed tether due to the Coriolis force and environmental perturbations are inevitable and that the impact between the space tether and end-body at the end of the deployment process leads to complicated nonlinear phenomena. Hence, a set of suitable control methods plays a fundamental role in tether deployment. This review article summarizes previous work on aspects of the dynamics, control, and ground-based experiments of tether deployment. The relevant basic principles, analytical expressions, simulation cases, and experimental results are presented as well.

Keywords Tethered satellite · Deployment · Dynamics · Control · Experiment

1 Introduction

As shown in Fig. 1, a tethered satellite system (TSS) consists of a mother satellite (i.e., a spacecraft), a sub-satellite (i.e., a payload), and a connecting space tether. All tasks of the TSS begin with the deployment of the sub-satellite with the aid of the space tether. For decades, the deployment of the tether from the spacecraft has always been a significant issue for a TSS. As a key technology, it has shown great application potential in orbital missions, such as atmospheric sounding [1–4], orbital transfer [5–8], target capture [9–13], and tether-assisted re-entry [14–18].

The deployment process of an on-orbit TSS is subject to instability caused by the negative-damping effect of the tether. A further instability is due to the tether alternating between taut and slack because of its elasticity and flexibility. This will occur in the absence of a proper control method.

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This makes controlling a deployed tether more difficult than controlling a suspended tether (i.e., the space tether under a station-keeping phase). Moreover, the dynamics of a TSS depends on a large number of perturbation factors in the space environment (e.g., heating effect, air drag force, J_2 perturbation, and solar pressure). The effect of the friction, impact, and shape of the tether is usually ignored in idealized models. Accordingly, to reveal the detailed dynamics and to design effective controllers for tether deployment, constructing a simple, but reasonable model for the system is a topic of substantial current interest. In addition, the stability analysis, control strategy design, and ground-based experiments are hot issues as well.

From the viewpoint of orbital experiments, deployments of tethers have been achieved in several space missions listed in Table 1. Nonelectrodynamic tethered systems include Gemini-XI [19], Gemini-XII [19], the small expendable deployment system (SEDS-1) [20], SEDS-2 [21], the tether physics and survivability (TiPS) experiment [22], the young engineers' satellite (YES-2) [23], the advanced tether experiment (ATEx) [24], and the multi-application survivable tether (MAST) experiment [25]. Electrodynamic tethered systems include the tether payload experiment (TPE) series [26], the cooperative high altitude rocket gun experiment (CHARGE-1) [26], CHARGE-2 [27], observations of electric-field distribution in the ionospheric plasma —a unique strategy (OEDIPUS-A) [28], OEDIPUS-C [29], the tethered-satellite

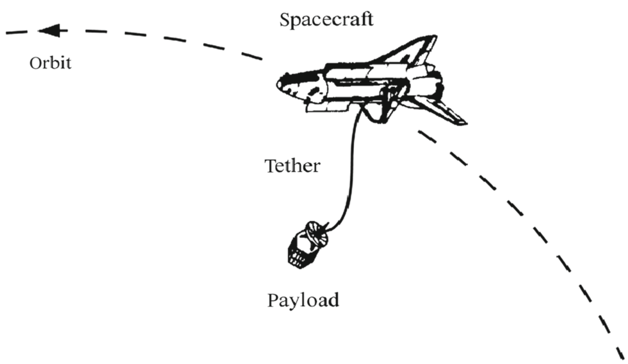

Fig. 1 An orbiting TSS

system (TSS-1) [30], TSS-1R [31], the plasma motor generator (PMG) [4,21], and the tether rocket experiment (T-Rex) [32]. The experimental details (e.g., the deployment hardware structure, deployed tether length, and deployment dynamics) have been published in the above literature. However, note that the space tether is not always deployed completely in these orbiting experiments. For example, during the MAST experiment [25], the tether deployment was terminated because the deployment spool abruptly lost control. In the first two experiments of the TPE (i.e., the H-9M-69 and S-520-2 missions) [26], the tether deployment speeds slowed and stopped suddenly at only 38 m and 65 m, respectively, due to excessive friction in the deployment devices. In the TSS-1 mission [30], the space tether was accidentally jammed by a screw installed in an inappropriate position, and only 268 m of the 22 km tether was deployed. Consequently, designing a tether deployment device which can be employed in complex space environment would be a great challenge. It is significant to acquire a stable control law of tether deployment subject to external perturbation.

The remainder of this paper is divided into four major sections. The dynamics of the tether deployment is elaborated in Sect. 2. The methods of deployment control are classified in Sect. 3. The experimental studies are introduced in Sect. 4. A brief summary and directions of future development of tether deployment technology are given in Sect. 5.

2 Dynamics of tether deployment

It is not easy to grasp the dynamics of a TSS due to undesirable factors (e.g., flexibility, friction, impact, Coriolis force, and a variety of environmental perturbations). Hence, numerical simulation may be an effective way to reveal dynamic behaviors. However, an analytical analysis can be developed also, provided the tether is in some special state (e.g., a flexible tether is taut, similar to a straight rod).

2.1 Modeling

To gain insight into the deployment dynamics of the TSS, three models (a continuous model, a discrete model, and a rod model) for the TSS are typically established. An important model for the continuous tether with the reeling mechanism is constructed using Hamilton's principle [33]. The corresponding dynamic equation acquired by the energy method can accurately depict the flexibility and the elasticity of the space tether in the process of deployment [34,35]. The oscillations of the tether and various nonlinear phenomena is presented through the use of this model.

By dividing the space tether into a series of mass points (tether nodes) connected by massless springs, a discrete model is formulated as illustrated in Fig. 2a. Configuration changes of the flexible tether during deployment can be accurately described by this model. Generally, the dynamic differential equations of the model are developed by means of conventional methods such as Lagrange's equations [36], the variational principle of Hamilton–Ostrogradski [37], and Newton's laws [38]. To calculate the dynamic response, these equations are usually discretized via the Galerkin modal method [39] or the finite element method [40]. A time-varying dynamic model was established by Yu et al. [41]. In their studies, the number of tether nodes in the system changed as the tether was deployed. This indicated that the number of degrees of freedom of the system was time-varying. By utilizing an improved finite difference method [42], the configuration changes of the flexible tether during free deployment in an orbital frame *o-xy* is clearly shown in Fig. 2b. Although the discrete model is capable of depicting the deployed tether in either a slack or taut state, the calculation of this model with its multiple degrees of freedom probably takes too much time.

Moreover, a simplified rod model is frequently discussed when the space tether remains taut due to an appropriate external force (e.g., a control force) acting on its end. As shown in Fig. 3a, the in-plane pitch angle θ, out-of-plane roll angle ϕ, and deployed tether length l are selected as the generalized coordinates, and application of Lagrange's equations can lead to a set of dynamic differential equations (as presented in Ref. [43]). Based on the rod model, the deployment of a taut space tether is exhibited in Fig. 3b. Clearly, the rod model is a possibility for the study of tether tension control during deployment.

2.2 Stability

Even if the TSS operates on a circular orbit, its uncontrolled deployment would result in the occurrence of large-amplitude oscillations [44]. Therefore, to achieve stable deployment requires exerting effective controls. The stability of the tether deployment depends on whether the controls

Table 1 Existing space missions

No.	Date	Mission	Tether deployment
1	1966.09	Gemini-XI	The tether was successfully deployed to 30 m
2	1967.11	Gemini-XII	The tether was successfully deployed to 30 m
3	1980.01	K-9M-69	The deployment process was braked abruptly when the tether was deployed to 38 m
4	1981.01	S-520-2	The deployment process was braked abruptly when the tether was deployed to 65 m
5	1983.08	CHARGE-1	The tether was successfully deployed to 418 m during 283 s
6	1985.12	CHARGE-2	The tether was successfully deployed to 426 m during 290 s. The initial velocity of deployment was 1.05 m/s
7	1989.01	OEDIPUS-A	A reel type deployer was adopted. The tether was successfully deployed to 958 m
8	1992.07	TSS-1	The tether was jammed accidentally by a screw during deployment
9	1993.03	SEDS-1	A friction type deployer was adopted. The 20 km-long tether was successfully deployed using an open-loop control law
10	1993.06	PMG	A friction type deployer was adopted. The tether was ejected initially and was successfully deployed to 500 m
11	1994.03	SEDS-2	A friction type deployer was adopted. The 20 km-long tether was successfully deployed using a closed-loop control law
12	1995.11	OEDIPUS-C	A reel type deployer was adopted. The tether was successfully deployed to 1174 m
13	1996.02	TSS-1R	A reel type deployer was adopted. The tether was deployed to 19.7 km
14	1996.06	TiPS	The tether was successfully deployed to 4023 m
15	1997.04	ATEx	The tether was deployed to only 22 m due to the failure of a local angle sensor
16	2007.04	MAST	The tether was not fully deployed due to the failure of a spool mechanism
17	2007.09	YES-2	The tether was successfully deployed to 31.7 km using a feedback control law
18	2010.08	T-Rex	A reinforced aluminum tape-shaped tether was successfully deployed to 132.6 m

can avoid or depress in-plane and out-of-plane oscillations of the tether during deployment. In a series of studies, it was noted that the stability of the system was determined by the current tether length l, the rate of change of the length $\dot{l}$, and the orbital angular velocity of the system ω [45–48]. Exploiting the theory of Lyapunov stability, a feedback control law that guaranteed the stability of the closed-loop system during the tether deployment was designed by Vadali and Kim [49]. A mission-function control algorithm was proposed by Kokubun and Fujii [50]. The goal of their studies was to suppress the longitudinal and transverse oscillations of the deployed tether. The effects of several control methods for oscillation suppression were compared by Barkow et al. [44]. To decrease the amplitude of oscillations of the deployed tether, an optimal tension control scheme was presented by Wang et al. [51]. The stability of the tether deployment process was investigated numerically by McKenzie [52]. The results indicated that the stability depended on the orbital eccentricity, tether braking, and the deployment control law. Based on the Lyapunov functions, the stability of the deployment of a tethered system along a particular trajectory was analyzed by Malashin et al. [53]. Additionally, a control law for the rate of deployment of the tether length was suggested by Yu et al. [54]. The local and global stability of the law were verified via the Floquet theory and cell mapping, respectively.

With regard to tethered satellite formations (i.e., a cluster of tether-connected satellites), the stability of the deploy-

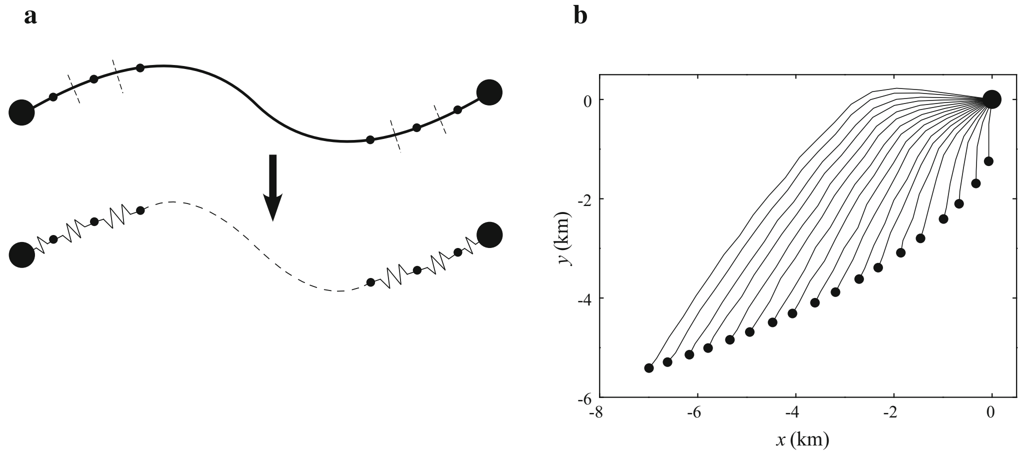

Fig. 2 A discrete model for a flexible tether. **a** Discrete model. **b** Configuration changes of the tether during free deployment

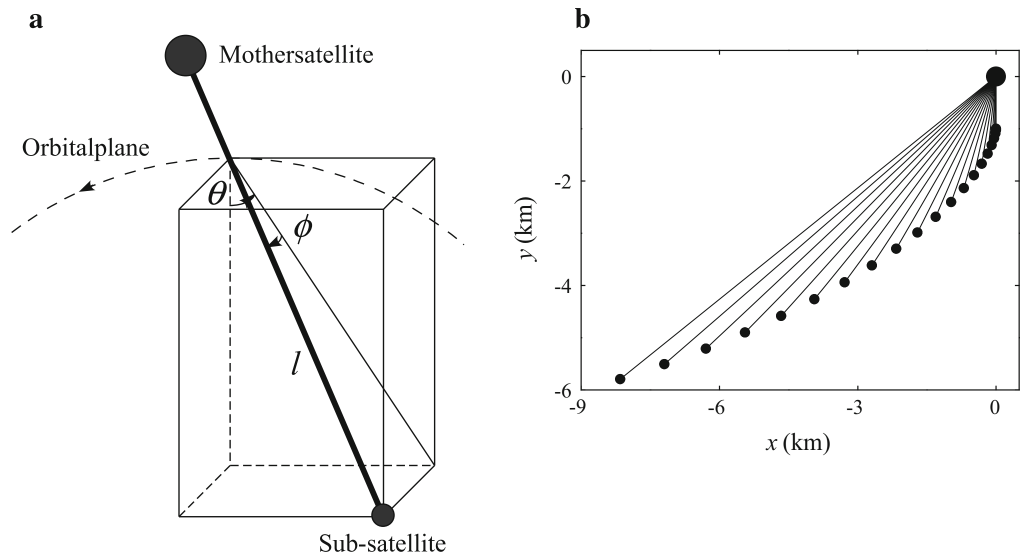

Fig. 3 A rod model for taut tether. **a** Rod model. **b** The deployment process of the tether

ment mainly depends on whether the imposed control law has the ability to maintain the configuration of the formation. Because of an open-loop deployment control law, an unstable local horizontal configuration of multi-body tethered satellites was stabilized by Kumar et al. [55,56]. By simulating a nonrotating multi-connected satellite in the vicinity of the libration point (L_2), Zhao et al. [57] noted that the tether librations during deployment were more stable than those during retrieval. The study was extended to a rotating system, whose stability could be improved by increasing the initial rotation rate or reducing the length rate [58]. The attitude dynamics of a three-body tethered satellite system was discussed by Jung et al. [59]. They emphasized that the Coriolis force generated during deployment would lead to oscillation of the tethers even if the system moved on a circular orbit.

2.3 Tether

For a flexible tether, the existence of slack due to uncontrolled deployment or negative controlled tension is often neglected. This unpleasant state appears frequently in practical space missions and can cause uncontrolled flight of the sub-satellite [60,61]. According to the slack-taut state of the tether, the impact (i.e., the tether suddenly becomes taut) and free-flight (i.e., the tether is slack) phases in the process of the deployment were defined by Kane and Levinson [62]. The two phases occur alternately until the tether becomes permanently taut. Based on a discrete model, the complex configuration of the tether during free and controlled deployment was presented by Auzinger et al. [63], in whose research the slack states of the tether could be clearly observed. The effect of environmental perturbations (e.g., the J_2 perturba-

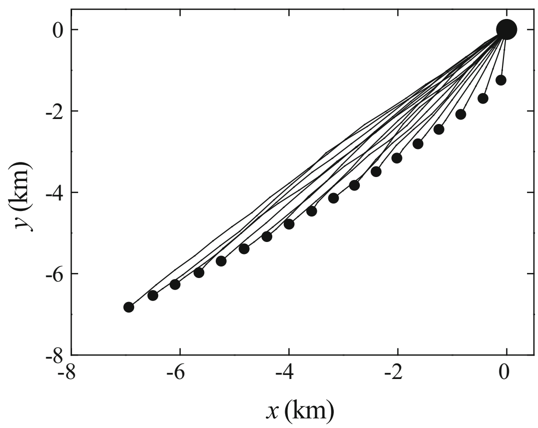

Fig. 4 Configuration changes of the tether under J_2 perturbation, heating effect, and sliding friction force

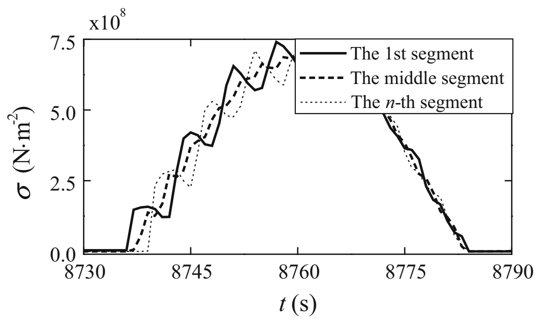

Fig. 5 Stress changes of tether segments versus time

tion, the heating effect, and the sliding friction force between the deployment device and the tether) on the tether configuration during the free deployment phase was investigated by Yu and Jin [64]. It was found that the coefficient of linear expansion played a fundamental role in the change of the tether configuration. Compared to the free deployment without perturbations as shown in Fig. 2, the configuration changes of a flexible tether under the J_2 perturbation, the heating effect and sliding friction force are shown in Fig. 4. Furthermore, an impact will occur at the moment of the end of deployment since the deployment velocity along the tether abruptly becomes zero. For the discrete model with n tether elements, the change of the stress σ of the distinct tether segments is shown in Fig. 5. As observed in Fig. 5, there exists an obvious stress wave along the space tether after the impact.

To avoid the slack state for a deployed tether, a constrained optimal control scheme has been applied [44,65,66]. However, the synthesis of a nonlinear optimal control law is very difficult. A fractional-order controller with constant gains for tether deployment was designed by Sun and Zhu [67], who noted that an unrealistic negative tension still existed in the initial phase. A nonlinear control law with an explicit tension constraint for the deployed tether was presented by Wen et al. [68]. That the effect of the tension constraint on the stability of the TSS had not been fully discussed was stressed [69].

Additionally, it is important to further the detailed study of the deployment dynamics of the tethered system. For example, based on a three-dimensional model of the TSS, five important system parameters (the initial separation velocity, the tether tension force, the orbital height, the effective mass, and the desired final tether length) were identified by Mantri et al. [70,71], whose studies showed that the percentage of the total length of the deployed tether was affected by the five parameters. To complete a debris removal mission, a deployed tape-shaped electrodynamic tether several kilometers long was utilized by Mantellato et al. [72] to produce a drag force according to the Lorenz law. Numerical simulations indicated that the deployment dynamics was greatly dependent on thruster misalignment errors of the end-body.

2.4 Satellite attitude

When the tension force acting on the end of the tether does not pass through the mass center of the satellite, this results in an external torque that directly leads to attitude motion of the satellite body in the tether deployment phase. An example of fast tether deployment was investigated by Liu and Zhou [73]. They concluded that the deployment method gave rise to small-amplitude oscillations of the attitude of sub-satellite body. Afterwards, thrusters were adopted to provide active control for the attitude motion [74]. By using a controllable arm, the position-attitude control of the in-plane motion of a tethered sub-satellite during deployment was addressed by Wen et al. [75]. The position-attitude adjustment using a controllable arm was also recommended by Nohmi et al. [76] and Wang et al. [77]. In view of the classical Kissel's deployment control law, the attitude motion of the spacecraft body was extremely sensitive to its initial attitude angle [78]. Numerical results showed that a large-amplitude oscillation appeared when the spacecraft was in an unstable equilibrium position at the initial time.

Moreover, studies of attitude motion subjected to the impact caused by a sudden tautness of the deployed tether are relatively few. Taking the rigid motion of the spacecraft into account, Yu et al. [78] simulated the impact dynamics of the TSS during deployment. The case studies indicated that, in the absence of control action during the tether's deployment, an impulse arising from the velocity jump at the end of the deployment would result in the rotation of the spacecraft.

2.5 Nonlinear dynamics

The appearance of chaotic motions is largely determined by the selection of the tether model [63]. Compared to the simple dissipative model, a slightly more chaotic phenomenon is usually shown in the viscoelastic space billiard model. The transient chaotic motion will occur, since weak damping exists in the viscoelastic tether. In addition, the large-amplitude oscillation due to the unstable deployment also brings about chaotic motion. In terms of a deployment control law of the length rate, the stability of the fixed point and limit cycle through the Lyapunov theory and bifurcation diagram was analyzed by Yu [79]. It was found that the unstable limit cycle occurred with the system parameters varying. To retain the configuration of the deployed tether in the vicinity of the radial direction, a chaos control strategy combined with a targeting algorithm was applied by Barkow [80].

3 Control methods of tether deployment

To accomplish the deployment of tethers stored in satellites, an abundance of deployment control laws have been proposed. The laws can be classified into several types, depending on the control mode, such as length control, length rate control, tension control, thruster control.

3.1 Length control

Length control means that the tether is deployed to an assigned length determined through a real-time calculation. The majority of length control laws are of exponential form, the most classical expression of which reads

$$l(t) = l_i \exp\left(c_1 t\right), \tag{1}$$

where l_i represents the initial length, c_1 an undetermined constant, and t the time. In the 1990s, the control law attracted even more attention. For example, the deployment process of a tethered system that moved on a circular orbit was focused by Rajan and Anderson [81]. The stability of the system subjected to the exponential control law was analyzed with Lyapunov's theory. The influence of the control law on a tethered payload raising on an elliptic orbit was discussed by Kumar et al. [82].

Moreover, with the assumption of a circular orbit, another exponential control law was derived by Peláez [83,84] in the following form

$$l(t) = \frac{1}{c_2} \exp\left(c_2 t - 1\right), \tag{2}$$

where $c_2 = \dot{l}/l$ is a ratio. The dynamic behavior with the change of the parameter c_2 was presented in the phase plane. Taking the tether mass into account, a so-called crawler system operating on an elliptical orbit was analyzed by Pascal et al. [85,86]. A tether deployment control law was proposed in a non-dimensional form

$$\xi = \exp\left(\pm\sqrt{\delta}\nu\right), \tag{3}$$

where $\xi = l/l_r$ denotes the non-dimensional tether length, l_r the reference tether length, δ the undetermined constant, and ν the non-dimensional time (i.e., orbit true anomaly). Numerical cases demonstrated that tether vibrations are suppressed during deployment. Recently, the deployment process of the tether was divided into two stages, and an open-loop control law of the tether length in the second stage was proposed by Zakrzhevskii [87]

$$l(t) = l_i \exp\left\{-\int_{t_m}^{t}\left[\frac{3\omega^2\sin(2\vartheta(\tau)) + 2\ddot{\vartheta}(\tau)}{4(\omega+\dot{\vartheta}(\tau))}\right]\mathrm{d}\tau\right\}, \tag{4}$$

where l_i represents the length of the taut tether in the initial stage, ω the orbital angular velocity, $\vartheta(t)$ the required law of the pitch angle that can be presented in the form of a polynomial of the seventh degree, and t_m the moment of the maximum pitch angle in the negative direction. A tether subjected to the proposed control law can be deployed along the local vertical direction.

The length control law is usually expressed as an analytical form, which is relatively convenient for the achievement of the spool control. Hence, length control might be a more favorable method of tether deployment.

3.2 Length rate control

The length rate control, namely, deploying the tether at a real-time calculated rate, is a similar concept. This means of control and the above length control can be transformed into each other, and there exists an obvious differential/integral relation between them. Several analytical control laws are summarized as follows

(1) Uniform deployment rate [88]

$$\dot{l}(t) = c l_i, \tag{5}$$

where c is an undetermined constant, and l_i is the initial length of the tether.

(2) Deployment rate at any instant is proportional to the current deployed length [88]

$$\dot{l}(t) = c l(t). \tag{6}$$

The exponential control law of Eq. (1) follows by integrating this expression.

(3) Several stages of deployment with uniform rates [88]

$$\dot{l}(t) = c l_{ik}, \tag{7}$$

where l_{ik} is the initial length of the k-th stage.

(4) Uniform acceleration deployment [89]

$$\ddot{l}(t) = c. \tag{8}$$

(5) Variable acceleration deployment [89]

$$\ddot{l}(t) = 3l\omega^2 - T/m_s, \tag{9}$$

where T is tether tension, and m_s the mass of the sub-satellite. Numerical studies have demonstrated that the control laws Eqs. (6) and (8) can more effectively suppress tether oscillations. Furthermore, an open-loop tether deployment law was considered by Kumar and Yasaka [55,90]. Additionally, the deployments of a linear array and a triangle-like configuration of a rotating tethered formation have been investigated. Simulation results confirmed the feasibility of achieving a rotating tethered formation with any desired size.

A combination of exponential and uniform deployment was proposed as a simple and efficient procedure [91,92]. The deployment process was divided into three phases, and the corresponding control law was expressed as follows

$$\dot{l}(t) = \begin{cases} cl(t) & (l_0 \le l \le l_1) \\ cl_1 & (l_1 < l \le l_2) \\ c\,(l_1 + l_2 - l(t)) & (l_2 < l \le l_f) \end{cases}, \tag{10}$$

where l_0 and l_f denote the initial and final lengths, respectively, and l_1 and l_2 the switch lengths. Clearly, the first and third rates are exponential, while the second rate is uniform deployment. The control law Eq. (10) has only a slight influence on suppressing oscillation of the out-of-plane motion. However, it was emphasized that this control law could be extended to the suppression of out-of-plane oscillation through introducing a nonlinear equation instead of a linearized equation [91].

A control law for tether length rate has also been designed using the classical proportional-derivative (PD) control. For example, a fuzzy logic law of tether-angle-rate feedback was recommended by Licata [93] to address the deployment problem of a tethered system with a tracked passive tethered end-body. Based on a discrete model of the TSS, a control law of the commanded length rate was suggested by Williams and Trivailo [94] through a PD controller.

On account of the state equation of the TSS, an analytical control law of the tether length rate in non-dimensional form was derived by Yu et al. [54,95]

$$\xi' = \frac{\xi}{1 + e\cos\nu}\left[e\sin\nu - \frac{3}{4}\sin(2\theta_e)\right], \tag{11}$$

where ξ denotes the non-dimensional tether length, $()'$ the derivative with respect to the orbit true anomaly, ν, e the eccentricity of the Earth's orbit, and θ_e the expected in-plane angle whose value range is given by

$$-\frac{\pi}{4} \le \theta_e < -\frac{1}{2}\arcsin\left(\frac{4}{3}e\right),\ e < \frac{3}{4}. \tag{12}$$

The control law can make the tether deploy along an expected direction (in the range of Eq. (12)) and effectively suppress the out-of-plane oscillation in conjunction with the in-plane oscillation of the tether during deployment. In addition, a parameter domain that guarantees that the tether maintains in a taut state can be obtained for stable deployment [95]. Supposing that the expected in-plane angle θ_e is -0.15 rad and the total tether length L is 10 km, a numerical case is shown in Fig. 6. As observed from Fig. 6a, b the in-plane and out-of-plane oscillations are suppressed with the passage of the non-dimensional time ν. As shown in Fig. 6c, d, the phase trajectories in the θ - θ' and ϕ - ϕ' planes ultimately converge to $(-0.15, 0)$ and $(0, 0)$, respectively. Figure 6e illustrates the trajectory of the sub-satellite for radial deployment. Figure 6f demonstrates that the tension in the tether is always greater than 0 (The change of the tension force can be calculated in the light of the dynamic differential equations of the system.). It is worthy of note that the deployment rate increases with the increase of the tether length according to Eq. (1). Thus, this control law in general applies to the mission of space target capturing.

Similar to the length control law, the length rate control law can also be written as an analytical solution. These simple forms are convenient for the spool control.

3.3 Tension control

The tension control acting on the tether is an interesting issue also; that is, the space tether is deployed and eventually reaches a desired state through the torque generated by the reel in the deployment device. In 1970, an approximately analytical solution of tension control was first derived by Ebner [96] from two coupled nonlinear partial differential equations of a TSS. Then, a classical Kissel's control law was given by Rupp [97]. The law is realized by applying force on the tether

$$T = 0.02\,(l(t) - l_c(t)) + 2\dot{l}(t) + 3m_s l(t)\omega^2, \tag{13}$$

where m_s denotes the mass of the sub-satellite, and $l_c(t)$ is expressed as

$$l_c(t) = l_0 + l_f\left[1 - \exp\left(-t\frac{\ln(l_f/l_0)}{t_f}\right)\right], \tag{14}$$

in which l_0 and l_f are the initial and final lengths of the deployed tether, respectively, and t_f is the total time of

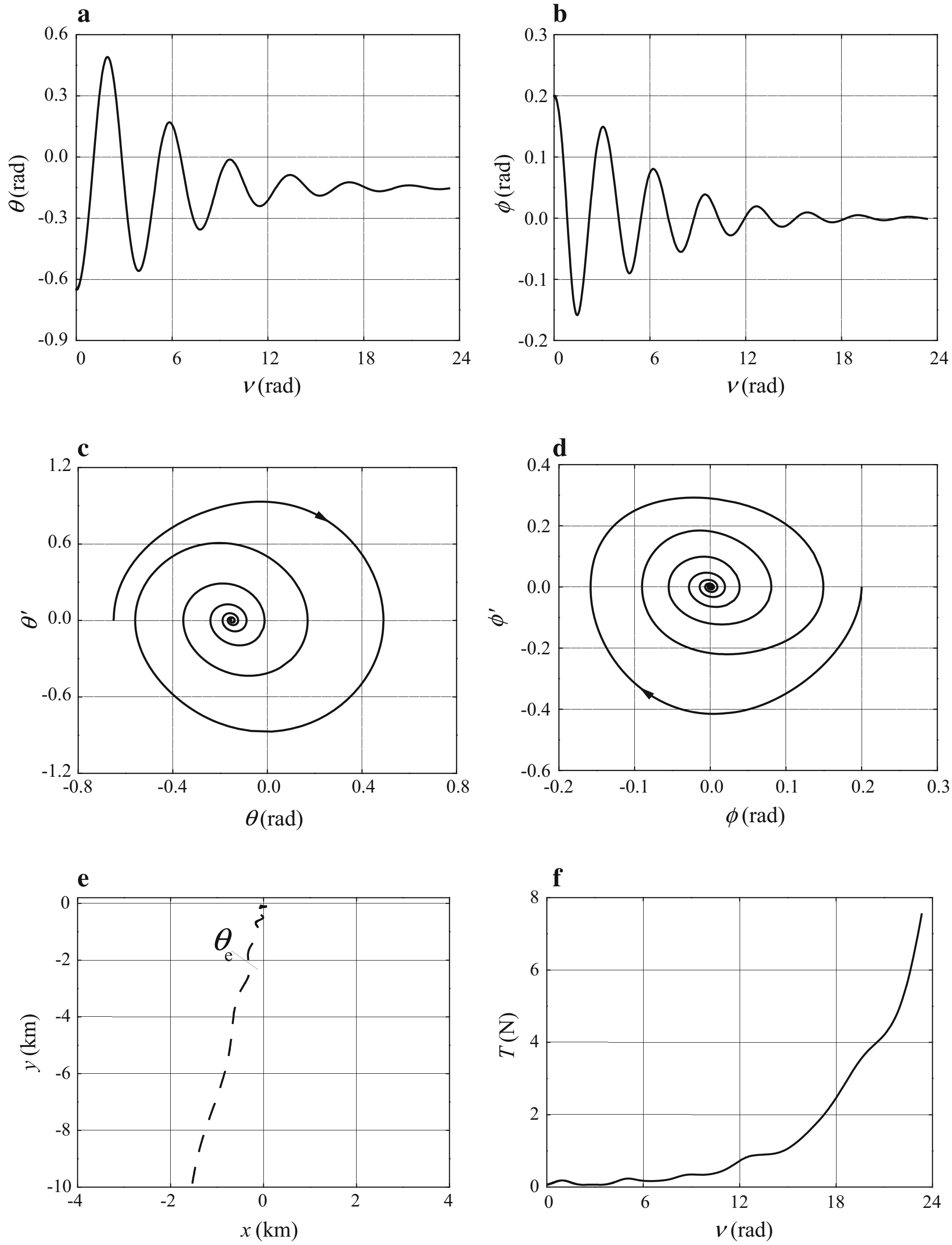

Fig. 6 Deployment control law of tether length rate. **a** Pitch angle versus ν. **b** Roll angle versus ν. **c** Phase portrait in the θ - θ' plane. **d** Phase portrait in the ϕ - ϕ' plane. **e** Trajectory of sub-satellite. **f** Tensions versus ν

the control law. Kissel's control has been mentioned repeatedly [44,63,78] and enables the tethered sub-satellite to be deployed along the local vertical direction. A numerical case is plotted in Fig. 7. The trajectory of the tether deployment governed by Kissel's control law is depicted in Fig. 7a. The changes of the deployed tether length and control force with the time t are shown in Fig. 7b, c, respectively.

In addition, to accomplish the deployment of a sub-satellite in a three-dimensional space, a mission function control was introduced by Fujii et al. [50,98–100]. Based on the Lyapunov function, an analytical control law for the tethered system was designed by Vadali et al. [60,101]. The stability of a closed-loop system subjected to the nonlinear feedback control law was analyzed, and it was emphasized that positive tension could be guaranteed under this control

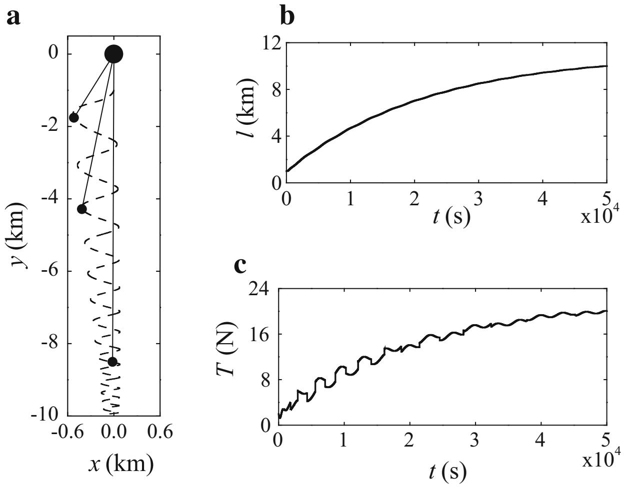

Fig. 7 Kissel's control. **a** Trajectory of sub-satellite. **b** Deployed tether length versus t. **c** Control force versus t

law. In the case of a circular or nearly circular orbit, a linear feedback control law was obtained by Zhong and Xu [102]. However, the control law was simply derived from the stability theory of linear autonomous systems. Assuming linear density of a space tether, a tension control law was derived by Zabolotnov [103]. The tether could be deployed along the vertical direction under the control law. The ability to realize control laws was estimated with a model of the controlled motion of the TSS with distributed parameters. Tether deployment along a certain trajectory under an analytical solution was achieved by Malashin et al. [53] for a tension control law. Both the longitudinal and transverse oscillations of the tether were suppressed together.

The optimal control strategy for tether deployment has been developed in recent decades. One of the major advantages is that this method can sufficiently take the actual constraints of the system states into account to deploy the tether subject to the constraints. Works by Fujii and Anazawa [100] and Kentaroh et al. [104] transformed the problem of the deployment of a tethered sub-satellite into the two-point boundary-value problem with an unspecified terminal time. Subsequently, a real-time optima1 state feedback controller was designed by virtue of the receding horizon control method. Based on a gravity-gradient stabilized model for a tethered sub-satellite, the optimal trajectory for the deployment was developed by Fujii et al. [105,106] using a Riemannian metric. The numerical simulations showed that suppressing the in-plane oscillation of the tether was successful. Additionally, the time optimal control for the tether deployment was concentrated by Steindl and Troger [107] through varying the tether tension. The key point of their work was the ability to deploy the sub-satellite from a periodic oscillation close to the local vertical position to a periodic motion away from the mother satellite in the shortest time. Some detailed problems (e.g., the perturbation [108], restricted tension force [109], and massive tether [110]) were also introduced in their studies. The optimal control problem was comprehensively addressed by Williams et al. [43,111]. They also summarized the common cost functions as well as the boundary conditions for diverse models. To avoid negative controlled tension in a tether deployment, the synthesis of a nonlinear optimal control law for the TSS was employed by Williams [65]. For a spinning tethered formation with a triangle-like configuration, the optimal deployment trajectories of the system via tension control were discussed by Williams [112,113]. Numerical results showed that the spin rate of the formation tended to decrease in the process of the deployment, but could be returned to the expected rate by over-deploying the tethers and then immediately reeling them in. A nonlinear optimal feedback control for the deployment process of a tethered sub-satellite was designed by Wen et al. [66,114]. They discretized the optimal control problem first and then solved the presented large-scale optimization problem to obtain the optimal control solution [115]. Additionally, an online quasi-linearization iteration was proposed to transform the nonlinear optimal control problem into a series of linear optimal control problems that could be solved in a series of sampling moments [116]. For the optimal control problem, the solution process might cost too much time, and numerical solutions are often acquired instead of analytical solutions.

In recent years, sliding mode control has been used for tether deployment. This is a nonlinear control approach and has strong robustness and adaptability for uncertainties and exogenous disturbances. For example, with the input limitations and uncertain external perturbations, modified adaptive state feedback sliding mode control was introduced by Ma et al. [117,118] to implement tether deployment through tension control. It guaranteed that during deployment the system state converged to the expected sliding mode surface in finite time. Additionally, full-order sliding mode control was applied with the limit of the positive tension, and an ideal sliding mode surface was designed to assure the asymptotically stable deployment of the tether [119]. For realizing robust trajectory tracking of the tether deployment, the equivalent control and switching control methods were adopted by Wang et al. [120] in designing a sliding mode controller. A fractional-order sliding mode control for the deployment of the tether was proposed by Kang et al. [121], who analyzed the stability of the control law. They noted that not only do all states converged to the expected states at the equilibrium position, but perturbations due to uncertainties were suppressed also.

Most of the tension control laws are not easily written in an analytical form and are frequently acquired through substantial calculation. Moreover, accomplishing the control law requires high-precision tension sensors. However, the tethered payload determined by the control law is capable of being deployed along a designated trajectory.

3.4 Assisted control

Because of the complicated system and external environment, the effectiveness of the tether deployment governed by only one control force might be not satisfactory. As an auxiliary method of deployment control, a thruster acting on the end-body deserves attention. The thrust-aided deployment of an electrodynamic tether system from a spool-type reel was simulated by Iki et al. [122]. The thrusters were used to ensure the deployment of a multi-kilometer tether. Further, a set of ground experiments was performed for the study [123]. The deployment dynamics and stability of a long tape-shaped tether deployed from an orbiting spacecraft with the aid of thrusters were investigated by Mantellato et al. [72].

The combination of tension and thruster control was the focus of much early work. For example, a linear control law that suppressed in-plane and out-of-plane oscillations of the tether by means of tension and thruster control was examined by Kumar and Pradeep [124]. The proposed controller worked very well for the nonlinear tethered system and was very robust, even though it was designed only for the linear system. The deployment of a spinning tethered formation was analyzed by Nakaya et al. [125] through two control methods: the tether tension and the angular momentum caused by thruster, the control methods were validated by ground-based experiments. To achieve the optimal deployment process, Jin and Hu [126] constructed and minimized a performance index using radial tether tension and tangential and normal thrusters. To suppress the in-plane and out-of-plane motions of a sub-satellite to be deployed to a designated position in the shortest time, the tether tension and a thruster were employed by Wen et al. [127]. Fast deployment of a short tethered satellite via combined control was investigated by Liu et al. [74,128]. In their studies, the tether tension was positive due to the accelerated deployment, and a thruster was utilized to adjust the direction of the deployment.

Some other combined control methods have been described also. For example, to improve performance and reduce fuel consumption during deployment, the optimized length law together with an optimized thruster was used by Netzer and Kane [129]. Based on a three-dimensional electrodynamic tether system, an analytical feedback control law for the deployment was synthesized by Wen et al. [130] to stabilize the system motions. The proposed controller was decomposed into two parts, the electrical current control and tension control. The current control generated by the Lorentz force was strengthened by the tension control to achieve extra damping injection into the attitude motion. The deployment process of a bare electrodynamic tether system was investigated by Zhang et al. [131], who succeeded in reducing the in-plane pitch angle only using the Lorentz force.

The mentioned assisted control methods play important roles in tether deployment and make the length/length rate/tension control laws more effective.

4 Ground experiments for tethered deployments

The ground experiment is one of the important tools to evaluate the deployment dynamics of an orbiting TSS. Research has been conducted continuously by numerous scientists. For example, a micro-tether reeling mechanism (MTRM) was studied by Nakamura and Hashimotot [132]. The deployment function of the MTRM was verified in the ground experiments. To estimate the control methods proposed by Nakaya et al. [125] in the previous section, experiments on the deployment of a tethered formation were performed. A separation mechanism for the deployment of an electrodynamic tether system was designed by Yamanaka et al. [133]. The feasibility of the tether deployment function of the mechanism was validated in a three-dimensional microgravity environment. The deployment of a bare electrodynamic tape-shaped tether was addressed by van de Heijning and Zandbergen [134,135], whose experimental results demonstrated the possibility of applying a cold gas thruster to eject the tethered end-body at the initial phase of the deployment. A bare electrodynamic tape-shaped tether was discussed by Watanabe et al. [136] as well, who expected rapid deployment of the tether would be successful. A set of ground-based experiments on the deployment of an electrodynamic tether was implemented by Iki et al. [123]. Various key parameters were evaluated successfully. The tether deployment of an orbiting TSS was emulated by Bindra and Zhu [137]. An Earth-based experimental environment was developed, and appropriate scaling factors were used for numerous physical experimental parameters (e.g., the length and deployment rate of the tether) to compare the dynamic behaviors of the experimental system to those in orbit. It was concluded that the dynamics of the tether deployment was chiefly concentrated in the ground experiment. It is not easy to realize the control strategy accurately in the ground laboratory due to the complicated perturbation factors. Furthermore, the deployment device deserves particular attention since it plays a critical role in the deployment process, with considerable literature available [138–141].

Additionally, a ground experiment on the deployment of a tethered simulator is also focused by the authors' team. A ground-based experimental system is established as illustrated in Fig. 8. Satellite simulators act as sub-satellites on a marble testbed. A deployment device with the ability to

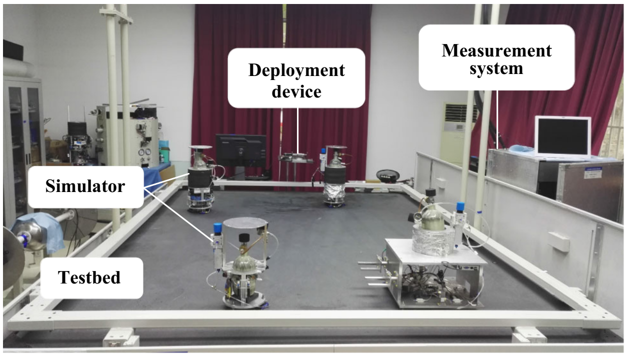

Fig. 8 Ground-based experimental system

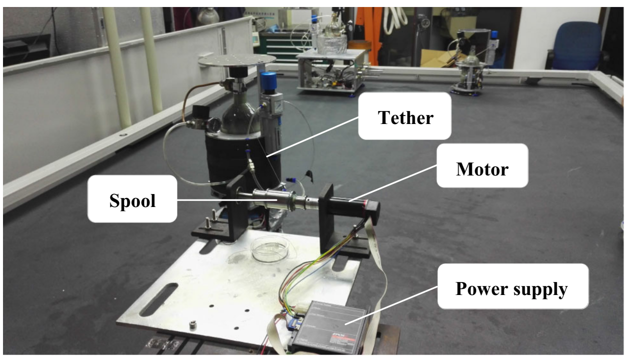

Fig. 9 Deployment device

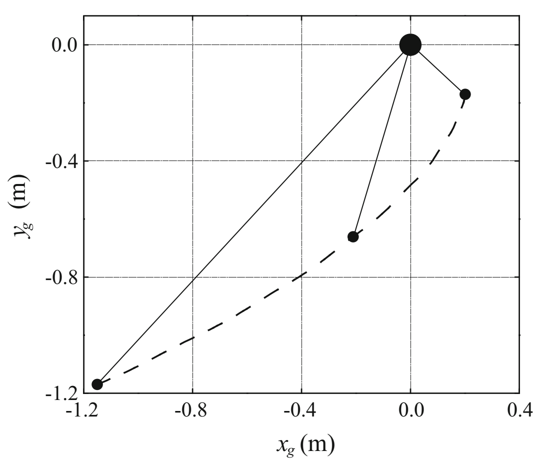

Fig. 10 Free deployment of ground-based tethered simulator

release the tether is treated as the mother satellite restricted to a Keplerian orbit. The measurement system can capture the real-time states of the simulators.

The key deployment mechanism is shown in Fig. 9. The device consists of a motor, a spool, a tether, and other auxiliary apparatuses. The brushless direct current (DC) motor can operate in different modes, such as position mode, speed mode, and current mode. The three modes correspond to length control, length rate control, and tension control of the tether, respectively. The spool with diameters of 15, 20, 30 mm is driven by the motor. The experimental tether, which connects the spool and the satellite simulator, is called Dyneema and is highly flexible.

According to the principle of dynamics similarity, a ground-based experiment for the free deployment of the tethered simulator was conducted as follows. An experimental tether approximately 1.6 m long was used. The deployment trajectory of the tethered simulator acted on only by the Coriolis force in a ground-based reference frame o' - $x_g y_g$ is presented in Fig. 10. The experimental result is consistent with the numerical cases of the orbiting TSS mentioned above in Figs. 2b and 3b. Another experimental example was executed to check the length rate control law Eq. (11). With an expected pitch angle $\theta_e = -0.15$ rad, the deployment process of the tethered simulator is shown in Fig. 11. The deployment trajectory of the satellite simulator is plotted in Fig. 11a. The simulator ultimately completed the deployment task and arrived at the expected pitch angle after swinging around $\theta_e = -0.15$ rad. The changes of the tether pitch angle are displayed in Fig. 11b. As observed in Fig. 11b, the pitch angle gradually reached the expected angle of -0.15 rad after two cycles.

5 Conclusions

The rapid development of space tether deployment technology will promote the progress of the space exploration and exploitation. This review article briefly introduces the background, applications, and crucial problems of tether deployment. Three typical models for the space tether are discussed. The continuous model, discrete model, and rod model are suitable for the study of the deployment dynamics and control methods, respectively. The control laws are classified in the light of the mode of control. Length control and length rate control of the tether are more convenient for the deployment, since they are in general analytical expressions. Tension control (optimal control in particular) can make the tethered end-body deploy to an expected state. Thruster control is an important auxiliary method of deployment control. The majority of experiments demonstrate only the feasibility of the tether deployment in an artificial microgravity environment.

In the future deployment dynamics based on some special tether models (e.g., a tape-shaped tether model) are worthy of deeper investigation. Dynamics control subject to the rigid-flexible coupling effect between the spacecraft body and a flexible tether is a valuable topic for study. It is important to improve the technology of ground-based experiments for tether deployment to verify proposed control methods.

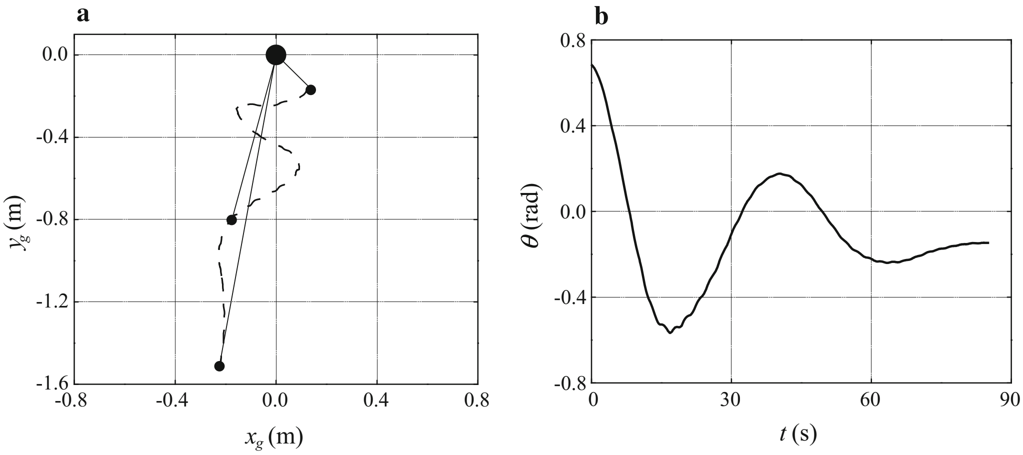

Fig. 11 Tether deployment control of ground-based simulation system. **a** Trajectory of satellite simulator. **b** Pitch angle versus t

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