

Simulation of the Dynamics and Control of Tethered Small Satellite Deployment



G. R. Sangeetha and Harikumar Ganesan

Abstract This paper presents the simulation studies of the dynamics of short tethered satellite system during the deployment phase. The deployment dynamics of the tethered system is dominated by the tether oscillations and the three-dimensional attitude dynamics of the sub-satellite. The dynamic characters of the system are investigated, and probable control strategies that can be adopted for the faithful and hassle-free deployment of the tether are discussed. Tether is proposed to be released with an initial velocity with constant deceleration using tension in tether. Dynamics of a short tether of 10 m length connected to a 10 kg 3U sub-satellite is considered in the study. Deployment with tether in tension and without tension in tether is discussed.

Keywords Dynamics · Short tethered satellite · Tether oscillations · 10m tether

1 Introduction

India is entering an ambitious new trajectory in its space research and is steadily keeping pace with the developments in space arena across the globe. With more and more long-life exploration missions planned, on-orbit servicing, refueling, inspection and repair, executing repeated and monotonous maintenance operations are indispensable auxiliary functions. In addition, due to proliferated space activity over past 60 years, the number of space debris has reached a whopping 17,000 [1]. Of these, the small-sized debris is found to inflict profound damage to serve spacecrafts. This also calls for immediate human intervention.

An autonomous system that can independently carry out inspection and repair activities, as well as serve to collect small size debris in the immediate vicinity of the spacecraft, is the need of the hour. It is proposed to develop a smart sub-satellite tethered to a parent spacecraft, which can deploy itself, perform inspection and repair operations, collect space debris, return and re-attach to the parent body

G. R. Sangeetha (✉) · H. Ganesan
ISRO Inertial Systems Unit, Trivandrum, India
e-mail: sangeetha_gr@vssc.gov.in

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on its own. The operations of the smart sub-satellite were spread across three major phases—deployment, station keeping, and retrieval.

Space tether missions have a long history, beginning with the GEMINI-11 and GEMINI-12 missions, pioneered by NASA in 1996. Then, there was a brief lull for nearly 10 years, following which a number of tethered experiments have been carried out by various space agencies since the 1980s, details of which are listed in [2] and [6]. These missions have served to demonstrate various tethered system concepts such as generation of artificial gravity by spinning, gravity stabilization, upper atmospheric studies, generation of electrical energy using electrodynamic tethers. Though most theoretical studies, as well as early experiments, have concentrated on long tethers, the current focus is on short tethered system applicable to small satellites.

In this paper, the dynamics of the tethered sub-satellite during deployment is studied. The sub-satellite is of the 3U category with 10 kg mass. It is attached to the parent body through a 10-m-long tether. Two scenarios have been studied: (1) deployment assuming zero tension in tether, (2) deployment to nearly 5 m tether length under controlled tension. Case (1) is significant in developing initial insights into the qualitative and quantitative features of the tethered satellite motion. Case (2) is of practical importance in developing control laws for deployment.

The translational dynamics has been expressed both in terms of the motion of the CG of the sub-satellite in the 3D space and in terms of the in-plane and out-of-plane angles of the tether. The attitude dynamics has also been modeled to study the rotational dynamics of the sub-satellite with and without tension.

2 Assumptions

For the purpose of modeling the dominant dynamics, the base satellite is considered as a massive spacecraft, tether as massless, and the sub-satellite is of comparatively lower mass. The sub-satellite moves away from the base satellite due to delta V imparted by separation mechanism/thruster. The assumptions are as follows:

Sub-satellite Mass: 10 kg

Base satellite: Mass > 2 tons, circular sun-synchronous polar orbit at 800 km altitude, unperturbed by sub-satellite motion

Tether:	Material	Kevlar 49
	Young's modulus	83 GPa
	Tensile strength σ^* :	3.8 GPa
	Density ρ :	1.44 g/cm ³
	Length:	10 m
	Diameter of tether (cylindrical):	2 mm (45 g)

3 Translational Dynamics

The tethered satellite system is shown in Fig. 1. The base satellite is depicted as B , and the sub-satellite is depicted as A .

The motion of sub-satellite, A , has been developed based on

$$m_A w_A = T_A + F_A + G_A \tag{1}$$

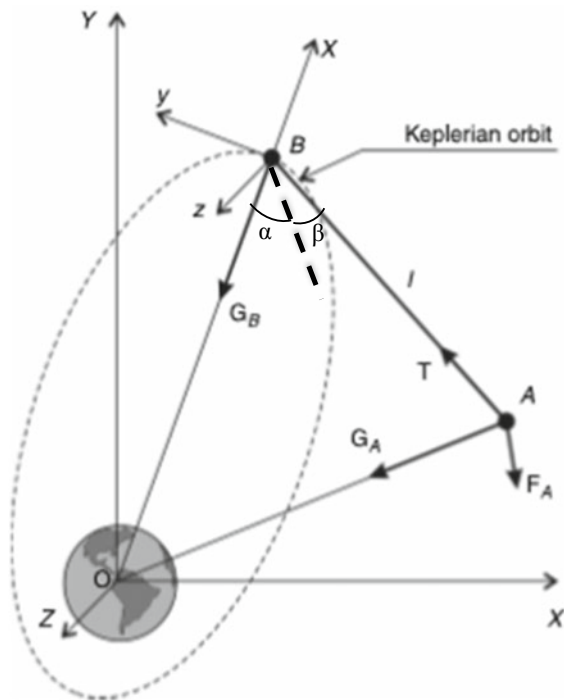
w_A —acceleration of the particle which is the sum of coriolis, relative, and reference-frame accelerations, T_A —tension in tether, F_A —non-gravitational forces, G_A —gravitational force on particle A .

The motion of base satellite, B , is modeled as follows based on the assumption of Keplerian motion for the vehicle:

$$\ddot{r}_B = -\frac{\mu r_B}{r_B^3} \tag{2}$$

The motion of the tethered satellite system in the base satellite orbital coordinate frame is as follows [2, 3]:

Fig. 1 Tethered satellite system depicted as point masses connected by a tether [2]



$$\left. \begin{aligned} \ddot{x} - 2\dot{y}\omega - \dot{\omega}y - (1 + 2k^{-1})\omega^2x &= \frac{T_x + F_x}{m_A} \\ \ddot{y} - 2\dot{x}\omega - \dot{\omega}x - (1 - k^{-1})\omega^2y &= \frac{T_y + F_y}{m_A} \\ \ddot{z} + k^{-1}\omega^2z &= \frac{T_z + F_z}{m_A} \end{aligned} \right\} \quad (3)$$

$$T = ES \left(\frac{\rho_A}{l_0} - 1 \right) \quad (4)$$

where T : tension force on tether attached from c.o.m, F : non-gravitational external forces, m_A : TSR mass, ω : orbital angular velocity, $k: 1 + e\cos(\Psi)$ where $e =$ eccentricity, $\Psi =$ true anomaly, E : Young's modulus of tether, S : cross-sectional area of tether, l_0 : length of tether, ρ_A : TSR radial position in xyz frame, r_B : radius vector of base satellite in geocentric coordinate system, μ : Earth's gravitational constant.

When the tether is massless rigid rod, the motion of the sub-satellite can be expressed in terms of the in-plane and out-of-plane angles of the tether. As given in Fig. 2, α denotes the in-plane angle and β denotes the out of plane angle and the x , y , z coordinates of the sub-satellite can be expressed as

$$x = -l \cos \alpha \cos \beta, \quad y = -l \sin \alpha \cos \beta, \quad z = -l \sin \beta$$

The dynamics of system in terms of tether angles is given as

$$\left. \begin{aligned} \ddot{\alpha} &= -2(\dot{\alpha} + \omega) \left(\frac{\dot{l}}{l} - \dot{\beta} \tan \beta \right) - 3\omega^2 \sin \alpha \cos \alpha + \frac{u_1}{m_A l^2 \cos^2 \beta} \\ \ddot{\beta} &= -2 \left(\frac{\dot{l}}{l} \dot{\beta} \right) - [(\dot{\alpha} + \omega)^2 + 3\omega^2 \cos^2 \alpha] \sin \beta \cos \beta - \frac{u_2}{m_A l^2} \\ \ddot{l} &= -l(\dot{\beta}^2 - \omega^2) + 3l\omega^2 \cos^2 \beta \cos^2 \alpha + l \cos^2 \beta (\dot{\alpha} + \omega)^2 - \frac{T}{m} + u_3 \end{aligned} \right\} \quad (5)$$

where u_1 , u_2 , and u_3 are the control forces, which is a resultant of the actual control force applied and the disturbances.

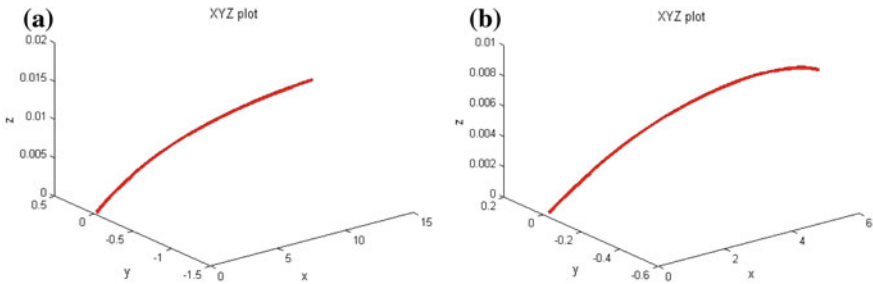


Fig. 2 **a** Plot of tether motion in 3D space (without tension). **b** Plot of tether motion in 3D space (with tension)

4 Attitude Dynamics

The attitude of the sub-satellite is coupled with the motion of the tether [4] and is given as

$$\left. \begin{aligned} I_{sy}\ddot{\theta}_s + (I_{sy} + m_s l)\ddot{\theta}_t - m_s\ddot{l}\theta_s + m_s\dot{l}\dot{\theta}_t &= 0 \\ I_{sx}\ddot{\varphi}_s - (I_{sx} + m_s l)\ddot{\theta}_t - m_s\ddot{l}\varphi_s - m_s\dot{l}\dot{\varphi}_t &= 0 \\ I_{sz}\ddot{\vartheta}_s + m_s l(\varphi_s\ddot{\theta}_t + \theta_s\ddot{\varphi}_t) &= 0 \end{aligned} \right\} \quad (6)$$

where θ_s = subsatellite pitch angle, φ_s = subsatellite roll angle, ϑ_s = subsatellite yaw angle.

5 Results and Inference

Based on the dynamic model for translational and rotational motion of sub-satellite, obtained above, simulation was performed to study the possibilities of deployment.

Case study: Ensure stable deployment to a length of 5 m in 100 ms and station keeping at 5 m for 500 s

The sub-satellite is deployed along the local vertical. The deployment conditions are as given below

$$\begin{aligned} \alpha_0 &= 0 \text{ degree (along local vertical - } Ox \text{ axis), } \dot{\alpha}_0 = 0.02^\circ/\text{s,} \\ \beta_0 &= 0 \text{ degree (in plane deployment), } \dot{\beta}_0 = 0.05^\circ/\text{s,} \end{aligned}$$

Initial length of tether = 0.2 m

Release velocity = 0.1 m/s

$$\theta_{s0} = 0.2^\circ, \dot{\theta}_{s0} = 0.05^\circ/\text{s}, \varphi_s = -0.1^\circ, \dot{\varphi}_s = -0.03^\circ/\text{s}, \vartheta_s = -0.5^\circ, \dot{\vartheta}_s = 0.1^\circ/\text{s}$$

Case 1: Deployment without tension in tether: It is seen that without any tension in the tether, the tether gets released to about 10 m in 100 s due to the initial velocity of 0.1 m/s. Also, acceleration of the order of $2 \times 10^{-5} \text{ m/s}^2$ is experienced by the tether due to the effect of Coriolis force. The rate of change of in-plane angle of the tether settles to the orbital rate of $0.06^\circ/\text{s}$ in 100 s, and hence, the in-plane tether angle deflects to 6° , as shown in Fig. 4a. The rate of change of out-of-plane angle of tether also settles to 0, and in the influence of the initial rate of $0.05^\circ/\text{s}$, the out-of-plane angle settles to 0.1° in 100 s. Even in the absence of tension in tether, the translational dynamics remains stable (Figs. 3, 5 and 6).

The attitude dynamics of the sub-satellite is coupled with the tether motion. The rate of in-plane and out-of-plane angles settles to zero and does not introduce any disturbance on the attitude; however, the acceleration on the tether introduces instability in attitude due to high rates coming on the sub-satellite.

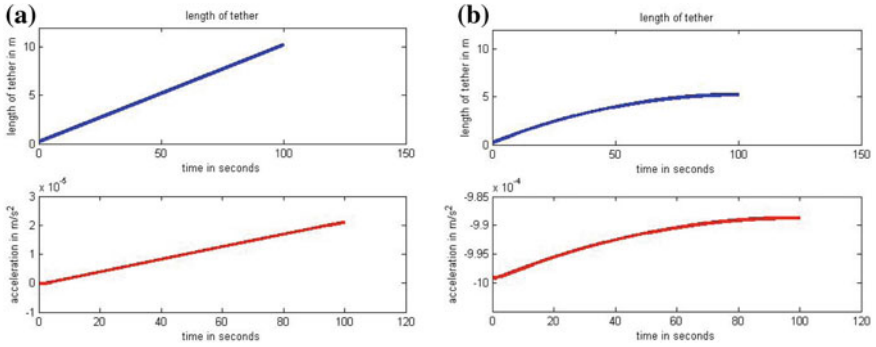


Fig. 3 a Deployed length and acceleration on tether (without tension). b Deployed length and acceleration on tether (with tension)

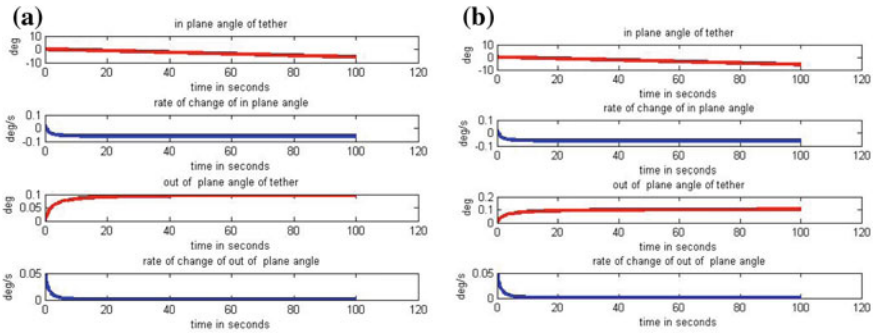


Fig. 4 a In-plane and out-of-plane angles of tether (without tension). b In-plane and out-of-plane angles of tether (with tension)

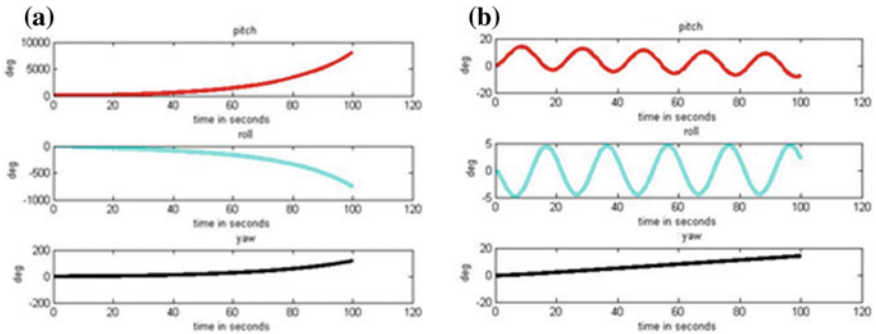


Fig. 5 a Sub-satellite attitude angles (without tension). b Sub-satellite attitude angles (with tension)

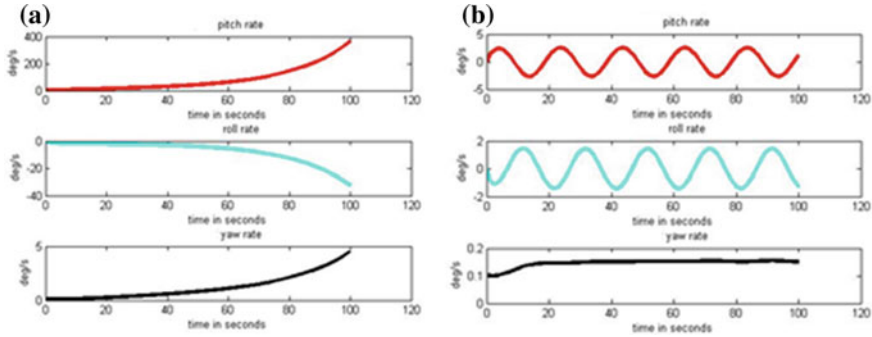


Fig. 6 **a** Sub-satellite attitude rates (without tension). **b** Sub-satellite attitude rates (with tension)

Case 2: Deployment with tension in tether: To ensure deployment of the tether to the desired length, the tether has to be maintained in tension. A tension which imparts an acceleration equivalent to 0.001 m/s^2 is given on the tether. The tether tension can be maintained to required value, by controlling the tether releasing mechanism [5].

In this scenario, it is seen that with the tension in the tether, required length of deployment is achieved and the in-plane and out-of-plane angles of the tether and the respective rates, follow the same trajectory as in the case of the deployment without tension, as expected. Due to the negative acceleration imparted on tether, the sub-satellite motion is stable and due to its coupling with the tether motion, the sub-satellite attitudes display vibratory sinusoidal motion with attitudes less than $\pm 10^\circ$ in pitch, $\pm 5^\circ$ in roll, and a gradual increase of up to 18° in yaw. The pitch and roll rates oscillate at $< \pm 3^\circ/\text{s}$, and the yaw rate settles to a constant value of $0.15^\circ/\text{s}$ due to which the yaw is seen to steadily increase.

The disturbance forces at the 800 km orbit have not been modeled. Aerodynamic drag would be a significant component. The presence of this could further dampen the swing in the attitude of the sub-satellite and reduce it to the level of vibrations [4].

6 Summary

The dynamics of deployment of a tethered satellite system has been studied. A controlled deployment method to achieve a desired station-keeping distance has been simulated.

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