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Research on the tether assisted observation of an asteroid

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ABSTRACT

The exploration of asteroids attracts much attention due to its potential in both scientific research and engineering application. However, the observation of an asteroid is a difficult task as the gravitational attraction of the asteroid is limited and complex. This paper proposes a concept of keeping probes in hovering above the asteroid by space tethers. The dynamics of a tethered probe attached to the surface of an asteroid is analyzed and the equations of motion are derived using Lagrange's equation. Then the equilibrium points of the dynamic system are calculated. The equilibrium tether libration angles are determined by the tether length and tether attaching location, while subjected to the constraint of positive tether tension. Afterwards, the stability of the equilibrium points are studied based on Lyapunov's theory. The variation of the equilibrium points with respect to the tether attaching location is numerically analyzed in the scenarios of different tether lengths. A parametric study of the stability of the equilibrium points is also provided. Finally, the dynamic behavior of a tethered probe perturbed from the equilibrium states is simulated to verify the proposed tether assisted technology for the observation of the asteroid.

1. Introduction

The space tether technology has shown great potential in enabling a broad range of scientific and engineering tasks since it was proposed by the forerunners of aerospace engineering [1]. This technology has several advantages. For instance, the tethers are lightweight and compact, which can be folded and stowed in a small device before deployment. Therefore, they are especially appropriate for the application that require remote operation or a long range baselines, such as space tug system [2,3], formation flying [4,5], and interferometer [6]. Another important proposal in using tethers is achieving propellantless orbital maneuver through momentum exchange between the end-bodies connected by tethers, while larger momentum is transferred to the target spacecraft if the tethered system spins faster [7]. Moreover, there has been continuous interest in the conductive tethers moving in the Earth's geomagnetic field. Due to the electromagnetic effect, current is induced along a conductive tether with electron emitting and collecting devices when the system orbits the Earth. This enables power generation [8] or propellantless deorbiting as the tether with current is subjected to the electrodynamic force/Lorentz force [9]. Oppose to the eletrodynamic tether, the electrostatic tether is highly positive or negative biased using high-voltage source onboard, and then the tethered system is affected by the Coulomb force [10].

The merits of space tethers make them an appropriate tool for space application, including exploration of asteroids. The study on the physical and dynamical properties of asteroids and comets may answer fundamental questions about the origin and early evolution of solar system, possibly including the development of life on Earth [11]. Space technologies have been used in the asteroid exploration for several decades. Space missions have been developed and enriched the knowledge of asteroids significantly, such as NASA's Near Earth Asteroid Rendezvous (NEAR) mission and JAXA's Hayabusa mission. Besides, the JAXA's new Hayabusa 2 mission is now flying toward asteroid Ryugu, and NASA's asteroid sample return mission OSIRIS-REx will be launched in September 2016. Existing literature on the application of space tethers in asteroid missions mainly focused on the redirection ability of tethered ballast mass due to its capability of changing the mass center of the asteroid or providing momentum exchange between the asteroid and the ballast mass. French and Mazzoleni [12] proposed a scheme of using a long tether with a tip mass as a mitigation technique against asteroids on an Earth intersecting trajectory. This technique ensures that the entire asteroid is deflected, and takes advantage on traditional ways, such as a direct impact causing unpredictable consequences. The technique is further analyzed by studying the affection on the redirection effectiveness of the design parameters including the tether length

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and the ballast mass ratio, as well as the orbital size and the shape of the asteroid [13]. Mashayekhi and Misra [14] shows that the close approach distance between the asteroid and the Earth can be further increased by cutting the tether at an appropriate time. A numerical optimization scheme is proposed to determine the best point of tether severance [15]. Numerical simulation proves that the best severance condition is determined both by the tether orientation and rotational rate, where the angle between the tether orientation and the local vertical is close to π, and the tether rotational rate is close to its maximum. Although promising, the disadvantage of the technique compared to other redirection method is obvious, such as the long timeframes as well as large volume and mass requirements [16].

Unlike many existing works, this work concerns another aspect of tether application in asteroid missions, which takes into consideration of the affection of the asteroid's gravitation. It is well known that the gravitational field of asteroid is much different from a spherical celestial body, such as the Earth, and the gravitational attraction of the asteroid is rather weak. This makes the probe difficult to accomplish a long time fly-around for observation of the asteroid. Numerical analysis show that there exist equilibrium points in the vicinity of the asteroid, where the gravitational force equals to the centrifugal force. These equilibrium points provide natural hovering positions for observation and close-proximity operations during the asteroid mission. However, the number of equilibrium points of asteroids is usually limited, and the positions of the equilibrium points are determined by the parameters, such as the mass distribution and the self-rotation rate of the asteroid. Intuitively, by adopting the tether, the number of equilibrium points will increase sharply because the tether provides tension to keep the probe in hovering. Thus, the tether is an effective tool in the asteroid exploration, e.g. a mission to observe an arbitrary area on the asteroid can be operated in the following sequence, firstly land the probe on the target area of the asteroid, then attach the tether to the surface and depart with tether loosen, finally tighten the tether after the probe reach the desired height (see Fig. 1). However, it should be noted that the existing condition and the stability of the equilibrium points are complicated due to the irregular gravitational field of the asteroid.

In the following part of the paper, the gravitational field model for an asteroid will be established using a homogeneous polyhedron, and then the equations of motion of the tethered probe attached to any point on the surface of the asteroid will be conducted based on the built model of gravity. Thereafter the equilibrium points of the system will be calculated and their stability will be analyzed. Parametric analysis will be provided that the affection of the tether attaching location and the tether length to the equilibrium condition will be investigated. Finally, the obtained results about the equilibrium points will be verified by numerical simulations of dynamic behavior of a tethered probe in the vicinity of an asteroid.

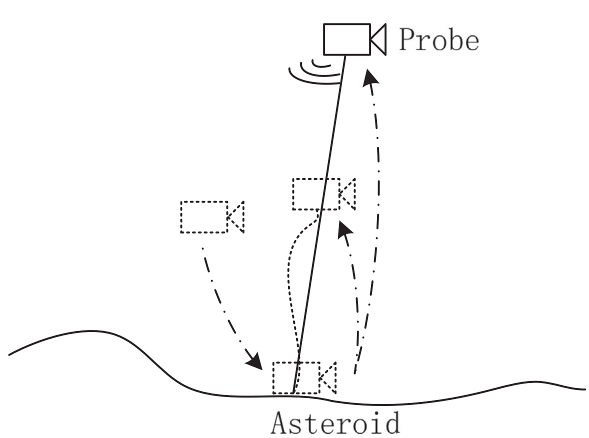

Fig. 1. Mission concept of tether assisted observation of an asteroid.

2. Dynamic formulation of tethered probe in the vicinity of an asteroid

2.1. Description of the system

Assume that the probe is attached to any surface point of an asteroid, then the probe is subjected to the gravitational attraction and the tether tension, whereas the other space environmental perturbations are ignored. The probe is modeled as a point mass because the size of the probe is rather small compared to the asteroid. The tether is treated as a massless rigid rod that cannot sustain pressure for simplicity. Assume that the asteroid rotates about its maximum-moment principal axis, which is a common case in the universe.

The dynamics of the tethered probe in the vicinity of the asteroid can be described by the following coordinate system as shown in Fig. 2. First, the asteroid body-fixed frame, S_a, is defined with its origin at the center of the asteroid where x_a-axis is the self-rotation axis of the asteroid, y_a-axis and z_a-axis are the other two principal axis of inertial of the asteroid and complete a right-hand coordinate system. Secondly, the local coordinate system of the tether attaching point, S_l, which can be obtained by rotating S_a about x_a-axis with the longitude of the tether attaching point, λ, followed by the latitude, φ, about y'-axis (the y_a-axis after the first rotation), and moving the origin to the tether attaching point. Finally, to describe the libration of the tether, a coordinate frame fixed to the tether, S_b, is defined by rotating S_l with an in-plane angle α about y_l-axis, and then followed by an out-plane angle β about x_b-axis (the x_l-axis after the first rotation). The origins of S_b and S_l are identical.

Based on the above coordinate systems, the motion of the tethered probe is determined by five parameters, the longitude λ and the latitude φ of the tether attaching point, the tether length l, and the in-plane and the out-plane libration angles of the tether, α and β. The coordinate transform matrices between the defined coordinate systems are directly obtained as follows,

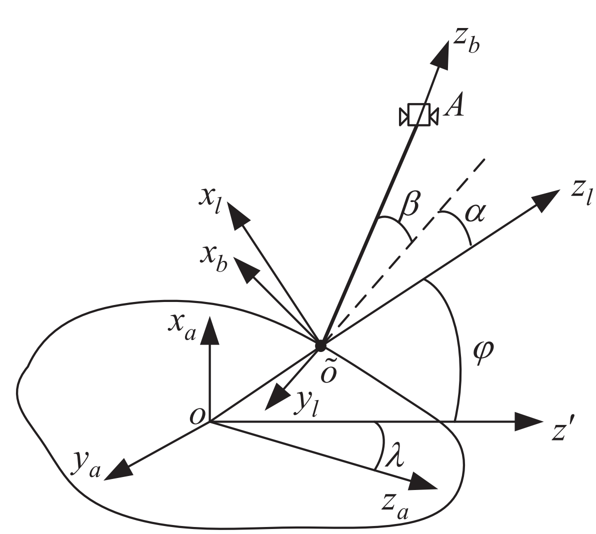

Fig. 2. Schematic of coordinate systems for the tethered probe in the vicinity of an asteroid.