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Modeling and experimental validation of sawing based lander anchoring and sampling methods for asteroid exploration

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Abstract

This paper presents a novel lander anchoring system based on sawing method for asteroid exploration. The system is composed of three robotic arms, three cutting discs, and a control system. The discs mounted at the end of the arms are able to penetrate into the rock surface of asteroids. After the discs cut into the rock surface, the self-locking function of the arms provides forces to fix the lander on the surface. Modeling, trajectory planning, simulations, mechanism design, and prototype fabrication of the anchoring system are discussed, respectively. The performances of the system are tested on different kinds of rocks, at different sawing angles, locations, and speeds. Results show that the system can cut 15 mm deep into granite rock in 180 s at sawing angle of 60°, with the average power of 58.41 W, and the "weight on bit" (WOB) of 8.637 N. The 7.8 kg anchoring system is capable of providing omni-directional anchoring forces, at least 225 N normal and 157 N tangent to the surface of the rock. The system has the advantages of low-weight, low energy consumption and balance forces, high anchoring efficiency and reliability, and could enable the lander to move and sample or assist astronauts and robots in walking and sampling on asteroids.

Keywords: Asteroid exploration; Anchoring method; Sawing modeling; Motion planning; Walking and sampling assists

1. Introduction

Asteroids are minor planetary bodies which have significances for scientific research because they may carry evidences of the formation of the solar system and hold secrets about the beginnings of life on earth (Marais et al., 2008). Asteroids contain rare metals and even water. The concepts and technologies for resources mining on asteroids had been proposed and studied in recent years by space agencies and companies (Badescu, 2013). Moreover, some Near Earth Asteroids (NEAs) may hit the earth. This poses dangers to our planet and living environment. The significances for scientific research, commercial value, and threat to our civilizations of asteroids have drawn increasing interest from research institutes worldwide. There are a great many exploration missions such as the NEAR (Anderson et al., 2001), Dawn (Memarsadeghi et al., 2012), and OSIRIS-Rex (Sankaran et al., 2013) of NASA, Hayabusa 1 (Kubota et al., 2008; Shoemaker et al., 2013) and Hayabusa 2 (Tsuda et al., 2013) of JAXA, and Rosetta of ESA (Ulamec et al., 2006; Capaccioni et al., 2015).

In the first successful asteroids sample-return mission Hayabusa 1, the spacecraft performed touch-and-go surface operation for sampling without landing and anchoring (Kubota et al., 2008; Shoemaker et al., 2013). Hayabusa 2 and OSIRIS-Rex sample-return missions will also employ the touch-and-go sampling approach, to avoid the difficulties in landing and anchoring. However, landing and anchoring are necessary to provide enough balance forces

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and torques for moving, sampling, and executing other tasks. Especially, for massive sampling, subsurface materials mining, and manned exploration missions carrying out, reliable landing and anchoring are very important.

There are many challenges for landing and anchoring. One of them is the microgravity environment on these small bodies which brings troubles for anchoring (Steltzner and Nasif, 2000), moving (Yoshimitsu, 2004; Chacin et al., 2009; Koenig et al., 2014; Helmick et al., 2014; Palmer et al., 2015), and sampling (Parness, 2011; Gao et al., 2007; Zacny et al., 2008). Anchoring of the lander after landing on the surface of asteroids is a prerequisite for other missions. Robots or astronauts can leave the cabin and move on asteroids with assists of the anchored lander. Besides the low gravity environment, the surface properties of asteroids, such as hardness and brittleness, are not very well known, making the anchoring method design more difficult (Sipilaet et al., 2014). Moreover, the surface substance may contain regolith and rubble covering on the rock layer. The reliable and safe anchoring to provide enough forces for moving and sampling assists is that the lander has to be fixed on the rock layer after penetrating through or cleaning up the regolith and rubble.

Surface anchoring on asteroids has been studied for many years. Researchers have proposed several anchoring approaches for sampling, operation, and return missions. Drilling is a method for penetrating hard rocks. This method is feasible for drilling in low-strength materials such as plaster and limestone. But this method is not well adapted for higher strength materials like basalt (Zacny et al., 2013). Nailing is another approach for anchoring, but it can only work when the nail is perpendicular to the surface of rocks. Grippers are sharp fingers or microspines positioned opposite each other which work well only on uneven and rough solid surfaces (Parness et al., 2013). Fluid anchor provides anchoring force by injecting a wetting fluid onto the surface or into the soil on asteroids. But this method has the stability issue and may not be reused. The bio-inspired adhesion of climbing robots provides another approach to keep the lander pinned to the surface of asteroids (Murphy et al., 2011; He et al., 2014). The Rosetta lander Philae planned to utilize a self-adjusting landing gear for absorbing the energy of impact, ice screws for engaging the soft surface, and harpoons for penetrating the hard surface of comet 67P/Churyumov-Gerasimenko (Thiel et al., 2003; Biele and Ulamec, 2008). It also intended to use reverse thrusters to keep Philae fixed on the comet's surface. Unfortunately, the thrusters did not thrust and the harpoons failed to fire. Fortunately, after several times of bounces, Philae touched down on the comet successfully (Hand, 2014).

However, excessive high-strength surface covered by regolith and rubble might limit the functionality of all the anchoring methods mentioned above. In the China's manned asteroid exploration pre-research program, we are designing anchoring method, which also could be used in astronauts walking and sampling assist system design. As a base, the anchored lander can provide forces for walking and sampling assists. After many rock penetrating methods tests, we propose a novel sawing based anchoring method. It should be noted that this anchoring method is well adapted for solid rock layer and boulders but not for loose sand, regolith, and dust ground. If landing regions with thin regolith and rubble can be detected by the probe before the lander descends, the lander could land on these regions. If the regolith and rubble are not very thick, the robotic arm and cutting disc are able to penetrate through them or clean up them locally by scraping. More complex devices such as high pressure and mechanical brushes could also be utilized to clean up thicker regolith. If the thickness is too large, clean may be difficult. Other kinds of anchors like the harpoon or fluid anchor could be coupled with sawing based anchor to increase the probability of success.

In this paper, we focus on the feasibility and effectiveness validations of sawing based concept by modeling, simulation, and experiments, assuming that the lander could be controlled to touch down on the surface of asteroids and the lander has a reverse thruster to provide balance force for anchoring. The rest of this paper is organized as follows. Section 2 introduces the models of the cutting disc and robotic arm. The trajectory planning, control, and simulations of the motion of the robotic arm are presented in Section 3. System design and fabrication, sawing angle (SA) and sawing location (SL) variation range simulations are described in Section 4. Experimental tests are conducted in Section 5. Discussions and analysis are shown in Section 6. Conclusion and future work are given in Section 7.

2. Modeling

2.1. Sawing modeling of cutting disc

The force model of the cutting disc is illustrated in Fig. 1. The forces from the rock, on the disc-rock contact zone of the disc, can be simplified as a force F, which is the resultant force of the vertical force F_v and horizontal

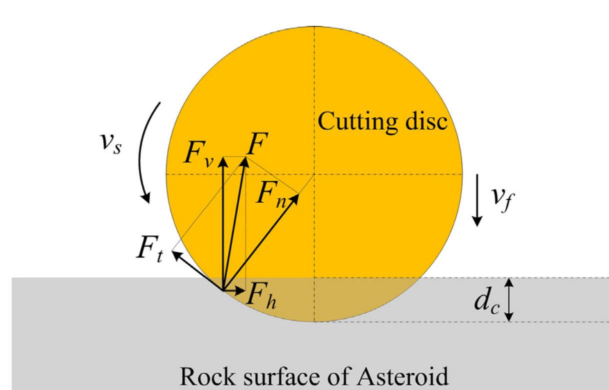

Fig. 1. Force model of the cutting disc during rock sawing.