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Multi-state autonomous drilling for lunar exploration

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Abstract Due to the lack of information of subsurface lunar regolith stratification which varies along depth, the drilling device may encounter lunar soil and lunar rock randomly in the drilling process. To meet the load safety requirements of unmanned sampling mission under limited orbital resources, the control strategy of autonomous drilling should adapt to the indeterminable lunar environments. Based on the analysis of two types of typical drilling media (i.e., lunar soil and lunar rock), this paper proposes a multi-state control strategy for autonomous lunar drilling. To represent the working circumstances in the lunar subsurface and reduce the complexity of the control algorithm, lunar drilling process was categorized into three drilling states: the interface detection, initiation of drilling parameters for recognition and drilling medium recognition. Support vector machine (SVM) and continuous wavelet transform were employed for the online recognition of drilling media and interface, respectively. Finite state machine was utilized to control the transition among different drilling states. To verify the effectiveness of the multi-state control strategy, drilling experiments were implemented with multi-layered drilling media constructed by lunar soil simulant and lunar rock simulant. The results reveal that the multi-state control method is capable of detecting drilling state variation and adjusting drilling parameters timely under vibration interferences. The multi-state control method provides a feasible reference for the control of extraterrestrial autonomous drilling.

1. Introduction

The uncertainty of drilling media in lunar environment is a challenge for autonomous drilling devices because it is difficult to determine the geological structure of a landing site along longitudinal direction in lunar subsurface drilling and coring missions.[1–3] According to lunar samples, images and data obtained in the lunar exploration missions from the United States and the former Soviet Union, two types of typical

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drilling media distributed in lunar environment are loose granular lunar soil and massive lunar rocks. In the Chinese unmanned drilling and coring mission of Chang'e-5, drilling device should be designed to be adaptable to the indeterminable drilling environments. Unlike automatic ground drilling, lunar subsurface drilling is restricted by rocket delivering capacity and complex lunar environments. The lunar drilling devices only rely on an intelligent drilling controller equipped with limited sensor resources.[4–7]

The Soviet Union has achieved unmanned autonomous extraterrestrial subsurface drilling and sampling in last century.[8] LUNA 16 and LUNA 20 controlled drilling processes with fixed drilling parameters, which may have poor adaptation to the complex lunar environments. Once the monitoring signal of drilling condition exceeds a safe threshold, the system will alarm experts on the ground to perform troubleshooting. LUNA 24 is the last lunar exploration mission returning lunar soil samples to the earth, implemented by the former Soviet Union. The drilling device was equipped with an adaptive mechanism to achieve autonomous drilling through a mechanical way. Due to limited intelligence, the sampler paused several times during the drilling procedure for excessive drilling loads, failing to achieve expected drilling depth and sampling quantity.[9]

Currently, Honeybee Robotics focuses on the autonomous extraterrestrial drilling research and has developed DAME, MARTE and CRUX intelligent ground drilling devices for future Mars drilling and sampling missions.[10] The control algorithms of the ground drilling devices were based on empirical models, fuzzy rules, and vibration modals. Experiments indicated that the DAME can identify six types of drilling faults and subsequently tune the drilling strategy accordingly. However, additional online monitoring sensors are required in the drilling control.[11,12] Despite the limitation of the DAME, the Honeybee Robotics emphasized the importance of intelligent drilling control in space autonomous drilling and provided a promising way.

The core of the intelligent drilling is to identify the types of the current drilling media and then tune corresponding drilling parameters. Owing to the existence of drilling states for different drilling media and the interfaces, a recognition method and a control algorithm should be developed for identification of each drilling media and transition among the drilling states, respectively. This paper presents a multi-state autonomous drilling method based on online recognition. Support vector machine (SVM) and continuous wavelet transform were employed for the online recognition of drilling media and interface, respectively. Finite state machine was utilized to control the transition among different drilling states. This method is capable of detecting drilling state variation and adjusting drilling parameters timely at different drilling loads under vibration interferences.

The remainder of the paper is organized in the following manner. The types of lunar drilling media and corresponding appropriate drilling parameters are presented firstly. Online recognition based autonomous drilling is then introduced. The recognition of drilling media is presented subsequently. The autonomous drilling based on the finite state machine is stated thereafter. Finally, validation experiments with multi-layered drilling media are conducted.

2. Lunar drilling media and drilling parameters

Since China has not acquired lunar regolith samples, research for drilling parameters is based on lunar regolith simulant which is produced according to images and data collected by telemetry, in situ and laboratory tests of lunar soil samples and activities of landers, rovers and astronauts on the lunar surface. As lunar regolith has a considerable amount of mechanical properties, it is rather difficult to identify all the parameters individually online. To be convenient to conduct the drilling parameter research of the lunar regolith, the lunar regolith was divided into different drillability grades based on planetary drillability in the authors' previous research.[13] Different types of drilling media should match the corresponding drilling parameters.[13–15] Since this paper focuses on the multi-state drilling control algorithm, in the recognition of drilling media we chose two typical drilling media: lunar soil simulant and lunar rock simulant (marble), which represent two extreme drilling conditions during the lunar drilling process: lunar soil and lunar rock.[16]

2.1. Lunar soil

Lunar soil which is distributed widely on lunar surface is a type of loose granular material. As lunar soil has fine flow characteristics, appropriate drilling parameters should be selected to keep the coring rates under limited drilling power. Since the mechanical properties of the basaltic simulant bracket that of the actual lunar regolith, the basaltic simulant was used to mimic the lunar soil in this paper. The basaltic simulant was created using basaltic pozzolana collected from Nanjing, China. Main mineralogical compositions of the simulant are similar to the compositions of the lunar soil on Apollo 14 landing site.[17] The simulant particle size range is 0.1–1 mm; the minimum density is 1.63 g/cm^3; the maximum density is 2.15 g/cm^3; the internal friction angle is 30.53° (relative density = 75%); the cohesion is 0.33 kPa. According to the authors' previous research, suitable drilling parameters for the basaltic simulant are: rotary speed $n = 100$ r/min, and penetrating speed $v_p = 100$ mm/min.[13–15]

2.2. Lunar rock

Since the lunar rocks are widely distributed in the lunar regolith, lunar rock drilling is an inevitable drilling condition in lunar drilling process. According to the rock drillability of geology, the drillability grade of the marble is similar to the complex polymict breccia which is distributed widely in the lunar regolith. In terrestrial rock drilling, main drilling methods are rotary drilling, percussive drilling and rotary-percussive drilling. According to the former marble drilling experiments, the rotary torque and penetrating force in rotary-percussive drilling strategy are lower than those in rotary drilling strategy.[18,19] Appropriate drilling parameters for the marble are acquired as the following combination under experimental environments in this paper: rotary speed $n = 100$ r/min, penetrating speed $v_p = 10$ mm/min and percussive frequency $f_p = 5$ Hz.[13–15]