Chapter 2

Intelligent Drilling and Coring Technologies for Unmanned Interplanetary Exploration

Junyue Tang, Qiquan Quan, Shengyuan Jiang,
Jieneng Liang and Zongquan Deng

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Abstract

The robotic technology, especially the intelligent robotics that can autonomously conduct numerous dangerous and uncertain tasks, has been widely applied to planetary explorations. Similar to terrestrial mining, before landing on planets or building planetary constructions, a drilling and coring activity should be first conducted to investigate the in-situ geological information. Given the technical advantages of unmanned robotics, utilizing an autonomous drill tool to acquire the planetary soil sample may be the most reliable and cost-effective solution. However, due to several unique challenges existed in unmanned drilling and coring activities, such as long-distance time delay, uncertain drilling formations, limited sensor resources, etc., it is indeed necessary to conduct researches to improve system's adaptability to the complicated geological formations. Taking drill tool's power consumption and soil's coring morphology into account, this chapter proposed a drilling and coring characteristics online monitoring method to investigate suitable drilling parameters for different formations. Meanwhile, by applying pattern recognition techniques to classify different types of potential soil or rocks, a drillability classification model is built accurately to identify the current drilling formation. By combining suitable drilling parameters with the recognized drillability levels, a closed-loop drilling strategy is established finally, which can be applied to future interplanetary exploration.

Keywords: interplanetary exploration, drilling and coring, intelligent robotics, planetary soil simulant, closed-loop drilling strategy

1. Introduction

Just as some imaginative descriptions on the interplanetary traveling in scientific fictions, human beings through decades' striving have made a great step forward to that scenery. From the successful launch of Sputnik, the first man-made earth satellite in 1957 [1] to the first man-made lunar landing in 1969 to collect lunar soil samples [2] and the Rosetta Landing Project launched in 2014 on Comet 67P to collect asteroid rocks [3], mankind's extraterrestrial explorations have covered the vast majority of planets, satellites and asteroids in the solar system. However, it should be noted that although tremendous advancements are achieved in space exploration, mankind also suffered a great loss, especially when astronauts encounter emergency risks even lost their lives for various technical reasons [4, 5]. Hence, as deep space exploration having been conducted, an up-and-coming replaceable solution by employing unmanned robots has been gradually acceptable to carry out some uncertain and dangerous tasks, such as interplanetary drilling and coring activities [6–8].

For future interplanetary exploration, there is an urgent demand for a reliable method to pierce the planetary surface to a specified depth and effectively collect soil samples [9, 10]. Once the in-situ soil sample acquired, the original geological information at the sampling site can be investigated for further usage. Compared with other soil failure technological solutions, such as explosion, melting, etc., the traditional drilling and coring method by only utilizing the compound motion of rotation and penetration still has great advantages in extracting the subsurface soil sample in a relatively efficient and convenient way [11, 12]. Therefore, this method has been widely applied to previous interplanetary missions. Considering the technical advantages of unmanned robots and the unique space drilling and coring conditions, interplanetary drilling and coring compared with terrestrial drilling could be more dependent on intelligent drilling techniques.

Commonly speaking, interplanetary drilling control architecture contains remote control from Earth and autonomous drilling control on the planet [13]. Since time delay inevitably exists in the long distance remote communication, remote control mode is usually employed to deal with serious drilling faults and in the majority of the cases the sampling drill should work in an autonomous way [14, 15]. Furthermore, restricted by the delivery capacity of rocket and limited power consumption, interplanetary drilling system can hardly apply plenty of sensor resources and sufficient penetrating force to accomplish the online control. On the other hand, in most planetary drilling missions, there is not enough prior geological information in a longitudinal direction on sampling sites to guide the online drilling [16]. Given the uncertain and variable mechanical properties of drilling formations, the drill tool under above strict resources should adjust suitable drilling parameters correspondingly to overcome potential drilling faults and acquire as much as volume of the soil sample. To resolve the problems, researchers have been striving for decades to find effective solutions.

So far, the former Soviet Union's Luna series is the only unmanned detectors that successfully implemented the lunar subsurface soil's sampling and returning [17, 18]. Among them, the Luna 16 detector launched in 1970 with a stretched out arm mounted rig sampling method successfully drilled into 350 mm beneath the lunar surface, acquiring 101 g soil sample finally

[19]. The following Luna 20 detector launched in 1972 landed on a lunar plateau with a similar sampling device to the Luna16 and was forced to stop drilling at 250 mm depth due to multiple times of overheat fault, eventually sampling only 55 g lunar soil [20]. The last sampling task Luna 24 in 1976 applied a threshold-based approach to autonomously control the drill tool. When the detected penetrating force exceeds a preset threshold, the impact motor will be activated in time to overcome the drilling resistance. Based on this drilling strategy, the received remote data revealed that in the Luna 24 detector's drilling process the impact motor was frequently switched on and finally the sampler reached to a depth about 2250 mm, returning about 171 g lunar soil sample [21]. Although the applied threshold-checking strategy indeed improved the automation level of the unmanned drill tool, it should point out that there exists a high probability of tripping and need a long time to wait (often hours to days) for human troubleshooting from afar [22]. Hence, this simple limit-checking strategy may be more suitable for shallow drilling missions like Mars Science Laboratory drill (50 mm depth).

After laboratory tests aboard NASA's Phoenix Mars Lander identified water in a soil sample at Green Valley, Mars (Arctic pole) in 2008 [23], NASA has been preparing for an another Mars exploration mission to search for biomolecular evidence for life around 2018. The proposed "Icebreaker" mission would use an automated rotary-percussive drill to reach and retrieve samples from up to 1.2 m deep in the ground ice at Mars Arctic pole [24]. To support for this drilling mission, NASA Ames, together with Honeybee Robotics Ltd., and Georgia Tech., proposed a novel drilling faults diagnosis control method by acquiring the vibration signals from external laser doppler vibrometers (LDVs) to identify drilling faults [25, 26]. Based on two diagnostic methods of rules and model prediction, the "Icebreaker" drill can recognize six types of drilling faults (e.g. auger chocking, hard material, etc.) and switch to the preset recovery parameters. Test results from the recent Arctic and Antarctic field campaigns demonstrated this drill has been already capable of a hands-off ability [27].

The above drilling strategy relatively improved the automation level of the system, however, besides drilling loads or power consumption, soil's coring morphology should also be considered in designing its control method. As the primary goal of interplanetary exploration is to exam the evidence of lie by scamping the subsurface soils, it is extremely important to acquire as much soil core as possible under acceptable drilling loads. Furthermore, as the stratification information of planetary samples reflects the evolutionary history of early stars [28], it is necessary to preserve its stratification during the coring process for further analysis. Therefore, the authors proposed a novel flexible tube coring method to preserve the stratification of soil sample [29]. In order to comprehend the core flowing characteristics and optimize the final coring results, a non-contact type measurement based on ultrasonic wave reflection mechanism and vision techniques is applied to online monitor the coring and removal characteristics [30]. Once the drill-soil interaction mechanism comprehended, suitable drilling parameters for different types of drilling formations considering both power consumption and coring morphology can be optimized then.

Apart from suitable drilling parameters, to identify what kind of formation the drill bit is currently drilling is another key point to the unmanned drill tool. Only if these two key parameters matched correspondingly, the unmanned drill tool may be smoothly penetrated into the uncertain formations and finally retrieve valuable core samples. Since planetary regolith has a considerable number of geological and mechanical properties, it is rather difficult to identify all the parameters individually online. Hence, the authors proposed a control strategy based on planetary regolith drillability (PRD) recognition [31]. Herein, the drillability of formation is a consolidated index to stand for drilling difficulty. A recognition model based on support vector machine (SVM) has been established to evaluate the drillability of current formation and subsequently control the algorithms that can tune drilling parameters to adapt to the current drilling conditions.

The remainder of this paper is organized as follows. The unique challenges in interplanetary drilling and coring are discussed first. Next, the specific drilling and coring characteristics containing the drilling loads characteristics and soil flowing characteristics are elaborated. A drillability recognition method is proposed based on monitoring the signals then. Finally, an intelligent real-time drilling strategy is achieved based on drillability recognition and drilling experiments in multi-layered drilling formations indicated that this unmanned control method could effectively reduce the drilling loads and keep a relatively complete stratification.

2. Challenges in interplanetary drilling

In general, if neglecting the economic factors, terrestrial drilling can be conducted with advanced auxiliary facilities to investigate the in-situ drilling formations and can automatically apply liquid lubricant to improve the drilling conditions [32, 33]. Compared with terrestrial drilling, interplanetary drilling and coring restricted by the extreme environmental conditions on the planet will have to solve several unique challenges. To assure the operability of the required drill tool and its control strategy, it is thoroughly necessary to comprehend the in-situ environment conditions and existing applicable resources. The following drilling and coring characteristics investigation and recognition based drilling strategy will be both based on these understandings. The following subsections will discuss four main challenges in interplanetary drilling.

2.1. Long-distance between planet and Earth

At present, wireless teleoperation is widely used in the monitoring and control of spacecraft operation status. For example, in the second phase of China lunar exploration, based on acquired visual images the lunar rover completed the entire inspection survey mission by means of ground teleoperation [34]. However, different from rover's navigation control, the buried drilling and coring activity is a quite dynamic and rapid process and any signal delay caused by long-distance teleoperation may directly result in a serious drilling fault. Once the drilling faults happened, specialists from Earth also need a long time to diagnose and recovery, making the drilling and coring process last for hours or days. Even though the drilling faults can be handled successfully, the final coring quality and core's stratification could be destroyed during this long time recovery process. Considering for future deeper space explorations, for example, the round-trip delay between Mars and Earth will be as long as 40 min, this long time delay by teleoperation will definitely not acceptable for interplanetary drilling and coring operations [35]. Hence, in general only when a serious abnormality occurs in the sampling process, the sampling device could be automatically forced to stop drilling and wait for the ground specialists to make a fault judgment and determine the corresponding treatment plan. Otherwise, the sampling device should work in a thoroughly autonomous condition.

2.2. Complicated and uncertain drilling formations

Given the short execution time of Mars and asteroid exploration compared with the lunar exploration, the data of soils on Mars and asteroids are rarely found yet. Herein, this chapter mainly focuses on the physical properties of lunar soil. According to previous investigations on the material returned from the moon, the terrestrial term "regolith" is also used for the interplanetary exploration [36]. Regolith has been defined as a general term for the layer or mantle of fragmental and unconsolidated rock material. According to the published literature, lunar regolith ranges from granular soil to hard rocks [37, 38], and it mainly consists of five types of material: rock detritus, mineral dust, breccia, agglutinate and impacting molten glass. The physical characteristics of above lunar soil components are quite different and the distribution of different components of lunar soil in the depth direction at the sampling site is also uncertain. During future planetary drilling processes, either soil or rock will be randomly encountered, resulting in that the final coring quality and drilling loads may both be influenced by unpredictable properties. There are numerous parameters, including cohesion, friction angle, relative density, compression ratio, particle size distribution, etc., to describe the physical properties of lunar soil [39], further increasing the difficulty to identify the physical parameters of lunar soil at different depths one by one. Therefore, it is necessary to simplify the mechanical parameter identification of lunar soil.

2.3. Lacking of prior investigation on sampling site

Similar to terrestrial mining, prior investigation on the sample site will extraordinarily guide the following drilling and coring activities. In the second phase of China lunar exploration, a novel lunar penetrating radar (LPR) has already been applied to detect the morphology of the lunar surface and stratification information of subsurface lunar regolith for supporting further detector's landing site's selecting, however, it should be noted that until now due to the mass and power constraints its detection accuracy can only reach to about 30 cm [40]. Considering that any unclear detected drilling formation may bring out a serious drilling fault once inappropriate drilling parameters are operated. Therefore, it is still difficult to apply the LPR's detecting geological layering information to guide the sampling drill before drilling begins. It indicates that the drill tool should better work in a passive adaptive control mode, in which the drill tool during the whole drilling and coring process should online switch suitable drilling parameters according to the recognized current drilling formation on the drill bit, nor in the active control mode.

2.4. Limited on-orbit sensor resources

According to the discussion in above subsection, the control architecture of unmanned interplanetary drill should better work in a passive adaptive control, in which the drill tool will totally rely on the feedback data by sensors. However, compared with the planetary rover's surface navigation control, the planetary unmanned drilling has a more limited sensing resources. In addition to the constraints of quality, power consumption and high and low temperature vacuum environment, the sensors used for drilling condition's monitoring also need to overcome the restrictions like small installation space of drilling tools and the prevention of sample contamination as well as the high frequency vibration caused by the impact of drilling tools, etc. Combing above tough working conditions together, perhaps only traditional load cells and displacement transducers can be applied to the interplanetary drilling. Hence, to realize the intelligent drilling control the sample drill need to fully integrate the existed sensors' information, which should all be imported to the controller to decide its online strategy.

Besides above challenges, there also exists some negative factors affecting the interplanetary drilling. For example, the non-water environment on the planet surface that will cause the drill tool will work in a dry condition without any liquid lubricant to improve the drilling conditions. The only effective removing cutting chips solution is the spiral auger flute. Due to the fact that drilling loads or power consumptions are highly dependent on the removal condition [41], during this dry drilling process drilling loads will be more sensitive to the drilling parameters. Overall, these harsh working conditions will definitely aggravate the risk of the interplanetary drill, which all require a more robust and reliable control strategy.

3. Drilling and coring characteristics

The ultimate goal of interplanetary sampling exploration is to acquire as much as possible planetary regolith for further scientific analysis. Apart from the volume of planetary regolith, the stratification of the sample should also be seriously considered in the drilling process. If the geological information of soil sample was not be preserved completely, its geological value would be significantly reduced. In China Chang'e drilling and coring mission, a novel flexible tube coring (FTC) method referred from Luna 24 mission is being adopted to solve the above problem [42]. As shown in **Figure 1**, its drilling and coring process is illustrated.

In the FTC penetrating process (rotary speed n and penetrating velocity v_p), the in-situ subsurface regolith destroyed by the cutting edge of drill tool can be divided into two parts: the wrapped sample into the flexible tube and the cutting chips conveyed along the spiral flute. Since the wrapped core soil is adjacent to the cutting soil through the holes at the bottom, it may result in a sudden collapse of the inner surface of the flexible tube when cutting chips are removed, resulting in a decline in the height of core. However, considering that there is no relative locomotion between the sample and the flexible tube in stable conditions, the sample can be continuous along the depth direction. Although the adopted FTC method has a great advantage in maintaining the core stratification, there still exists a considerable possibility that a very small amount of core soils are finally acquired in drilling process. Therefore, to

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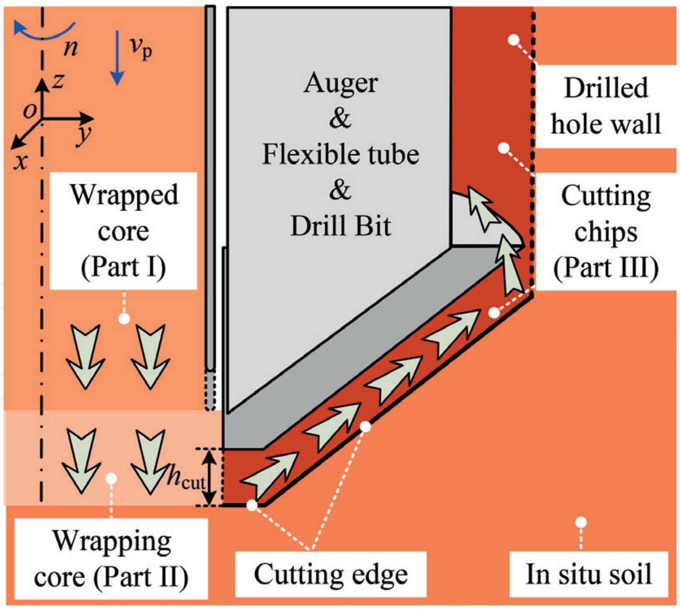

Figure 1. Illustration of drilling and coring process in flexible tube coring.

a certain degree, the height of core index H_s or the coring ratio K_c index (the ratio of coring height H_s to drilling depth H_d) can represent the core flowing characteristics and should be monitored in real-time.

It can be also found that there inevitably exists a vertical distance between the bottom of the flexible tube and the bottom of the drill bit, connecting the internal core to the external cutting chips, as shown in **Figure 1**. Due to the fact that the external cutting chips' removal flowing characteristics is heavily determined by the operated drilling parameters [43, 44], the removed cutting chips may have a negative influence on the inner coring soil and make the coring results drop correspondingly. Therefore, besides monitoring the coring characteristics, the soil removal characteristics should also be online detected. As shown in **Figure 2**, in order to comprehend the drilling and coring characteristics, a noncontact soil flowing characteristics monitoring method has been proposed for experimental verification.

Since the cored soil is wrapped into the closed space, it's fairly difficult to measure the cored soil without affecting soil's original states. To solve this problem, an ultrasonic displacement sensor is deployed into the hollow flexible tube, as shown in **Figure 2(a)**. To assist measurement, a protective hollow tube is installed at the front of the sensor, allowing the sonic wave to pass through it without disturbance. Besides that, avoiding unnecessary disturbing reflection from the uneven upper surface, one Teflon made reflect board with a small mass (4 g) is elaborately designed to put on the in situ soil. As a result, the online coring ratio K_c can be indirectly calculated by acquiring the ultrasonic sensor's online value H_u, its initial value H_{uo}, and the online drilling depth H_d. Apart from the coring states, soil removal characteristics are acquired by measuring the accumulation morphology on a PE plastic wrap by an external camera, as shown in **Figure 2(b)**. By converting the colorful images into binary images, the outline of accumulation soil can be obtained thereby. Meanwhile, by searching the right, left, and upward points of current outline and summing up each accumulation volume, the total

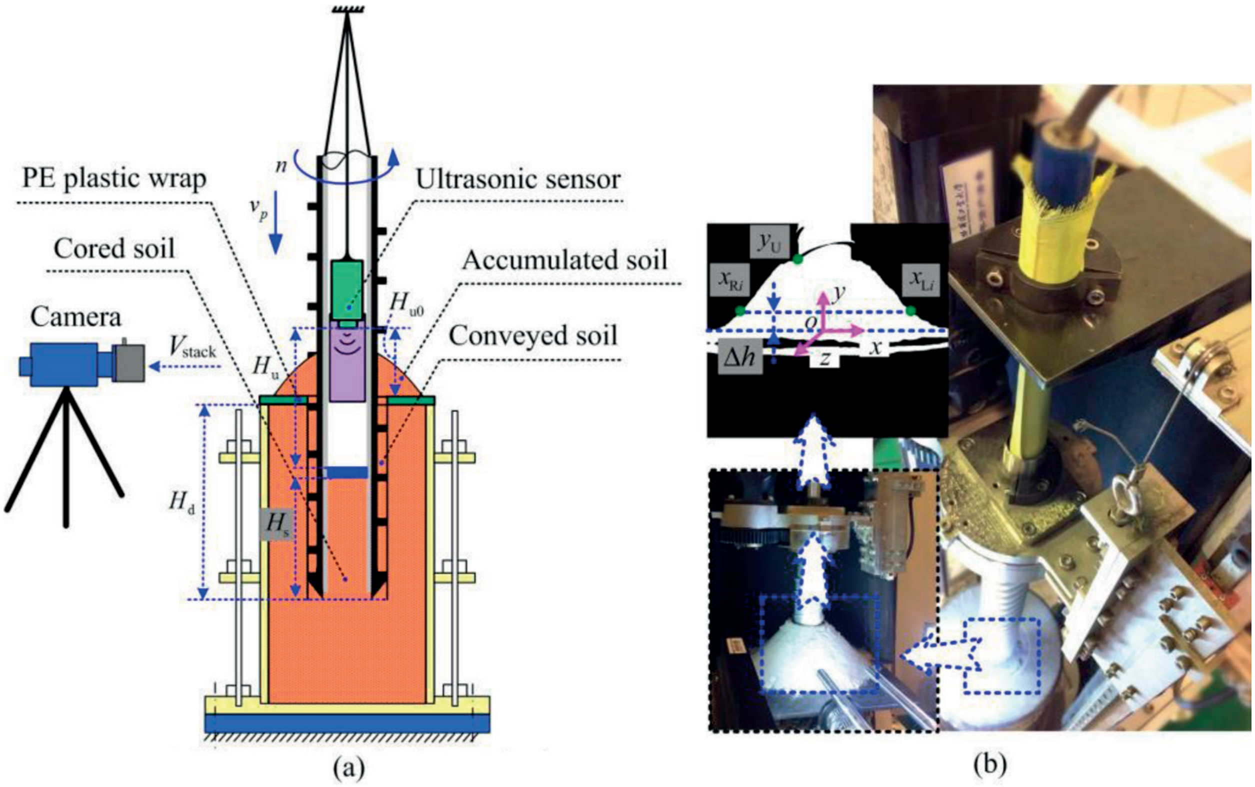

Figure 2. Scheme of the noncontact soil flowing characteristics monitoring method. (a) Scheme of monitoring method; (b) Acquired images in monitoring process.

volume of accumulated soil V_{acc} can be finally online acquired. Hence, based on above noncontact measurement the soil flowing characteristics during the drilling and coring process can be accurately monitored without any damage.

To verify the proposed measurement, drilling experiments under the condition of $n = 400$ rev/min, $v_p = 150$ mm/min are conducted. The online coring results containing the ultrasonic sensor's value, the coring height, and the coring ratio are illustrated respectively in **Figure 3**. It can be seen that during the first 105 mm drilling depth, the ultrasonic sensor's value keeps stable, meaning that the coring soil stays at the original position making the coring height climb stably to the 105 mm and coring ratio keeps around the 100%. After then, the monitored sensor's value reveals that it has a sudden increase, resulting in a turning point at the 105 mm drilling depth. According to the definition, the corresponding coring height and coring ratio both has a sharp decline. Finally, during the 200 mm depth, the coring height slips to approximately 70 mm and the coring ratio reaches to less than 40%.

Based on above founding, it can be inferred that there exists a sudden collapse of the cored soil in the flexible tube. Actually, this interesting phenomenon can be explained by the state of the cored soil. As shown in **Figure 1**, the cored soil and the conveyed soil are inevitability connected at the bottom of the drill bit. Under proper drilling parameters or penetration per revolutions ($PPR = v_p/n$, mm/rev), once the drill bit drills into the regolith the cutting chips will be conveyed from the bottom by auger's spiral locomotion, which may make the cored soil stays in a positive stress, and vice versa. Since there exists a small side failure zone at

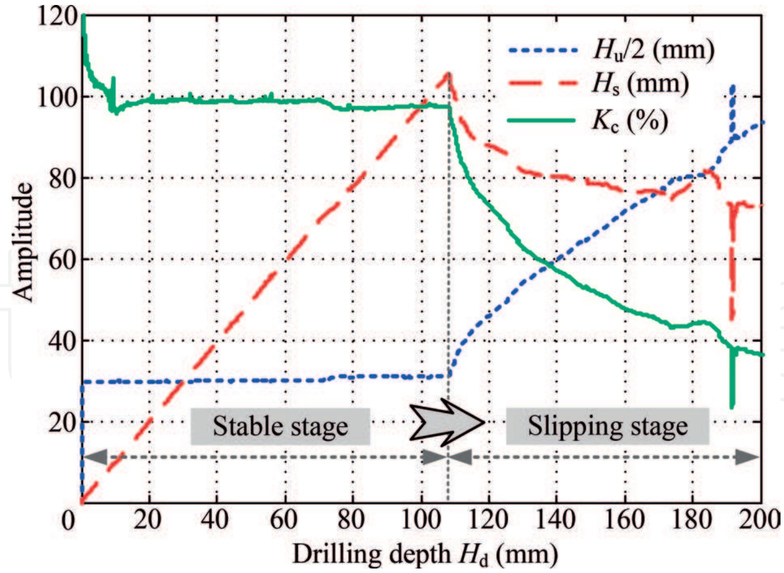

Figure 3. Monitored height of core and coring ratio in experiments.

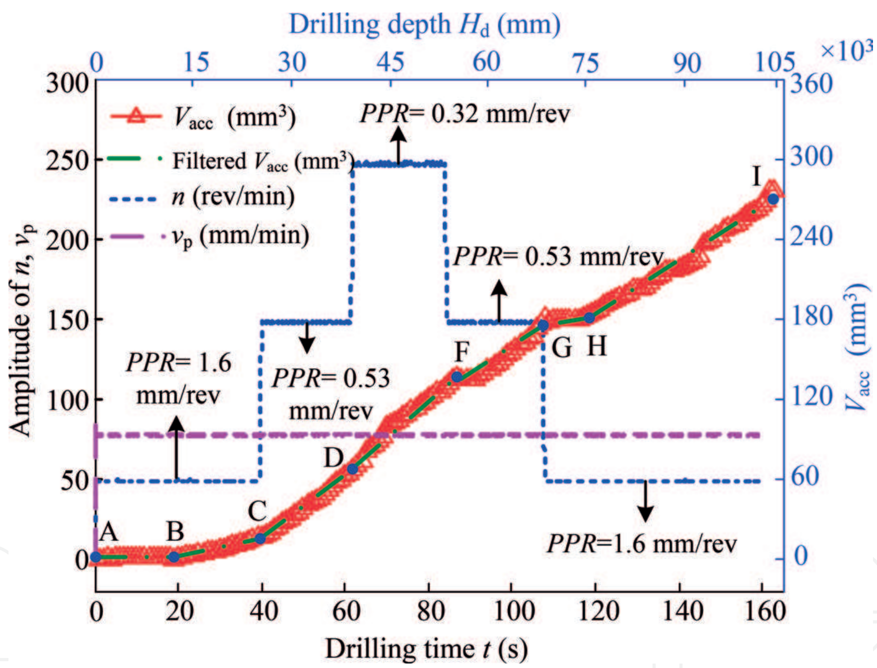

Figure 4. Monitored volume of accumulated soil V_{acc} under different *PPR*s.

the outer annular space of cored soil by the inner edges of cuter [45], once the bottom of soil become totally granular at a certain depth, cannot be able to sustain the upward positive stress, it will result in a sudden broken or collapse along the longitudinal direction.

Apart from the core flowing characteristics, cutting chips' removal flowing characteristics is also investigated. By identifying the outline image of the wedge-shaped of the removed soil outside the surface and calculating its 3D volume per second, the online volume of removed soil V_{acc} under three different *PPR*s (1.6, 0.53, and 0.32 mm/rev) is shown in **Figure 4**. It can be seen that during above drilling and coring process, the penetrating velocity is kept constant (80 mm/min), while the rotary speed will be adjusted (50 rev/min → 150 rev/min → 250 rev/min → 150 rev/min → 50 rev/min). Meanwhile, the monitored volume V_{acc} can be divided into seven stages (AB → BC → CD → DF → FG → GH → HI).

During the AB stage of the first 20 s, since drill bit constantly cuts the in situ soil simulant without spiral auger's participant, there is almost no soil accumulated upon the surface. After then, the drill bit is buried in the soil, the auger starts to remove soil from the borehole bottom with a low removal speed during the BC stage. At the 40 s moment (C point), the rotary speed is suddenly switched to 150 rev/min with the result of the sudden increase of V_{acc}. It can obviously be seen that the removal speed during CD stage is higher than that during BC stage. Above phenomenon is almost same with that in conditions between DF stage and CD stage. At the 85 s moment (F point), the corresponding PPR is regulated back to 0.53 mm/rev, which results in a slow increase trend of the V_{acc}. After about 5 s, the removal speed becomes normal. This slow increase trend of the V_{acc} also exists in the sudden change on G point. Based on above experimental results, it can be concluded that the monitored volume of accumulated soil can reflect the online removal states well and the PPR index has a great effect on the removal states and should be optimized further.

According to preliminary experiments, the proposed non-contact drilling and coring characteristics monitoring method has been validated well. Next, to provide suitable drilling parameters database for the following intelligent drilling strategy, more drilling and coring experiments taken the drilling loads and core's quality into account will be conducted in several different drilling formations, such as limestone, sandstone, compacted soil, etc.

4. Recognition based drilling strategy

Intelligent drilling control algorithm needs to be able to effectively identify the drilling formation, and timely adjust appropriate drilling parameters according to the recognition result. As an effective pattern recognition method, support vector machine (SVM) has been widely applied for several linear and nonlinear separable problems because of its high generalization ability [46, 47]. In previous works, a drillability classification covering from granular soil to hard rocks has been established based on the mechanical penetrating tests [48]. Herein, both rotary torque and penetrating force are selected as the drilling states monitoring signals x to imported into the proposed support vector machine recognition model to predict the corresponding drillability level y, as shown in **Figure 5**. Once the current formation's drillability level recognized, control algorithm will switch the optimized drilling parameters to drive the rotary motor and penetrate motor.

Actually, traditional SVM algorithm is based on the two classification mode, which is not suitable for multiple patterns of drillability classification. Compared with other classification methods, the decision directed acyclic graph (DDAG) based on the decision tree has a better training speed and a higher classification accuracy on the normal scale separation problems [49]. Considering that for covering potential drilling formations on the planets there are

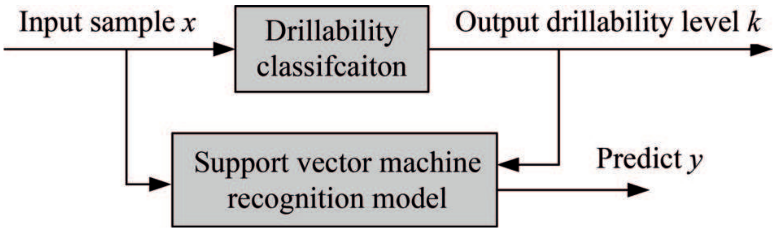

Figure 5. Scheme of drillability recognition based on SVM.

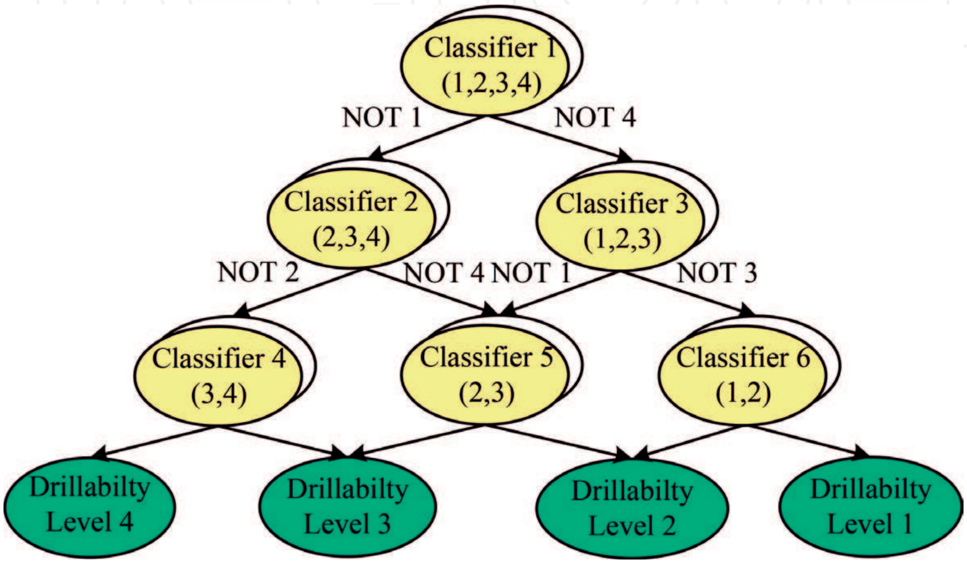

Figure 6. Drillability recognition algorithm based on DDAG.

at least three different formations for validation. Herein, DDAG is adopted to conduct the drillability recognition. The classification's structure diagram for four levels of lunar regolith simulants' drillability is shown in **Figure 6**.

As can be seen from the above algorithm structure, this method constructs a classifier with a two-way directed acyclic graph. Among them, the classifier 1 is located at the top of the root node to complete the first and second levels of drillability level 1–4 drillability comparison. By comparing the drillability level of 1 and drillability level of 4, the most samples may not belong to drillability level 1 (drillability level 4) can be excluded. After 3 times of excluding, the remaining category will be the drillability 1. Experiments indicated that by successive comparison this classification algorithm can guarantee a higher recognition accuracy.

In fact, model parameters in SVM play an important role in affecting recognition's accuracy. In the kernel function of SVM, scale parameter g and penalty coefficient C have the most significant effect on recognition's accuracy. When the two parameters do not match well, SVM will be overtraining or overfitting, which is an unstable situation in recognition. Herein, based on a grid search method, these two SVM model are optimized. To verify the optimized SVM model's generalization ability, drilling characteristics of different drillability samples under constant drilling parameters should be imported to conduct recognition training. Herein, a combination of rotary speed $n = 100$ rev/min and penetrating velocity $v_p = 10$ mm/min is used as recognized drilling parameters. Typical simulants of drillability level 1, 3, 5 and 6 are selected as drilling media. Recognition results of un-optimized and optimized are shown in **Figure 7**. It can be found that the recognition accuracy of optimized SVM model is about 94.37%, which is obviously higher than the 78.15% of un-optimized model. When recognizing the closed drillability level 5 and level 6, the un-optimization model identifies 109 samples in 160 test samples and the recognition accuracy is just 68.13% in total. However, under the same conditions, the optimized model identifies 150 samples and the accuracy reaches roughly 93.75% in total. Therefore, it indicated that the optimized SVM recognition model indeed improves its recognition accuracy and becomes more practical in recognizing multilayered drilling media's drillability.

Once the optimized drillability SVM recognition model has been acquired, a multi-layered simulant mixed with granular soil and rocks has been constructed for conducting closed-loop validation experiments. There are five layers of three different compositions including granular soil (level 1), limestone (level 5) and marble (level 6) along the depth. As shown in **Figure 8**, signals acquired in the closed-loop drillability real-time recognition experiment are the drilling

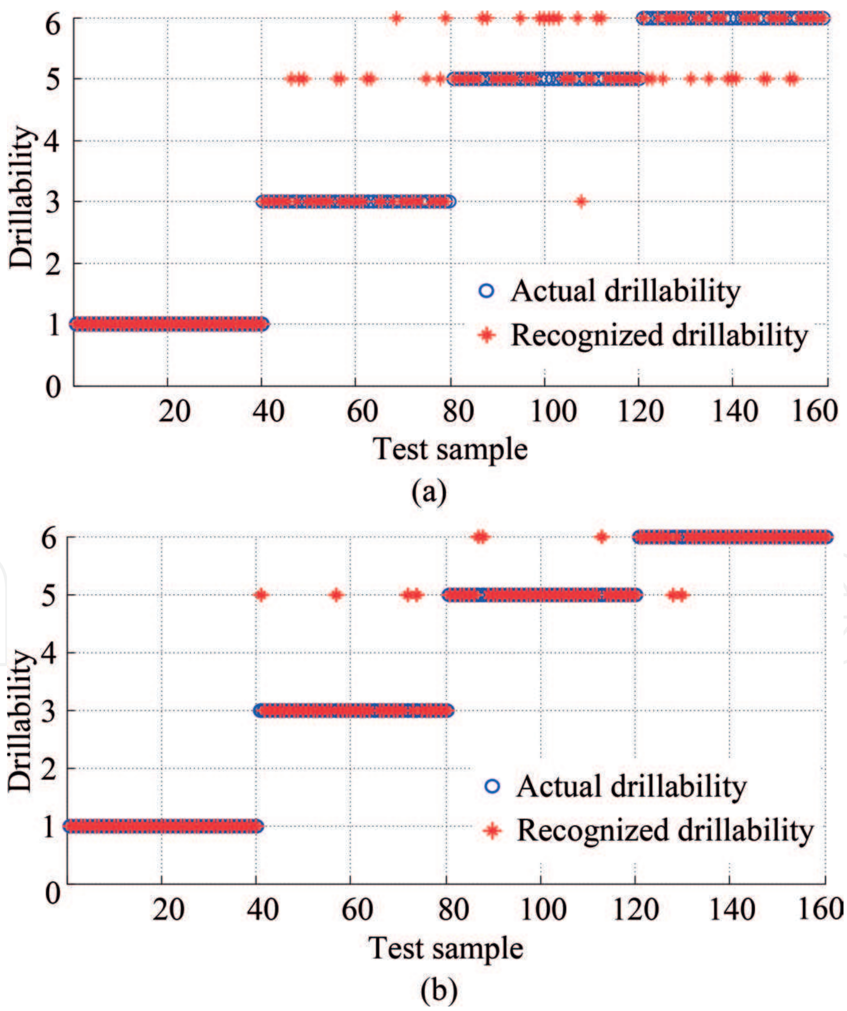

Figure 7. Comparison of drillability recognition before and after optimization.

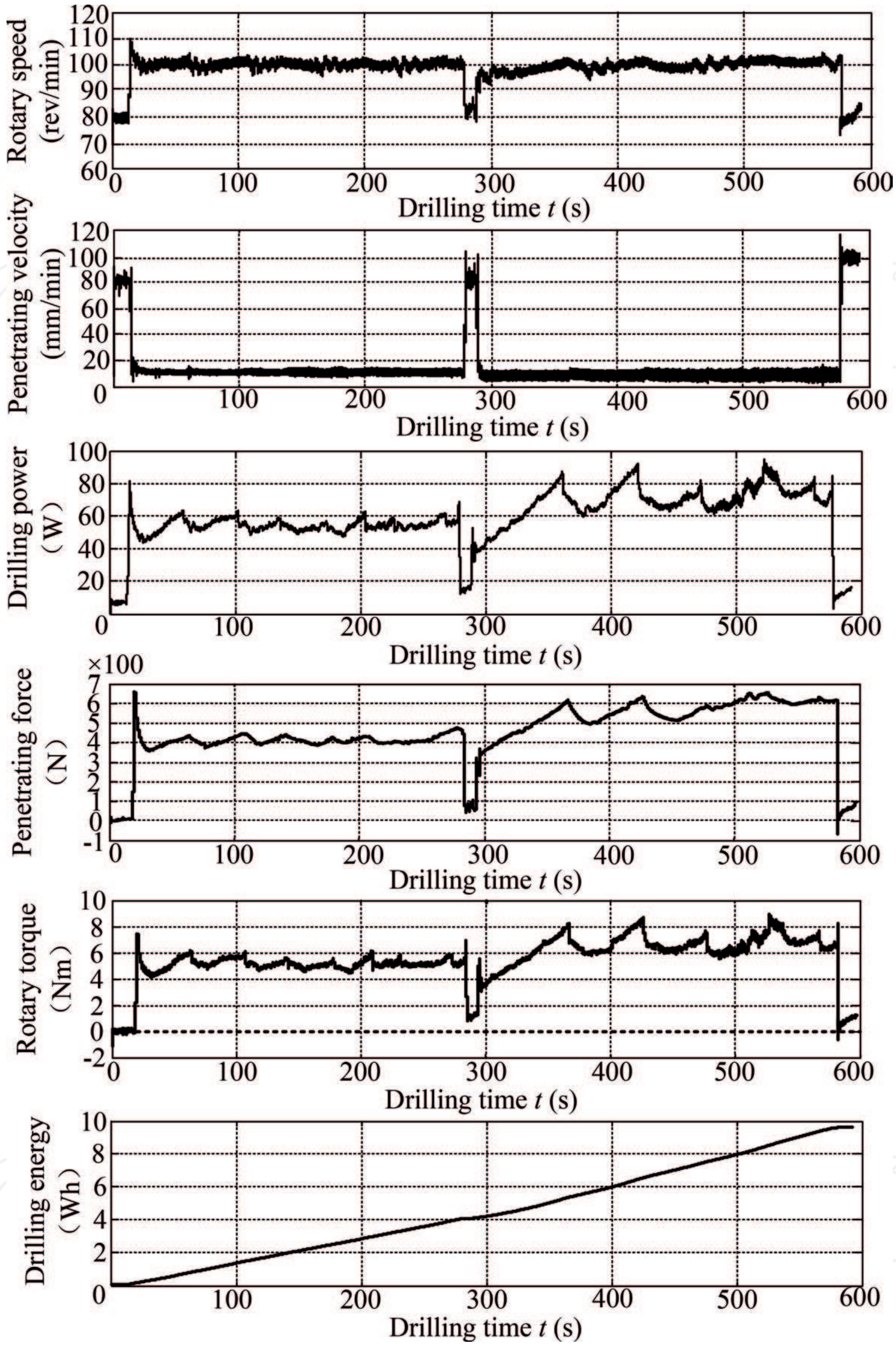

Figure 8. Drilling states during the multi-layered simulant drilling process.

state signals such as rotary torque, penetrating force, rotary speed, penetrating velocity, drilling power, and drilling energy. Among these signals, rotary torque and penetrating force were chosen as the recognition signals to identify drillability, and rotary speed and penetrating velocity are the corresponding drilling parameters adjusted to adapt to different drilling formations. For granular soil, rotary and penetrating control mode is adopted while rotary and percussive control mode are employed for rocks. When penetrating the granular soil from 0 to 22 s, the rotary motor keeps a constant rotary speed 80 r/min and penetrating motor exerts a constant velocity 80 mm/min. In this period, penetrating force is less than 50 N, rotary torque is no more than 0.6 Nm and drilling power is less than 10 W. When penetrating to the formation of limestone, penetrating force booms up meanwhile recognition drilling parameters are adopted to start real-time recognition. When recognizing limestone's drillability level, rotary motor switches rotary speed to 100 r/min and penetrating velocity is maintained a constant value 10 mm/min. In this period, penetrating force maintains a low level of less than 650 N, rotary torque is also no more than 10 Nm and drilling power is controlled no more than 90 W.

According to the monitored drilling states, by matching the appropriate drilling parameters with corresponding drillability level, the drilling loads in penetrating five formations keep relatively stable and do not surpass drill tool's load limits. As a result, it takes only 600 s and 10 Wh drilling energy in the 0.5 m drilling process. Overall, this drillability real-time recognition drilling strategy has been verified by this multi-layered drilling experiments.

5. Prospect for future application

Although the proposed non-contact drilling and coring characteristics monitoring method, SVM pattern recognition method, and drillability recognition based drilling strategy in this chapter are more specific to the interplanetary drilling actives, it should point out that these technologies may also be applied to terrestrial oil and gas well drilling operations. Specially speaking, even although by detecting devices applied into terrestrial oil and gas well drilling operations, the in-situ geological information can be acquired before, due to the unpredicted and variable online drilling conditions, there still exists great challenges in drill bits' selection, fluid system monitoring and parameters' optimization, adjustment of drilling parameters, well drilling faults' diagnosis, etc., [50, 51].

To solve the above problems, intelligent drilling technologies have been gradually widely employed in oil and gas well drilling activities. However, so far more attention was paid into the drill bit's wearing recognition, drilling faults' identification, formations' lithology evolution, etc. [52–54], few works were conducted to focus on the coring characteristics monitoring and adjustment. Since the ultimate goal of commercial drilling is to extract oil as much as possible, it perhaps is better to apply some facilities to monitor the online coring results into the inner tube. Herein, the proposed non-contact drilling and coring characteristics monitoring method is developed to conduct experimental validations, but once its specific structure parameters and installation conditions can be optimized further it may be employed into practice to enhance the online coring monitoring performance.

Given suitable drilling parameters in oil and gas well drilling are more dependent on the empirical formula concluded by experts [55], it is also urgently necessary and important to conduct rigorously theoretical calculation and experimental validation works on the soil-machine interaction, wherein the soil or rock's flow monograph can be comprehended more basically and the minimum power of the actuator under specific formation could then be referenced for future application. Therefore, the proposed drilling and coring characteristics monitoring method may be applied to further experiments. Moreover, considering the increasing costs of human resources in the future, the unmanned oil and gas drilling is being more popular than before. The proposed drillability recognition based online drilling strategy is exactly developed for this issue. By only required some basic force sensor resources, it can be simply applied to recognize different drillability levels of uncertain drilling formations in practice. However, it should be noted that for future application, more considerations should be taken into optimizing the fluid system's disturbance on the recognition and the longer depth's coupling influence on the mechanical system.

6. Conclusions

This chapter elaborates the unique challenges in interplanetary drilling and coring mission. To comprehend the specific drilling and coring characteristics, a non-contact drilling and coring characteristics monitoring method has been proposed and verified. By establishing a drillability classification model, different types of drilling formations are evaluated by a combined index. Based on the SVM pattern recognition method, a drillability recognition model has been built up that can accurately identify four different drillability levels after optimization. Experiments under a multi-layered drilling simulant revealed that this intelligent drilling strategy can effectively reduce the drilling loads and can be applied to future interplanetary unmanned drilling and coring exploration.

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Author details

Junyue Tang, Qiquan Quan, Shengyuan Jiang*, Jieneng Liang and Zongquan Deng

*Address all correspondence to: jiangshy@hit.edu.cn

State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, PR China

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