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Excavation model of soil sampling device based on particle image velocimetry

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Abstract

This work aims to establish an energy-efficient strategy for sampling Martian subsurface soil for future extraterrestrial-life exploration missions. To this end, requirements for a robotic arm are carefully examined and an end-effector shape suitable for subsurface soil sampling is determined. A soil–tool interaction model is formulated based soil-flow measured by particle image velocimetry (PIV). The proposed model calculates the resistance forces and torque generated during the sampling procedure and is validated through a comparison of experimental data obtained from the force sensor and numerical data calculated from the proposed model. Results indicate that the proposed model provides an accurate estimation of the force generated during soil sampling. Furthermore, the interaction model is capable of estimating the robotic arm's energy consumption and calculating the most efficient tool size to use.

Keywords: Planetary rovers; Robotic arm; End-effector; Soil sampling

1. Introduction

A primary mission in recent Mars explorations has been to look for extraterrestrial life. Such planetary exploration missions not only play a big role in investigating the geological and climatological characteristics of planetary bodies but also in searching for microorganisms. A robotic probe (such as a lander or rover) deployed on a target body is the most effective tool for these tasks and is capable of pursuing its mission.

Places where microorganisms are likely to form are very limited because, free energy (for example, methane or water), being indispensable to microorganisms, must be available on location. As of September 2013, NASA has concluded that they could not find any trace of methane on Mars; however, water was observed at a crater, called Newton Crater, located in the southern hemisphere of that planet. Yet we must assume that several areas of the planet, such as behind rocks, where they would be safe from dust storms, or underground, where they would be safe from lethal ultraviolet rays, may still be habitable for microorganisms. Therefore, an exploration robot has to be able to approach these places and carry out sampling missions. After the sample is collected, it must be stored in a scientific apparatus mounted on the robot.

Robotic arms are the most effective tool for such sampling missions, but their designs tend to focus on ability (i.e., maneuverability or degrees-of-freedom), and not energy efficiency. However, energy efficiency is important since the main energy resource available on Mars is solar, which only generates up to about 600 W h/m^2 per Martian day, and even this amount varies seasonally. In addition, as Martian dust piles on the solar array panel, power generation decreases. Furthermore, while excavating soil, the robotic arm has to tolerate relatively large resistance forces, which results in large energy consumption. For

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Nomenclature

R	shovel radius (m)
θ	shovel rotation angle (rad)
θ_f	shovel entry angle (rad)
θ_{end}	shovel exit angle (rad)
θ_{back}	shovel inner rear contact angle (rad)
ϕ	soil internal friction angle (rad)
β	failure surface angle (rad)
δ	friction angle between soil and shovel (rad)
h_0	shovel rotation axis height (m)
S^{start}	soil area before excavation (m^2)
S_1^{end}	external soil area after excavation (m^2)
S_2^{end}	internal soil area after excavation (m^2)
c	soil cohesion (N/m^{n+1})
k_c	cohesive moduli of deformation (N/m^{n+1})
k_ϕ	friction moduli of deformation (N/m^{n+1})
w	tool width (m)
w_p	tool plate thickness (m)
W	soil weight (N)
q	pseudo thickness ratio (%)
ρ	soil density (kg/m^3)
σ	(N/m^2)
K_0	coefficient of static earth pressure (–)
τ	shear stress (N/m^2)
$\tau_{\max}$	maximum shear stress (N/m^2)
j	soil displacement (m)

example, NASA reported that the robotic arm of its Phoenix lander experienced a resistance of 20 N in order to dig to a depth of 30 mm and scoop Martian soil about 30 times over the course of 5 months (Arvidson, 2009).

Specific technical requirements for any robotic arm used on such sampling missions to Mars must be met. First, excavation resistance must be small enough to reduce energy consumption and improve durability of the device itself. Second, fewer actuators are preferable to more since the actuators often malfunction in harsh environments. Third, mechanical components must therefore be durable. Fourth, the device should be able to capture dry sand. Fifth, the end-effector (EE) must be capable of digging to more than 50 mm below the surface, where microorganisms may exist. Finally, the arm must have dexterity because the particle size of a target sample may be less than a centimeter.

This work aims to establish an energy-efficient strategy for sampling Martian subsurface soil for future extraterrestrial-life exploration missions. To this end, the above-mentioned requirements for a robotic arm are carefully examined and an EE shape suitable for subsurface soil sampling at shallow depths is determined. Subsequently, excavation mechanics between the tool and the soil are formulated in order to estimate excavation forces/torques. Then, using a soil–tool interaction model, energy-efficient sampling techniques (including a design of the robotic arm, actuator size, or control strategy) can be discussed.

The goal of this paper is to determine the shape of the sampling tool and to propose a soil–tool interaction model along with a method of soil-flow measurement that uses particle image velocimetry (PIV). The proposed model is then experimentally validated; several findings from the experimental results imply a possible control strategy for energy-efficient sampling techniques.

In order to formulate the excavation model, we apply soil mechanics approaches to static force and terramechanics approaches to soil deformation behavior. Similar works related to an excavation models have examined the wheel loader model and scooping motion (Takahasi and Saito, 2004; Fujiwara et al., 2011). However, those studies have mostly focused on an application in gravel pits which are very different from the finally grained Martian soil (Arvidson, 2009). The discrete element method (DEM) is often utilized as another solution to calculating the excavation resistance (Yoshida et al., 2012). DEM calculations can be applied to irregularly shaped rocks by considering each particle to be an aggregate of a spherical particle. However, this can only be applied when the shape of each particle is already known (Cundall and Strack, 1979). The shape of the particles in Martial soil is too irregular and their size is too small, resulting in prohibitively large calculation cost, for DEM to be applied. Thus, soil mechanics is a more suitable approach for calculating excavation resistance.

The rest of this paper is organized as follows. Section 2 discusses an EE tool shape. In Section 3, PIV is employed to observe the soil deformation profile. In Section 4, the soil–tool interaction model is formulated based on PIV analysis. Finally, model validation using a sampling tool test bed is described in Section 5.

2. Sampling tool: end-effector design

The robotic arm is expected to dig and deliver samples to an on-board scientific instrument mounted on the rover or lander. Also, the requirements previously mentioned have to be tested with each tool shape (see Table 1). Here,

Table 1
Requirements and comparisons of possible end-effector design.

Requirements	Shovel	Drill	Hand
1. Resistance force	B	B	B
2. Number of actuators	A	B	C
3. Durability	A	C	C
4. Scooping ability	A	B	C
5. Digging ability	A	A	C
6. Dexterity	B	B	A