MEASUREMENT OF LUNAR AND MARTIAN REGOLITH THERMAL PROPERTIES USING SUBSURFACE ROBOTIC TEAMS

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ABSTRACT

This paper presents a scenario for measurements of soil thermal parameters using a group of subterranean robots. First, the robots are unloaded from the planetary lander or carrier rover. Next, they are burying themselves to the specified depths. After reaching expected positions, thermal sensors mounted on the robots will measure a temperature profile of the near-surface material. This approach represents an alternative to the measurements using single penetrator equipped with several thermal sensors, which is limited to studying thermal profiles only along one axis.

In this paper we will focus on the subsurface navigation problem. The value of the results depends strongly on the precision of the determining position during movement. In our approach, positions of the robots are determined by sensors installed on the lander or, alternatively, by a three-dimensional odometry system supported by measurements of the relative distances between the robots. The estimates of position and orientation are obtained from an Extended Kalman Filter, which uses odometry readings as inputs and relative measurements of distances as feedback information. The paper presents results of simulations and preliminary evaluation of the concept.

INTRODUCTION

Already in the early stage of space exploration, when the first probes landed on the surface of the Moon, subsurface penetration was considered as one of the mission objectives. Soviet devices dedicated to lunar regolith investigations included penetrometers [1] and drills [2]. Similarly, American missions tried to acquire information from below the surface employing observations of lander footpads, i.e. Surveyor 1-7 [3], observations / measurements of drilling (e.g. Apollo 15-17), etc. The main scientific goals of these experiments were: to measure the temperature, to study the soil structure and to collect data on chemical composition of the lunar material.

The next wave of penetrating instruments was designed at the turn of the century, when such missions as Mars-94, Rosetta, Deep Space-2 and Mars-Express were launched. Unfortunately, most of them failed to perform the penetration part of their goals; only Rosetta with its lander Philae still has a chance to reach in 2014 comet Tchurumov-Gerasimenko and insert MUPUS penetrator into the comet’s nucleus. These new penetrating devices were constructed according to different ideas and operated on different principles. The spring-driven mole-like penetrator on Mars-Express Beagle-2 inherited its concept from the earlier geo-technical instrument in VNIITRANSMASH [4]. Two impact-driven penetrators on Deep Space-2 had to survive enormous deceleration and significant temperature increase during insertion following a free fall [5]. Drilling device on Rosetta will be the first autonomous tool of this kind to be operated on a small body of the solar system (asteroid or comet). MUPUS uses a new principle of insertion: electromagnetic hammer [6].

This trend will be continued in the future. Although the Bepi-Colombo surface probe with a mole was cancelled, it is very likely that most of next decade landers will be equipped with penetrating devices of different types [7], [8].

Applications of subsurface penetrators can be numerous. Firstly, they can serve as thermal probes that measure depth-dependent temperature profiles, temperature gradients, thermal conductivity and diffusivity and, in consequence, heat fluxes. Such measurements and their interpretation are important in assessing thermal balance of the whole investigated planet/satellite/comet/asteroid as well as in drawing conclusions about the structure of subsurface layers. Secondly, mechanical properties of the penetrated medium can be measured by observing insertion progress as a function of depth and applied power. Compressive strength of the investigated body is correlated with material structure and related to mass and heat transport in the medium. Finally, subsurface probes can be used to take samples of material and either transport them to the surface, where their chemical analysis can be carried out, or even perform such analysis, although much simpler, by a set of microsensors on the penetrator.
There are several technical problems to be solved in operating penetrators buried in the regolith. In this paper we will concentrate on only one of them: the accurate localization of penetrator(s) in the ground and, what follows, navigation of its motion. There are at least three methods of determining the underground position of a moving object: (i) by measuring the length of a cable that connects the penetrator with its host structure on the surface, (ii) by employing accelerometers that record second time derivative of the position vector as it changes during the motion, and (iii) by using geophones – i.e. sound (acoustic wave) detectors that can measure time delay of the signal sent by the penetrator to be received on the surface. All these solutions refer to the case of a single penetrator. Quite different concept, borrowed from the field of mini-robot swarms and satellite formations, is to send into the ground a number of penetrators that are able to measure (via acoustic sensors) distances among them and, in that way, find their coordinates with respect to a ground-based reference frame. Such approach shows many advantages over a single penetrator solution. A few penetrators operating together can provide more information, they can measure simultaneously physical parameters at different depths, thus removing time dependent factors, and they guarantee redundancy, since damage of any one of them does not prevent the others from performing their tasks.

In the following part of the paper, we first present the system of one or several penetrators that can use different methods of localizing their positions. Next, we describe a mathematical model that will allow the penetrators to find their positions from measured data with the best possible accuracy. Then, we will show results of simulations carried out for different penetrator configurations and measuring techniques. Finally, we conclude the paper with a short summary and discussion.

**DESCRIPTION OF THE PENETRATING SYSTEM**

We assume that any penetrator that operates as a single object or belongs to the group can move under the surface down to a depth of a few meters (10 m can be considered as an upper limit). A flexible cable that provides the penetrator with power and serves as a communication line connects it with its surface home station (lander, rover, or probe). The penetrator uses an engine (for instance a spring with a motor) to dig itself into the ground. This engine acts in short strokes, during which it releases substantial mechanical energy and, consequently, emits an acoustic signal. Each penetrator can measure the actual length of the cable that is released from a spool attached to the penetrator. The penetrator can be equipped with a simple inclinometer that measures the angle between the penetrator body and the cable. Additionally, in the case of penetrators operating as a group, they can use geophones to receive signals from their companions whenever any of them executes a stroke. A special case of a single penetrator and a number of geophones distributed on the surface will be considered. Assuming that the number of geophones is not less than three, the travel times between the source (the penetrator) and the receivers (geophones) can be used to determine the penetrator’s position even if the sound speed in the medium is not known precisely.

The penetrator (Fig. 1) is modeled as a simple rod (with circular cross section) with a conical tip in the front and a blunt end in the rear. The penetrator’s length and diameter are chosen as 20 cm and 1.5 cm, respectively. In this concept the penetrator body hosts: (i) driving system comprising a spring that can be compressed by a stepper motor with a gear and then released to hit a foot inside the penetrator, (ii) on-board front-end electronics, (iii) small processing unit, (iv) cable spool with encoders, (v) basic payload (thermal, chemical and mechanical sensors).

![Fig. 1. Schematic view of the penetrator](image)

We assume that the penetrator, during its motion, can change slightly the direction after each stroke, due to random scattering of the tip on hard obstacles of various sizes. However, we also assume that there is no systematic declination of a straight line trajectory of the penetrator. This assumption is justified by the fact the penetrator’s length is much larger than its diameter, therefore any significant change of the direction requires additional energy, as compared with a straight-line motion, to compress the material on the sides (walls) of the penetrator, not only in front of it. As far as the value of standard deviation of a random direction change (assumed to be normal) is concerned, we take it as $s/l$, where $s$ is the penetrator depth increase after a stroke and $l$ is penetrator length. The numerical factor takes into account the fact that $s/l$ is the maximum possible change. One can easily find that for $s=1$ mm (typical value for sand [9]) and $l=20$ cm, one gets standard deviation 0.1 deg.

Similarly one can estimate the error of determination of the cable length. The standard deviation strongly depends on construction of the spool. If the cable is unrolling freely, it can get slack in the tunnel formed behind the mole. In such case the error of traveled distance will be huge and difficult to estimate. In order to reduce this error the spool should be
equipped with a mechanism tightening the cable by small counter-torque on the spool. For such mechanism we assumed that the standard deviation amounts to 0.3 mm, i.e. 30% of the distance covered per single stroke.

Finally, the error of position determination by sonar can be estimated from following considerations. The sound speed in regolith is of about 100-300 m/s [10]. The distances to be measured are of the order of 10 m. Taking into account parameters of existing acoustic profiling systems (i.e. Benthos CAP-6600 Chirp II), we can assume that the standard deviation is equal to 10 cm.

**MATHEMATICAL MODEL**

The full description of the state of the penetrator (position and configuration) in its underground motion requires six parameters: \( X_n = [x_n, y_n, z_n, \theta_n, \phi_n, \psi_n]^T \). Three parameters describe the position of a chosen point on the penetrator (e.g. the tip or the centre of mass) and three angles correspond to the orientation of the penetrator with respect to an inertial reference frame (Fig. 2). In fact, the orientation of an axially symmetric body, such as penetrator, can be described by only two parameters; however for the sake of general description we will keep all three angles in the following considerations.

We assume that the motion is discretized into a number of steps, where each step corresponds to a fixed number of strokes (say 100). The description of the state at the step \( n+1 \) as a function of the state at the step \( n \) as well as of observables and random errors reads:

\[
X_{n+1} = X_n + \begin{bmatrix} R v_m (U_n + v_m) -1 \end{bmatrix} + \begin{bmatrix} v_{en} \\ v_{in} \\ v_{an} \end{bmatrix}
\]

(1)

Where \( U_n \) is the observed length of the cable (odometric measure of the position) and \( V_n = [v_{en}, v_{in}, v_{an}, v_{ln}]^T \) is the set of random (Gaussian) errors of three angles and the cable length. Rotation matrices \( R_e, R_t, \) and \( R_a \) are:

\[
R = R_e R_t R_a
\]

(2)

\[
R_e = \begin{bmatrix} \cos(e) & 0 & -\sin(e) \\ 0 & 1 & 0 \\ \sin(e) & 0 & \cos(e) \end{bmatrix} \quad R_t = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(t) & -\sin(t) \\ 0 & \sin(t) & \cos(t) \end{bmatrix} \quad R_a = \begin{bmatrix} \cos(a) & -\sin(a) & 0 \\ \sin(a) & \cos(a) & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

![Fig. 2. Description of the rotation angles](image-url)
When geophones are used one should add a number of observational equations:

\[
Z_n = h\left(X_n, \omega_n\right) = \begin{bmatrix} z_{n,1}^i \\ \vdots \\ z_{n,k}^i \end{bmatrix} = \begin{bmatrix} \sqrt{(x_n - x_1)^2 + (y_n - y_1)^2 + (z_n - z_1)^2 + \omega_n^1} \\ \vdots \\ \sqrt{(x_n - x_k)^2 + (y_n - y_k)^2 + (z_n - z_k)^2 + \omega_n^k} \end{bmatrix}
\]  

(3)

where \(Z\) is a vector of distances between the geophones and mole, \(\omega\) is the set of random errors of the measured distances.

The description presented above can be easily accommodated into the Extended Kalman Filter (EKF), in which description of motion and observation is required (1) and (3). In the general form one has:

\[
X_{n+1} = f\left(X_n, U_n, V_n\right) \\
Z_n = h\left(X_n, \omega_n\right)
\]  

(4)

Our model makes use of Extended Kalman Filter to estimate the current configuration (position and orientation) of the moving moles. The Kalman Filter uses encoder readings \(U\) and observations \(Z\) to estimate the values of parameters, and does it in two steps: prediction and correction.

The prediction equations link the steps \(n+1\) and \(n\) and project estimates of the state \(X\) and the error matrix \(P\):

\[
\hat{X}_{n+1} = f\left(\hat{X}_n, U_n, 0\right) \\
P_{n+1} = A_n P_n A_n^T + W_n Q W_n^T
\]  

(5)

where \(W\) is the Jacobian matrix of partial derivatives of \(f\) with respect to random error \(V\), \(A\) is the Jacobian of partial derivatives of \(f\) with respect to state \(X\) and \(Q\) is the covariance matrix of \(V\).

At the correction step, the state parameters and covariance estimates are updated according to recent measurements:

\[
K_n = P_n H_n^T \left(H_n P_n H_n^T + R\right)^{-1} \\
\hat{X}_n = \hat{X}_{n+1} + K_n \left(Z_n - h(\hat{X}_{n+1}, 0)\right) \\
P_n = \left(I - K_n H_n\right) P_{n+1}
\]  

(6)

where \(K\) is the Kalman gain matrix, \(H\) is the Jacobian matrix of partial derivatives of \(h\) with respect to \(X\), \(R\) is the covariance matrix of \(\omega\).

RESULTS

We consider four different cases, showed in Fig. 3: (i) the moles navigate using odometry supported by geophones distributed on the surface; (ii) odometry navigation is corrected by measurements of distances between the penetrators. As a reference we consider also: (iii) position estimation using only odometry, and (iii) position estimation using only geophones located on the surface.
The first case corresponds to the situation when penetrators navigate independently, using 5 sonars located in the centre and in the corners of a square with a side length of 2 m. The four penetrators are inserted into the ground in the middle of each side of the square, hence they are initially at a distance of 1.4 m one from another. The navigation is performed using EKF, as it was described in the last section. In Fig. 4, the errors determining the position of penetrators and distances between them are presented. Also, the exact (lines) and the estimated (marks) positions in their underground motion are shown. The errors increase systematically with depth, but at the same time show random variations, typical for a random walk process.

In the second case, the same number of penetrators (four) navigates by using odometry and inter-penetrator distances measured by acoustic sensors mounted onboard. The initial distribution of penetrators is the same as in the previous case. Again, Extended Kalman Filter is employed as a mathematical model of the considered process. The results presented in Fig. 5 indicate that the error can be significantly reduced (factor 3-4) in comparison with the case when geophones are located on the surface. This supports the idea of using groups of moles in order to improve the position determination of each one of them.

In the case no 3, the odometry information (cable length) is not used and the position determination is obtained from sonar measurements of distances between the penetrators and geophones on the surface. The mathematical model, in this case, employs only observation (3), hence instead of EKF classical least square method is used: we have got $N \cdot M$ observation equations for $3N$ unknown coordinates ($N$ is the number of penetrators, $M$ is the number of geophones). The errors (Fig. 6) are larger than in the previous cases and can amount to 0.5-1 m at a depth of 10 m.
The fourth case (Fig. 7) of cable length odometry alone (i.e. without sonar) shows the largest errors from all considered simulations. One can easily understand it, taking into account that the penetrators do not cooperate and that each one of them uses only one single measurement to determine its own position. The EKF cannot be used in this situation, therefore only the information about the distance covered by the moles is used.

**Thermal properties**

There are two interesting aspects of thermal properties’ measurements by a group of moles. The first one refers to the heat flux determination, which requires the temperature gradient as an input value. Assuming that the regolith is locally uniform and the temperature depends only on the depth below the surface, one can use temperature sensors on two moles that are at different depths to obtain the temperature gradient. If the measured temperatures are $T_1$ and $T_2$ at the depths $z_1$ and $z_2$, and the corresponding errors of temperature and depth determination are $\delta T_i$ and $\delta z_i$, respectively ($i=1$, 2), then the measured gradient is related to its real value by the formula:

$$
\frac{\Delta T}{\Delta z}_{\text{measured}} = \left(\frac{T_1 - T_2}{z_1 - z_2}\right) + \left(\frac{\delta T_1 - \delta T_2}{\Delta z}\right) = \left. \frac{\Delta T}{\Delta z}\right|_{\text{real}} \cdot \left(1 + \frac{\delta \Delta T}{\Delta T} - \frac{\delta \Delta z}{\Delta z}\right)
$$

(7)

Here $\delta \Delta T = \delta T_1 - \delta T_2$ and $\delta \Delta z = \delta z_1 - \delta z_2$. The latter value depends on $z$ (see Figs 4-7). From the above formula one can see that the error in the temperature gradient determination, provided that the real value is constant, will decrease with the distance between the penetrators ($\Delta T$ increases) and increase with depth ($\delta \Delta z$ increases).

The second issue to be considered is how to measure thermal parameters of the regolith, i.e. its conductivity and diffusivity. One approach is to use a pair of moles that are not too far one from another (at about 10 cm distance) and to use one of them as the heater and the other as the temperature sensor. An increase of the second mole temperature due to heat wave emitted by the first mole can be recorded as a function of time and used to extract the sought parameters. However, this method can only be applied to the medium with thermal conductivity greater than 0.2 W/mK. In this parameter is smaller, the temperature of the heater will increase to large value before the temperature sensor will be able to measure the signal above the thermal noise, which is of the order of 1 mK. Hence, this method can probably be employed on Mars, where thermal conductivity is possibly not too different than that of terrestrial soil (0.5 W/mK), but not on the Moon, where thermal conductivity of the regolith is extremely low (0.01 W/mK). The way out could be to measure the temperature of the heater itself, i.e. to use any penetrator as the emitter and receiver at the same time. The rate of temperature growth will clearly indicate how large the thermal conductivity (and diffusivity) is. To investigate
In this method we assume the spherical heat source with a diameter $a=1.5$ cm is a part of the penetrator. The source is supplied with a power of $P=5$ W. The temperature increase at a distance $r$ from the source centre after time $t$ for a medium with thermal conductivity $K$ and diffusivity $\kappa$ reads [11]:

$$T(t,r) = \frac{3KPt}{2\pi rKa} \left\{ t^2\text{erfc}\left(\frac{r+a}{2\sqrt{\kappa t}}\right) + t^2\text{erfc}\left(\frac{r-a}{2\sqrt{\kappa t}}\right) + \frac{2\sqrt{Kt}}{\kappa} \left[ t^2\text{erfc}\left(\frac{r+a}{2\sqrt{Kt}}\right) - t^2\text{erfc}\left(\frac{r-a}{2\sqrt{Kt}}\right) \right] \right\} \quad (8)$$

The results for $r=a$ are presented in Fig. 8. We have simulated heat generation in three media: lunar regolith ($K=10^{-2}$ W/mK, $\kappa=5\times10^{-9}$ m$^2$/s), sand, which can be considered as an analogue of Martian soil ($K=0.35$ W/mK, $\kappa=2.8\times10^{-7}$ m$^2$/s), and sandstone that serves as a reference ($K=1.7$ W/mK, $\kappa=10^{-6}$ m$^2$/s).

![Fig. 8. Temperature increase for regolith, sand and sandstone.](image)

**CONCLUSIONS**

We have presented several methods of underground navigation, in which odometry measurements of the length of the cable connecting the penetrator with the probe on the surface are used independently or in combination with sonar technique. The latter can be implemented by either distributing several sound receivers on the surface or by using the penetrators as transmitters and receivers. In fact, the last method when combined with odometry gives the best results and guarantees quite high precision of position estimation (10 cm) even at a depth of 10 m. Therefore, the group navigation should be recommended when accuracy of depth determination is important (for instance for heat flux measurements). The second best method is to use sonars located on the surface that record the signals from non-cooperating penetrators.

Measurements of thermal properties of the lunar regolith or Martian soil can be, at best, carried out if the sensor on each penetrator operates as active heater and temperature probe. One can then easily determine thermal conductivity by observing the rate of temperature increase of the heater being in contact with the surrounding medium. Alternatively, but only for the medium with reasonably large thermal conductivity, one can employ two penetrators as a heat emitting and receiving pair. When the temperature gradient (and heat flux) is going to be measured, two penetrators at different depths should be used. To make the error as small as possible, the distance between the sensors should be rather large (several meters). On the other hand, since the error of position determination increases with depth, the sensors should not be located too deep. Also, one should take into account the fact that surface layer of the regolith reacts to changes in insolation. Consequently the sensors should be located deep enough not to be affected by this effect.

We have not discussed here technical issues related to the penetrator deployment and initial phase of their insertion, when the direction of penetration should be perpendicular to the surface. These problems have already been approached.
in the missions that employed (Mars-Express) or plan to employ (Rosetta) the penetrators. From the point of view of using group of penetrators, the most important is to design the penetrator as a simple, light, and easy to launch device. In our opinion several (up to 5) small penetrators, of the kind described in this study, should not weight more than 200 g each and consume not more than 5-10 W. Such solution seems to be feasible even at the current stage of the exploration technology development.

REFERENCES


