Modeling and Estimation of Robotic Soil Interactions

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The Problem: One of the goals of future Mars exploration missions is to collect geological information about the Martian surface. Previous attempts have been made to spin the wheels of rover vehicles to obtain some measure of physical soil properties. Future Mars missions will very likely include a lander or rover based manipulator arm. In this work, we attempt to address two problems related to these missions. The first is to develop techniques to estimate unknown soil parameters from force interaction data. The second is to apply knowledge of these soil parameters to enhance future soil interactions.

Motivation: Many people are interested in automating the digging/excavation process. In addition to earth based digging applications, NASA has a need for well designed autonomous digging robots for Lunar and Mars exploration. Mars and Lunar landers and rovers are increasingly being equipped with manipulator arms in order to collect samples, conduct experiments, and for all-purpose manipulation of instruments and the environment[1]. This includes interaction with soil mediums either for geological purposes, excavation, sample collection, or for buried object retrieval. In the future, by using techniques which we develop, scientists will be able to determine the density, soil-soil friction, and soil-tool friction through basic soil interactions. Sets of experiments could be conducted in different regions to map out variations in properties and perhaps help hypothesize the geological history of the soil.

Previous Work: There has been a good amount of work on robotic excavation but the work has primarily focused on planning, development and coordination of systems, or simple rule based control schemes to avoid stalling. Our current proposed research is intended to fill a gap in the existing body of research. Researchers have primarily focused on high level planning and have not taken a close look at improving techniques for accurately predicting interaction forces, developing specialized control systems for interacting with soil, attempting to classify soils from interaction data, or constructing measures of performance. A good reference on the existing state of research in this area can be found in Singh [4].

Approach: This research proposes to improve the sensing capabilities of robotic manipulators when interacting with soil. In addition, we propose to improve the state of the art in control of manipulators for interaction with soil mediums and buried obstacles [3]. We are working to develop techniques to enable the use of the manipulator arm as a science instrument by extracting measures of soil properties from interaction force data and observations of resulting deformation of the environment.

To accomplish these goals, we have constructed a slightly larger than rover scale manipulator arm with inherent force sensing capabilities (through compliant transmissions equipped with potentiometers) [1, 2]. We have also equipped this arm with a six-axis force/torque sensor in order to have a dependable measurement with which to compare. The end-effector of the arm consists of a flat plate which is inserted into the soil. The insertion is carried out using a software-based remote-center of compliance technique so that we have minimal disturbance of the surrounding soil during insertion and minimal residual forces. Multiple strokes in the sand are carried out with different angles of inclination for the plate and different insertion depths. The resulting resistance data is combined with our models for soil behavior to generate estimates for soil parameters which are consistent with the observed force measurements.

There exist many different models for predicting the interaction forces between plates and soil mediums given a known set of soil parameters. These methods are not always in agreement. We have selected a few representative models of

[1] Examples of these type of systems include the ill-fated Polar Lander expedition which was scheduled to land on Mars in December 1999. It was equipped with a three meter manipulator arm which was to conduct multiple tasks, one of which was to dig a half meter trench in the soil, time permitting. Another example is the future 2003 dual-rover mission in which two identical rovers each will use an instrumented robotic arm to do grinding and imaging of rock samples.

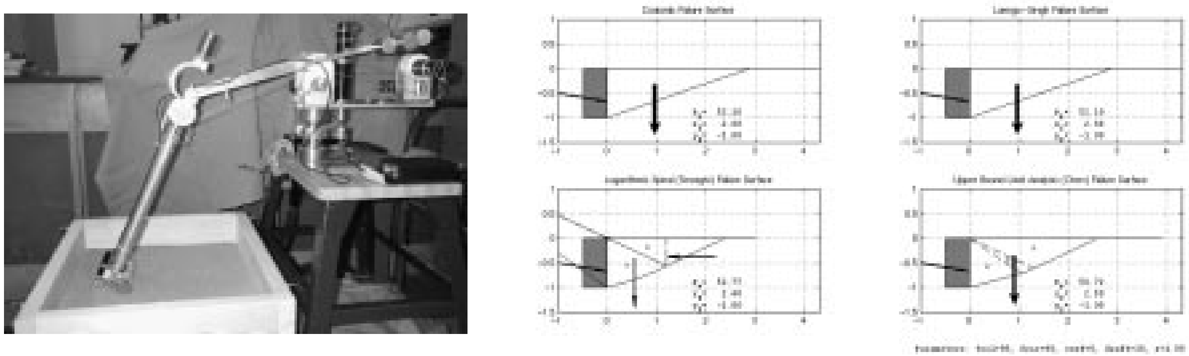

Figure 1: Manipulator arm with plate inserted into soil (left). Example failure surfaces for four of the seven predictive models for a vertical plate (right). Models are in close agreement for simple configurations.

draft force prediction existing in literature. The problem which we are addressing is equivalent to the well known case of passive earth pressure on a retaining wall in Civil Engineering. The classical approaches to this problem include Coulomb's Theory (1776), Ohde's Logarithmic Spiral (1938) (as presented by Terzaghi (1943)), and Caquot and Kerisel's Passive Earth Pressure Tables (1948). In addition, the model used recently by Luengo and Singh (1998) is also incorporated, which is similar to Coulomb's Theory. In addition to these methods, we also consider the results from limit analysis techniques. We use Chen's upper bound equations (1990) and we also use the numerical limit analysis techniques developed by Sloan (1995) and expanded by Ukritchon and Whittle (1998) to compute upper and lower bounds.

Difficulty: We must overcome mechanical difficulties resulting from backlash in the motor gearheads and flexibility of the manipulator links. This causes difficulty in accurately controlling and sensing endpoint position. We also are dealing with small interaction forces, on the order of a pound, and need to keep the measurement percentage error small in order to increase the accuracy of the parameter prediction. The parameter prediction requires the inversion of the predictive models given sets of measurements of resistance force. This is not a trivial problem as the models are highly nonlinear. Use of standard nonlinear optimization procedures is ineffective due to the existence of many local minima as well as the global minimum of the weighted sum squared error often not corresponding to the correct solution. Instead, we have developed a graphical technique which looks promising for estimating soil properties from a small number of measurements with bounded uncertainty.

Impact: This research will allow us to use a manipulator arm as a science instrument for future Lunar/Mars science experiments interacting with soil mediums and for sample acquisition. Our methods will allow researchers to determine physical soil properties from a small sequence of soil interactions. We also hope to develop novel methods for utilizing soil parameter information to enhance future interactions. In addition, this work provides a basis for accurate soil interactions for virtual soil simulations, teleoperation, and remote geology.

Future Work: In the future, control techniques must be developed which can take advantage of the detected soil properties to enhance future interactions. Also, our models and work here address static interaction problems, the dynamic interaction between the soil and the manipulator needs to be modeled and put into a form which can be used in real-time, which has not been successfully accomplished to date.

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References:

[1] A. Curtis. *A Nonlinearly Compliant Transmission Element for Force Sensing and Control*. M.S. Thesis, Department of Mechanical Engineering, MIT, January 2000.

[2] A. Katz. *The Design and Application of a Nonlinear Series Compliance Actuator for Use in Robotic Arms*. M.S. Thesis, Department of Mechanical Engineering, MIT, September 1999.

[3] W. J. Hong and J. K. Salisbury. Obstacle Negotiation in Robotic Excavation. In *Proceedings of the IASTED Robotics and Applications 1999 Conference*, Santa Barbara, CA, October 28-30, 1999.

[4] S. Singh. State of the art in automation of earthmoving. *Journal of Aerospace Engineering*, 10(4), October 1997.