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## Robotic Exploration of Surfaces to Measure Mechanical Properties

### Abstract

This paper presents an overview of ongoing research on surface exploration at the GRASP Lab. We are investigating the necessary components and modules that must be embedded into a robot for it to have the exploratory capabilities required to recover *mechanical* properties from a surface, given minimal *a priori* information. Eventually, this information will be used to enable a robot to stand and walk stably on a surface that is unknown and unconstrained. A robot in the agricultural environment will specially benefit from such capabilities since it will need to step and walk on soils with variable properties. The paper proposes a framework for the recovery of the attributes of interest, and describes the laboratory setup designed to test the framework. The design and implementation of *exploratory procedures (ep's)* to recover penetrability, material hardness and surface roughness by exploring the surface is also described.

### Comments

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**Robotics Exploration Of Surfaces  
To Measure Mechanical Properties**

**MS-CIS-90-41  
GRASP LAB 221**

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**July 1990**

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ROBOTIC EXPLORATION OF SURFACES  
TO  
MEASURE MECHANICAL PROPERTIES <sup>1</sup>

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## Abstract

This paper presents an overview of ongoing research on surface exploration at the GRASP Lab. We are investigating the necessary components and modules that must be embedded into a robot for it to have the exploratory capabilities required to recover *mechanical* properties from a surface, given minimal *a priori* information. Eventually, this information will be used to enable a robot to stand and walk stably on a surface that is unknown and unconstrained. A robot in the agricultural environment will specially benefit from such capabilities since it will need to step and walk on soils with variable properties. The paper proposes a framework for the recovery of the attributes of interest, and describes the laboratory setup designed to test the framework. The design and implementation of *exploratory procedures* (*ep*'s) to recover penetrability, material hardness and surface roughness by exploring the surface is also described.

## 1 Introduction

With the increase in applications of robots to agriculture and other unstructured and possibly hazardous environments, there has been some emphasis on research in designing systems for sustained locomotion on unstructured terrain. While there has been a lot of discussion about the best form of locomotion, what is of particular relevance to the field of agriculture is that Bekker [1] has applied soil mechanics to show the superior mobility of legged locomotion in comparison to wheeled or tracked locomotion. In the design of most of the legged robots, however, it is assumed that the material properties, the geometry, and conditions of the environment, are known *a priori* or are controllable [2]. The motivation for the research on surface exploration stems from the need to have a robotic system that actively explores the environment to recover its characteristic properties, and then applies this information to successfully step or walk on surfaces with varying material properties.

In this paper, we wish to report the results of some of our investigations of the necessary components and modules that must be embedded into a robot with exploratory capabilities. We have limited ourselves to the specific task of exploring a surface to recover *mechanical* properties for *mobility* purposes. We would like to be able to predict if a certain surface is stable enough to support the loads and forces exerted by a foot, when the robot is standing or walking on a surface, or carrying out certain tasks while in contact with the surface. We would also like to be able to predict if a surface can provide the required traction in such applications. We are particularly interested in investigating the behavior of soils and sands and recovering the properties that determine the stability of such material surfaces to a moving robot. In the next section, we propose a framework for the recovery of surface attributes for applications to robot mobility.

## 2 Proposed Framework

Our first objective was to identify the attributes that are needed to determine the stability of surfaces during standing or walking. As described in our earlier work, this turns out to be a classical problem of system identification and parameter estimation, and a detailed description of our investigations into the attributes of interest can be found in [3, 4]. Guided by the goals of our application, we chose to define the structure of our environment by the attributes of penetrability, hardness, compliance, compressibility, deformability and surface roughness. This choice of attributes was supported by a review of work in soil mechanics [5, 6] which showed that these are the important properties which determine the behavior of soils and sand with respect to stability and mobility.

At present, the framework we propose is that for stable stepping and walking in an unknown environment, it is necessary to recover the attributes of penetrability, hardness, compliance, compressibility, deformability and surface roughness. These attributes must be

recovered by “exploratory procedures” (*ep*’s) that are built in to the mobile robotic system.

## 2.1 Attributes and Exploratory Procedures

Under the paradigm of exploratory robotics, the concept of *ep*’s provides a solid framework for exploration and recovery of attributes - for details refer to our earlier work [3, 4]. By *ep* we mean a procedure that is salient to the recovery of a specific attribute of interest. From a review of most available testing methods from scientific and engineering fields other than Robotics, most methods seemed completely unsuitable for Robotics applications. For example, soil engineers do most of their testing by taking soil samples and measuring the properties with specially designed equipment. The methodology of our research, therefore, is to design exploratory procedures that will attempt to recover the specific attributes of interest from the environment. These *ep*’s are then to be implemented to predict the stability of a surface to a standing or walking robot.

### 2.1.1 Penetrability

In measuring the penetrability of a surface we are interested in determining whether the surface is penetrable or not. It would give the robot the ability to decide whether its foot would sink into a surface or find a stable footing. This is particularly of interest in detecting materials like quicksand, mud or soft snow, the surfaces of which would not support the weight of the robot and cause the foot to sink.

The *ep* for penetrability is analogous to the penetration tests that are used to examine soil properties [5]. Soil engineers usually press a sharp mechanical probe into the surface and measure the resistance to penetration of the probe into the surface. In the case of a robot foot, however, it is more important to determine *whether* the surface is penetrable or not, rather than *how* penetrable it is. If a surface merely deforms or gets compressed initially (like soft sand or soil, for example), but then offers a stable surface due to its compressive strength, then it is considered to be impenetrable.

Our *ep* for penetrability, therefore, is designed to push the foot against the surface with a specified force. If the foot sinks below the surface, beyond a specified limit of stability, then the surface is classified as penetrable. On the other hand if the surface is able to withstand the force exerted by the foot, before the stability limit is reached, the surface is classified as impenetrable and the *ep* for hardness and compliance can then be implemented.

### 2.1.2 Hardness and Compliance

In measuring the attributes of hardness and compliance, we are highlighting those characteristics of an impenetrable surface that determine how the surface will behave when the foot exerts forces normal to it while standing or walking. Hardness and compliance can be interpreted in a number of ways [3, 7]. Our interpretation is that hardness is the resistance

(measure of deformation) to a load when the surface is rigid, while compliance is the same property measured for deformable surfaces. The basic concept of the *ep* for hardness and compliance is based on this interpretation.

A viable way to measure hardness and compliance is to measure the resistance to a load as deformation in a compliant probe when it is pressed against a hard material with increasing pressure [8]. In the *ep* for hardness and compliance, the foot (that is rigid, but mounted on to a compliant wrist) is pressed against the material surface and then moved into the surface with small increments. Deformation in the compliant wrist is measured with each movement. This *ep* gives a measure of the material hardness and compliance which is proportional to the rate of deformation in the wrist. In addition, for materials that are compressive, the rate of deformation gives a measure of the compressibility and the extent of the maximum deformation is a measure of the compressive strength of the materials.

In the execution of this *ep*, what the robot really measures is the stiffness of the environment, where the stiffness is proportional to the rate of deformation in the wrist. In the discussion of the implementation of this *ep* in Section 3.2.2, we use some simple lumped-parameter dynamic models to show why this assertion is more than just intuitive.

### 2.1.3 Surface Roughness

The surface roughness is a measure of the tangential forces due to friction that result when two surfaces in contact slide against each other. It would be of utmost importance to measure the surface roughness of surfaces to determine the forces that a robot should exert while walking on it. The knowledge of the roughness of a surface would give a walking robot the ability to avoid slipping when walking from a very rough surface on to a very smooth and slippery surface. Of course, the roughness will also determine the amount of traction the surface can provide to a moving robot.

The *ep* for surface roughness is very similar to the classical methods of measuring the coefficient of friction between the two surfaces. The *ep* is simply designed to perform relative lateral motion between a surface of known roughness (in our case, the foot) and the unknown surface, while keeping them forced into contact. The measurement of tangential forces generated when this *ep* is carried out will give us a measure of the surface roughness.

## 3 Test of the Framework

To provide a robot the ability to sense the material properties of the surface while standing, or indeed walking on it, is the ultimate goal of this research. Keeping this in mind and to test the framework proposed earlier, we have built a system and implemented the *ep*'s described in the previous section with the intent to ultimately execute these *ep*'s on the fly, that is, while the robot is in motion and the foot is executing the movements for walking.



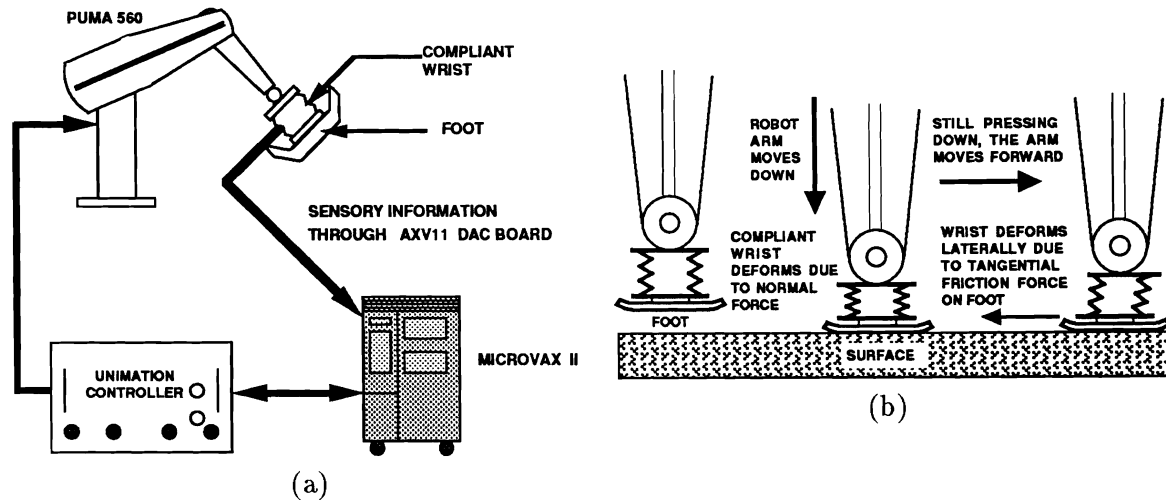


Figure 1: (a) System Setup (b) A Typical Run

### 3.1 System Setup

The system setup is shown in Figure 1(a). The primary sensing mechanism is a compliant wrist device that incorporates passive compliance and a sensing mechanism to provide six degree-of-freedom flexibility and measurement (designed by Y. Xu and R.P. Paul [9]). This device is mounted on to a PUMA 560 robot arm and has a fixture that allows the prototype foot to be mounted on it. The passive compliance of the device allows the robot to avoid transition and excess impact forces as the robot makes contact with the environment. The six degree-of-freedom sensing mechanism allows the measurement of three translational and the three rotational deformations in the wrist, which can be translated into force and torque measurements since the effective stiffnesses in each degree-of-freedom are known. A hybrid position/force control algorithm has been implemented that allows force control in certain degrees-of-freedom while the others are position controlled. In the force controlled directions, the arm trajectory is modified by the sensed contact forces so that the effective stiffness is decreased. The device allows the robot to accurately sense when contact is made with the surface. More importantly, it allows the robot to exert forces specified up to a limit as well as to maintain certain contact forces while the arm is in motion. Further details on the wrist can be found in [9].

The base of the compliant wrist is mounted on the PUMA 560 arm and our prototype foot has been mounted on the other end. The design of the foot is quite intuitive and we have just built a simple device that looks like a short ski. The foot is made of aluminum and the bottom surface (the one that interacts with the environment) is a well-machined metal surface. The dimensions of the foot are roughly 2.5in x 5in x .25in.

While carrying out a typical implementation of the  $ep$ 's described above, the robot arm

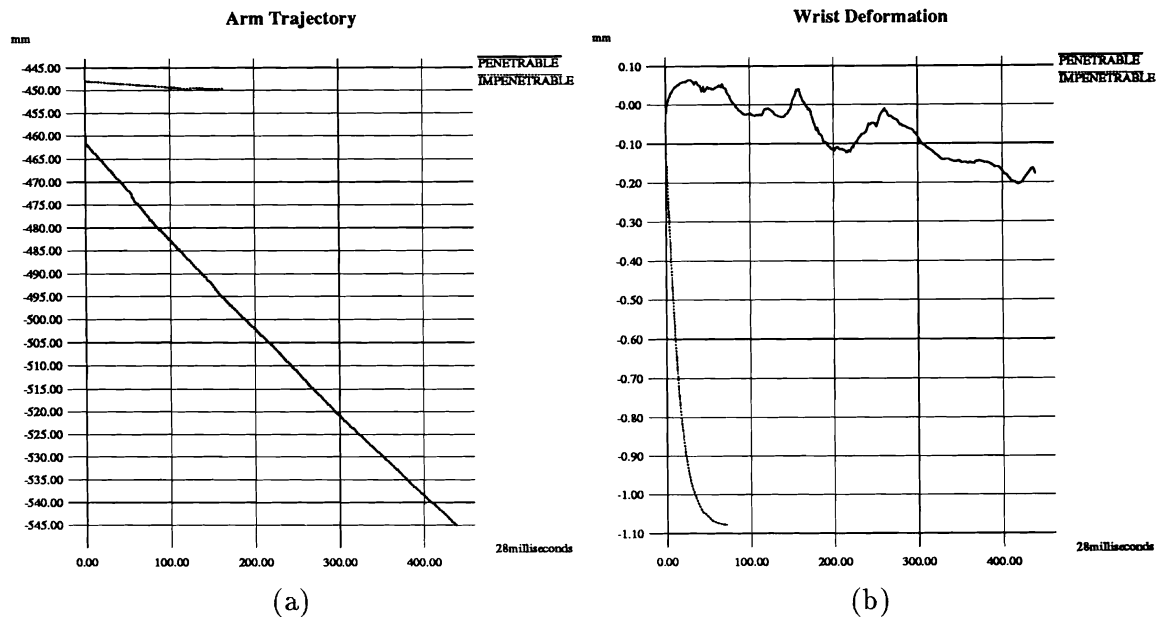


Figure 2: Measurement of Penetrability (a) Plot of arm end-point position (in mm) vs time (1 unit = 28 milliseconds) (b) Plot of deformation in the wrist (in mm) due to normal force vs time (1 unit = 28 milliseconds)

pushes down on the surface to execute the  $ep$ 's for penetrability, hardness and compliance (see Figure 1(b)). The compliant wrist deforms in a direction normal to the surface due to the resultant normal forces. These deformations are recorded to give a measure of the penetrability, hardness and compliance. The  $ep$  for surface roughness is then employed. Now, while keeping the wrist pushed against the surface with a constant force, the arm is moved relative to the surface, thus sliding the foot over it. This causes the wrist to deform laterally in a direction opposite to the motion of the arm. This deformation is due to the tangential friction on the foot due to the roughness of the surface. Therefore, a measure of this lateral deformation gives a measure of the surface roughness.

## 3.2 Recovery of Attributes

In this section, we would like to particularly discuss the attributes of penetrability, hardness and surface roughness because those are the three mechanical properties that we have so far succeeded in recovering.

### 3.2.1 Penetrability

This  $ep$  involves pressing down on the surface till a certain maximum normal deformation is measured in the wrist (which means that the surface is impenetrable, and can support

the weight exerted by the foot), or till the arm has moved too far down (which means that surface is penetrable and the foot will sink into the surface). In the actual implementation, the maximum allowable normal deformation will be the equivalent to the deformation corresponding to the maximum normal force that the foot will exert on the surface. How far the arm should move down will be dictated by the limit on the sinkage of the foot, such that robot does not become unstable and fall. For our implementation of this  $ep$ , we have restricted the maximum normal deformation to be about -1.1mm (which corresponds to a normal force of about 6 lbs) and the maximum distance moved by the arm to about 80mm. If we find, by monitoring the distance moved down by the arm and the amount of deformation in the wrist, that the wrist deformation is very small compared to the large distance moved down by the arm, we classify the material as penetrable. Hence, penetrability is measured as a combination of arm trajectory and wrist deformation in a given time interval.

Some results from the  $ep$  for penetrability are shown in Figure 2. In the case of the penetrable surface, there is hardly any deformation in the wrist, in fact, only about -0.2mm (solid line in Figure 2(b)), even after the arm moves down the allowed 80mm (solid line in Figure 2(a)). On the other hand, for the impenetrable case, the arm moves down a very short distance (dotted line in Figure 2(a)) and most of the downward motion shows up as deformation in the wrist (dotted line in Figure 2(b)). Also, in the penetrable case the duration of the  $ep$  is very short as the wrist deforms rapidly and reaches the maximum permitted value.

### 3.2.2 Hardness

Our system can be modeled as a simple lumped-parameter dynamic model shown in Figure 3(a). We assume that the dynamics of the environment are adequately modeled by a second order dynamic model. Let us consider the arm to be a rigid body with no vibrational modes and model it as a mass with a damper to the ground. The mass  $m_r$  represents the effective moving mass of the arm. The viscous damper  $c_r$  gives the appropriate rigid body mode to the arm. The compliant wrist sensor connects the arm and the environment with some compliance - it has stiffness  $k_w$  and damping  $c_w$ . The environment is represented by a mass  $m_e$  and has a stiffness  $k_e$  and damping  $c_e$ . The state variables  $x_r$  and  $x_e$  measure the positions of the arm and environment masses, respectively. The actuator is represented by the input force  $F$ . The contact force  $F_c$  and the wrist deformation  $x_w$  are related as follows:

$$F_c = k_w x_w \quad (1)$$

$$\text{also, } x_w = x_r - x_e \quad (2)$$

$$\text{therefore, } F_c = k_w(x_r - x_e) \quad (3)$$

The governing equations for this system are:

$$m_r \ddot{x}_r + k_w(x_r - x_e) = F - c_r \dot{x}_r - c_w(\dot{x}_r - \dot{x}_e) \quad (4)$$

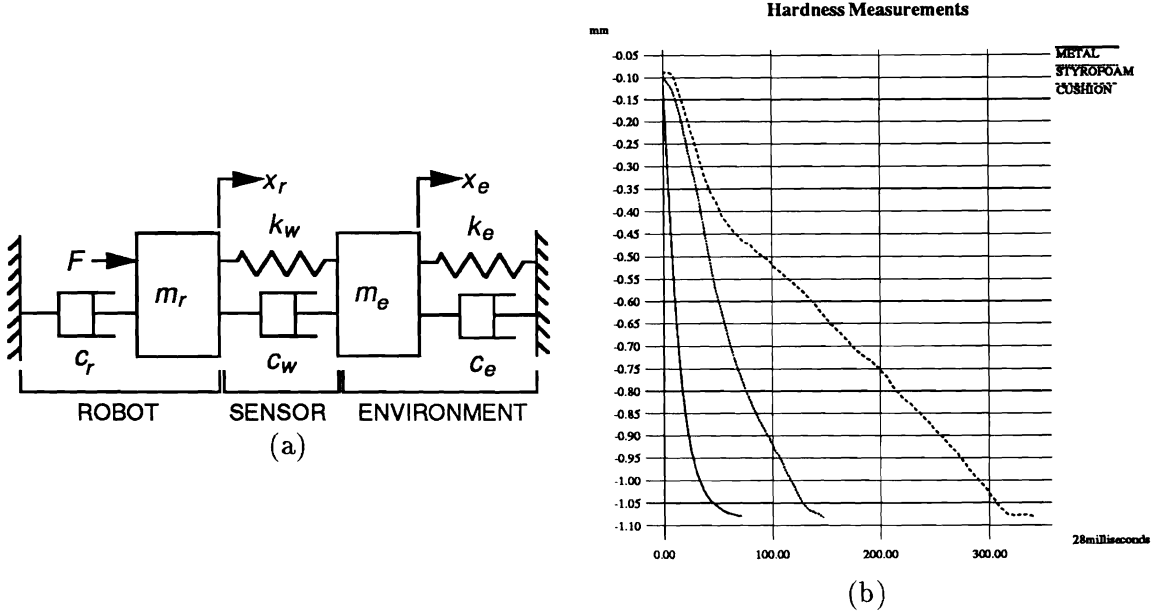


Figure 3: (a) Model of system for measurement of hardness (b) Plot of deformation in the wrist (in mm) due to normal force vs time (1 unit = 28 milliseconds)

$$m_e \ddot{x}_e + k_w(x_e - x_r) + k_e x_e = c_w(\dot{x}_r - \dot{x}_e) - c_e \dot{x}_e \quad (5)$$

For the implementation of our *ep* for hardness, we can reasonably assume that  $\ddot{x}_r = \ddot{x}_e = \dot{x}_r = \dot{x}_e = 0$  for the velocities and frequencies of this *ep* are well within the dynamic range of the system. Therefore, the above equations reduce to:

$$k_w(x_r - x_e) = F \quad (6)$$

$$k_w(x_e - x_r) + k_e x_e = 0 \quad (7)$$

Substituting for  $x_e$  in Equation (7), using Equation (6) and differentiating, we get:

$$k_e = \frac{k_w \dot{x}_w}{\dot{x}_r - \dot{x}_w} \quad (8)$$

Since  $k_w$  is a known constant obtained by calibration, and  $\dot{x}_r$  is the constant commanded robot velocity, the environment stiffness,  $k_e$ , that the *ep* for hardness and compliance tries to measure, is just a function of  $\dot{x}_w$ , the rate of deformation of the wrist.

In our system, the *ep* for hardness involves moving down the arm such that the foot is pressed into the surface at a constant rate till the normal deformation experienced by the wrist is about -1.1mm (which corresponds to a normal force of about 6 lbs). It is first determined if the foot has encountered the surface. Then the foot is slowly pushed against the surface at a constant velocity ( $\dot{x}_r$ ). The deformation history of the wrist is examined

from the point the  $ep$  begins till it ends when the wrist is experiencing a normal deformation of about -1.1mm. The steeper the slope ( $\dot{x}_w$ ) of the normal deformation versus time curve, the harder is the material.

The results from the  $ep$  for hardness measurements is shown in Figure 3(b). The slope of the deformation versus time plot is clearly the steepest for the metal surface. The Styrofoam surface is less hard, however, the curve is still mostly linear. In the case of the softer cushion, while the slope is clearly the least, the curve does not stay linear.

The interpretation of the changing slopes of these curves will help us in recovering attributes related to compliance, compressibility and deformability. These curves are actually analogous to load-sinkage curves that recover soil properties. This  $ep$  could thus be useful in measuring soil properties and its results could be interpreted to examine the behavior of soils. However, the precise basis of such interpretations is still being investigated.

### 3.2.3 Surface Roughness

The lumped-parameter model of the last section is modified for the measurement of surface roughness as shown in Figure 4(a). The surface roughness generates the tangential friction force  $F_f$  at the interface of the wrist sensor and the surface (in our case, the interface is the foot). Now, the friction force,  $F_f$ , is the same as the contact force,  $F_c$ , therefore, using Equation (1):

$$\text{since, } F_f = F_c \quad (9)$$

$$F_f = k_w x_w \quad (10)$$

To measure the tangential force in order to obtain a measure of the surface roughness, therefore, all the robot needs to do is measure the deformation,  $x_w$ , in the wrist sensor. In the implementation of the  $ep$  for surface roughness, the robot records the wrist deformations,  $x_w$ , in the direction opposite to the direction of lateral motion. This deformation is actually perpendicular to the deformation due to the normal force measured in the  $ep$  for hardness. In our experiments, the robot also adjusts, according to the hardness of the material, the normal force with which the foot is pressed against the surface and laterally moved along it.

The results of our  $ep$  for surface roughness are shown in Figure 4(b). The solid line denoting the normal force is really a plot of the deformations due to the normal force in the wrist. The flat part of that curve corresponding to a deformation of about -0.4mm signifies the constant normal force of about 2 lbs maintained during the sliding motion of the foot over the surface. The two curves above the x-axis are the plots of tangential deformations due to frictional forces encountered during the  $ep$ . The lower of the two curves shows the wrist deformation corresponding to the surface roughness of a smooth plate. There is a constant deformation (corresponding to  $x_w$  in Equation (10)) of about 0.2mm. The curve at the top of Figure 4(b) shows the wrist deformation corresponding to the surface roughness of

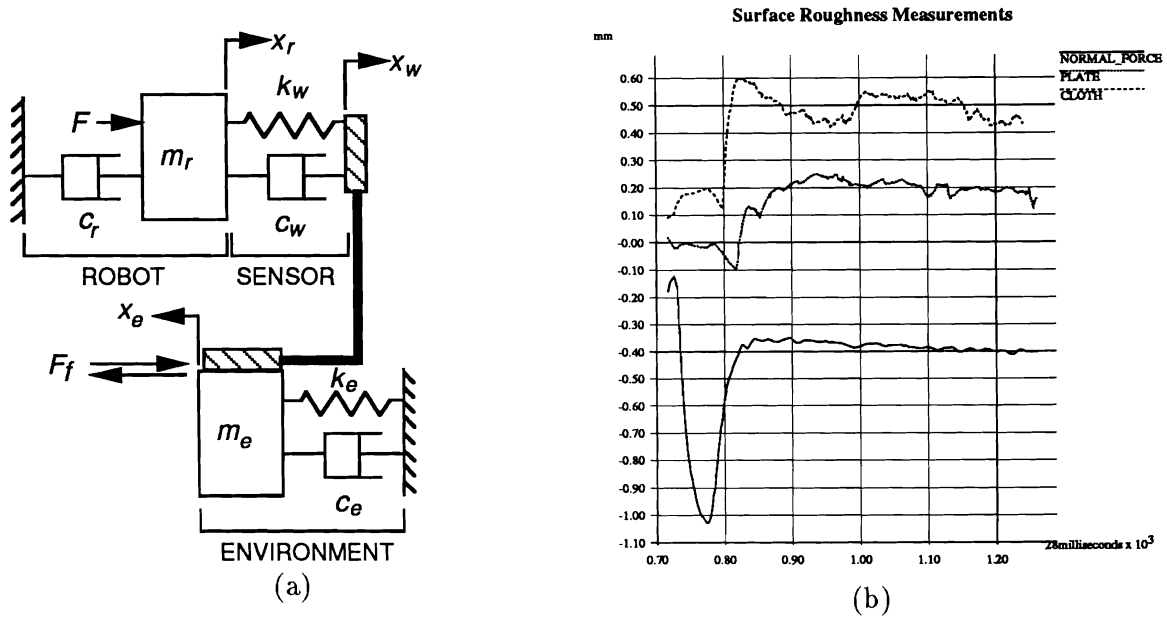


Figure 4: (a) Model of system for measurement of surface roughness (b) Plot of tangential and normal deformations (in mm) vs time (1 unit = 28 milliseconds) during surface roughness measurements

the plate covered by a rough cloth. In this case, the tangential forces are larger for the same normal force, due to the increased roughness of the surface, and as a result, the deformation,  $x_w$ , is larger, about 0.5mm. We have chosen an example where the material hardness is constant but the surfaces have different roughness properties. This shows conclusively that the robot is able to distinguish between surfaces of different roughness.

## 4 Conclusion

The ability to measure and sense the variation in the mechanical properties of different soil surfaces is indispensable to mobility of robots in agricultural environments. To ensure that a robot does not slip and fall or sink and get stuck when standing or walking on a surface composed of soil or sand, the robot needs to measure the characteristic properties of the surface and continuously or periodically apply this information to adjust the forces it exerts on the surface during standing or walking.

With this in mind, we have succeeded in designing and implementing *ep*'s to recover the penetrability, hardness and surface roughness characteristics of a surface. The immediate goal is to also measure the compliance, deformability, compressibility and compressive strength and apply the information to predict the stability of surfaces to a standing or walking robot. Ultimately, we would also like to account for variations in the geometry of the

surface and, for example, also predict the stability of surfaces that are composed of rocks or pebbles.

## 5 Acknowledgements

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## References

- [1] M. Bekker, *Introduction to Terrain-Vehicle System*. Ann Arbor, Michigan: University of Michigan Press, 1969.
- [2] *The International Journal of Robotics Research*. MIT Press, 55 Hayward Street, Cambridge, MA 02142, Volume 9, Number 2, April 1990. Special Issue on Legged Locomotion.
- [3] R. Bajcsy and P. Sinha, "Exploration of Surfaces for Robot Mobility," in *Proceedings of the Fourth International Conference on CAD, CAM, Robotics and Factories of the Future*, (New Delhi, India), Tata McGraw-Hill, December 1989.
- [4] P. Sinha, R. Bajcsy, and R. Paul, "How Does a Robot Know Where to Step ? Measuring the Hardness and Roughness of Surfaces," in *Proceedings of the IEEE International Workshop on Intelligent Robots and Systems '90*, (Ibaraki, Japan), July 1990. To be published.
- [5] J. Bowles, *Engineering Properties of Soils and their Measurement*. McGraw-Hill Book Company, 1970.
- [6] M. Bolton, *A Guide to Soil Mechanics*, ch. 2, pp. 22–23. John Wiley & Sons, 1979.
- [7] E. Petty, *Hardness Testing*, ch. 10, pp. 157–222. Vol. V Part 2 of *Techniques of Metals Research*, John Wiley & Sons, 1971.
- [8] R. Bajcsy, "What can we learn from One Finger Experiments ?," Tech. Rep., Grasp Laboratory, Department of Computer and Information Science, University of Pennsylvania, Philadelphia, PA 19104, August 1983.

- [9] Y. Xu, R. Paul, and P. Corke, "Compliant Wrist Design for Hybrid Position/Force Control," in *Proceedings of First International Symposium of Experimental Robotics*, (Montreal, Canada), 1989.