

**How Does A Robot Know Where To Step?
Measure The Hardness and Roughness
Of Surfaces**

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HOW DOES A ROBOT KNOW WHERE TO STEP ?
MEASURING THE HARDNESS AND ROUGHNESS OF
SURFACES ¹

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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 stand and walk stably in an environment that is unknown and unconstrained. The laboratory setup involves a compliant wrist with six degrees of freedom, mounted on a robot arm, and a prototype foot mounted on the wrist. We have successfully designed and implemented *exploratory procedures* (*ep*'s) to recover penetrability, material hardness and frictional characteristics by exploring the surface.

1. INTRODUCTION

With the increase in applications of robots to underwater, mine and space exploration, we need robots that are able to explore and adapt to an unconstrained and unknown environment. In most traditional Robotics applications, it is assumed that material properties, the geometry, and conditions of the environment, are known *a priori* or are controllable. 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 the successful execution of specified tasks.

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. In general, this investigation will be formidable, hence, we shall limit 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, or a probe, when the robot is standing 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. If such a system can be successfully built, then the applications can be wide-ranging, and of particular relevance to locomotion and manipulation. We are particularly interested in investigating the behavior of soils, sands and recovering the properties that determine the stability of such material surfaces to a moving robot.

In order to decide if a surface is stable enough for a robot to stand or walk on, we need to determine certain relevant mechanical properties of the material that forms the surface. The goal of this research then, is to design and implement a system that will explore a surface and recover the relevant mechanical properties from it. The measured properties can then be applied to predict the stability of surfaces for standing and walking.

2. STRUCTURE OF THE ENVIRONMENT

We first need to determine which mechanical properties are particularly relevant for our research, given the nature of the system that is available to us for our experiments, and the fact that we are ultimately interested in examining at the surface behavior under different loading conditions that are created particularly during robot locomotion. This turns out to be a classical problem of system identification and parameter estimation. With some help from available literature on the subject [1], we decided that prior to building this system, we would like to establish some kind of model for the environment in which we expect this system to function. With the idea of selecting an environment model based on

physical knowledge, we examined different classes of commonly encountered materials and some attributes that seemed salient to these materials. The results of these investigations have been reported in [2].

To describe this initial investigation in brief, we looked at work done by material scientists, metallurgists, mineralogists, geologists and soil engineers to identify some of the material attributes that they use to characterize materials and to examine their behavior. Our list of the commonly encountered materials included metals, glass, ceramics, rubber, polymers, wood, rocks, concrete, gravel, pebbles, soil, sand and viscous mixtures like mud and water. Some of the characteristic attributes that we could identify were penetrability, deformability, hardness, brittleness, compressibility, compressive strength, surface roughness, thermal conductivity, electrical conductivity, magnetic permeability, optical properties and viscosity. Given the limitations of our available hardware we chose to model our environment on just penetrability, deformability, hardness, compressibility, compressive strength, and surface roughness. These were the only properties from the original list that we could conceivably recover using the experimental setup in the laboratory.

Having selected a model for our environment, the next step was to choose the structure of our environment guided by the type of applications we are interested in. The structure will determine which parameters of this environment need to be estimated by our system so that we can successfully employ it to achieve our specific goals. As mentioned earlier, we are specifically interested in the ability of the surface to support a standing or walking robot and with this objective in mind, it was decided that that we would restrict our research to certain attributes that are more meaningful to our application than others. However, it turned out that all the parameters that we had chosen to model our environment seemed important to define its structure for our applications. Intuitively, this seems to make sense, and even from a review of work in soil mechanics [3, 4, 5], all these properties seemed important as far as examining the behavior of soils and sand is concerned.

An interesting observation needs to be made here. All the attributes we have chosen have a common character as far as human perception is concerned. None of the attributes can really be extracted from an unfamiliar surface by just looking at it, that is, on its own, our vision system fails completely to give us an idea of properties like hardness, deformability and others we have chosen, unless additional information is provided by actually exploring the surface with our hands or feet. In fact, all of these attributes are recovered very reliably when the surface is explored using hands, and it was this observation that led us to look at research done in the area of Haptic exploration by some prominent psychologists. It was a review of this very relevant piece of work that brought forth the concept of exploratory

procedures (*ep*'s) that we discuss in the following section.

The only basic assumption that we are making about the environment is that the surface is much larger than the robot and is at least locally planar so that there is space to move around. The planarity assumption is relative to the size of the robot. We also do not consider the problem of obstacles.

3. EXPLORATORY PROCEDURES

The term “exploratory procedures” has been used liberally throughout this paper. We feel that under the paradigm of exploratory robotics the concept of exploratory procedures (*ep*'s) provides a solid framework for exploration and recovery of attributes. The concept owes itself to the work in the area of Haptic exploration by Lederman and Klatzky [6, 7]. We were prompted to examine their investigations due to the remarkable likeness of our problem to what we do as human beings, that is distinguish between different materials based on their material properties. Klatzky and Lederman have shown conclusively that properties like hardness and surface roughness are really best encoded in the perceptual system using manipulation of the objects by hand. Also hand movements during the exploration of objects can be classified as exploratory procedures (*ep*'s) - each *ep* extracting a particular object attribute.

The motivation behind introducing the concept of *ep*'s in this research is explained in more detail in [2]. It should suffice to say here that from a review of most available testing methods from scientific and engineering fields older than robotics, most methods seemed completely unsuitable for robotics applications. It became clear that we needed to design our own *ep*'s to be able to recover the attributes we are interested in. Also, it seemed that we could learn a lot from the Haptic *ep*'s described in [6, 7] because as mentioned earlier, the attributes we are measuring here are the same as the ones being recovered by the hand, and the *ep*'s seemed easier to model compared to classical methods used in the testing of materials.

The whole concept of exploratory procedures and their relation to surface attributes is really the focus of our own investigation. The objective being to design procedures that will specifically attempt to recover the attributes that we have chosen to define the structure of our environment.

4. SYSTEM SETUP

Aside from the environment model, it is really important for us to describe our system of sensors and their set up, before we design our *ep*'s. In fact, the design of the *ep*'s depends

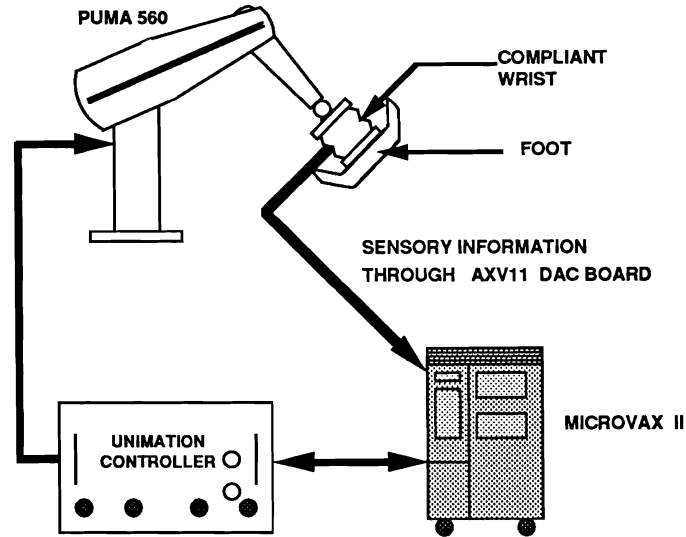


Figure 1: System Setup

on the nature of the sensors and the tools available, in addition to being by their very nature linked to the attributes of our interest.

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 [8, 9]. This device is mounted on to a PUMA 560 robot arm and has a fixture that allows a probe (in our case, 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 makes it possible to actively control position and force during motion or contact. 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 [8, 9].

One end of the compliant wrist is mounted on the PUMA 560 arm and on the other end our prototype foot has been mounted. 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 just a well-machined metal surface. The dimensions of the foot are roughly 2.5in x 5in x .25in.

It is important to evaluate the information that is available to the robot from the system. The forces and torques that the wrist is experiencing in terms of the deformations in the compliant mechanism are known. The three translational and the three rotational deformations in the wrist are being constantly measured and can be translated into force and torque measurements since the effective stiffnesses in each direction (degree of freedom) is also known. The end point trajectory of the PUMA 560 arm (the wrist is mounted on the end point of the arm) is available, and that is being controlled based on the deformation information received from the wrist sensors.

5. ATTRIBUTES AND THEIR MEASUREMENT

A complete evaluation of the object attributes that seem to be salient with respect to Haptic exploration, as we know it, and robotic exploration, as we have envisioned it, is given in [2]. 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.

We have tried to keep the *ep*'s, for recovering the attributes mentioned above, as simple as possible. Most classical methods rely on measurements made from specimens, however, we would like to design our *ep*'s such that they can be executed directly on the surface. While on the issue of measurement, it is important to realize that at this point we are not interested in precise measurements of the attributes. In fact, all we are attempting to do is to distinguish between surfaces of different materials by measuring some of the attributes that we have chosen to define our structure. While precisely these characteristic attributes make it possible to make the distinction between different surfaces and materials, accurate measurements are not needed until we start using the recovered information to simulate standing or walking on a surface with unknown material properties.

Therefore, at this point we have not attempted to match our results to any scale. The hardness measurements could be compared to a standard scale of hardness measurements, like the Rockwell scale. Similarly, the surface roughness could be equated to the Coulomb friction of surfaces. While it is clear from the results shown here that such a comparison is indeed possible, at this point in our research we have not attempted to quantify our measurements in terms of the prevalent standards.

The plots shown in the subsequent sections all have deformations plotted against time. However, these have been treated as force versus time plots as we know the stiffness of the wrist and the deformations are directly proportional to the forces.

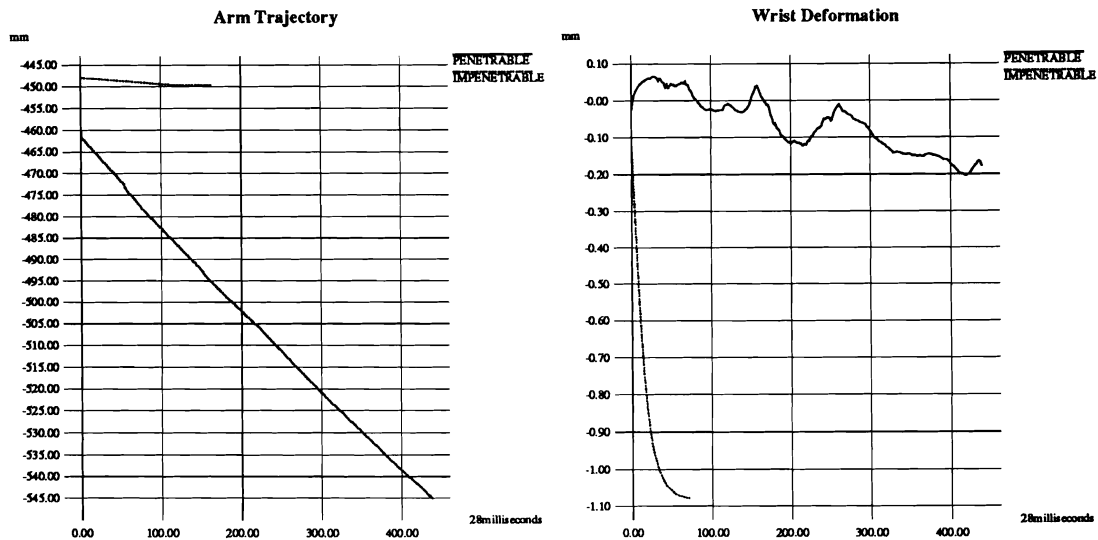


Figure 2: Measurement of Penetrability

5.1 Penetrability

Penetrability is a relatively simple attribute to measure - all we are interested in is whether the surface is penetrable or not. In fact, this is a good attribute to recover for a primary level of classification and makes it possible for the robot to choose which other *ep*'s need to be employed. For example, once it is known that a surface is penetrable it does not make much sense to get a measure of

its hardness - under the present scheme and in general, it is not possible to get a measure of hardness if surfaces are penetrable.

The *ep* is analogous to the penetration tests that are used to examine soil properties. In fact, for humans, the *ep* to determine if a surface is penetrable or not is to stick a finger into the surface. In our case, however, the probe is not sharp and is, in fact, a flat surface. Therefore, materials like soil and sand, which would be termed penetrable, are *not* really penetrable and but are actually just *deformable* (actually compressible, as is explained later). While it would not be of interest to measure hardness of such materials, it is certainly of interest to measure their compliance and compressive properties. However, that is the subject of future research and is not discussed here.

This *ep* involves pressing down on the surface till a certain normal force is experienced or till the arm has moved too far down. How hard to press and how far to move down is at presently decided in a heuristic manner. From the safety point of view and with the materials we have examined in the laboratory, we have restricted the maximum force to be

6 lbs and the maximum distance moved by the arm to 100 mm. If we find by monitoring the distance moved down by the arm and the amount of deformation in the wrist that the wrist is experiencing negligible forces (less than 0.5 lbs) compared to the large distance moved down by the arm, we classify the material as penetrable.

The 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 even after the arm moves down the allowed 10 mm. On the other hand, for the impenetrable case the arm moves down a very short distance and most of the downward motion shows up as deformation in the wrist.

This experiment will fail for materials like water (dilute mixtures), or fresh snow (very powdery), because it assumes that the wrist is able to sense when the surface of the material is first encountered. However, while the wrist is compliant, it is also too stiff to actually sense very small changes in forces. This problem is a serious one, perhaps, but can be easily solved if we have some knowledge of where the surface lies. Most robotic systems that are built for locomotion have laser range scanners or sonar detectors that are able to give an approximate idea of the location of the surface. Our own system can also be made more sensitive by mounting a small sensor on the underside of the foot, just to determine when contact is made.

To show the limitations of our experiment we have used a fairly extreme example. The device was in fact able to successfully sense that a surface of a pile of scrap paper was indeed penetrable. It successfully sensed the first encounter with the surface and then determined that it was penetrable.

5.2 Hardness

Hardness can be interpreted in a number of ways [2, 10]. One interpretation is that it is the resistance (measure of deformation) to a *load*. The other view can be that it is the resistance to *permanent deformation*. For the moment, however, we will only concern ourselves with the measure of resistance to load.

A viable way to measure hardness is to measure the deformation with respect to increasing pressure [11]. The basic idea is to place the probe against the material surface and then move it into the surface with small increments. Force readings are taken after each movement. Plots of the force versus the deflection obviously show that the force increases with increased deflection. But more importantly, the hardness of the material can be characterized by the slope of the linear portion of the curve. The larger the slope is the harder the material is. This is how the *ep* for hardness measurements is designed.

In our system, the *ep* for hardness involves moving down the arm such that the foot is

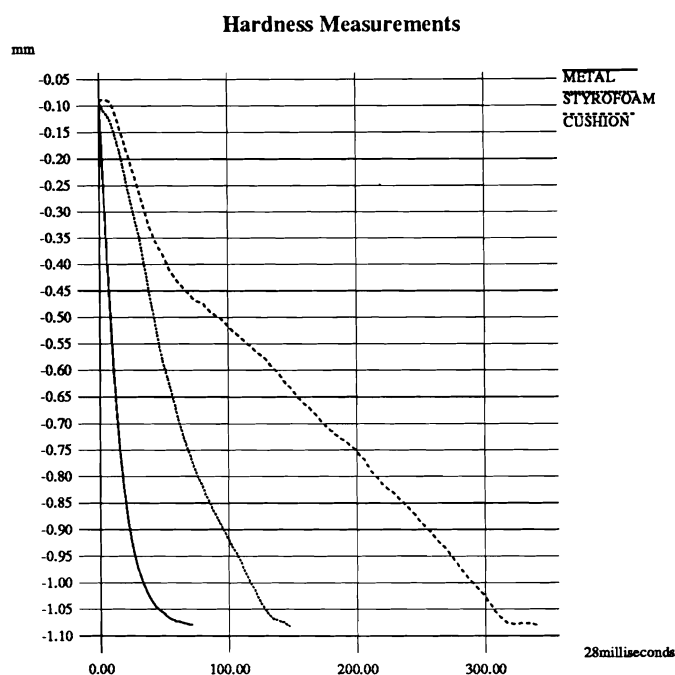


Figure 3: Measurement of Hardness

pressed into the surface at a constant rate till the normal force experienced by the wrist is 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. The normal force history of the wrist is examined from the point the ep starts till it ends when the wrist is experiencing a normal force of about 6 lbs.

The larger the slope of the normal force versus time curve, the harder is the material. Once again, at this stage in our research, we are not really distinguishing between the linear and nonlinear parts of the curve. That will become important when we start examining the materials for deformability and compressibility. The stiffness of the wrist device has been experimentally evaluated to be constant up to a force of about 13 lbs, so the variation in stiffness due to increasing forces is not a concern.

The results from the ep for hardness measurements is shown in Figure 3. The slope of the deformation versus time plot is clearly the greatest for the metal surface. The styrofoam surface is less hard, however, the curve is still linear. In the case of the softer cushion, while the slope is clearly the least, the curve does not stay linear and it is this property we want to later exploit in recovering attributes related to compressibility and deformability.

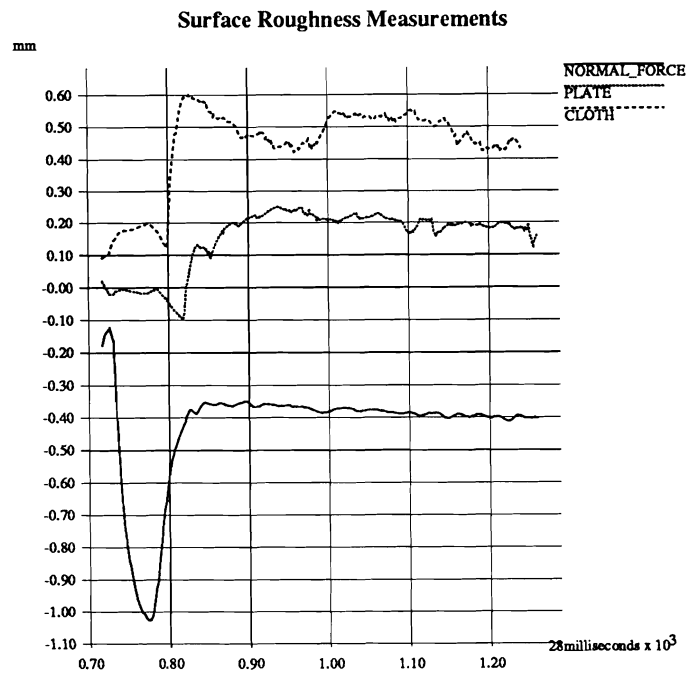


Figure 4: Surface Roughness Measurements

5.3 Surface Roughness

The roughness of the material surfaces will probably vary from very smooth glasslike surfaces to very rough and fragmented rocky surfaces. In the *ep* for roughness, our probe must touch the surface and move relative to the surface as well. As far as our own

fingers are concerned, the surface roughness is extracted by the “lateral motion” *ep* (as postulated by Lederman and Klatzky [6, 7]), a quick rubbing movement that does not require an extended sample surface and can be performed well within the interior of the surface.

The *ep* that is employed in our experiments measures the amount of tangential force generated when the foot is pressed against the surface with a specified force, and then moved along the surface laterally, maintaining the specified force. This is very similar to the classical methods of measuring the coefficient of friction between the two surfaces. It is easy to maintain the specified force, even if the surface is not totally planar, since the hybrid control algorithm adjusts the trajectory of the arm according to the changes in surface geometry.

One of the problems that the system had with this *ep* was when the foot (has hard and smooth surface) was pressed against a hard and very smooth surface. The measurements of

the tangential deformations in the wrist tended to be just sensor noise, when the force with which the foot was pressed against the surface was small. So the foot had to be pressed harder against the surface to get meaningful data on the surface roughness (really a measure of the friction coefficient). While this may not make sense intuitively, it can be explained by the fact that the sensor is not sensitive enough to very small tangential deflections on account of its stiffness. This is analogous to the problem of detecting contact with surfaces like water, which was mentioned above, and is really an example of an extreme case. And the problem can really be solved by just pressing down harder on the surface if meaningful data is not obtained.

In our experiments, the robot adjusts the amount of force with which the foot is pressed against the surface and moved along it, according to the hardness of the material. Since this measurement has already been made prior to employing the *ep* for surface roughness, it is possible to use the available information. This method seems to work well for the materials that we have experimented with, but it is obvious that given the sensitivity of our sensor, the force specified will also depend on the roughness of the surface, if the robot is intent on measuring its roughness even when it is very smooth. At present, the robot presses down with a normal force of about 6 lbs if the material is found to be very hard and a force of about 2 lbs if the material is very soft. For materials that lie in between the very hard and very soft range, linear interpolation is done to decide how hard to press when moving the foot along the surface.

The results of our *ep* for surface roughness are shown in Figure 4. We have chosen an example where the material hardness is constant but the surfaces have different roughness properties. The surface coated with cloth is rougher and is easily distinguished from the smoother plated surface as can be seen from the plot (the generated tangential forces have a larger magnitude in case of the cloth surface). The normal force exerted while the foot slides over the surface is the same in both experiments (about 3 lbs, indicated by the level part of the normal force curve) and we are still able to get different tangential forces, thus allowing us to distinguish between surfaces of different roughness.

5.4 Implementation of *ep*'s

The *ep*'s postulated above, and those planned, have been implemented, or will be implemented, such that we are able to differentiate between different types of surfaces. They are organized in a hierarchical/parallel fashion in the sense that while they are executed in some order, *ep*'s that are similar are employed at the same time. Also, the information collected from already executed *ep*'s is used to decide which *ep*'s should be executed next and also determine the parameters that may be required for subsequent *ep*'s.

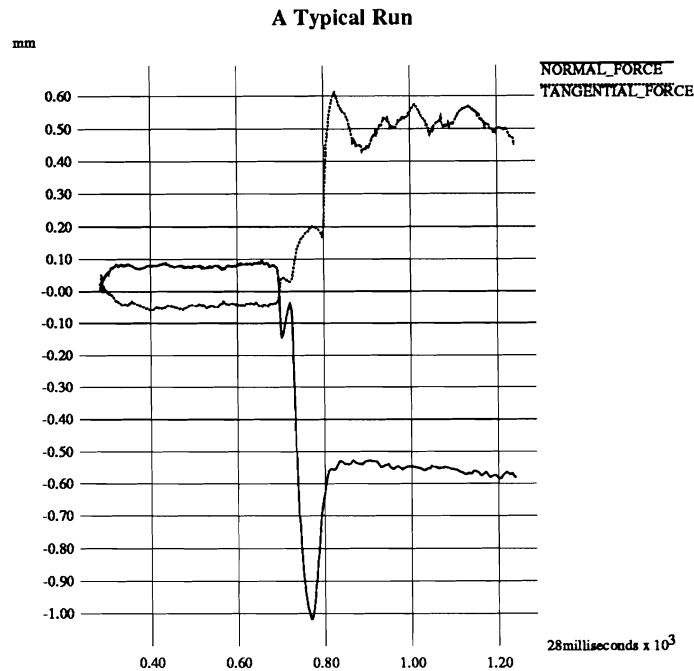


Figure 5: A Typical Run

Presently, the scheme is organized as follows. First, the robot checks for contact with the surface. Then the foot is slowly pressed into the surface till a force of 6 lbs is achieved (monitoring the arm trajectory at the same time in case it is a penetrable surface). It can be easily seen now that if the surface is indeed not penetrable,

then the ep for penetrability also becomes the ep for hardness. The slope of the deformation history in the wrist gives a measure of the hardness, which provides the force information for carrying out the ep for surface roughness, as described above. The arm then moves the foot up or down, depending on how hard it must press to recover the surface roughness meaningfully, and then slides the foot along the surface for a short distance to record the tangential forces on the foot.

Figure 5 shows a typical sample run of our robot as it executes the ep 's mentioned above. Let us follow the solid line that corresponds to the normal force, to understand the process. The point where the solid line crosses over the x-axis is where the foot first contacts the surface. The foot actually presses into the surface a little bit before the controller pulls it back to zero out the forces. This corresponds to the first upward spike on the plot. After this the foot slowly presses down into the surface till a force corresponding to 6 lbs is registered in the wrist. During this period, both the ep 's for penetrability and hardness are being

employed. After the hardness measurements were made, the robot decided to press down on the surface with a force of 3 lbs when employing the next *ep* to recover surface roughness. As can be seen on the plot, the robot pulls up the arm till the contact force decreases to about 3 lbs. The flat part of the curve signifies the constant normal force maintained during the *ep* for surface roughness. Corresponding to the start of the flat part of the curve, which signals the beginning of the sliding of the foot against the surface, there is a jump in the tangential force measurements that gives us a measure of the surface roughness.

6. FUTURE RESEARCH

The immediate plan is to implement the *ep*'s to recover deformability, compressibility and compressive strength. We distinguish deformability from compressibility by classifying compressible materials as those which undergo permanent deformation under the influence of forces (like sand, soil), while deformable materials deform when under the influence of forces but revert to their original shape when the forces are removed.

Of course, we would like to be able to make some of the features of our *ep*'s less heuristic and more robust. We hope to be able to achieve that through work done in older scientific fields in measuring the attributes of our interest, as well as, through extensive experimentation with most commonly encountered materials.

We would also like to simulate standing and walking experiments on different surfaces once we have the ability to measure all these properties. This will need further analysis into the modeling of surface behavior under the influence of forces, particularly analysis of the behavior of deformable surfaces like soil and sand. Such an analysis may further show that our model of the environment is inadequate and that certain other attributes like plastic properties or moisture content need to be measured. The creation of a model of surface behavior that can predict stability of the surface based on the attributes that we are currently interested in will be the major part of future research.

7. CONCLUSIONS

We have succeeded in designing and implementing exploratory procedures to recover certain mechanical properties from a physical surface. We have a system that can successfully predict the penetrability, hardness and surface roughness characteristics of a surface by executing some very simple procedures. The ultimate goal is to also measure the deformability, compressibility and compressive strength and apply the information to predict the stability of surfaces to a standing or walking robot.

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