July 1990

Exploration of Surfaces for Robot Mobility

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University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-90-42.

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Abstract

This paper presents an overview of ongoing research in surface exploration at the GRASP Lab. The objective of the work presented here is to design a system that will explore an environment that is unknown and unconstrained and will enable a robot to adapt to varying surroundings. We are investigating the necessary components/modules that must be embedded into a robot for it to have exploratory capabilities. We have designed and are implementing *exploratory procedures (ep's*) to recover the *mechanical* properties from a surface given minimal *a priori* information so that a robot or a vehicle can decide whether to and how to move on this surface. The laboratory setup involves a compliant wrist with six degrees of freedom, mounted on a robot arm, and a laser range finder, mounted on another robot arm, as the primary sensors to detect the response of surfaces with varying mechanical properties.

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GRASP LAB 222

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ACKNOWLEDGEMENTS:
This work was in part supported by Navy Grant N0014-88-K-0630, Air Force Grants AFOSR 88-0244, AFOSR 88-22719, IRI 89-06770 and DuPont Corporation

Exploration of Surfaces for Robot Mobility [1]

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[1] Also in *Proceedings of the Fourth International Conference on CAD, CAM, Robotics and Factories of the Future*, (New Delhi, India), Tata McGraw-Hill, December 1989.

Abstract

This paper presents an overview of ongoing research in surface exploration at the GRASP Lab. The objective of the work presented here is to design a system that will explore an environment that is unknown and unconstrained and will enable a robot to adapt to varying surroundings. We are investigating the necessary components/modules that must be embedded into a robot for it to have exploratory capabilities. We have designed and are implementing *exploratory procedures* (*ep*'s) to recover the *mechanical* properties from a surface given minimal *a priori* information so that a robot or a vehicle can decide whether to and how to move on this surface. The laboratory setup involves a compliant wrist with six degrees of freedom, mounted on a robot arm, and a laser range finder, mounted on another robot arm, as the primary sensors to detect the response of surfaces with varying mechanical properties.

1 INTRODUCTION

Much of the work in Robotics until now has been conducted in the so called knowledge driven framework. The justification for this approach is the fact that in the industrial environment the material, its geometry, the environmental conditions and the task are quite constrained, known *a priori*, and well controllable. This is, however, not the case in many other situations such as applications of robots to underwater, mine and space exploration. What we need is a robot that is able to explore and adapt to an unconstrained and unknown environment. This is the motivation for the research on surface exploration.

In this paper, we wish to report the investigations of the necessary components and modules that must be embedded into a robot with exploratory capabilities. The complete investigation involves examining what sensors, exploratory procedures, data processing, data reduction and interpretation capabilities such a robot should have. In general, this investigation will be formidable, hence, we shall limit ourselves to the specific task of exploration of surface properties for mobility purposes.

In order to decide if a surface is stable enough for a robot to stand or walk on, we need to determine the *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 mechanical properties from it. We are certainly not looking for any geometric properties or the shape of the surface - obstacle avoidance is not an issue we are addressing. The proposed system can then be applied to predict the stability of surfaces for standing and walking. In fact, such a system would also be extremely useful for grasping and manipulation tasks.

2 STRUCTURE OF THE ENVIRONMENT

Given the nature of this research, system identification and parameter estimation become important issues [Eyk74]. Keeping that in mind, prior to building this system, we would like to establish some kind of model for the environment in which we expect this system or process 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 are summarized in Table 1. The word salient is used here in the context of the attribute being not only prominent and distinguishing but, in a sense, also being measurable by our proposed system. Therefore, a 'Yes' in the table means that the particular attribute exists, is measurable and could be considered a distinguishing characteristic for the class of materials in question. However, if the attribute is known to exist and is a distinguishing characteristic but one that will be impossible to measure given the conceived capabilities of the system we are trying to build, the entry in the Table 1 is a 'No'. This should explain some of the apparent inconsistencies and paradoxes that show up in the the table when interpreting its entries with some of the classical notions of the listed attributes in mind. For example, we do not

MATERIALS AND THEIR SALIENT ATTRIBUTES								
ATTRIBUTES	CLASSES OF MATERIALS							
	Metals	Rocks Concrete	Glass Ceramics	Rubber Polymers	Wood	Soil Sand	Pebbles Gravel	Viscous Mixtures
Penetrability	No	No	No	No	No	Yes	Yes	Yes
Deformability	No	No	No	Yes	No	Yes	Yes	Yes
Hardness	Yes	Yes	Yes	Yes	Yes	No	No	No
Brittleness	No	Yes	Yes	No	No	No	No	No
Compressibility	No	No	No	No	No	Yes	Yes	No
Compressive Strength	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Surface Roughness	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Thermal Conductivity	Yes	No	Yes	No	No	No	No	No
Electrical Conductivity	Yes	No	Yes	No	No	No	No	No
Magnetic Permeability	Yes	No	Yes	No	No	No	No	No
Optical Properties	Yes	No	Yes	No	No	No	No	No
Viscosity	No	No	No	No	No	Yes	Yes	Yes

Table 1: Common Materials and their Salient Attributes

really expect to measure the deformability of metals given that our robotic arm (a PUMA 560) is not "stiff" enough and that the arm cannot be realistically expected to exert the large forces that would be required to cause a measurable deformation on a metal surface. Hence, the entry 'No' for deformability in the metals column of Table 1. Another point of clarification is the notion of viscosity that is used here in a sense that is, perhaps, different from the classical one. It is obvious that the classes of materials in the first five columns are not viscous as they are implicitly assumed to be in the solid state. And while viscous mixtures like mud and liquids are by their very nature viscous, the viscosity of soil, sand, pebbles and gravel is, perhaps, not so obvious. However, we would like to consider them to be viscous, motivated by the notion of being able to measure the drag or resistance to motion of a probe that could be dragged through surfaces of such materials, much in the same way as we as humans wade through dry sand or loose soil with our feet partially or fully immersed.

Now that we have selected a model for our environment, the next step is 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. Therefore, from the list in Table 1, we chose penetrability, deformability, hardness, compressibility, compressive strength, surface roughness and viscosity as the attributes or parameters for evaluating our environment. This seemed to be a fair choice to make considering that as human beings these are some of the material attributes that we always tend to examine, aside from geometric properties, shape and colors. Also thermal, electrical, magnetic and optical properties would, perhaps, not be very relevant in determining whether a robot would be able to stand or walk on a surface.

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 and as stated earlier, we do not consider the problem of obstacles. Also, we shall not consider materials like vegetables, textile, grass, leaves etc.

3 EXPLORATORY PROCEDURES

There are scientific fields older than robotics that have investigated the measurements the above attributes for a variety of materials. Primarily, material scientists and also metallurgists, mineralogists, geologists, soil engineers have a host of methods and tests to measure physical and geometric properties. However, a review of available methods [McG76, Pet71, Bow70, Spe86, KBU76] shows that most of them involve working with samples and specially designed equipment that is not suitable for robotics applications. Some of these tests are even destructive and would involve breaking through the surface if we design exploratory procedures based on them. It is quite clear that while the initial design and calibration process may involve destructive testing, it would be impractical to have a system that would need to actually break or badly deform the material in the testing process. Nevertheless, the conventional methods cannot be discounted completely as they provide an insight into the actual physical measurement of certain mechanical properties - an adaptation of a classical testing procedure (the theoretical basis would remain the same) for a robotics application is one conceivable path to our goal.

Our problem bears a remarkable likeness and is indeed equivalent in many ways to what human beings do all the time, that is, distinguish between different materials. As mentioned earlier, while our vision systems do most of the spatial reasoning, when it comes down to getting an idea of the hardness, deformability and surface roughness of the material we do bring our hands and fingers to work. Our exploration using robot manipulators is very much the same, which makes work done by psychologists and psychophysicists quite relevant to our design process.

The work of Lederman and Klatzky [KLR87, LK87] seems of particular relevance. According to them, hand movements during the exploration of objects can be classified as "exploratory procedures"(*ep*'s) - each *ep* extracting a particular object attribute. These are procedures that the hand executes in trying to discriminate objects and their attributes. Some attempt has also been made to classify these procedures into categories that then relate to certain object attributes. Four such categories - lateral motion, pressure, contour following and enclosure are related to texture, hardness, shape and size, respectively. Lederman and Klatzky also come to the conclusion that hardness and surface roughness are really best encoded in the perceptual system using manipulation of the objects by hand. Hardness has been defined in several ways, for example, by the distance the finger penetrates a surface when applying a normal force (analogous to our concept of penetrability and compressibility), by the force required to break through a surface (brittleness), and the extent of recovery after deformation (deformability).

The whole concept of exploratory procedures and their relation to surface attributes would really be 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 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 [Xu89, XPC89]. This device is mounted on to a PUMA 560 robot arm and has a fixture that allows an end-effector or probe to be mounted on it. The passive compliance of the device allows the robot to correct positioning error and 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.

The other sensing mechanism that we use is a laser range-finder and camera system mounted on another PUMA 560 robot arm. The range finder can be used to scan a scene and get two and a half dimensional depth images that describe surface geometries fairly well for our purposes.

Eventually, this set up will also comprise of a model of the foot to be mounted on to the wrist to implement our application to mobility of robots. The idea is to have the foot model serve both as a device for walking as well as sensing, much the same way as the human foot. This model foot when placed on a surface will, through the sensing mechanism on the compliant wrist, be able to sense whether the surface is stable enough to support a certain weight. At the same time, the model foot will serve as the probe for the implementation of our *ep*'s and the data from the sensing mechanism will help us evaluate the attributes we are trying to recover. The bottom surface of the model foot will have a certain roughness to help employ the *ep* for recovering surface roughness, which will talk about in one of the subsequent sections.

5 ATTRIBUTES AND THEIR MEASUREMENT

In this section we will try to evaluate some 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. The choice of the attributes has already been made in Section 2 and in the subsequent sections we would like to define them further and postulate possible *ep*'s for their measurement.

We would like to keep the *ep*'s as simple as possible, however. 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 for our purpose.

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 us to choose which other *ep*'s need to be employed. For example, once we know 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. So what we have here is basically a classification between materials like metals, concrete, rock, wood, glass, rubber and polymers that are solid and impenetrable and materials like soil, sand, gravel and viscous mixtures that allow for sharp objects to penetrate them.

The *ep* is analogous to the penetration tests that are used to examine soil properties. A sharp probe is pressed against the material surface with a specified force and the amount of displacement is measured. Some use of the laser range finder has to be made to detect if the probe has actually penetrated the surface or is just deforming it.

5.2 HARDNESS

Hardness can be interpreted in a number of ways. 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.

Of the conventional testing methods the scratch hardness test appeared to be the most useful to us. While the modalities of adapting it to the robot manipulator could be worked out, one serious disadvantage it suffers from is that it is destructive in a sense. While that may not be a problem in some cases, it could very well be undesirable in other cases. This forced us to examine tests that could possibly avoid damage to the material.

Another viable way to measure hardness is to measure the deformation with respect to increasing pressure [Baj83]. The basic idea is to place the probe against the material surface and then move it into the surface with small increments. Pressure readings are taken after each movement, and then the direction of movement is reversed and readings taken. Plots of the pressure versus the deflection obviously show that the pressure 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.

The idea of relative hardness is a useful one, too. However, it is not very clear how we could exploit it to our advantage and avoid damage to the material. The concept is basically the same one underlying most conventional methods where a object that is harder will cause a deformation on a less hard object when forced against it. Our objective would be to differentiate between objects by measuring their hardness relative to each other.

5.3 DEFORMABILITY

A good measurement of deformability obviously involves the manipulation of the material surface such that the changes in the geometry or the surface can be observed. In most deformable materials the surface geometry changes on the application of a load, but then reverts to its original or close to its original state when the load is removed. Once again, the measurement of deformability can be coupled with the measurement of penetrability and hardness because those measurements also measure effects of load applied to a material surface. However, in the case of deformability, in addition to a measurement of force and position, an element of time becomes involved, too. Therefore, the *ep* to recover deformability requires the use of our laser range finder to detect whether the surface remains unchanged after the load has been applied and removed. In fact, if the surface has indeed changed, the the material is probably compressible.

5.4 COMPRESSIBILITY

This is the kind of characteristic that one would like to extract from materials that are like soil and sand. These are surfaces that offer greater resistance to load than penetrable surfaces, however, they are also not deformable. That is, these surfaces undergo some permanent deformation when a load is applied and they also offer varying resistance to the applied load as it is increased. Typically, the way in which the resistance varies also gives us an idea of the compressive strength of the surface which is an important parameter in determining the stability for standing or walking.

Once again, the *ep* is primarily the application of a load and the recording of the response from the surface. The laser range finder determines for us if the surface has deformed permanently or not, thus differentiating between deformable and compressible surfaces.

5.5 SURFACE ROUGHNESS

The roughness of the material surfaces will probably vary from very smooth glasslike surfaces to very rough and fragmented rocky surfaces. So we are really looking for a robust method to measure surface characteristics. The only help we might have is from information about the other material properties, some of which would have been surely measured before we start characterizing the roughness.

In the analysis of roughness, our probe must touch the surface and move relative to the surface as well. The character of this motion is something that is difficult to predict and will probably be only determined once we have carried out some amount of experimentation with our model foot. Since we have not started using the probe yet, all that can be said now is that, as far as our own fingers are concerned, the surface roughness is extracted by the "lateral motion" exploratory procedure (as postulated by Lederman and Klatzky [KLR87, LK87]), 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 we envision here will have measure the amount of tangential force required to cause slip between two surfaces when they are pressed together with a certain force. This is very similar to the classical methods of measuring the coefficient of friction between the two surfaces. In our case, the measurement will depend on the kind of surface we choose to put on the model foot and the measurements will be again made by the wrist sensing device.

Another way to measure the surface properties would be to examine some of the characteristics of the motion of a probe, under the influence of forces, over the material surface. For example, the vibration of a probe that is dragged along a surface under a certain load and at a certain orientation could tell us something about the surface roughness.

5.6 VISCOSITY

As mentioned earlier, the classical notion of viscosity in fluids is extended to soil, sand and essentially all granular materials. This really corresponds to the conventional notion of permeability of the soil and sand. So we are essentially interested in measuring the resistance to the easy movement of a probe through the material. In this case, the *ep* would simply mean dragging the probe through the material surface by a certain force and measuring the resistance offered by the material.

6 IMPLEMENTATION OF *EP*'s

The *ep*'s postulated above have been implemented or are being 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 a current *ep* is used to update information collected from already executed *ep*'s and to decide which *ep*'s should be executed next or executed again.

Presently, the scheme is organized as follows. First, we check for penetrability and the same time check if the surface is deformable or compressible. If the surface is not penetrable, deformable or compressible, then we try to get a measure for the hardness of the surface. Otherwise, we investigate how deformable or compressible a surface is and get a measure for its compressive strength in the latter case. The *ep*'s for surface roughness and viscosity have not been implemented yet and work is being done to implement them and further refine the available *ep*'s.

7 CONCLUSIONS

We have succeeded in designing exploratory procedures to recover certain chosen mechanical properties from a physical surface. The next step is to create a mathematical model for our environment that will help in predicting the stability to standing and walking using the parameters estimated by the exploratory procedures. In the final outcome we would like to have a model of a foot that would sense the stability of the surface as well as its properties.

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