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Abstract

This paper presents some results of an ongoing research project in the GRASP Lab in the area of active exploration and perception for the legged locomotion of robots. We propose an active perceptual scheme that is based on the ability of the robot to extract material properties from a surface during locomotion. This ability is provided to the robotic system through a compliant sensing device which is used to monitor the response of the surface when exploratory procedures are executed during the stepping and walking motions of the leg. Such a system will actively perceive changes in the surface properties and prevent the robot from slipping, falling, or sinking during locomotion. The paper describes the proposed perceptual scheme, the system set-up, and the implementation of the exploratory procedures.

1 Introduction

Robotic systems are being increasingly applied to the areas of agriculture, underwater, mine and space exploration, and hazardous environments. In such applications, where the environment is quite unstructured, there is a need to equip robots with capabilities such that robots can actively explore and adapt to the unconstrained environment. Active exploration and perception are invaluable for the autonomous operation of robots in unstructured environments.

Motivated by the areas of application mentioned above, 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 is that Bekker [1] has demonstrated the superior mobility of legged locomotion in comparison to wheeled or tracked locomotion. For robots to successfully traverse rugged terrain using legged locomotion, not only do robots need to constantly maintain structural stability but also, and perhaps more importantly, detect and adapt to changes in the terrain properties. In this paper, we will address the issue of exploration to extract material properties from a given surface for the specific purpose of aiding in and improving the quality of legged locomotion. While it is important to evaluate terrain properties prior to the start of locomotion, it is even more important to actively evaluate these properties during locomotion.

We propose that the legs of a robot be used not only for stepping and walking but also as probes to examine those properties of the surface that would contribute to the efficiency of locomotion, one way or another. In the words of Krotkov [2], "active and purposeful use of the legs makes every step an experiment". Much in the same way as humans walk on surfaces of different material properties,

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constantly evaluating the behavior of the terrain and making adjustments in the foot forces so that they do not slip, fall or sink, we propose a device that serves as a probe or foot for a robotic system and a methodology to actively identify the material parameters of the surfaces that the robot would encounter during locomotion.

1.1 Related Research

Much of the work in robotics until now has been conducted in the so called knowledge–driven framework. The justification for this approach is 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 approach has also been used in the design of most legged robots [3]. Vision systems have been traditionally used to identify suitable footholds for walking machines, but the information perceived through a vision system can hardly be considered adequate when a robot has to answer the question – "Is it safe to step on this surface ?" In rugged and unstructured environments, some mode of contact sensing has to be employed to answer such questions by evaluating properties like terrain bearing capacity, compliance, and traction etc.

Recognizing this, Bicchi et al. [4] instrumented a leg–angle–foot system and used it experimentally to assess the deformation of rubber blocks and to estimate coefficients of static friction. Concurrently with this work, Krotkov [2] has done some initial trials on measuring the terrain stiffness and surface friction using a single leg of the CMU Ambler. He also emphasizes the role of active perception of material properties in autonomous legged locomotion and recognizes walking as a means for both locomotion and exploration.

The next section describes the choice of attributes salient to the efficiency of legged locomotion and the exploratory procedures designed to recover these attributes. The proposed perceptual scheme is detailed in the subsequent section. The system set up used to implement this scheme is described in the next section. This is followed by a presentation of some results that show that our system has the ability to recover material properties during locomotion by successfully implementing the designed exploratory procedures.

2 Attributes and Exploratory Procedures

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 a detailed description of our investigations into the attributes of interest can be found in [5, 6]. Guided by the goals of our application, we chose to define the structure of our environment by the attributes of penetrability, compliance, compressibility, deformability and a measure of surface traction. This choice of attributes was supported by a review of work in soil mechanics [7, 8] 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, compliance, and surface traction (we certainly do not claim that this is a complete list). These attributes must be recovered by "exploratory procedures" (*ep*'s) that are built in to the mobile robotic system. By *ep* we mean a procedure that is salient to the recovery of a specific attribute of interest.

In the following sections we describe the relevance of each of the chosen attributes of interest to legged locomotion and also the design of the corresponding *ep*'s.

2.1 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 [7]. 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 is 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 compliance can then be implemented.

2.2 Compliance

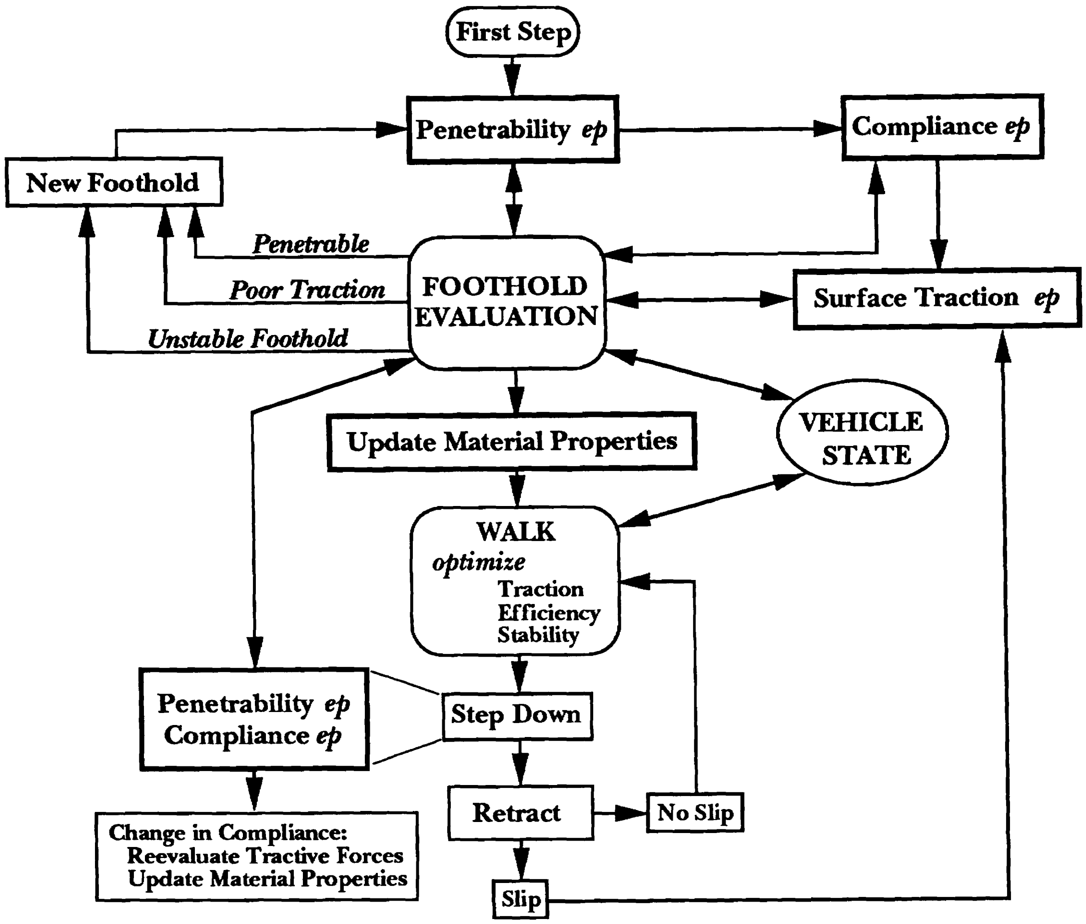
In measuring the attribute of compliance, we are highlighting the characteristic of an impenetrable surface that determines how the surface will behave when the foot exerts forces normal on it while standing or walking. From a knowledge of the compliance of a terrain the robot can avoid regions that are unsuitable for the support vertical foot-terrain interactions and it can also optimize its energy use in maintaining stability.

Compliance can be interpreted in a number of ways [5]. Our interpretation is that compliance is the resistance (measure of deformation) of a surface to a load. The basic concept of the *ep* for compliance is based on this interpretation. In the *ep* for 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 compliance which is proportional to the rate of deformation in the wrist (see Section 5.2 for detailed explanation). 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.

2.3 Surface Traction

The available surface traction 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 available surface traction of surfaces to determine the forces that a robot should exert while walking on it. The knowledge of the available traction 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 available traction will also determine the speed and efficiency of a walking robot.

The *ep* for surface traction 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



AN ACTIVE PERCEPTUAL SCHEME FOR LEGGED LOCOMOTION

Figure 1: Block Diagram of Proposed Perceptual Scheme

them forced into contact. The measurement of tangential forces generated when this *ep* is carried out will give us a measure of the available surface traction.

3 Proposed Perceptual Scheme

The proposed perceptual scheme is summarized in the block diagram in Figure 1. The blocks and the connections are described in some detail here. It is important to bear in mind that this scheme takes advantage of the fact that the exploratory procedures can be executed as part of the normal motion of the leg during locomotion.

3.1 Foothold Evaluation Module

All decisions regarding the quality of a foothold are made within this module. This module is constantly monitoring the information extracted through the execution of the various *ep*'s and deciding whether the robot should continue to use the particular foothold or try to find a new one. The module will have available to it information such as the allowable minimum and maximum forces for each foot, the range of prescribed traction forces, the maximum distance that a foot can be allowed to sink into the surface etc. For taking the first step this information will be adequate but as the robot starts moving the foothold evaluation module will also have information available from the vehicle state module to help make decisions about the foothold. This module is described below.

3.2 Vehicle State Module

Within this module, information is kept regarding the state of the whole walking robot system. Of particular importance to us is the state of the other legs of the system. There might be a situation where because of an slightly unsuitable new foothold some weight of the system might need to be transferred to a leg that is already stably placed. A decision on how to transfer the weight will depend on the state of all the legs, both those on and off the ground. The vehicle state module is meant to provide such information as and when needed. This information is also made available to the walk module which is described next.

3.3 Walk Module

The walk module actually controls the walking motion and the foot forces that the robot exerts on the surface. During the walking motion the basic considerations are to optimize the available traction, efficiency, and stability. Here the stability referred to is the stability of the foot and not the overall structure. Once again the walk module is constantly in touch with the vehicle state module.

3.4 Overall Scheme

When taking its first step the robot encounters the surface and immediately the *ep* for penetrability starts being executed. If the foothold evaluation module deems that the surface is penetrable and the foot would sink through it making the robot unstable, a new foothold is sought. If the surface is impenetrable, the *ep* for compliance begins. If the surface is deemed unstable or too compliant by the foothold evaluation module, then a new foothold is sought. Otherwise, the *ep* for surface traction is executed. If the surface is found to be too slippery and has poor traction, a new foothold is searched for, else the material properties are stored and the walking process begins.

The main features of the walk module have already been mentioned. The walk module is executed using the information available about the material properties, the vehicle state and requirements of the locomotion that robot is supposed to carry out. There are two parts to the execution of this module. The first part is the stepping down motion. Taking advantage of this motion, both the *ep*'s for penetrability and compliance are executed simultaneously. Once again the foothold evaluation is taking place as the foot interacts with the ground. If the surface now turns out to be unexpectedly penetrable or compliant, a new foothold is sought. Sometimes a change in compliance would not really need a change in the foothold but a change in the foot forces and reevaluation of the tractive forces. In such a situation the material properties also need to be updated. This first part of the walk module is intended to prevent the robot from sinking and getting stuck in a surface in addition to optimizing the vertical foot–terrain interactions.

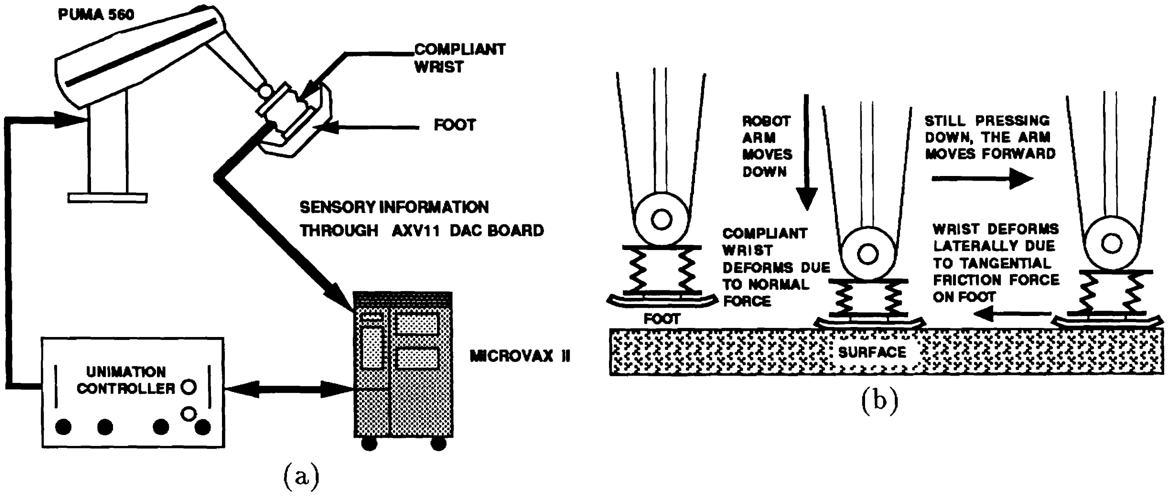


Figure 2: (a) System Setup (b) A Typical Run

In the second part of the walk module the foot that is now placed on the ground with a certain normal force retracts in the direction opposite to that of the required motion to propel the robot forward. If the foot slips during this motion, retraction is quickly stopped and the foothold is evaluated again and a new foothold sought depending on whether the foothold can provide the required traction to the foot. If the foot does not slip, then the cycle carries on and locomotion is accomplished. This part of the walk module prevents the robot from slipping and falling during walking. Also, it makes it possible for the robot to change its foot forces when it encounters a terrain of unexpected traction characteristics and optimize its energy use and stability.

4 System Setup

The system setup is shown in Figure 2(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]) shown in Figure 3. This device is mounted on to a PUMA 560 robotic 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. The PUMA arm–wrist–foot system simulates the leg–ankle–foot system for our research. In addition, a piezoelectric accelerometer is also mounted in the foot in order to detect slip (prompted by the use of accelerometers for a similar purpose by Howe and Cutkosky [10]) between the foot and the terrain.

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,

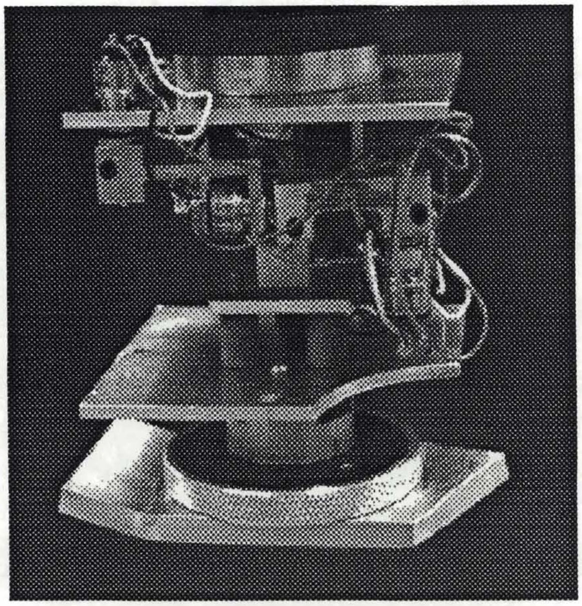


Figure 3: Compliant Wrist Sensor with Foot

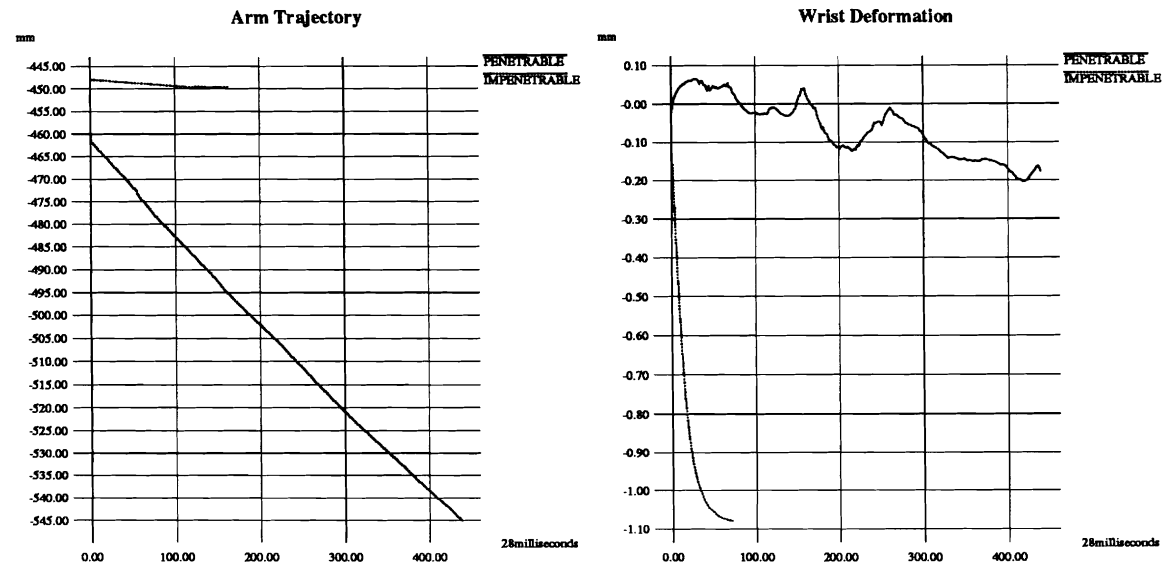
it allows the robot to exert forces specified up to a limit as well as to maintain certain contact forces while the arm is in motion. Further details on the wrist and the control scheme can be found in [11].

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 pushes down on the surface to execute the *ep*'s for penetrability and compliance (see Figure 2(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 and compliance. The *ep* for evaluating surface traction 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 forcing the foot to slide 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 available surface traction. In the actual implementation of this *ep* during walking, the foot will not really slide on the surface but retract just enough to propel the robot forward.

5 Implementation of *ep*'s

The *ep*'s have been implemented using the setup described above. These results demonstrate our system's ability to recover a measure of penetrability, compliance, and surface traction from surfaces. These results are described and interpreted in greater detail in [12].



(a) (b)

Figure 4: 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)

5.1 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. 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 4. 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 4(b)), even after the arm moves down the allowed 80mm (solid line in Figure 4(a)). On the other hand, for the impenetrable case, the arm moves down a very short distance (dotted line in Figure 4(a)) and most of the downward motion shows up as deformation in the wrist (dotted line in Figure 4(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.

5.2 Compliance

Our system can be modeled as a simple lumped-parameter dynamic model shown in Figure 5(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

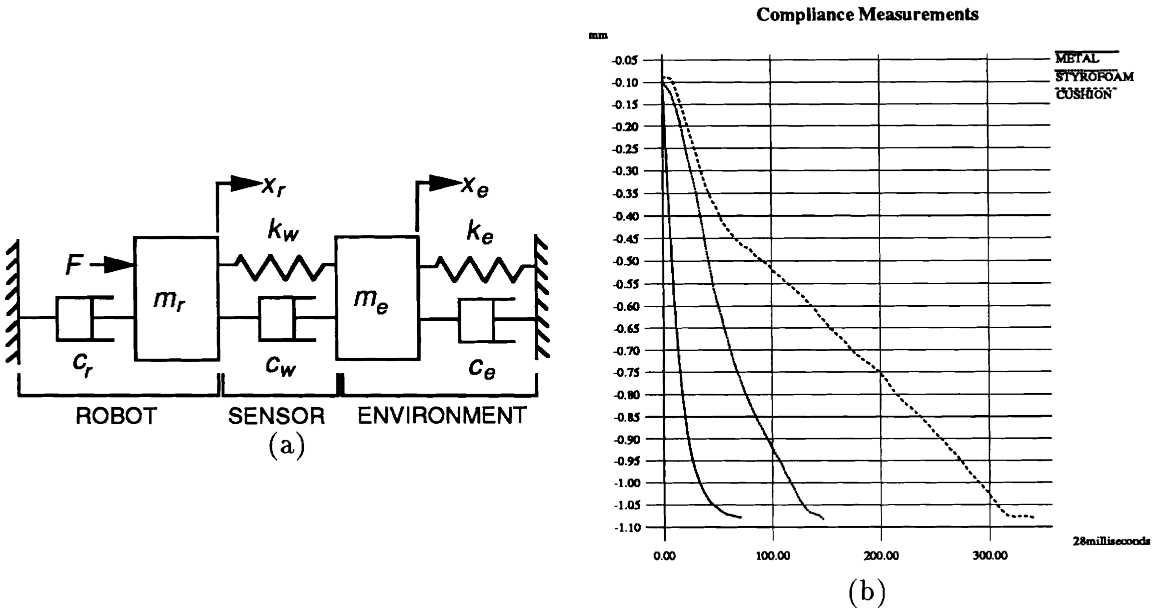


Figure 5: (a) Model of system for measurement of compliance (b) Plot of deformation in the wrist (in mm) due to normal force vs time (1 unit = 28 milliseconds)

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:

$$F_c = k_w x_w \tag{1}$$
$$\text{also,} \quad x_w = x_r - x_e \tag{2}$$
$$\text{therefore,} \quad F_c = k_w(x_r - x_e) \tag{3}$$

The governing equations for this system are:

$$m_r \ddot{x}_r + k_w(x_r - x_e) = F - c_r \dot{x}_r - c_w(\dot{x}_r - \dot{x}_e) \tag{4}$$
$$m_e \ddot{x}_e + k_w(x_e - x_r) + k_e x_e = c_w(\dot{x}_r - \dot{x}_e) - c_e \dot{x}_e \tag{5}$$

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

$$k_w(x_r - x_e) = F \tag{6}$$
$$k_w(x_e - x_r) + k_e x_e = 0 \tag{7}$$

Substituting for x_e in Equation (7), using Equation (2) and differentiating, we get:

$$k_e = \frac{k_w \dot{x}_w}{\dot{x}_r - \dot{x}_w} \tag{8}$$

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 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 compliance involves moving down the arm such that the foot is pressed into the surface at a constant rate ($\dot{x}_r$) till a specified normal deformation is experienced by the wrist. The steeper the slope ($\dot{x}_w$) of the normal deformation versus time curve, the less compliant is the material.

The results from the *ep* for compliant measurements is shown in Figure 5(b). The slope of the deformation versus time plot is clearly the steepest for the metal surface. The Styrofoam surface is more compliant, 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.

5.3 Surface Traction

The lumped-parameter model of the last section is modified for the measurement of available surface traction as shown in Figure 6(a). The surface roughness generates the tangential traction force F_f at the interface of the wrist sensor and the surface (in our case, the interface is the foot). Now, the traction force, F_f, is the same as the contact force, F_c, therefore, using Equation (1):

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

$$F_f = k_w x_w \tag{10}$$

To measure the tangential force in order to obtain a measure of the available surface traction, therefore, all the robot needs to do is measure the deformation, x_w, in the wrist sensor. In the implementation of the *ep* for evaluating surface traction, 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 compliance. In our experiments, the robot also adjusts, according to the compliance 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 6(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 6(b) shows the wrist deformation corresponding to the surface roughness of the plate covered by a rough cloth. In this case, the tangential forces are larger for the

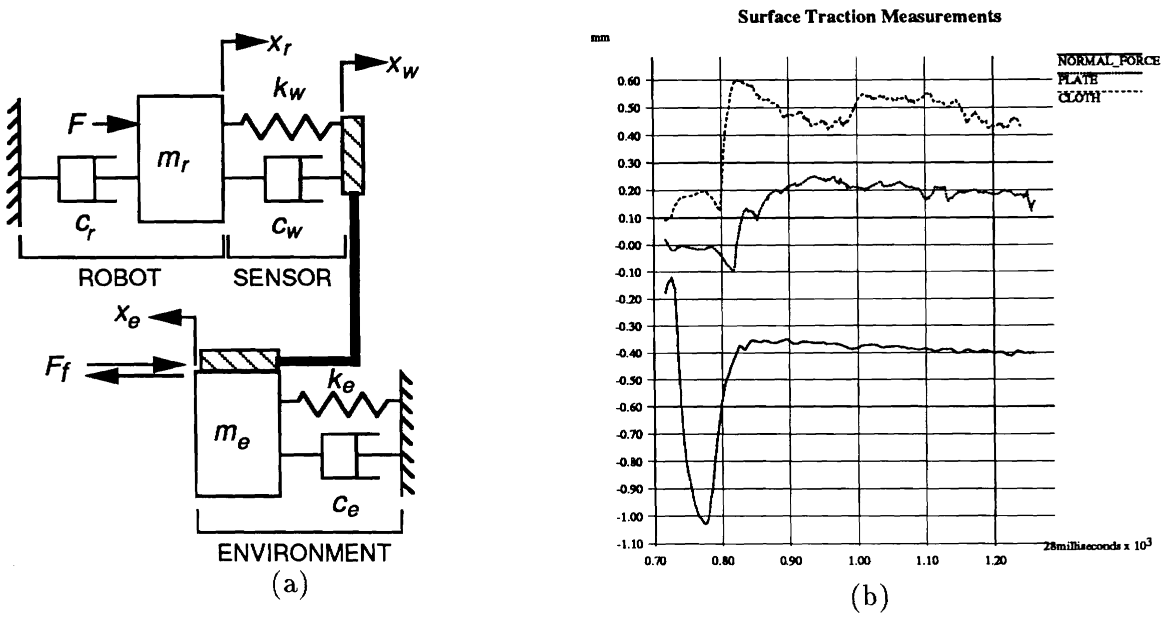


Figure 6: (a) Model of system for measurement of surface traction (b) Plot of tangential and normal deformations (in mm) vs time (1 unit = 28 milliseconds) during surface traction measurements

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 compliance is constant but the surfaces have different roughness properties. This shows conclusively that the robot is able to distinguish between surfaces of different roughness and available traction.

While relative motion and sliding does occur between the two surfaces during the implementation of this *ep*, this does imply that this is how the robot will execute the surface traction *ep* even will walking. As mentioned earlier, during the retract part of the walking motion the leg pushes back against the surface and this will suffice to give a measure of traction and the compliant wrist sensor will deform proportional to the encountered resistance due to traction.

6 Conclusion

The ability to measure and sense the variation in the material properties of different soil surfaces is indispensable to mobility of legged robots in unstructured 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. This paper proposes an active exploration and perception scheme for the legged locomotion of robots based on the ability to extract material properties from a surface.

With this in mind, we have succeeded in designing and implementing *ep*'s to recover the penetrability, compliance, and surface traction characteristics of a surface. The immediate goal of this research is to implement these *ep*'s as part of the walking motion such that they are executed on the fly, thus completing the implementation of the perceptual scheme proposed in this paper. 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.

7 Acknowledgements

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