Estimating Friction Using Incipient Slip Sensing During a Manipulation Task

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Abstract

This paper presents a scheme by which a manipulator can use dynamic tactile sensing to detect when it is about to lose hold of a grasped object and take preventive measures before gross sliding occurs. By detecting localized slips on the gripping surface which precede gross slip, the controller can modify the grasp force to prevent the object from slipping. Also, by monitoring normal and tangential forces at the contact when these "incipient" slip signals occur, the controller obtains an accurate estimate of the friction coefficient which can then be used during the manipulation task. Accurate knowledge of the friction coefficient is essential when grasping fragile objects or manipulating with sliding.

1. Introduction

Typically, when robots manipulate objects, they must do so with a predetermined grasp force. By contrast, humans are skilled at manipulating objects with grasp forces maintained only slightly above the minimum required to prevent slipping. They can roughly estimate the weight and friction properties of an object by looking at it and using knowledge based on previous experience. As they grasp and lift the object, they make use of dynamic, or “fast acting” receptors in the skin that respond to small, localized slips that are precursors to gross sliding of the object [11, 13]. These dynamic tactile sensors enable them to gain a better estimate of the friction conditions at the contacts and thus maintain the normal/tangential force ratio with a margin of safety that varies from 15% to 100% depending on the task and the material and texture of the object being handled.

Accurate knowledge of the coefficient of friction is particularly important for manipulating gently and manipulating with sliding. When performing fine manipulation with fragile objects, it is essential that the grasp force be kept just above the minimum required to prevent damage to the object. When manipulating with sliding, accurate and current knowledge of friction conditions is essential to keep the object from unexpectedly accelerating or ceasing to slide.

While an estimate of the friction coefficient can be obtained from knowledge of the material being handled, the estimate is likely to be inaccurate; large variations commonly result from changes in surface texture, cleanliness, moisture, etc. [2]. It is therefore desirable to provide robots with a counterpart to the human ability to obtain continuous and accurate updates of the friction coefficient.

Although it is evident that humans benefit from the ability to continually adjust their grasp forces based on incipient slip sensing, comparatively little has been done to provide such capabilities for robots. A number of efforts have been made over the years to develop sensors that can detect the onset of slip [3, 4, 5, 12]. With varying degrees of success, these sensors are able to detect when an object has begun to slip. However, they all require motion of the grasped object before being activated. In other words, for these sensors to send a signal, gross sliding must already have begun, and consequently there is little time to increase the grasp force before significant object motion occurs.

In an attempt to detect incipient slip signals that occur before gross motion of the object, Howe and Cutkosky [6, 8] developed a dynamic tactile sensor for use with soft robotic fingers. Grasp force control based on incipient slip detection was performed by Tremblay, Packard and Cutkosky [14] . Finally, Howe [9] has found that skin acceleration sensors can be used with a force-reflecting master-slave manipulator, thereby permitting a human operator to determine not only how hard the slave gripper is grasping, but also when the grasp force approaches the minimum required to prevent slipping. This paper describes an improved version of the dynamic tactile sensing approach that can provide a regularly updated, accurate estimate of the coefficient of friction for use in the control of manipulation.

2. Sensor Design

The sensor used for the experiments described in this paper is a modification of the skin acceleration sensors described in [6, 8, 14]. It consists of a thin outer skin of textured silicone rubber bonded to a hemicylindrical core of foam rubber (Figure 1). The foam helps the fingertip conform to the surface of the grasped object to provide a better grip and reduces the instability problems often associated with grasp force control. The foam also partially isolates the skin and dynamic sensors from structural vibrations in the manipulator. The skin is covered with “nibs”, or projections, that form local contact regions that can slip independently from one another and

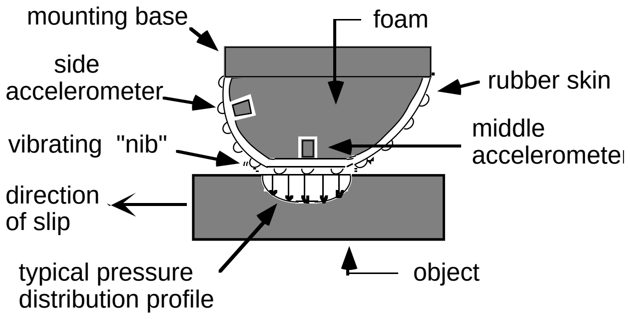

Figure 1: Sensor Design

produce small vibrations. Like the ridges on human fingertips, the nibs also provide more reliable friction properties than smooth skin when grasping wet or dirty objects. The skin is made of self-leveling silicone rubber (General Electric RTV 118) and is 0.06 in. thick. The nibs have a 0.063 in. diameter with a rounded tip and a length of 0.08 in. They are spaced 0.125 in. apart in a cross-pattern fashion.

The sensor performs similarly to the human FAII tactile receptors described by Johansson and Westling [10]. When the finger is pressed against an object, it compresses to conform to the surface of the object. Figure 1 illustrates a typical pressure distribution under such a contact. One can see that the pressure at the periphery of the contact is lower than in the middle. When the finger is about to start slipping, some of the lightly loaded nibs near the periphery will break free and vibrate. These small vibrations propagate throughout the skin for a brief period of time. There are two accelerometers bonded to the skin, located in small cavities in the foam (Figure 1). The cavities ensure that the accelerometers respond to vibrations in the outer skin, and not the foam. Although both accelerometers can detect skin vibrations, the accelerometer mounted in the middle is significantly less sensitive because skin vibrations are attenuated by the skin/object contact at the center of the contact region.

By detecting the small vibrations associated with incipient slips, a manipulator can increase its grasp force in time to prevent noticeable sliding of the object. Grasp force control based directly on incipient slip sensing is complicated by the tendency for disturbances, such as sudden changes in loading and vibrations in the manipulator, to produce spurious skin vibrations. However, by comparing the outputs of the two sensors, incipient slip signals can generally be discriminated from spurious vibrations. The approach presented in this paper is to record the values of the normal and tangential forces when incipient slips are detected, thereby providing an accurate, up-to-date measurement of the coefficient of friction. This information can then be used in any grasp force control scheme.

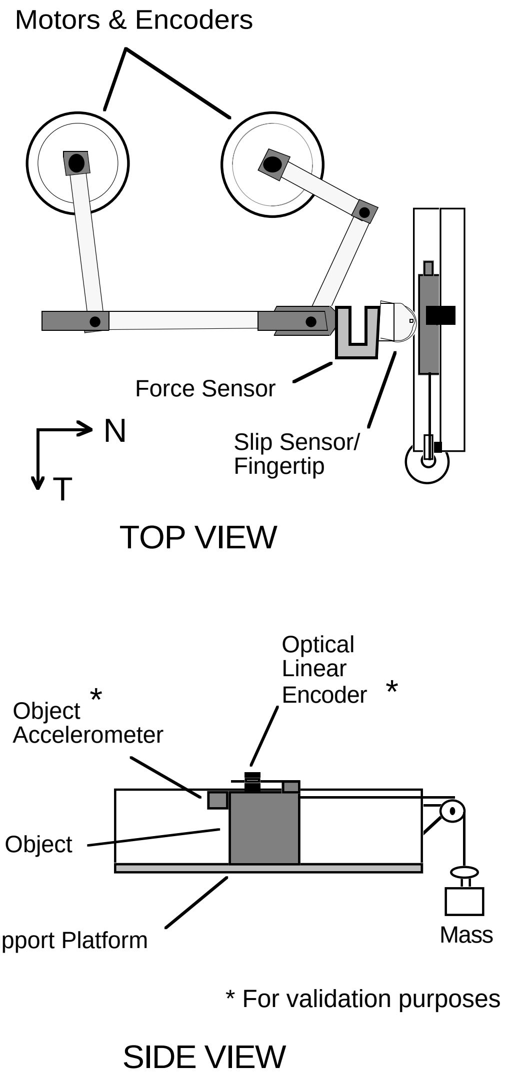

Figure 2: Experimental Setup

3. Experimental Setup and Approach

Figure 2 illustrates the setup that was used to perform the experiments. Basically, it consists of one half of a symmetric two fingered grasp. The finger is part of a direct drive manipulator that has been described previously in Howe et al. [7]. It is a two degree of freedom, direct-drive 5 bar linkage and is well suited to perform force control experiments due to its low inertia and the absence of mechanical noise from backlash and cable elasticity. A three-axis force/torque sensor is mounted just behind the fingertip and can accurately measure normal and tangential forces. For the experiments presented in this paper, a hybrid position/force control scheme was used to control the position of the finger in the tangential direction, while controlling the force in the normal direction. The controller has an operating frequency of 320Hz.

The manipulated object consists of a Teflon™ block that is free to slide on a support platform, also made of Teflon. Teflon is chosen to ensure that friction between the object and the platform is kept to a minimum. The grasping surface of the object is covered with fine grain #410 sandpaper. A mass and pulley setup enable tangential forces to be applied to the object. A non-contact linear encoder monitors the displacement of the object with a resolution of 0.042mm per count. A small accelerometer is also mounted on the object to detect object vibrations during a run. This is done to ensure that the vibrations detected by the slip sensors are in fact due to vibrations of the skin and not of the object. It should be noted that the object accelerometer is not part of the control loop and is present for validation purposes only

A previous paper [14] has demonstrated the sensors' ability to reliably detect incipient slip signals for a variety of materials and conditions. In the previous experiments, the grasp force was slowly decreased until incipient slip signals were detected and then the grasp force was increased back to its original value before noticeable sliding could occur. In those experiments, the output of the accelerometer was sent through an RMS/DC converter to ensure that the slip signals, which have a very short duration, where reliably detected by the controller running at 320Hz. For the present experiments, several design improvements were made to the fingertips:

- The skin material, texture and thickness were changed to provide a more "lively" skin with longer nibs and less damping (see section 2).
- The skin was bonded to the foam substrate to eliminate noise associated with rubbing at the skin/foam interface.
- The main slip sensor was moved to the side of the fingertip for greater sensitivity to the small vibrations associated with incipient slips and a second sensor was added at the contact region.

With these changes, the skin vibrations associated with incipient slips lasted long enough that an RMS/DC converter was no longer needed. Eliminating the converter enables faster response since the converter circuit introduces some time lag in the sensor output.

As mentioned previously, a second accelerometer was added to the fingertip. A problem that arises with using only one accelerometer is that the controller has no way of distinguishing slip signals from disturbances that might occur during manipulation. For example, if the manipulator were to be tapped during a run, the slip sensor would mistake the ensuing vibrations for incipient slip signals. The second accelerometer remedies this problem. The idea is to set its threshold slightly above the signal level normally obtained with incipient slips. Therefore, if an incipient slip does occur, the sensor on the side will detect it, but the one in the middle will not. However, if the manipulator (or the tabletop) is tapped, even lightly, a large signal will be read simultaneously by both sensors thus telling the controller that this is a disturbance. The approach taken in this paper when reacting to a disturbance force is to stop decreasing the grasp force until the vibrations subside. In a real manipulation task it might even be desirable to increase the grasp force if the disturbance is judged to be large enough as to cause the object to slip.

4. Experimental Results

The experimental results shown in Figures 3 and 4 demonstrate the basic control strategy and the ability of the system to reject spurious disturbances. In the typical run illustrated in Figure 3, the normal force is decreased until an incipient slip is detected. The friction coefficient can be computed at that instant by measuring the normal and tangential forces in the finger. From that point on the desired normal force is computed as:

$$F_n = (F_t / \mu_s) \cdot K_s \qquad (1)$$

where K_s is a safety factor. For the experiments presented in this paper K_s was set to 1.2. The above mentioned approach is used as a simple example of how the recently acquired friction information can be used to effectively grasp the object. Controlling the grasp force based on the measured load is not new and has been discussed previously by Bicchi et al. [1].

The first plot in Figure 3 shows the normal force, or grasp force, being applied on the object during an eight second run. The manipulator initially grasps the object with a force of 2N. At point (A), the decay process begins until an incipient slip signal is detected at point (B). At that instant, the controller reads the normal and tangential forces present and computes the friction coefficient. A new grasp force is computed, which is 20% higher than the force required to prevent slip (C).

At point (D) the load on the object (tangential force) is suddenly doubled. This can be seen in the second plot of Figure 3. The force sensor detects this new increase on the tangential loading and a new grasp force is promptly computed based on the friction coefficient that was found at (B) and the measured tangential force (Eqn.1). The grasp force quickly ramps to the new desired value (E), which is twice the previous value.

The third plot in figure 3 shows the output of the side slip sensor throughout the run. Discernible spikes can be seen at events (B) and (D). It should be noted that only the leading edges of these signals (especially at (D)) are due to incipient slip; the subsequent large signals are due to the finger increasing its grasp force.

The fourth plot in Figure 3 shows the object position throughout the experiment. It can be seen that the object motion is negligible at (B) (< 0.05mm), and limited to 0.5mm at (D), despite the sudden increase in tangential force.

The last plot in the figure shows the output of an accelerometer mounted directly on the object. As further evidence that the dynamic tactile sensors are responding to local skin accelerations, and not minor accelerations or "bobbles" of the object, it can be seen that the output from this sensor never rises above the ambient noise level, except while the manipulator is adjusting to the doubled load force. Note again that this sensor is there for validation purposes only and is not part of the control loop.

As second run is shown in Figure 4 to illustrate the system's ability to reject disturbances due to mechanical noise. The procedure follows that described for Figure 3. The first plot again shows the normal force during the run. The grasp force begins at 2N and is allowed to decay starting at point (A). Just under 2 seconds into the run, the manipulator is tapped with the hand. At this point (B), both accelerometers in the fingertip simultaneously register large signals and the controller knows that this is not an incipient slip, but a disturbance that can be ignored. Therefore the grasp force is held constant until these vibrations subside (C) and then the decay process resumes until a real incipient slip signal is detected at point (D). As in the previous run, the grasp force is increased to a value that is 20% above the minimum required to prevent slip (E). From then on, the grasp force continues to be computed according to equation (1).

In order to better illustrate how the controller actually distinguishes between a disturbance and an incipient slip signal, Figures 5 and 6 have been included. Figure 5 is a magnified plot of the sensor signals during event (B). One can see that both sensors surpass their thresholds within one sampling interval of one another; therefore the controller identifies event (B) as a mechanical disturbance. Conversely, Figure 6 shows the magnified output of both sensors at event (D), when incipient slip is detected. Here, the side sensor surpasses its threshold, but the middle sensor does not because its threshold is set higher (and it is less sensitive). The controller collects two more samples after the side sensor has passed its threshold and, if the middle sensor is still low, it determines that an incipient slip has occurred. At this point, the friction coefficient is computed and the grasp force is increased to prevent slip. When the middle slip sensor finally surpasses its threshold, just before 5.22 seconds, this is because it is excited by the sudden increase in the grasp force.

It should be noted that in both runs, with or without the disturbance, incipient slip was detected at approximately the same grasp force (1.33N vs 1.35N). This demonstrates the sensor's ability to repeatedly detect incipient slips and accurately compute the friction coefficient at the contact.

5. Conclusions and Future Work

In this paper, a strategy was presented by which a controller can repeatedly and accurately estimate the friction coefficient at the contact between a robotic finger and an object, and use this information to control the grasp force. The results show that by detecting incipient slip signals using dynamic tactile sensors, and by

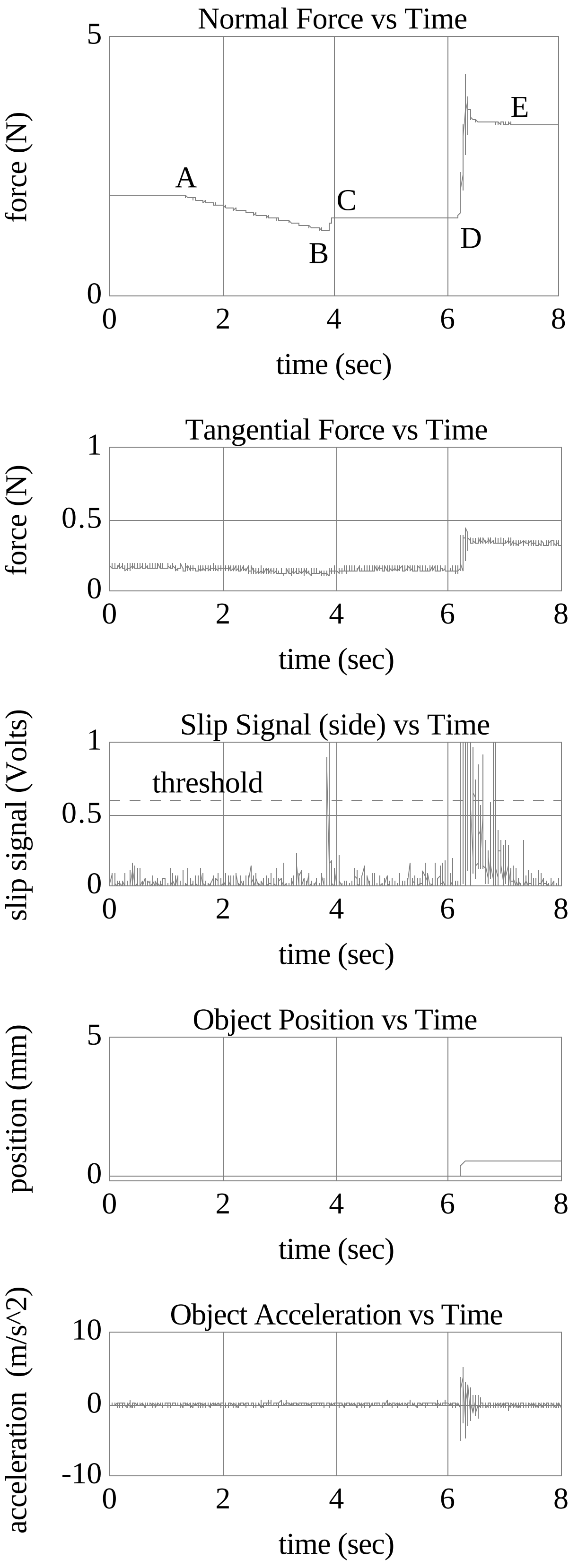

Figure 3: Experimental Results (Run #1)

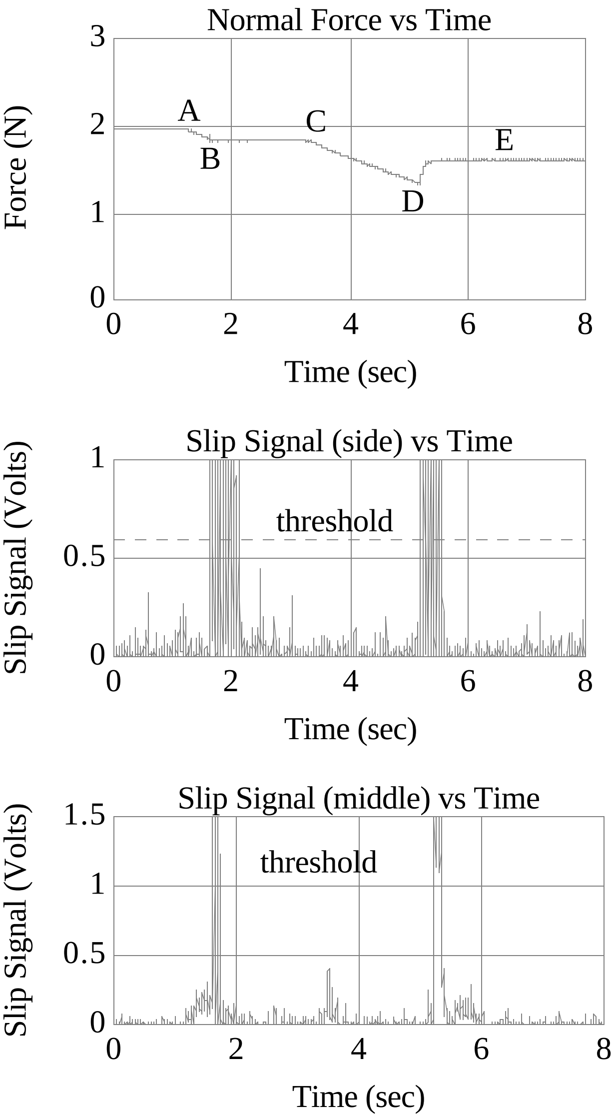

Figure 4: Experimental Results (Run #2)

simultaneously measuring normal and tangential forces at the finger, a controller can compute the coefficient of friction at the contact. This approach is similar to responses reported in the physiology literature for human subjects [10]. The incipient slip signals are caused by lightly loaded protrusions in the skin near the periphery of the contact which break loose just before gross sliding occurs. The ensuing vibrations propagate throughout the skin and can be detected by miniature accelerometers bonded to the skin surface.

The results also show how recently acquired friction information can be used to minimize slip of an object after sudden changes in loading conditions and show that the system can be made to reject spurious signals caused by mechanical disturbances.

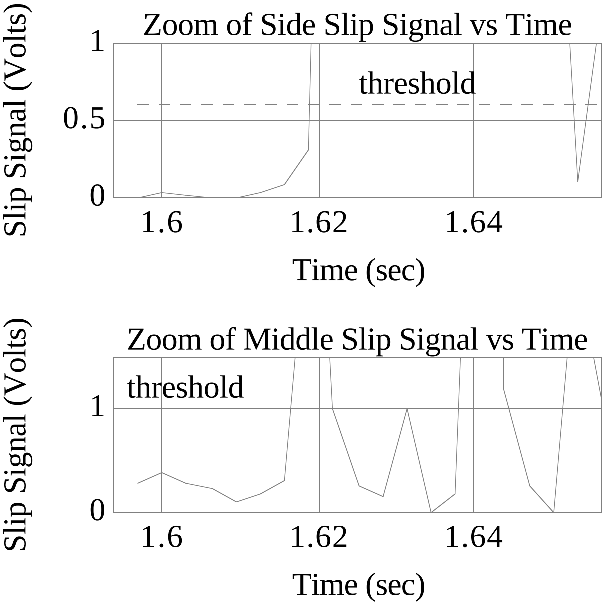

Figure 5: Magnified plot of sensor output for disturbance

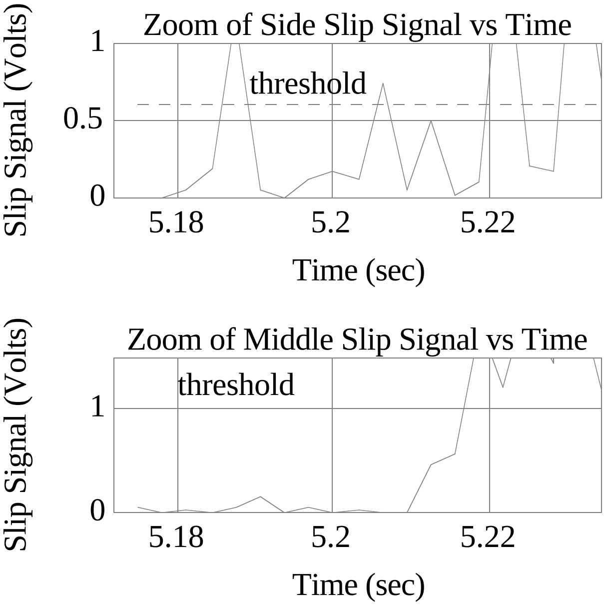

Figure 6: Magnified plot of sensor output for incipient slip

A number of extensions of this approach are evident. On a practical level, further improvements in sensor design, including variations in foam density, skin characteristics (thickness, texture, composition, etc...) and sensor location, may result in both greater sensitivity to incipient slips and a better ability to reject spurious signals.

Much work remains to be done in applying the sensor to manipulation tasks. A good starting point is to examine the effects of manipulating with multiple fingers. Do the incipient slips at one finger, and the subsequent adjustments in contact force, produce signals at the other fingers that cannot be rejected easily? This could prove quite challenging.

A longer-term goal is to make continual, on-line estimation of the friction coefficient a sub-process in an overall manipulation strategy. It would be desirable to use not only the latest incipient signals, but also a weighted function of the "n" most recent slips to provide an optimal estimate of μ_S:

$$\hat{\mu}_{s(i)} = \sum_{j=1}^{n} \left(w_{(i-j)} \cdot (f_t / f_n)_{(i-j)} \right) \quad (2)$$

where $w_{(i-j)}$ is the weight assigned to a specific event. Therefore, whenever a manipulator is at rest, it could perform this quick test to update the friction information. Obviously, one could not hope to use an accelerometer-based sensor during rapid motion of the manipulator due to the presence of large mechanical vibrations that would render the incipient slips undetectable.

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