Slippage Control in Hand Prostheses by Sensing Grasping Forces and Sliding Motion

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Abstract

Controlling grasp and avoiding object slippage is very important in hand prosthetic systems. At present the amputee must use vision to monitor grasp, and adjust grasping force based on this estimate.

We have investigated the problem of measuring normal and tangential forces at the gripper-object interface, and designed a slip tactile sensing system for this purpose.

In this paper we discuss the design, fabrication and testing of a tactile sensing system intended for application to a myoelectrically controlled hand prosthesis, and outline a control strategy for preventing object slippage using sensory feedback.

1. Introduction

The problem of restoring dexterous manipulation capabilities in amputees wearing hand prostheses has been addressed by many investigators but not solved yet.

The human limb system includes a complex network of multilevel controllers, actuators and information receptors, connected by afferent and efferent pathways. This enables the neuro-musculo-skeletar system to modulate a wide range of voluntary behaviors.

Generally, arm movements are achieved involuntarily, but with considerable skill. Thus in developing an artificial limb to be used by an amputee, care must be taken to ensure a high level of controllability. Such controllability largely depends on the design of the interface between the amputee and the prosthesis [1], besides depending on the mechanical and sensory features of the prosthesis.

Different kinds of prostheses have been proposed. Most of the prostheses presently available are myoelectric prostheses controlled by the very small signals from the muscles. The hand is used as a terminal device, that offers only a simple open-close function, but with a very strong grip force.

The hand prosthesis that we utilised to apply and test the tactile sensors we developed is a Ottobok Gripper [11]. The maximum force that it can exert is 140 N, with an average speed of 120mm/s and a weight of about 540 g.

In humans, object slippage is controlled by the nervous system by detecting microvibrations at the contact surface by means of glabrous skin receptors [2],[3].

Designing an artificial sensory system capable of replicating in an artificial hand the performance of the human tactile system for controlling slippage is very difficult. In order to obtain dexterous hand prostheses, many different sensors have been developed [4]. Two basic approaches have been proposed: the first involves sensing the displacement of the object as it begins to slip; the second is based on sensing the vibrations produced just before and during sliding. One limitation to sensing slip through object displacement is that by the time the object has translated a significant amount, it may have already acquired substantial speed, thus making it difficult to take corrective actions before the object is lost from the hand. Sensing vibration, on the other hand, can reveal that slip is imminent, providing an early warning to the hand controller.

A sensor for detecting object displacement has been developed by Masuda et al. [5]. The sensor utilises a roller incorporated in the gripper surface to directly detect object movements. In order to sense vibrations, other type of sensors have been proposed, making use of piezoelectric elements [6] or small accelerometers [7] to sense minute vibrations of a compliant sensor skin. A more sophisticated approach detects incipient slip by sensing simultaneously normal and tangential local forces, thus allowing the control system to prevent object slippage by estimating a "safe" friction coefficient [8]. Recently a quite detailed analysis of the problem of controlling grasping force by sensing static friction has been presented by Yamada et al [9], who also reported interesting experimental results by using a strain gauge-based 3-axis force sensor.

In this paper we describe a sensor system we developed in order to sense simultaneously tangential and normal contact forces applied during grasp, and vibrations induced by slip. The proposed sensor, derived from other sensors developed in our laboratory for the study of tactile perception in robotics [10], has been designed purposely to be incorporated in hand prostheses.

The prosthesis we used to test the sensory system [11] utilises cutaneously measured electromyogram (EMG) signals sensed by electrodes over two antagonist forearm muscles as means for detecting motor commands sent by the central nervous system and to decide for the opening and closing of the prosthesis.

2. Slip sensory system

Tactile sensors are used to derive information between the end-effector and the environment. When we manipulate an object, tactile information is processed by the central nervous system to apply the appropriate force during grasp.

This force must be sufficient to avoid the falling of the object, but not too strong in order not to damage the object. Once the object is in the grasp, a sudden increase of its weight (for example a glass being filled with water) or a sudden movement of the hand can cause its slippage. To detect this possible slippage, humans make use of different sensory information, and in particular of information related to local microvibration.

Our approach to slip sensing is based on measuring simultaneously both the normal and shear forces between the gripper and the grasped object, and the vibration occurring at or around the contact area. Together with an estimate of the friction coefficient between the gripper and the object, this information may allow the controller to adjust the grasping force in order to prevent slippage.

The static and dynamic friction coefficients (μ_s and μ_d respectively) can be estimated before grasping by actively exploring the object surface and by monitoring the ratio between the shear force (F_t) and the normal force (F_n) before and during sliding. However, since the friction coefficient may vary from part to part of the surface of an object, and is often affected by unpredictable factors (such as humidity), the sensor system is also equipped with sensing elements that may detect local microvibrations related to incipient and actual object slippage. This information provides a "dominant" feedback signal used to command the quick closure of the gripper.

The sensor we designed comprises two different sensing elements: the first, a force sensor, can detect both normal and shear forces; the second, a dynamic sensor, can detect local vibration.

The force sensor is based on Force Sensing Resistor (FSR) technology. The sensor, originally manufactured by Interlink Inc.[12] for application in a force and direction-sensitive mouse for computer cursor control, includes four distinct areas on a square sensing surface of 18 by 18 mm^2. Each area incorporates a variable resistor based on a proprietary piezoresistive semiconductor material screened on a polymer film. The electric resistance of each area varies with the normal load acting on it. If the external force acting on the sensor is transmitted to the central area of the FSR sensor through a tilting element comprising a metal disk and a rubber cylinder (as depicted in Figure 1), the resistance of each sensor area provides a means to calculate separately the normal and the tangential components of the resultant force acting on the metal disk, as indicated in Figure 2.

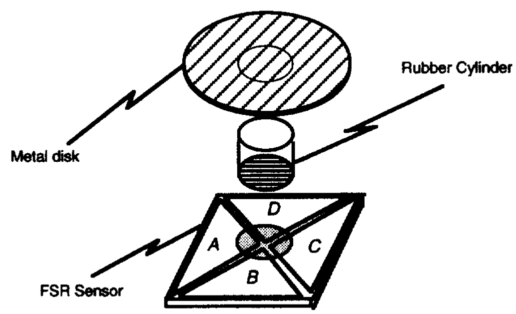

FIG. 1 FSR sensor and tilting element

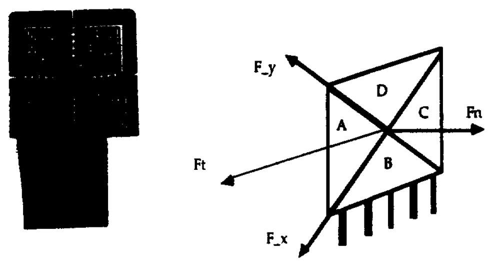

FIG. 2 FSR sensor

In particular, the resultant normal force F_n is calculated from the sum of the signals from the four sections, A, B, C and D, whereas the tangential components F_x and F_y are calculated from the differences of the resistances of the sections D and A, and B and C, respectively.

The dynamic sensor is made out of a piezoelectric polymer film (polyvinylidene fluoride or PVDF), that is very sensitive to mechanical deformations. The piezoelectric polymer has been cut into strips and embedded in an elastomer rubber so as to obtain "grooves", with the double aim of protecting the PVDF strips and of accentuating their mechanical deformation.

The force sensor is located under the PVDF sensor.

3. Experimental Setup

In order to test the slip sensory system performances, the sensor has been mounted on a cylindrical probe, as depicted in Figure 3.

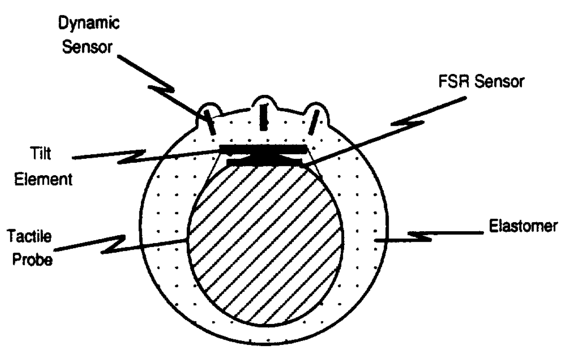

FIG. 3 Sensor configuration used for experiment

The fingertip was then mounted at the wrist of a PUMA 560 manipulator as illustrated in Figure 4.

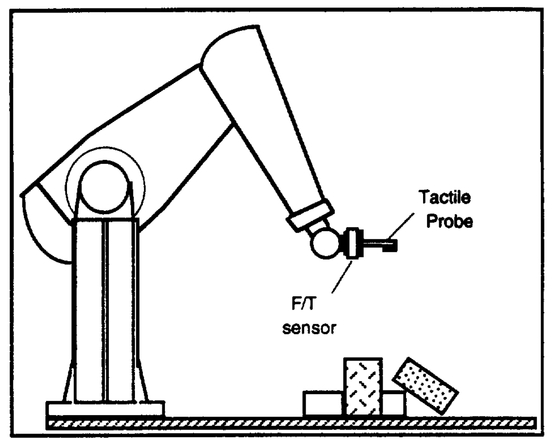

FIG. 4 Robotic system used during the experiments on slippage.

A 6-axis force/torque sensor was located between the probe and the wrist of the PUMA arm.

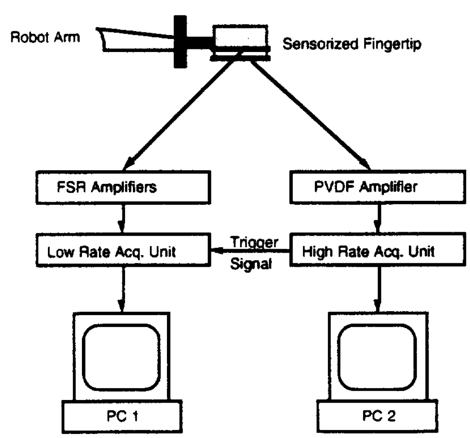

FIG. 5 Experimental Setup

With regard to the experimental setup, shown in Figure 5, the PVDF sensor was connected to a charge amplifier, whose output was acquired by a High Rate Acquisition Unit (14 bits, 2 KHz). The four FSR components were connected to a dedicated amplification unit, whose signals were multiplexed by a Low Rate Acquisition Unit (12 bits, 15 Hz). A synchronizing signal, constituted by a trigger impulse generated by a High Rate Acquisition Unit, was used in order to obtain the same time reference for both the acquisition systems.

4. Experimental Results

First, the FSR sensor was calibrated by applying constant forces. The sensor was supplied with a 5 Volt constant voltage and its outputs were buffered using amplifiers.

The four separate signals from the amplifier outputs were processed to obtain the resultant normal and tangential forces. The values of normal and tangential components and results were calculated as follows:

$$Fn = \sqrt{[Out(A)]^2 + [Out(B)]^2 + [Out(C)]^2 + [Out(D)]^2};$$

$$F\_x = \{[Out(A)] + [Out(B)]\} - \{[Out(C)] + [Out(D)]\};$$

$$F\_y = \{[Out(A)] + [Out(D)]\} - \{[Out(C)] + [Out(B)]\};$$

$$Ft = \sqrt{(F\_x)^2 + (F\_y)^2}.$$

The obtained values for tangential (solid line) and normal (dashed line) forces are shown in Figure 6.

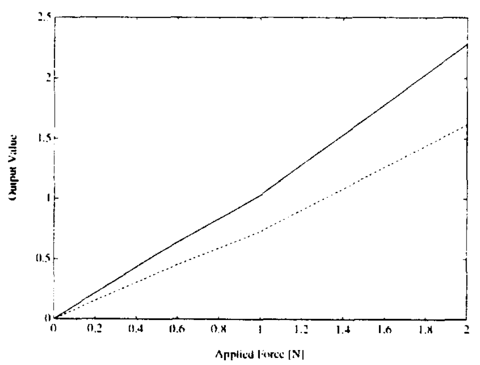

FIG. 6 Calibration Curves

Then experiments were carried out by sliding the sensorized probe along objects having different surface textures and shapes, at constant velocity. A piece of wood, a piece of glass and a cardboard box were used as test objects.

The sensing probe was pressed against the object with a constant normal force. Then the tangential force was increased till slippage occurred.

Resultant normal (F_n) and tangential (F_t) forces were calculated from the FSR signals. The ratio between tangential and normal forces was plotted vs time and compared to the signal acquired by the PVDF sensor. Typical results are illustrated in Figure 7a.

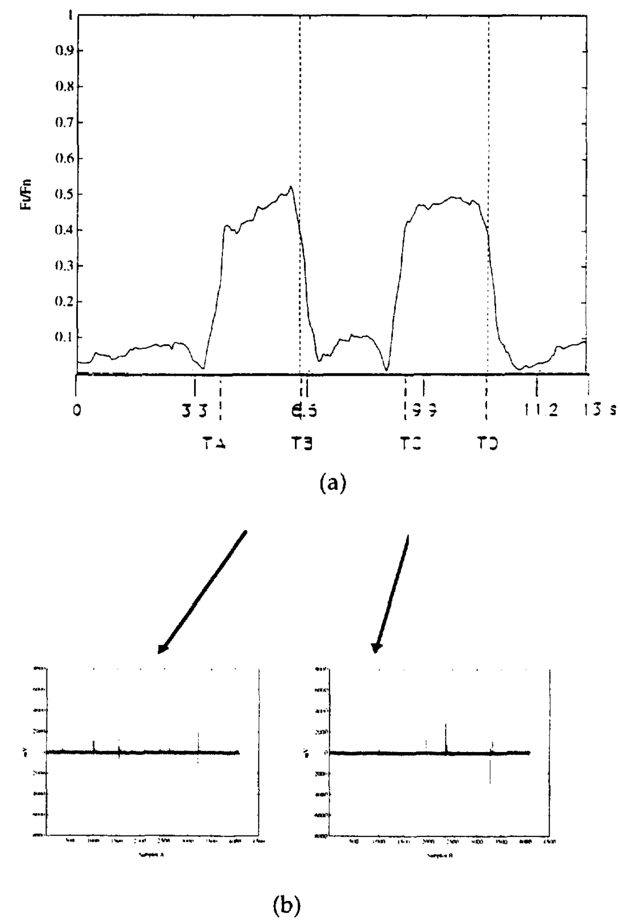

FIG. 7 a,b Experimental Results

In Figure 7b the data obtained during the exploration of a raw wood surface are reported.

At time T_A the tangential force is increased by means of the robot arm. The ratio Ft/Fn increases too, reaching a maximum. The sudden decrease that occurs later can be attributed to a loss of contact. The signal detected by the PVDF sensor, represented in the subplot A, indicates that spikes of vibration are detected, corresponding to the pitch of the object surface texture.

When the contact is recovered (at time T_C), the tangential force increases again reaching the same critical value as before, estimated to be about 0.5 times the normal force. At T_D the contact is lost again and slippage occurs.

Monitoring the Ft/Fn ratio allows us to estimate the instant of contact loss in case of known object material, and may allow to prevent the critical conditions for slip.

The dynamic sensor response allows us to detect the actual sliding conditions and to detect if a low value of Ft/Fn is due to a safe grip condition or rather to a displacement of the sensor surface respect to the object.

The experiments for calculating the critical friction coefficient μ_S have been carried out by applying increasing normal forces to the same object. We observed that μ_S is independent on Fn (a larger Ft is required to make the finger sliding on the object surface).

The slippage control strategy we propose to exploit the above information is described next.

5. Control System

The sensor system, described above, has been mounted on the hand prosthesis as depicted in Figure 8.

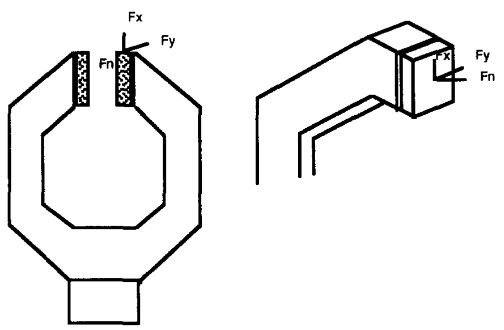

FIG. 8 References axes for the fingertip force sensor.

The aim of the control system is to render slippage control as natural as possible. The stimulus response in humans can be represented as a process articulated into three phases:

1) sensor stimulation by external agents;
2) signal acquisition by the control system;
3) system response based upon signal amplitude.

We tried to reproduce the relationships between the magnitudes of the nervous impulses during these phases. The control strategy used is based on the considerations described in the previous paragraph.

The flow chart of the control algorithm is represented in Figure. 9.

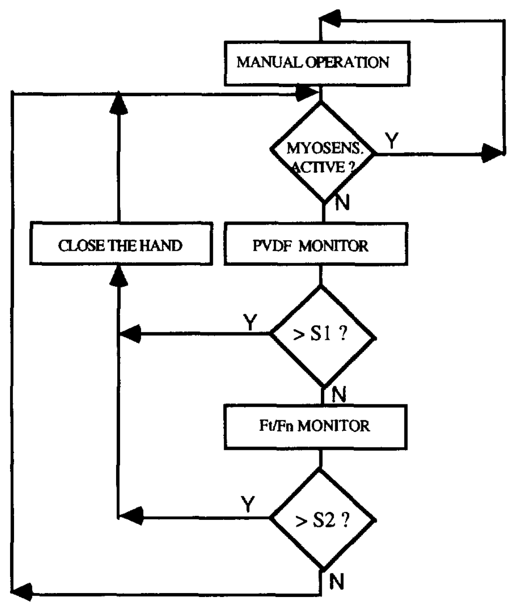

FIG. 9 Flow Chart of the control algorithm

The signal generated by the myosensors, by the PVDF Sensor and by the Force Sensor are read simultaneously.

Although a sort of automatic control of the grasp is required by the hand prosthesis, it is very important that the operator maintains the full control of the prosthesis. That is why the sensor system should be activated only in case the myosensors are not active.

During grasp, in fact, the slip sensor generates significant signals due to movements of the grasping surface on the object surface. These signals would not mean slippage, but just an adjustment of the object in the grasp.

Also, in case the patient wants to loosen the grasp and let the object fall, if the slip sensor system were active the feedback signal would not permit it.

When the myosensors are not active the slip sensor system is monitored and the slippage control starts.

First, the PVDF signal is monitored, in order to reveal a possible slip. The case of a signal whose value is larger than a threshold value (S1), means that slippage is occurring and a close signal is sent to the driver.

In the opposite case, the ratio Ft/Fn is tested. If it exceeds the critical pre-computed value (S2), an incipient slippage situation occurs.

6. Conclusions

A sensor system based on two different types of sensing elements has been designed and fabricated in order to detect slippage at the fingertip of a hand prosthesis during grasp.

With the experimental setup described, the "before sliding" and "during sliding" situations have been monitored. In particular, a significant increment of the Ft/Fn ratio has been observed in the immediately "before sliding" situation; it may be used as a "warning" signal for the detection of a probably incipient slip. In the "during sliding" period a high signal level is generated by the dynamic sensor also for a small diplacement of the grasped object; this output gives a useful signal to detect a contact loss.

From the discussion of these results a control strategy has been derived that, utilising the information provided by the sensors, would allow to prevent the grasped object from sliding.

According to these considerations, we are going to design a control system for hand protheses, based on the strategy described. A simple control system implemented on a micro-controller architecture is being studied to achieve the integration of the system aboard a hand prothesis.

In this design, particular attention is given to the problems of reducing the size and the power consumption of the system.

Acknowledgement

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