A Biologically Inspired Sensor for the Prevention of Object Slip during Robotic Grasping and Manipulation

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Abstract

In this paper, we present an overview of our work in the development, realization, dynamic analysis, and simulation of an innovative sensing method for the prevention of object slip during robotic grasping and manipulation. The new sensor is biologically inspired, and measures the extension of a rubber skin to detect impending slip before it occurs, and to provide feedback for active control of the finger contact force during grasping. The sensor has low size and weight, and does not interfere with the finger-object interface. Comparison between experiments and simulation have yielded very good agreement, and we are extending the simulations to the case of a three-fingered gripper with slip-sensing capability that grasps an asymmetric and varying load using minimum contact forces. The simulations will be used to optimise the design parameters and control strategies of the gripper.

1 Introduction

One of the most desirable properties of a dexterous hand is its ability to detect the incipient slip of a held object relative to the fingers during a grasping or manipulation operation. In the grasping and relocation of a fragile object, for example, the hand may be required to apply contact forces that are as low as possible, in order to minimize the risk of damage to the object, while at the same time the forces must be large enough to maintain a stable grasp, and therefore to avoid object slip, throughout the whole procedure. Similarly, intermediate stages during a manipulation task may require the application of minimum contact forces that are just large enough to prevent the onset of slip. In these cases, an effective method for sensing object slip is necessary in order to achieve the required active control of the contact forces.

Early slip sensors utilized either vibration sensing or displacement sensing to detect the presence of object slippage relative to a robot hand [1],[2]. These methods however had the drawback that slip could only be detected after it had started to occur. This limitation led to the development of several approaches to detect slip at its onset. In [3]-[7] the friction coefficient μ between the finger and the object was estimated during grasping by measuring in various ways the normal and tangential forces, using sensors mounted on the fingers, and this was used to set the value of the grasping force in order to prevent slip. Although this approach offered a significant improvement, it still presented a number of drawbacks in that an exploratory strategy was required, and in that some slip would still need to occur, in order to obtain the value of μ. Moreover this method required the use of a number of force/torque sensors in order to obtain the required measurements.

In [8] the method of measuring μ was used in conjunction with an artificial skin that had small surface projections that produced small vibrations at the onset of slip. The vibrations were sensed by small accelerometers beneath the skin (see also [9]). The use of a rubber-based skin for the detection of incipient slip was also investigated by other authors. In [10],[11] a tactile sensor constructed out of a conductive rubber sheet, with resistance measurements available at discrete locations across the rubber surface to give a matrix sensory output, was used to calculate the centre of pressure distribution on the rubber in real time. An analysis of the Fourier transform of the calculated positions of this centre of pressure from consecutive samples taken over time was used to provide information on whether an object that was pressing against the rubber was about to start slipping. In [12],[13] the authors used a skin-like matrix of piezoelectric polymer transducers to validate their theoretical model for incipient slip detection, based on the ratio of stick and slip regions over the contact surface estimated using a neural network. In [14],[15] a set of strain gauges were embedded obliquely inside an elastic fingertip made of silicon rubber, and a change in the shear strain in the fingertip material at the edges of the contact surface was used to detect the onset of slip.

2 The New Slip-Sensing Concept

In this work, we have taken a new approach to the use of a deformable rubber skin for the detection of incipient object slippage. We have decoupled the skin from the main structure, or *bone*, of the robot finger, to an extent such that a significant amount of relative movement is allowed between the inside of the skin and the finger bone. The addition of this new slipping surface has the effect of *increasing* the controllability of the fingertip contact force to prevent loss of control of the object due to gross slippage, as is explained below.

The concept of the new slip sensing mechanism is illustrated in Figure 1. The finger bone is fabricated out of a solid material such as aluminium. A rubber skin is attached to the bone only at specific locations, such as at the top and at the bottom attachment points shown in the figure. A small number of strain gauges, capable of measuring repeated high strains, are mounted on the rubber skin and measure the elongation of the rubber. When an object is being held against the finger, we define *two* contact surfaces over which slip can occur for this finger. The *primary contact surface* is the area of contact between the outside of the skin and the held object, while the *secondary contact surface* is the area of contact between the inside of the skin and the finger bone. The materials for the finger skin and bone are selected such that for the vast majority of objects that are typically grasped, the coefficient of friction will be lower at the secondary contact surface than at the primary contact surface. In this way slip will always tend to occur first at the secondary contact surface.

When the gripper lifts an object, if the grasping force F_g is too low, slip will initially occur only at the secondary contact surface, and this will be detected as a *change in strain* of the rubber by the strain gauges and control system. This is used as a feedback signal to indicate impending slip to the gripper controller, and the grasping force can be increased to stop this secondary slip before gross slip starts to occur at the primary contact surface, and therefore before control of the object is lost. This method has a number of very appealing features when compared to the earlier discussed methods of incipient slip detection. In particular, there can be a significant difference between the value of the grasping force at which secondary slip stops, which will be the value set by the control system, and the (smaller) minimum force required to prevent primary slip. This therefore provides an inherent safety margin for the grasping force that is applied by the gripper. This is very important in dynamic situations, where impending slip should be sensed preferably not just before it is about to occur, but rather some time in advance.

Other advantages of this approach are that it does not require the use of an intricate sensory matrix or of large force/torque sensors, and that the system can be made to be relatively simple and inexpensive. The concept illustrated in Figure 1 can be extended to respond to linear disturbances of the object in directions other than downwards, and also to respond to rotational disturbances. We believe that this method is similar to one of the ways used by humans to detect impending slip during grasping and manipulation, in that the human skin is allowed to have significant deformation and even to slip over the bone structure, and that at the conscious, or even reflex, level humans can recognize an insufficient grasping force through the sensed stretching of the skin as it slips over the bone, and are then able to predict and prevent gross slip.

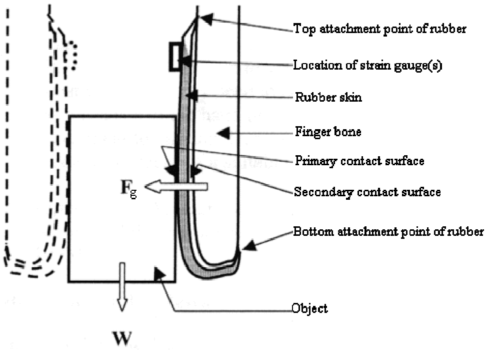

Figure 1. The slip-sensing concept.

3 Mechanical Considerations

The first part of the development work for the sensor focussed on the selection of appropriate materials for the finger bone and skin, in order to obtain the required frictional properties. It was also important to select the rubber material and dimensions that had appropriate strength, elasticity, repeatability, and other properties such as lack of hysteresis, that were appropriate for this application. In all we measured the static and dynamic friction coefficients between forty-eight different types of rubber and nine different materials that were being considered for the finger bone. The latter materials were tested at different grades of surface finish. The tensile tests on the rubber were carried out using the ASTM 412-98a standard, and the rubber elasticity, damping coefficient, repeatability and hysteresis were measured using careful experimental procedures.

The results of the above tests needed to be considered in conjunction with other mechanical requirements that were imposed by our design. The first of these was our decision to incorporate a cantilever type grasping force sensor into the gripper test rig. Although not necessary for the basic functioning of the slip-sensing device, a real time measurement of the grasping force would provide indispensable information during the eventual testing and evaluation of the slip sensor. The availability of force feedback would also eventually become necessary as part of an enhanced gripper control system. The material to be chosen for the finger bone, therefore, had to satisfy the mechanical requirements of a cantilever bar for the force sensor, as well as the frictional requirements for the slip sensor.

A further consideration that needed to be taken, this time in the selection of the finger skin, was the maximum elongation of the rubber within the designed operational range of the gripper. This was due to the limits on maximum permissible repeated strain that could be sustained by special-purpose strain gauges that were available on the market.

The schematic design for the combined force/slip sensor is shown in Figure 2, and the design of the test rig for the sensor is shown in Figure 3. The sensors and test rig were constructed in our laboratory. The finger skin consisted of 0.85mm thick neoprene, and the finger bone (cantilever) was 1.5mm thick and made of highly polished aluminium. For each finger slip sensor, two strain gauges were attached on the opposite surfaces of the rubber skin in quarter-bridge configuration, while for each force sensor, two strain gauges were attached on the opposite surfaces of the cantilever in half-bridge configuration. The slip and force sensors were calibrated prior to the grasping tests. The test rig consisted of a single-degree-of-freedom two-jaw gripper, capable of lifting an object weighing 1 kg. The grasping force was applied through a series of linkages and a compliance spring, by a linear stepper motor (rotary motor with lead screw) controlled via a micro-stepping driver. The compliance spring allowed a linear relationship to be obtained between the motor angular position and the grasping force on the object.

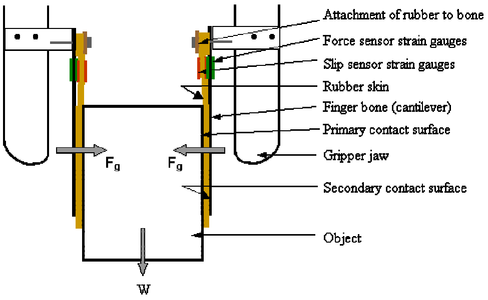

Figure 2. The force/slip sensor.

4 Slip-Sensing Control Strategy

In order to remove high frequency noise, the amplified signals from each bridge circuit were passed through a fifth-order Bessel filter as shown in Figure 4 before being fed into the data acquisition card of the controlling PC. The input signals from the strain gauge circuits however were still subject to considerable statistical noise. The elimination of this noise was particularly critical in the case of the slip sensor inputs, since the extension of the rubber (estimated from the change in the slip-sensor strain gauge output voltage over a specified time interval) was used to determine whether or not secondary slip was taking place. We reduced this noise to acceptable limits by considering the difference between the averages of two consecutive samples of 100 strain gauge readings, and moreover used a 5-point moving average of this difference to determine whether to take action to correct for the secondary slip.

The gripper used the following strategy to monitor and control incipient slip. The voltage difference ΔV between two consecutive readings of the moving average described above was calculated for each of the two slip sensors separately, and these values were updated continuously in real time during the grasping operation. If at any time either of the two values of ΔV exceeded a preset threshold (determined during sensor calibration) then a condition of secondary, or incipient, slip was declared, and the gripper motor rotation was set to a rotational speed ω, to increase gripping force, determined by

$$\omega = K_e \frac{\Delta V}{\Delta t}$$

where the time interval Δt is the duration of a complete sampling loop of the program, and K_e is the controller proportionality constant.

Whenever ΔV for both sensors were found to be below threshold, motor rotation would be stopped until incipient slip was detected again.

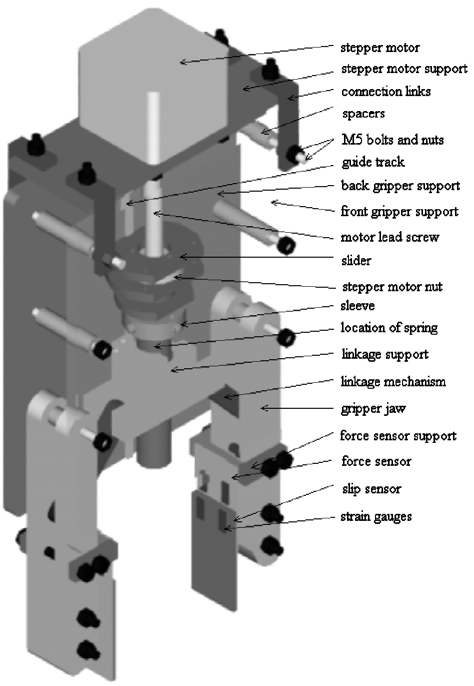

Figure 3. The gripper test rig.

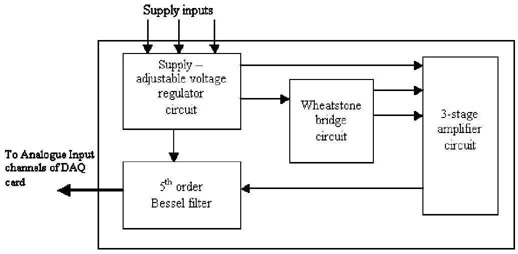

Figure 4. Circuitry for each force and slip sensor.

5 Experimentation

Two of the main contributions of the slip sensing and force control mechanism in a typical grasping application would be to, firstly, adjust the grasping force in real time as an object was being lifted off a surface by a robot, in order to compensate for different object weights; and secondly, to adjust the grasping force continuously in real time to compensate for changes in object acceleration and for varying external forces while the object was being held or transferred by a robot hand. In order to determine the characteristics of the system, however, we set up an experiment whereby the gripper was fixed to a rigid, stationary structure, and simulated the dynamics by changing, in real time, the weight of the object that was being grasped. This could be done by using a hollow container as the grasped object, and by pouring lead shot pellets into the object (or container) at various predetermined mass flow rates, while observing the response of the gripper to avoid slip.

Figure 5(a) shows the rig that was constructed to apply the lead shot into the container during grasping. The applied mass flow rate was varied by using funnels of different outlet diameters. Figure 5(b) shows the partly filled container being held successfully by the gripper jaws.

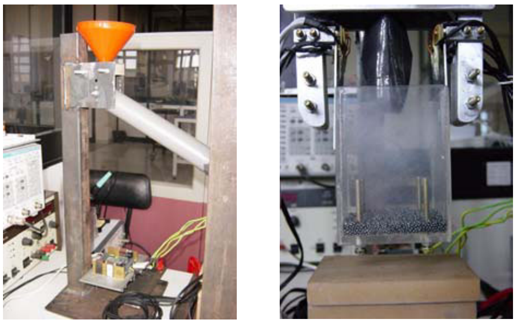
(a) (b)

Figure 5. (a) lead shot feeder, and (b) partly filled container held by the gripper.

The first series of experiments were carried out to confirm the feasibility of the slip-sensing method, and to determine the operational range of our prototype gripper. For these tests, the proportionality constant K_e was not applied, and the motor speed to be used whenever incipient slip was detected during a grasping attempt was set beforehand. The tests were carried out by first applying a grasping force that was just sufficient to prevent the empty container from falling, then turning on the slip-sensing algorithm and applying the lead shot into the container. The grasping operation was considered successful if the object reached its maximum weight of 1 kg without falling out of the grasp. The outputs from all of the strain gauges as well as the state of the motor were monitored throughout each experiment. In particular the final value of the grasping force for successful grasps was also recorded to check for overshoot, since the main objective of the slip sensor is to maintain the minimum possible grasping force at all times. The mass flow rate into the container for these tests was varied between 0.023 and 0.145 kg/s. The upper limit of this range would be equivalent to a *change in acceleration*, or jerk, of about 2.8 m/s^3 during the transportation by a gripper of an object weighing 0.5 kg.

The results of the above experiments were used to determine the range of values of K_e to be considered, by observing the range of the maximum values of $\Delta V/\Delta t$ incurred during the individual tests and the range of ω that was applied. The proportionality constant K_e was then included in the gripper control program, and a new series of grasping experiments were conducted to determine the optimum value of this parameter. The minimum value of K_e that gave successful grasps for all values of mass flow rate within the considered range had a value of 1.95 (rad/s)/(V/s) for our gripper. The numerical value of this parameter, of course, depends on the various design parameters of the gripper and sensors. In the present version of the system, a non-zero value of ω is only allowed to change to another non-zero value, during a specific grasping operation, if it first passes through a period of 0 rad/s due to a (temporary) stoppage in secondary slip.

Figures 6, 7, and 8 show the measured rate of slip, the measured grasping force, and the motor rotational speed respectively against time, for a mass flow rate of 0.1 kg/s with K_e = 1.95 (rad/s)/(V/s).

6 Analysis and Simulation

The slip sensor was modeled as shown in Figure 9. It is assumed that the rubber skin has negligible mass, so that the condition for secondary slip to occur in the downwards direction is

$$\mu_i F_g + c_r \dot{z} + k_r z \le \min[\mu_o F_g, W]$$

where for a two-jaw gripper W is equal to half the weight of the object at any time. The other variables are defined in the figure. After secondary slip has started, then primary slip can only be prevented if F_g is increased fast enough such that we get

$$\mu_o F_g > W$$

before

$$\mu_i F_g + c_r \dot{z} + k_r z > \mu_o F_g$$

The simulation involved the time evolution of the grasping process, as well as the simulation of the response characteristics of the sensors and circuitry. For the time evolution of the system, a forward Euler integration method was used. This was considered sufficient because computer processing power was not an issue in this application, and the integration time integral could be set as small as necessary to achieve the required accuracy. Furthermore, this problem did not involve integrations over lengthy periods of time. The response characteristics of the real system also had to be modeled carefully and certain response parameters, such as the actual sampling time of the gripper, were obtained from experiment.

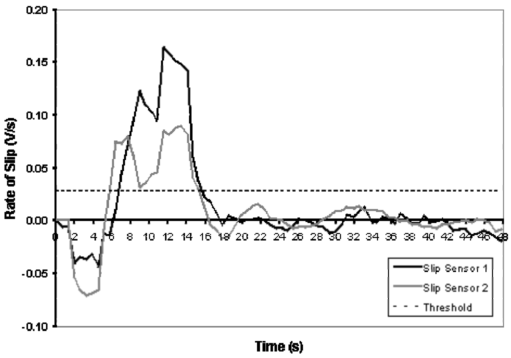

Figure 6. Rate of slip vs. time (experimental).

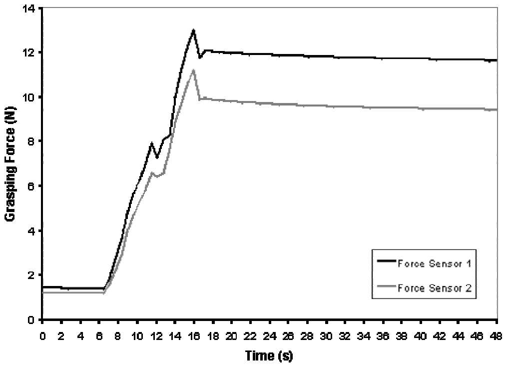

Figure 7. Grasping force vs. time (experimental).

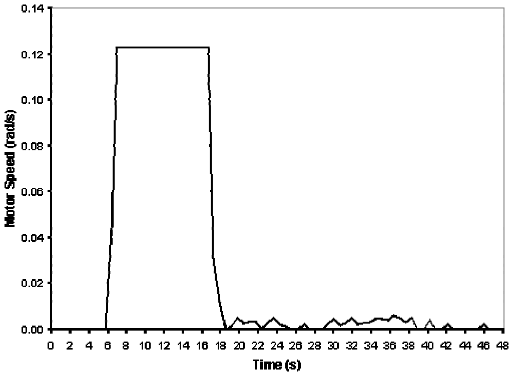

Figure 8. Motor speed vs. time (experimental).

The simulation programs were written in a manner that allowed maximum flexibility to the user in varying the values of all the parameters of the process. A simulation of the entire procedure carried out in the actual experiments yielded an optimum proportionality constant that varied from the experimentally determined optimum K_e by less than +14%. The simulations gave a discrepancy of about –30% in the rate of increase of the grasping force, and in the value of the final grasping force, when compared to experiment. Given the difficulties that are involved in reproducing and simulating frictional effects, the agreement between the experimental and simulated results is considered to be very good. A plot of the simulated grasping force for a mass flow rate of 0.1 kg/s is given in Figure 10.

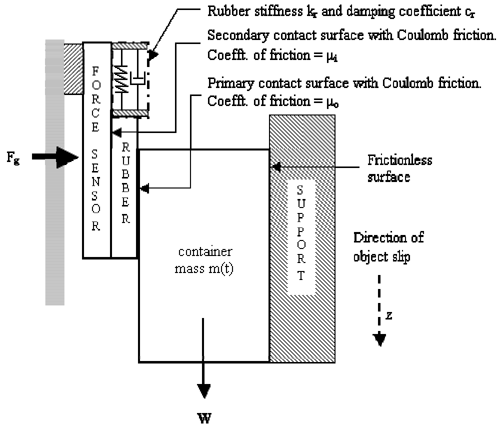

Figure 9. Analytical model of the slip sensor.

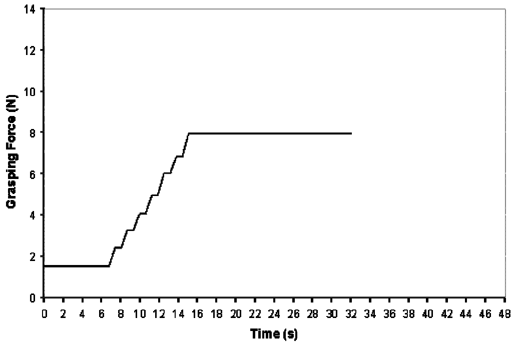

Figure 10. Simulated grasping force for a mass flow rate of 0.1 kg/s (compare to Figure 7).

The simulation has been extended to the case of a three-fingered gripper with slip-sensing capability that grasps an asymmetric and varying load using minimum contact forces, as shown in Figure 11. This work is still ongoing and we will be using the results of these simulations to optimise the design parameters and control strategies of the gripper.

7 Conclusion

In this work, we have developed and demonstrated a new method for sensing impending object slip in robotic grasping, and for applying corrective action before the onset of slip. The method provides an inherent safety margin for the grasping force, since the impending slip can be sensed well in advance of its occurrence. We have also carried out the detailed analysis of a practical slip sensor that is based on this method, and have used the results of this analysis to develop versatile simulation programs that can be used to optimize the design of grippers equipped with this type of sensor. The simulations have been validated by experimental work.

The slip sensor in its current form can only instruct the gripper to *increase* the grasping force. While this may be sufficient for basic grasping and relocation requirements, a more active control strategy allowing the grasping force to *decrease*, in response to a decrease in external disturbances, may be required for more complex manipulation operations. Part of our future work will address this area.

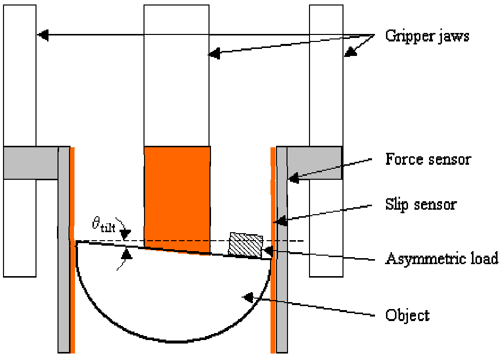

Figure 11. An asymmetrically loaded 3-fingered gripper.

Acknowledgements

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