

PRE-SLIP SENSING USING TACTILE SENSOR

Somrak Petchartee¹ and Gareth Monkman²

¹Federal Arms Force University Munich, Germany,
somrak.petchartee@gmail.com,

²University of Applied Sciences Regensburg, Germany,
gareth.monkman@e-technik.fh-regensburg.de

Abstract: A method to detect pre-slip by controlling the normal force as measured by tactile sensor arrays has been developed. A predictive model has been proposed which uses a basic method adapted to real applications in grasp optimization. Prevention of premature release with minimum prehension force is addressed without the need to measure the coefficient of friction between object and robot gripper. Predictive models have been used to develop a set of rules which predict the pre-slip based on fluctuations in tactile signal data. *Copyright 2007.*

Keywords: predictive control, vibration measurement, signal detection, transient oscillations, robot control.

1. INTRODUCTION

Many different slip sensor solutions have been investigated by a number of researchers with limited success. Although today there are still no real slip sensors included in any commercially available hand (Cotton et al. 2007), the idea of including them into a design can be tracked back to 1960s. In stage of designing artificial skin, some researchers analyzed the mechanical behaviour of the skin of a human finger with surface ridges (Yamada et al. 2000). Yamada et al. used a tactile sensor with surface ridges to measure slip vibrations. He showed a slip sensor that has elastic ridges at the surface and is capable of isolating a stick-slip vibration due to a total slip between the sensor and the grasped object. The sensor can detect the total slip and control the grasping force quickly and correctly to avoid dropping an object. However, the method is not adequate because the position of the object will slightly change due to the total slip. Measuring normal and tangential forces has also been used to detect a slip (Melchiorri, 2000). However, their work is actually slip avoidance, not slip detection.

In this research, grasp experiments concerning the ability of a deformed gripper finger surface to apply

normal forces over an area larger than a single point are considered. In addition, the way in which simple methods, such as determination of contact area geometries together with fluctuation in sensor data can be used for analysis and optimization of soft contact characteristics, is described. Specifically, the proposed resistive tactile sensor is applied in grasp experiments by identifying the least force required for prehension. As with most commercially available tactile sensors, strain results in electrical resistance changes which in turn are converted to analogue voltage levels. Using this simple tactile sensor array, the control unit is interfaced with the robot via a fast CAN-bus provided by a C167 microcontroller.

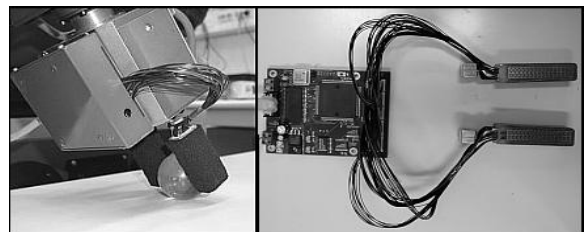


Fig. 1. Sensor assembly.

The gripper fingers are covered by a 3-mm thick electrically conductive foam which provides each

finger with 204 tactile elements. Each side of the fingers is designed to measure the force at one specified location. The tactile sensors have been developed to the following specifications: each finger consists of two arrays of 16x4 cells, two of 16x2 cells, and one of 6x2 cells, making up the total 408 cells for both fingers. The width of the fingers is 20 mm and the length is 55 mm excluding an aluminum core which has a thickness of 12 mm.

2. TACTILE SENSOR FOR ROBOT

Various factors, including environmental influences, must be considered in order to manipulate an object and prevent it from slipping when external loads exceed the frictional prehension forces. When an object is retained in the human hand, gripping forces are adjusted according to the object's weight and surface friction (Johansson and Westling, 1984). To determine whether similar mechanisms would be of help in the control of robot manipulation tasks, Howe and Cutkosky (1989) applied hypotheses from human studies to robotic systems. The robotic Grasp-Lift-Replace task involves five phases: approach, loading, manipulation, unloading, and release, linked together by four contact events. A change in the contact events marks the transition from one phase to another. Robotic tactile sensors described by them detect the contact events and trigger the transitions through the phases of the Grasp-Lift-Replace task. The specialized sensors detect slip during finger to object contact. In addition, information concerning vibration, helpful to contact event identification, is also obtained.

The proposed tactile sensor is applied in grasp experimentation by identifying the least force required for prehension. Two experiments are conducted. In the first experiments, the object is retained between the robot fingers above the surface. Prehension forces are then reduced until the first occurrence of pre-slip is detected and the applied force noted as the minimum retention force.

In the second experiments, an object, placed on a surface is prehended by a robot and the minimum retention force determined by active force variation. This experiment is divided into phases. In each phase, the signals sensed by the tactile sensors and the techniques used in controlling it are presented.

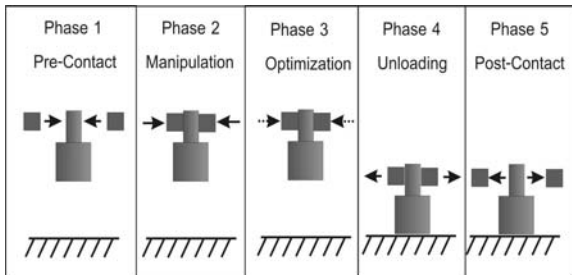


Fig. 2. Grasp-Optimize-Replace Experiments (GOR).

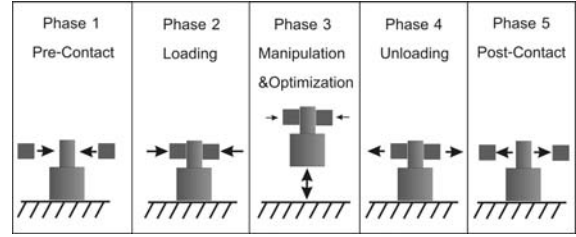


Fig. 3. Grasp-Lift-Replace Experiments (GLR).

The tactile interaction has been implemented on a real system consisting of a manipulator arm having 6 DOFs as shown in figure 4. The tactile sensor arrays are mounted on the gripper fingers. The prehended object is a solid cylinder having a mass of 420 grams.



Fig. 4. Robot Manipulator.

3. THE CONTACT MODEL AND APPLICATION

Fluctuations in tactile data are observed within a time interval during which a sequence of stresses is cyclically applied to the specimen at the contact point. The stress waves are generally triangular, square, or sinusoidal, and the typical cycles of stress are reverse stresses, fluctuating stresses, and irregular or random stresses (Dieter, 1981). An understanding of the nature of physical contacts will aid in analyzing robotic prehension. When two objects come into contact, they will exert forces at the contact point. The z-axis is the axis parallel to the normal contact point n and normal forces are represented by F_n . Contact friction forces perpendicular to the normal force are represented by F_t . Contact friction forces on the x and y axes are represented by F_x and F_y , respectively. The relationship between contact friction forces and the normal force on the contact plane are represented below.

$$F_x^2 + F_y^2 \leq \mu^2(x, y) F_n^2 \quad (1)$$

However, in this study the coefficient of friction $\mu(x, y)$ is a function of the coordinate system, which is different from Amantons' friction law (Dowson, 1979). The surface contact between two objects results in a temporary elastic deformation, whose magnitude depends on the size of the applied force. When the contact area is small, frictional forces on the surface are high, expanding the contact area due to its deformability. If the local direct stress σ_v is set as a constant, the area receiving the pressure N_i will

be equal to $A_i = N_i / \sigma_v$. Thus, the total area under stress will be:

$$A_T = A_1 + A_2 + \dots + A_i = \frac{N_1}{\sigma_v} + \frac{N_2}{\sigma_v} \dots + \frac{N_i}{\sigma_v} = \frac{N}{\sigma} \quad (2)$$

where N represents the vector sum of all the normal forces. For hard objects, the actual contact area will be proportional to the magnitude of the force. However, the situation becomes more complicated with less rigid, compliant viscoelastic surfaces such as the polymer foams used in simple tactile sensors. However, in many cases the frictional forces involved in the viscoelastic deformation of polymeric materials have non-linear components which cannot be calculated using the above formulas. In addition, the deformation does not only depend on the size of the normal force N but also on its direction and length, which in turn depends on the shape of the object in contact. If the deformation and the degree of force are held constant, then the contact area can be represented by the formula N^β . As an illustration, for an elastic rubber-like solid $\beta = 2/3$ (Lincoln, 1952), this is a general characteristic of most polymers. Howell's equation (Howell and Mazur, 1953) for friction force can be reorganized as $F = (KN^{\beta-1})N$, where $(KN^{\beta-1})$ is assumed to be equal to the coefficient of friction μ_0 . This equation shows the complexity of the relationship between the normal force and the coefficient of friction μ_0 , which consists of two variables. The effective coefficient of friction will reduce as the size of the exerted force increases. In other words, the compressive area has a lower coefficient of friction than the tensile area.

The generation of roughness induced dynamic grasping at a deformable contact may be viewed most simply in the context of the model shown in figure 5. Qualitative models to describe the behaviour of a typical polymer will now be introduced. The Kelvin-Voigt model gives retarded elastic behaviour which represents a crosslinked polymer. The Maxwell model gives steady state creep typical of an uncured polymer. With the composition model as shown, it can describe both types of behaviour. The models are simple and suitable for experimental representation of almost any polymer foam over an extended period of time.

The smooth rider in figure 5 sits in contact with a rough surface moving at a constant velocity v .

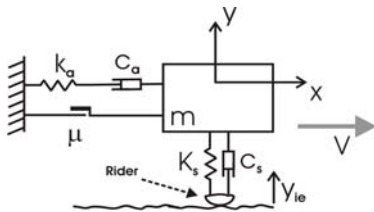


Fig. 5. Dynamic model.

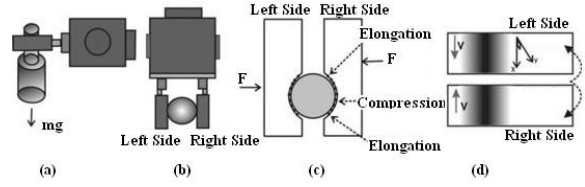


Fig. 6. (a), (b) Object prehension, (c), (d) area of contact deformation and pressure distribution.

The rider is connected to a frame through a suspension characterized by a spring stiffness k_a , a damping constant c_a and a degree of static friction μ . The normal contact stiffness k_s and any associated damping c_s are lumped between the mass and the moving surface. The normal stiffness, linearized about the mean rider position, can be computed from traditional Hertzian theory.

With regard to constant friction, the argument is that in order for friction to change, the real contact area, and thus the mean normal separation, of the surface must change (Ibrahim, 1994). Efforts to verify this were made by Godfrey (1967) who demonstrated a reduction in friction due to normal vibration. With the measured frictional shear force being a function of real contact area, an apparent reduction in friction in the presence of normal vibrations can be expected. The idea was that normal vibrations could influence the mean surface separation and hence the real area of contact. The two models in figure 5 can be applied to explain the operation of robot gripper fingers covered by such tactile sensor arrays, as shown in figure 6 where (a) side and (b) plan views of the prehension operation can be seen. Figure 6c shows the maximum deformation of the tactile sensor surface when the object is normal to the motion of the gripper jaws.

Both compression and elongation strains are apparent and shown as internal pressure distributions in figure 6d. To simplify the analysis as much as possible, but to retain the essential features to be investigated, the vibration considered at a contact point is a finite-cubic block attached to a rigid wall by a simple spring and dashpot. The system is controlled by the frictional forces between the finite-cubic block and the moving belt upon which it is resting. This results in a simple one-degree-of-freedom structure with a non-linear excitation term. A similar analysis including a many-degrees-of-freedom model for the wheel vibration, yet using only simple models for the friction, has been performed by Heckl and Abrahams (1996). The governing second order equation for this system is

$$m\ddot{x} + r\dot{x} + sx = F(\dot{x}, \ddot{x}) \quad (3)$$

where m is the mass of the finite-cubic block, s is the spring constant, and r is the damping coefficient. The friction force is given by $F(\dot{x}, \ddot{x})$, although it may be more natural to think of it as varying with time.

3.1 First Case: Grasp-Optimize-Replace

The governing equations for the contact surface, obtained by summing forces on the rider mass are

$$\begin{aligned} m\ddot{x} + c_d(\dot{x} - \dot{x}_{ie}) + k_d(x - x_{ie}) &= F_G(t) \\ m\ddot{y} + c_s(\dot{y} - \dot{y}_{ie}) + k_s(y - y_{ie}) &= F_N(t) \\ F_G(t) &= \mu_D F_N(t). \end{aligned} \quad (4)$$

$F_N(t)$ is the fluctuating force normal to the tactile surface while $F_G(t)$ is the fluctuating frictional force. Anand and Soom (1984) equates $F_N(t)$ to $F_G(t)$ using the reciprocal of μ_D as shown in (4). It is important to note that the deformation has a y component because some material passes underneath the contact which means that the sliding speed in x and the strain rate y , normal to the surface, are directly coupled (Vellinga and Hendricks, 2001).

$$\begin{aligned} m\ddot{y} + c_s(\dot{y} - \dot{y}_{ie}) + k_s(y - y_{ie}) &= \\ (m\ddot{x} + c_d(\dot{x} - \dot{x}_{ie}) + k_d(x - x_{ie})) / \mu_D \end{aligned} \quad (5)$$

When one of the contact points slips, the relationship between displacement and time will be approximated to a linear function (Howe and M. Cutkosky, 1989). Then, the slip displacement can be described as:

$$x = Ht \quad (6)$$

where H is slope of displacement. Substituting x from (6) into the right hand side of (5) gives:

$$m\ddot{y} + c_s(\dot{y} - \dot{y}_{ie}) + k_s(y - y_{ie}) = (c_d H + k_d H t) / \mu_D. \quad (7)$$

The deformation surface between the object and tactile surfaces can be presented by $z^2 - 2py = 0$, and from the definition of Howell and Mazur (1953) $\mu_D = KN^{\beta-1}$, with $\beta = 2/3$ and $K = 1$. Then, the minimized form is:

$$\begin{aligned} m\ddot{y} + c_s(\dot{y} - \dot{y}_{ie}) + k_s(y - y_{ie}) &= z^{2/3}(c_d H + k_d H t), \text{ and} \\ m\ddot{y} + c_s(\dot{y} - \dot{y}_{ie}) + k_s(y - y_{ie}) &= A + Bt, \end{aligned} \quad (8)$$

where $A = z^{2/3}c_d H$ and $B = z^{2/3}k_d H$.

The solution to the differential equation $\ddot{y} + \dot{y} + y = 0$ will be in the form: $y(t) = y_c(t) + y_p(t)$. The completed solution to the differential equation is:

$$y(t) = C_1 e^{-\frac{t}{2}} \cos\left(\frac{\sqrt{3}}{2}t\right) + C_2 e^{-\frac{t}{2}} \sin\left(\frac{\sqrt{3}}{2}t\right) + c_d H z^{\frac{2}{3}}(t-1) + k_d H z^{\frac{2}{3}} \quad (9)$$

Pre-slip on some contact points will appear before total slip occurs. This pre-slip can be detected by checking the oscillation frequency and is identified as a pre-slip condition for the whole object. In the Grasp-Optimize-Replace experiment, the object was held between the robot gripper fingers. The robot would then decrease the prehension force until it

could detect slip at some contact points which in turn would be indicative of complete slippage. The rule sets can be adapted by checking the oscillation frequency in the tactile array. If there exists some tactile elements having the same frequency of vibration, then whole pre-slip can be recognized.

3.2 Second Case: Grasp-Lift-Replace

In the second experiment, the deformation equation $z^2 - 2py = 0$ would not be correct any more because there exists additional deformation of the contact surface when the robot tries to lift the object. Dundurs and M. Comninou (1983) presented the solution for the shear tractions, $S(x)$ with dislocation distribution on an elastic material. He introduced geometry of the problem for elastic contacts as depicted in figure 7. The two components of force, shear force- $P(t)$ and normal force- $Q(t)$, can vary independently and are introduced as shear traction. The contact between objects is separated into three zones corresponding to point locations along the x -axis. He described the shear traction based on the locations of points in the slip zone (a) and stick zone (b) when they are dislocated.

Point locations a and b along the x -axis at initial distributions will be moved to locations a_1 and b_1 when variations in $P(t)$ and $Q(t)$ along the x -axis occur. Shear traction along the x -axis will simply be a function of x . By defining a set of regime (rules), Dundurs and Comninou (1983) presented the existence of shear traction fluctuations as shown in figure 8.

From the conclusions made by them, this means there exists an extra term varying with time in the equations pertaining to surface deformation, i.e. $\sin(at)$. Then the equation of surface deformation, for example, will be $y = z^2 / 2p + \sin(at)$. With Howell's definition (Howell and Mazur, 1953), the friction coefficient will be $\mu_D = K / \sqrt[3]{z^2 / 2p + \sin(at)}$ or $\mu_D = 1 / \sqrt[3]{C + D \sin(at)}$, where $C = K^{-3} z^2 / 2p$ and $D = K^{-3}$. Equation (4) will become:

$$m\ddot{y} + c_s(\dot{y} - \dot{y}_{ie}) + k_s(y - y_{ie}) = \sqrt[3]{C + D \sin(at)}(c_d H + k_d H t)$$

The same method can be used to find the solution to the differential equations, but this time $y_p(t)$ will be different.

Then, the solution will be

$$\begin{aligned} y_p(t) &= -\frac{2}{\sqrt{3}} e^{-\frac{t}{2}} \cos\left(\frac{\sqrt{3}}{2}t\right) \int e^{\frac{t}{2}} \sin\left(\frac{\sqrt{3}}{2}t\right) \sqrt[3]{C + D \sin(at)} (A + Bt) \\ &\quad dt + \frac{2}{\sqrt{3}} e^{-\frac{t}{2}} \sin\left(\frac{\sqrt{3}}{2}t\right) \int e^{\frac{t}{2}} \cos\left(\frac{\sqrt{3}}{2}t\right) \sqrt[3]{C + D \sin(at)} (A + Bt) dt \end{aligned} \quad (10)$$

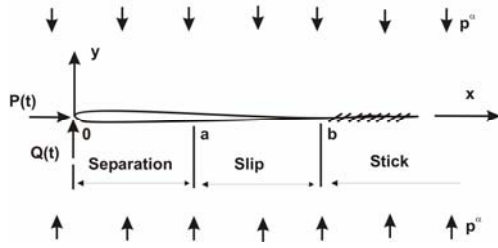


Fig. 7. Geometry of the problem by (Dundurs and Comninou, 1983).

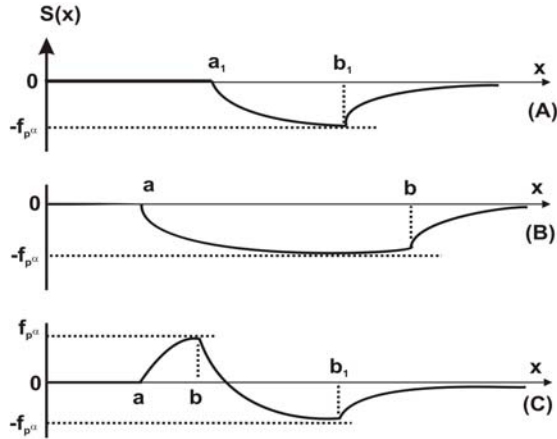


Fig. 8. Distributions of shear tractions for loading from (P1, Q1): (A)-Initial distribution; (B)-regime I; (C)-regime II; (Regimes are detailed by Dundurs and Comninou (1983).

It may not be necessary to find the integral solution because the solution, $y_p(t)$, will always contain the term “ $\sin(at)$ ”. That means in pre-slip situations, there is always more than one oscillation frequency (different numbers of fluctuation cycles) in the tactile array. One frequency is derived from the solution of $y_c(t)$, another from the solution of $y_p(t)$.

During prehension, the tactile sensor surface retracts in accordance to the object shape. Pre-slip causing tangential force components affects only certain tactile elements. To rapidly measure the pre-slip signal during prehension the computer memory may be organized in stacks. Locations $T_1, T_2, \dots, T_n$ hold information from tactile sensors in the form of $\bar{x}$ -bar (average x-axis coordinate of force) and $\bar{y}$ -bar, vibrating location, and vibration frequency (number of sensed vibrating waves). The subscript of T is the time of data collection - the number with the highest value in the stack being the most recent one.

To compare stack data, indexes (pointers) called ‘index 1’ and ‘index 2’ are used to scan the data. Index 1 locates the starting point of the scan or the oldest stored data, whereas index 2 locates the finishing point of the scan or the current data. The data located by index 1 is compared with those located by index 2. Index 2 values are continually compared with Index 1 and decreased until the latest data is located. The location of index 1 is repeatedly

scanned until index 2 locates the oldest stored data which means that the process is complete.

For the first experiment, there are three conditions which successfully indicate pre-slip. The first one is differences in vibrating tactile element location determined by different stack pointers. The second one is equal frequency of vibration determined by different stack pointers. The last condition is that the first two conditions are simultaneously true for both sides of gripper. For the second experiment, there are four conditions, which indicate pre-slip if they are true. The first one is unequal in $\bar{x}$ -bar and $\bar{y}$ -bar coordinates determined by both stack pointers. The second one is the differences in vibrating tactile element location determined by different stack pointers. The third one is the frequency of vibration as determined by higher stack pointers being larger than that determined by lower stack pointers. The final condition is that the first three conditions are simultaneously true on any of the fingers.

4. ANALYSIS OF RESULTS

The GOR experiment has been verified by the accelerometer chip to confirm the sensitivity of proposed algorithm. As shown in figure 9, the accelerometer is attached on the surface of a grasped object. Whenever the grasped object slipped or moved away from the gripper finger, the acceleration sensor would notify. The output vibrations produced by an acceleration sensor and the display were then recorded while the robot decreased its grasping force. The acceleration sensor, SCA3000 chip, is a three-axis accelerometer consisting of a 3D-MEMS sensing element. The sensor offers acceleration information via the SPI interface, and the measurement resolution is $0.75 \text{ mm/s}^2 / 0.04^\circ$. The measured response amplitude was flat within $\pm 2 \text{ m/s}^2$ across. There appeared to be severe mechanical vibrations or acceleration when the grasped object slipped from the finger gripper.

In observing ten trials of experimental results, it can be confirmed that proposed algorithm is faster and more sensitive than the detectability of the acceleration sensor. The ranges of the warning of a slip are three to six decreasing steps before the grasped objects begins slipping and falls down from the gripper finger.

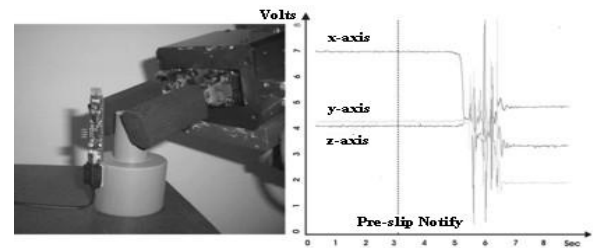


Fig. 9. The GOR experiment evaluated with the acceleration sensor

The robot will vocally warn “I found pre-slip signal” when it finds the pre-slip and then keeps decreasing the grasping force until the grasped object falls down. The impressive results are even when the robot are warning the pre-slip, acceleration sensor does not yet notify any vibrating status. Until the massive slips are happening, then the vibrating status can be captured by acceleration sensor.

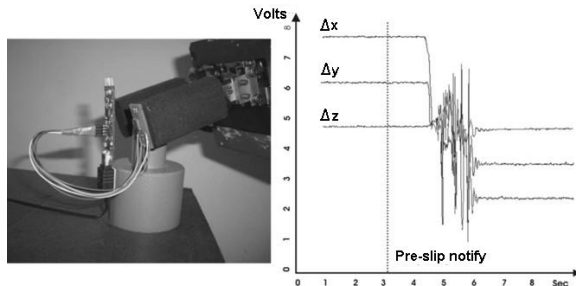


Fig. 10. The GLR experiments evaluated with the acceleration sensor

To verify the GLR experiment with the acceleration sensor, there exists additional steps in-between when the robot senses the pre-slip signal from its finger. In the GLR experiments, pre-slip detection will apply while the grasped objects are being lifted up. The grasped object will slip relatively to the gripper finger, but not to the earth, and hence two acceleration sensors are needed in this case. One accelerometer attached to the grasped object is used to indicate the acceleration of the grasped object relative to the earth. Another accelerometer is also attached to the tip of the robot finger, which indicates the acceleration of the robot finger relative to the earth as well. To notify the slip while lifting up the object, the transformation between two different frames of those sensor's coordination are needed before the slip status can be found in their comparisons. The GLR experiment has been repeated ten times and yielded the same results as the GOR experiment. Every time the robot finds the pre-slip signal, it will verify that signal by decreasing the grasping force until the grasped object falls down. The interval of the decreasing steps is perfectly in range of three and six.

5. CONCLUSIONS

Prevention of premature release and the application of minimum prehension force have been addressed without the need to determine the coefficient of friction between the object and the robot gripper. Predictive models were used to develop a set of rules to predict the pre-slip based on fluctuations in tactile signal data. The tactile is capable of measuring near static acceleration which is interesting to investigate. A proposed method for calibrating the tactile data to the measured pre-slip is useful. Needless to say, should the shapes of the objects used differ from those in these experiments then the global minimum forces obtained may not be the same. However, the

same principle applies and some modifications to the set of rules may be needed to deal with the specific situation.

REFERENCES

- Anand, A. and A. Soom (1984). Roughness-Induced Transient Loading at Sliding Contact During Start-Up. *Journal of Tribology*, Vol. 106, pp. 49-53.
- Cotton, D. P. J., P. H. Chappell, A. Cranny, N. M. White and S. P. Beeby (2007). A Novel Thick-Film Piezoelectric Slip Sensor for a Prosthetic Hand. *IEEE Sensors Journal*, Vol. 7, No. 5, pp. 752-761.
- Dieter, G.E. (1981). *Metalurgia Mecânica*. Mc Graw Hill Inc.
- Dowson, D. (1979). *History of Tribology* Longman Inc., New York.
- Dundurs, J. and M. Comninou (1983). An Education Elasticity Problem With Friction, Part3: General Load Paths. *Journal of Applied Mechanics*, Vol. 50, pp. 77-84.
- Godfrey, D. (1967). Vibration reduced metal-to-metal contact and causes an apparent reduction in friction. *ASLE Transactions*, Vol.10, pp. 183-192.
- Heckl, M. A. and I. D. Abrahams (1996). Active control of friction-driven oscillations. *Journal of Sound and Vibration*, Vol. 193, pp. 417-426.
- Howell, H.G. and J. Mazur (1953). Amontons' Law and Fibre Friction. *Journal of the Textile Institute*, pp. 59-69.
- Howe, R. and M. Cutkosky (1989). Sensing Skin Acceleration of Slip and Texture Perception. *IEEE International Conference on Robotics and Automation*, pp. 145-150.
- Ibrahim, R. A. (1994). Friction-induced vibration, chatter, squeal, and chaos: Part i-mechanics of contact and friction. *Applied Mechanics Reviews*, Vol. 47, pp. 209-226.
- Johansson, R. S. and G. Westling (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher and more slippery objects. *Exp Brain Res*, Vol.56, pp. 550-564.
- Lincoln, B. (1952). Frictional and elastic properties of high polymeric materials. *Apply Physics*, Vol. 3, pp. 260-263.
- Melchiorri, C. (2000). Slip detection and control using tactile and force sensors. *Mechatronics*, IEEE/ASME Transactions on 5(3), pp. 235-243.
- Vellinga, W. P. and C. P. Hendricks (2001). Sliding friction dynamics of hard single asperities on soft substrates. *Physic Review*, Vol. 63, pp: 12-14, 2001.
- Yamada, Y., H. Morita, and Y. Umetani (2000). Slip phase isolating: impulsive signal generating vibrotactile sensor and its application to real-time object regrip control. *Robotica*, Vol.18, issue 1, pp.43-49.