Multifingered Robotic Hands: Contact Experiments using Tactile Sensors

K.K. Choi S.L. Jiang Z. Li

Department of Electrical and Electronic Engineering
Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong, EMail: eezxli@ee.ust.hk

Abstract

Capacitive tactile sensors are constructed and installed to the fingers of the HKUST hands for measurement of position, force and direction of principle curvature of contact point. The hardware and software for signal processing are designed such that the contact information is sent to the motion control computer in real time. Experiments in rolling and sliding contact motions are then performed for testing the functionality of the tactile sensing system in motion control. The measurement of contact velocities obtained from the sensor is also compared with that calculated from the theoretical contact equations. This paper describes the tactile sensing system and the experimental result in contact motion control.

1 Introduction

Tactile sensor is a device for measuring contact position and contact force. Among the different methods of contact sensing [8], capacitive type is relatively robust, easy to construct and inexpensive. A typical block diagram is shown in figure 1. (See Fearing [1]). The actual constructed device consists of 16×16 capacitors, with an effective area of $14.3 \times 14.3 \text{ cm}^2$.

Figure 1: Schematic of Capacitive Tactile Sensor

2 Calculating Contact Information

The co-ordinate of contact point p_c is calculated by:

$$F = \sum_{p \in B_s} (I_p - I_{op})$$

$$p_c = \frac{\sum_{p \in B_s} (I_p - I_{op}) \cdot p}{F}$$

The symbols are defined as follow. S is the set $\{(x, y) \mid x, y = 0, \dots, 15\}$ of co-ordinates of the capacitors. p is the co-ordinate of a particular capacitor ($p \in S$). I_{op} is the amplitude of current flowing through capacitor C_p at no load. I_p is the measured amplitude of current flowing through capacitor C_p during operation. s is the point $\{p \mid p \in S \text{ and } (I_p - I_{op}) \text{ is maximum}\}$ which is the point with maximum increase in current amplitude. B_s is the 7×7 neighborhood of s . F is the contact force.

The summation is performed within B_s only in order to save computation time. In the above calculation, we have assumed a co-ordinate frame with the origin placed on the capacitor with index $(0, 0)$. The x axis is parallel to the direction of copper stripes in the top layer and the y axis is perpendicular to the x axis. The distance between two adjacent capacitors which are located along a line parallel to either axis is one unit. Initial calibration shows that the relationship between F and the applied load is linear.

If the region of the object surface in contact with the sensor is round shaped, the set of capacitors providing active (above idle) signals will be located within an elliptic region. In the extreme case, if a sharp edge is in contact with the sensor, the set of capacitors providing active signals will be located along a line. The following procedure is used to calculate the parameters of the ellipse of the contact region. Let

$$\begin{aligned}
N &= (\cos\theta, \sin\theta)^t = \text{Unit tangent vector} \\
&\quad \text{emerging from point } p_c \text{ of the sensor.} \\
\theta &= \text{Angle between } N \text{ and the } x \text{ axis.} \\
(x_c, y_c)^t &= \text{Co-ordinate of } p_c \\
(x, y)^t &= \text{Co-ordinate of } p
\end{aligned}$$

Define

$$\begin{aligned}
H &= \sum_{p \in B_s} (I_p - I_{op}) \cdot ((p - p_c)^t \cdot N)^2 \\
&= \sum_{p \in B_s} (I_p - I_{op}) \cdot ((x - x_c) \cdot \cos\theta + (y - y_c) \cdot \sin\theta)^2 \\
&= A \cdot \cos^2\theta + 2B \cdot \sin\theta \cos\theta + C \cdot \sin^2\theta
\end{aligned}$$

where

$$\begin{aligned}
A &= \sum_{p \in B_s} (I_p - I_{op}) \cdot (x - x_c)^2 \\
B &= \sum_{p \in B_s} (I_p - I_{op}) \cdot (x - x_c) \cdot (y - y_c) \\
C &= \sum_{p \in B_s} (I_p - I_{op}) \cdot (y - y_c)^2
\end{aligned}$$

H is the weighted sum of square of projection onto N of vectors from p_c to mid-points of active capacitors within the contact region. If vector N points in the direction of the major or minor axis of the ellipse, then H should be either maximum or minimum. Setting $\frac{dH}{d\theta} = 0$ and solving for θ , we get

$$\theta = \arctan\left(\frac{2B}{A - C}\right)$$

The angles θ and $\theta + \pi/2$ are the direction angles of the major and minor axis of the elliptic contact region on the tactile sensor. Let H_{max} be the value of H of the major axis and H_{min} be that of the minor axis. Under the same applied load, a higher value of H_{max} and H_{min} means that the contact surface has smaller principle curvatures. In a typical experiment, spherical objects of different radius R are placed onto the sensor and pressed until the reading of F is 10,000. The value of H_{max} is then recorded. The relationship between H_{max} and R is plotted in figure 2. The spherical objects are not equally rigid and deform differently at the contact points. Hence, the effective radius are different from the measurement. This causes the fluctuation in the result.

The ratio $r = \frac{H_{max}}{H_{min}}$ can provide a rough idea of the shape of the object surface in contact. If $r = 1$, the contacting surface is similar to that of a sphere. A huge value of r means that sensor is in contact with an edge. The angle θ of H_{max} is the direction angle of the major axis which can also be thought of as the direction of the minor principle curvature of the object

Figure 2: H_{max} and radius of spherical objects.

surface around the contact point. An experiment is performed in which an American football is placed onto a planar sensor and rotated horizontally. The change in calculated θ and the actual change in angle of rotation of the football is compared. The result is shown in figure 3. The accuracy of the calculated θ is good only if the contact area is large with significant number of active capacitors. In the experiment, extra weight (900 g) is added to the American football for increasing the contact force and the contact area.

Figure 3: Measurement of American football rotation

3 Contact Experiment

3.1 Rolling Motion

An experiment is performed to test the co-ordination of robot motion in contact with curved surface using tactile sensing. An American football is placed on a table. One of the robot arm of the HKUST hands [9] with a flat tactile sensor installed in the tool frame is

then programmed to touch the football. The tactile sensor then rolls in the direction of minor principle curvature of the American football. The co-ordinate of contact point and the direction of minor principle curvature measured from tactile sensor are used in real time for controlling the motion. The following is the algorithm of the rolling motion.

Initialize G_t with initial tool frame.

```

Repeat
{
  if (  $F \in D$  )
  {
     $v = (\cos \theta \quad \sin \theta \quad 0)^t$ 
     $n = (0 \quad 0 \quad 1)^t$ 
     $h = v \times n = (-\sin \theta \quad \cos \theta \quad 0)^t$ 
     $h' = (-\sin \theta \quad \cos \theta \quad 0 \quad 1)^t$ 
     $\omega = G_t.G_s.h' = (\omega_x \quad \omega_y \quad \omega_z \quad 1)^t$ 
     $\hat{\xi} = \begin{pmatrix} 0 & -\omega_z & \omega_y & 0 \\ \omega_z & 0 & -\omega_x & 0 \\ -\omega_y & \omega_x & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ 
     $G_t = G_t.G_s.e^{\hat{\xi}\phi}.G_s^{-1}$ 
  }
  else
  {
     $G_t = G_t + k_F.(F_d - F).G_t.G_s.(0 \quad 0 \quad 1 \quad 1)^t$ 
  }
  Move to  $G_t$ ;
  Delay 0.1 second;
}

```

The symbols are defined as follow. k_F is a constant. D is the range of desired contact force. F_d is the desired value of contact force. F is the measured value of contact force. θ is the measured angle between direction of minor principle curvature of object contact point and the x axis of contact frame on tactile sensor. v is the direction vector of object minor principle curvature in the sensor contact frame. n is the outward normal vector of the contact point on the sensor surface in the sensor contact frame. h is the axis of rotation around the contact point in the sensor frame. ω is the axis of rotation around the contact point in the world frame. ϕ is the angle of rotation in each step, which is set to $\pi/720$. G_s is the transformation matrix from the tool frame to the sensor contact frame. G_t is the transformation matrix from the world frame to the tool frame. It is also the target configuration of the tool frame ($G_s, G_t \in SE3$).

The robot repeatedly moves the tool frame G_t such that the sensor moves in the direction of the normal axis of contact until the contact force is within the desired range. Afterwards, the sensor will rotate around the

contact point for a small angle. The axis of rotation h is the vector of major curvature on the object at the contact point. The mixed sequence of contact force adjustments and small rotations build up the rolling motion.

3.2 Contact Equations

In order to show how well the tactile sensor measures the dynamic contact point, the motion data is tested with the contact equations derived by Montana [7]. The contact equations are:

$$\begin{aligned}
 \dot{p}_s &= M^{-1}(K_o + K_s)^{-1} \left(\begin{bmatrix} -\omega_y \\ \omega_x \end{bmatrix} - K_o \begin{bmatrix} v_x \\ v_y \end{bmatrix} \right) \\
 \dot{p}_o &= (K_o + K_s)^{-1} \left(\begin{bmatrix} -\omega_y \\ \omega_x \end{bmatrix} + K_s \begin{bmatrix} v_x \\ v_y \end{bmatrix} \right) \\
 \dot{\psi} &= T(K_o + K_s)^{-1} \left(\begin{bmatrix} -\omega_y \\ \omega_x \end{bmatrix} - K_o \begin{bmatrix} v_x \\ v_y \end{bmatrix} \right) + \omega_z \\
 0 &= v_z
 \end{aligned}$$

The velocity $V_s = (\omega_x \quad \omega_y \quad \omega_z \quad v_x \quad v_y \quad v_z)^t$ is the body velocity of the sensor relative to the object in the contact frame. $\omega_s = (\omega_x \quad \omega_y \quad \omega_z)^t$ is the angular velocity of the sensor and $v_s = (v_x \quad v_y \quad v_z)^t$ is the linear velocity. K_o is the curvature form at the contact point of the object and K_s is the curvature form at the contact point of the sensor. Both of the curvature forms are relative to the contact frame. p_s is the contact co-ordinate of the sensor in the sensor frame and p_o is the contact co-ordinate of the object.

$$\begin{aligned}
 M &= \begin{pmatrix} \|f_u\| & 0 \\ 0 & \|f_v\| \end{pmatrix} \\
 T &= \begin{pmatrix} \frac{f_v \cdot f_{uu}}{\|f_u\|^2 \cdot \|f_v\|} & \frac{f_v \cdot f_{uv}}{\|f_u\| \cdot \|f_v\|^2} \end{pmatrix}
 \end{aligned}$$

f_u and f_v are the vectors of co-ordinate axes of sensor frame at the contact point relative to the tool frame.

The tool frame is located at the centre of the sensor surface with its x and y axes parallel to the surface. We use a rectangular co-ordinate chart on the flat sensor surface for each contact point such that the co-ordinate of sensor contact point relative to the tool frame is $(u \quad v \quad 0)$. The orientation of the contact frame is always identical to that of the tool frame. f_u and f_v are then constant orthonormal unit vectors. Hence, M is the identity matrix. K_s and T are zero matrices and $\dot{\psi} = \omega_z$.

Imagine a plane passing through the two vertices of the American football. The plane intersect the football at a curve which is a portion of a circumference of a big circle. The tangent vector of the curve is always in

the direction of minor principle curvature. The radius of the circle is estimated to be 180 mm and hence the minor principle curvature $k_{x'}$ of the American football is $1/180$. Imagine again a line joining the two vertices of the football. A plane normal to the line will intersect the football in a smaller circle C . The major curvature is then estimated to be $1/r$ where r is the radius of the small circle C . We call this second curvature $k_{y'}$. The value of r is computed from the position of contact in the world frame.

In the contact equations, K_o is measured in the frame with the x and y axes in alignment with that of the sensor contact frame. Using the measured angle θ between the axis of the minor curvature and the x axis of the sensor contact frame, the object curvature form at each contact point is computed as follow.

$$\begin{aligned} B &= \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \\ K' &= \begin{pmatrix} k_{x'} & 0 \\ 0 & k_{y'} \end{pmatrix} \\ K_o &= B^t K' B \end{aligned}$$

The data of sensor motion is sampled such that $G_t(t_n)$ is the tool frame relative to the world frame at time t_n where n is the sampling index. Let $p_s(t_n) = (p_{sx}(t_n), p_{sy}(t_n))$ be the measured sensor contact co-ordinate at time t_n . From $p_s(t_n)$, the sensor contact frame $G_s(t_n)$ relative to the tool frame at time t_n is given by:

$$G_s(t_n) = \begin{pmatrix} 1 & 0 & 0 & p_{sx}(t_n) \\ 0 & 1 & 0 & p_{sy}(t_n) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The configuration $G(t_n)$ of the contact point relative to the world frame at time t_n is then given by $G(t_n) = G_t(t_n).G_s(t_n)$. At time t_{n+1} , the configuration of the original contact point on the sensor at time t_n will have moved to $G_p(t_{n+1})$ where $G_p(t_{n+1}) = G_t(t_{n+1}).G_s(t_n)$. The sensor body velocity $V_s(t_n)$ relative to the object in the contact frame at time t_n is then given by:

$$\begin{aligned} \widehat{V}_s(t_n) &= G(t_n)^{-1} \frac{(G_p(t_{n+1}) - G(t_n))}{\delta t_n} \\ &= \begin{pmatrix} 0 & -\omega_z & \omega_y & v_x \\ \omega_z & 0 & -\omega_x & v_y \\ -\omega_y & \omega_x & 0 & v_z \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{aligned}$$

where $\delta t_n = t_{n+1} - t_n$. Hence, the sensor velocity $V_s(t_n) = (\omega_x \ \omega_y \ \omega_z \ v_x \ v_y \ v_z)^t$ is computed.

The velocity of object contact point co-ordinate is estimated by the actual distance traveled in the sensor

frame, assuming that the object is static relative to the world frame. Let $\dot{p}_o(t_n) = (\dot{p}_{ox}(t_n) \ \dot{p}_{oy}(t_n))$ be the object contact velocity at time t_n . Let the x, y axes of $G(t_n)$ be $f_x(t_n), f_y(t_n)$ and the position vector of the origin of $G(t_n)$ be $q(t_n)$. Then,

$$\begin{aligned} \dot{p}_{ox}(t_n) &= \frac{1}{\delta t_n} (q(t_{n+1}) - q(t_n))^t \cdot f_x(t_n) \\ \dot{p}_{oy}(t_n) &= \frac{1}{\delta t_n} (q(t_{n+1}) - q(t_n))^t \cdot f_y(t_n) \end{aligned}$$

For each sample, the velocity and curvature values are calculated assuming $\delta t_n = 1 \ \forall n$. The values are then substituted into the contact equations for comparing with the expected $\dot{p}_o(t_n)$ and $\dot{p}_s(t_n)$. The result is shown in the following figures.

3.3 Rolling Contact

Figure 4 and figure 5 show the contact point velocities of the sensor ($\dot{p}_s$) and object ($\dot{p}_o$) in rolling motion. The graphs show close match of velocities measured from tactile sensor and that calculated from the contact equations.

Figure 4: Sensor Contact velocity of rolling motion.

Notice that the object contact velocity is very close to the sensor contact velocity. This is a special case of rolling motion when the same chart are used in the sensor frame and the object frame at the contact. The measured v_z is very small when compared to the contact velocity. This also agrees with the contact equations.

Figure 6 shows the comparison of calculated $\dot{\psi}$ and measured $\dot{\psi}$ in rolling motion. In ideal rolling motion, $\dot{\psi}$ should be zero. The figure shows that the $\dot{\psi}$ measured from tactile sensor varies with a mean value close to the $\dot{\psi}$ calculated from the contact equations.

Figure 7 shows the loci of sensor contact point and object contact point in rolling motion. Both loci agree

Figure 5: Object Contact velocity of rolling motion.

Figure 7: Loci of contact points in rolling motion.

Figure 6: Contact angular velocity.

Figure 8: Sensor contact velocity of sliding motion.

with that of rolling motion as the contact points move in both cases.

3.4 Sliding Contact

Another similar experiment is performed in which the sensor is programmed to slide on the American football in the initial direction of minor principle curvature. The algorithm of motion control is similar to that of rolling with the addition of sensor contact point position adjustment in each loop. The ultimate sequence of tool frame configurations are sampled and recorded. The comparison of the motion with that of the contact equations is shown in the following figures.

Figure 8 and figure 9 show the comparison of calculated and measured contact point velocities in sliding motion. In figure 8, both the measured and calculated $\dot{p}_s$ vary around zero since $\dot{p}_s$ should be zero for ideal sliding motion.

Figure 9 shows the comparison of calculated $\dot{p}_o$ and measured $\dot{p}_o$ in sliding motion. The figure shows bet-

ter match between the velocities computed from tactile measurement and that computed from contact equations. The actual motion consists of small sequential steps of rolling and sensor contact point adjustments. This causes extra interference to the motion of ideal sensor contact frames. Again, notice the small values of v_z which are in close match to the contact equations.

Figure 10 shows the comparison of calculated $\dot{\psi}$ and measured $\dot{\psi}$ in sliding motion. Similar to that of the rolling motion, the $\dot{\psi}$ from contact equation is near zero while that from tactile measurement varies with zero mean.

Figure 11 shows the loci of sensor contact point and object contact point in sliding motion. In the sliding motion, the sensor contact point oscillates around the initial contact location while the contact point moves along on the object surface.

The figures show that the measurements from the tactile sensor agree with that calculated from the Montana's contact equations.

Figure 9: Object contact velocity of sliding motion.

Figure 10: Contact angular velocity of sliding motion.

4 Conclusion

This paper presents the capacitive tactile sensor system of the HKUST hands. The signal processing operates in high speed which enables it to provide tactile information for real time motion control. Results of robot motion experiments in contact rolling and sliding utilizing the tactile signals are presented. The calculations of contact velocities based on the measurements from the tactile sensors agree with that derived from Montana's contact equations.

5 Acknowledgment

The authors would like to express their thanks to Professor R. Fearing and Mr. K. Kim of U.C. Berkeley who provided invaluable instructions and help in the construction of the tactile sensors.

Figure 11: Loci of contact points in sliding motion.

References

- [1] R.S. Fearing, "Tactile Sensing, Perception, and Shape Interpretation", PhD. dissertation, Department of Electrical Engineering, Stanford University, Dec 1987
- [2] R.S. Fearing, "Some Experiments with Tactile Sensing During Grasping", in Proceeding IEEE International Conference, Robotics, Automation, April 1987, pp. 1637-1643.
- [3] E. J. Nicolson, "Tactile Sensing and Control of a Planar Manipulator", PhD. dissertation, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, 1994.
- [4] Richard M. Murray, Zexiang Li and S. Shankar Sastry, "A Mathematical Introduction to Robotic Manipulation", CRC Press, 1994.
- [5] Zexiang Li, Ping Hsu and S. Shankar Sastry, "Grasping and Coordinated Manipulation by a Multifingered Robot Hand", The International Journal of Robotics Research, Vol 8, No. 4, Aug 1989.
- [6] David J. Montana, "The Kinematics of Multi-fingered Manipulation", IEEE Transaction on Robotics and Automation, Vol 11, No. 4, Aug 1995.
- [7] David J. Montana, "Tactile Sensing and the Kinematics of Contact", PhD. dissertation, Division of Applied Science, Harvard University, 1986.
- [8] Howard R. Nicholls, "Advanced Tactile Sensing for Robotics", World Scientific, 1992.
- [9] Y. S. Guan, Z. X. Li and Q. Shi, "Dextrous Manipulation with Rolling Contacts", ICRA' 1997, vol 2, pp. 992-997.
- [10] Jae S. Son and Robert D. Howe, "Tactile Sensing and Stiffness Control with Multifingered Hands", ICRA' 1996, Vol 4, pp. 3228-3233.
- [11] H. Zhang, H. Maekawa, K. Tanie, "Sensitivity Analysis and Experiments of Curvature Estimation Based on Rolling Contact", ICRA' 1996, Vol. 4, pp. 3514-3519.