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Design and Analysis of a Collision Detector for Hybrid Robotic Machine Tools

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Abstract: Capacitive sensing depends on the physical parameter changing either the spacing between the two plates or the dielectric constant. Based on this idea, a capacitive based collision detection sensor is proposed and designed in this paper for the purpose of detecting any collision between the end effector and peripheral equipment (e.g., fixture) for the three degrees of freedom hybrid robotic machine tools when it is in operation. One side of the finger-like capacitor is attached to the moving platform of the hybrid robotic manipulator and the other side of the finger-like capacitor is attached to the tool. When the tool accidently hits the peripheral equipment, the vibration will make the distance of the capacitor change and therefore trigger the machine to stop. The new design is illustrated and modelled. The capacitance, sensitivity and frequency response of the detector are analyzed in detail, and finally, the fabrication process is presented. The proposed collision detector can also be applied to other machine tools. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Machine tools, Collision detection, Sensor, Capacitance, Vibration, Modelling.

1. Introduction

A capacitor is defined as two conductors that can hold opposite charges. If the distance and relative position between two conductors change due to the external force, the capacitance value will be changed. This is the basic principle of capacitive sensing, which belongs to electrostatic sensing. The major advantages of electrostatic sensing can be concluded as follows, firstly, it is simple. No special functional materials (such as piezoresistive and piezoelectric materials) are required. The sensing principle is easy to implement, requiring only two conducting surfaces. Secondly, it has the characteristic of fast response. Capacitor-based sensing has high response speed due to the fact that the transition speed is controlled by the charging and discharging time constants that are small for good conductors [1-2]. There are two kinds of capacitive electrode geometries: parallel plate capacitor and interdigitated finger capacitor. For the interdigitated finger capacitor, it can be regarded as many parallel plate capacitors combining together. One side of the finger is fixed and the other side is suspended and can move in one or more axes.

Parallel mechanisms have been widely used in different kinds of areas [3-4], such as machine tools as shown in Fig. 1. Parallel robotics machine tools are the new trend for the manufacturing and automations. When machine tools are in operations, it is sometimes unavoidable to hit the peripheral equipment (e.g. fixture) by the tool, which can damage cutting tools, clamps and fixtures, or cause damage to the machine itself as shown in Fig. 2, which undermines the performance of the whole parallel robotic system and delays the productions.

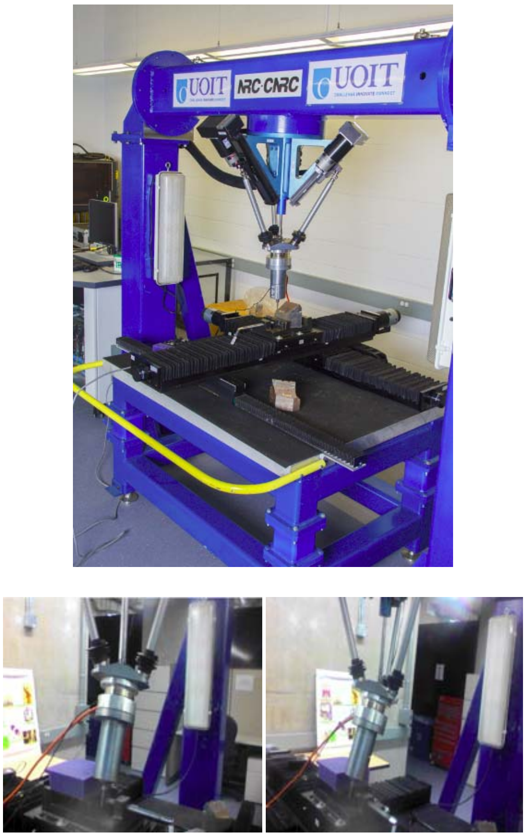


Fig. 1. 3-DOF parallel robotic machine tool developed in the R&A Lab in UOIT.

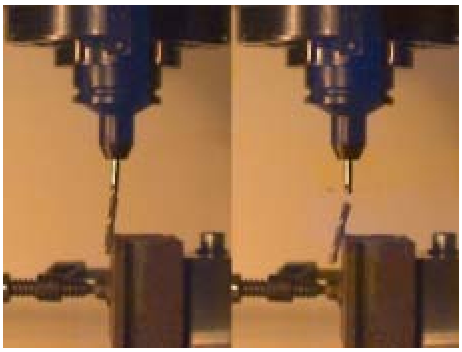


Fig. 2. Collision occurred during machining [10].

Therefore, how to prevent the collisions during machining is very important for machining processes. When the end-effector/tool of parallel robotic machine tool accidently hits the peripheral equipment, e.g. fixture, in a better case scenario, say an operator finds it and hits the emergency stop button, then sometimes it is too later. The machine tool should ideally stop immediately when the tool hits the peripheral equipment and stop causing further damage [5]. Based on this need and motivation, a sensor should be developed to address this goal. Some computer aided manufacturing software have the ability to perform a machine collision check, but some machine tools do not have this function. Most computer aided manufacturing programs determine the cutter paths considering sometimes just the tool. In machine tools, it is likely to drive the end effector outside the bounds, resulting in a collision with others. Many machine tools do not aware about the surrounding environment. The end effector just follows the code and it is totally dependent on an operator to detect if a crash occurs.

Let us image the following, when the tool hits the fixture, it is a collision, then there should be a vibration produced, so how can we harness this vibration and convert the vibration to an electrical signal that can be recognized by a computer. Capacitive based sensor depends on the physical parameter changing, e.g. the space between the plates and the dielectric constant between them, etc. For example, in the vehicle air bag deployment system, a crash acceleration makes one plate closer to the other and therefore trigger the bag to deploy. Inspired by this idea, we design a capacitance-based collision detector/sensor that can sensor the vibration and convert the vibration to an electrical signal.

In [6], vibration on a rotating spindle is generated by the sum of the variations in weight distribution. The corrective action is needed to have a force with an equal but opposite direction to cancel the imbalance condition. The first step to achieve this is to measure the vibration. There, a vibration sensor is installed in a grinding machine spindle, and the vibration is measured using a vibration sensor that is composed of a seismic mass that is connected to a piezoelectric transducer which converts the vibration into an electric signal. The above one is mainly measure the amount of vibration that the rotating spindle produced and it is not appropriate to use here as a collision detector. In [7], the chatter vibration is detected by using three different acceleration sensors that attached to three different axis of machine tool. In [8], a web learning tool with 3D simulation for axial table collision detection was proposed, but no device has been designed. In [9], a vibration detection algorithm was proposed and a speed regulator was designed for the backlash vibration of a machine tool. In [10], a new approach was presented to detect and avoid hard and soft collisions caused by user errors, and a capacitance based sensor was briefly mentioned for the collision of the machine tools, but it did not explicitly design and propose the capacitance based collision sensor. In [11], a six-dimensional wrist force/torque sensor based on E-type membranes is designed and fabricated, and it is applied onto the five-axis parallel machine tool to measure the tool forces and torques, previous one is force/torque sensor (used to detect forces and moments), but that is not a vibration sensor.

In this paper, a collision detection sensor is designed that can sense the vibration that the end-effector caused when the tool accidently hits the fixture. When the tool accidently hits the ground or something, it will produce vibration, the vibration will make the distance of the capacitor change and therefore trigger the machine to stop immediately. No one has ever designed the collision detector that gears towards the situation that the machine tool should stop immediately when the end-effector hits the peripheral equipment.

The structure of the paper is as follows. In Section 2, the new design will be illustrated. The capacitance and sensitivity will be discussed in Section 3. Section 4 analyzes the resonant frequency of the detector, and finally fabrication process is presented in Section 5.

2. New Design

Capacitive sensing depends on the physical parameter changing either the spacing between the two plates or the dielectric constant. Our vibration sensing method is based on this idea. Capacitive sensing needs external electronics to make the changes in capacitance to an output voltage that can be read by a computer.

One side of the finger-like capacitor is attached to the moving platform of the hybrid robotics manipulator and the other side of the finger-like capacitor is attached to the tool. When the tool accidently hits the ground or something, it will vibrate and the distance between the fingers will change and therefore, the capacitance will change and trigger the machine to stop. The capacitance between a pair of fingers is contributed by the surface of fingers in the overlapped region. Capacitance derived from multiple pairs are connected in parallel, so the total capacitance is the summation of capacitance contributed by neighboring fingers.

3. Capacitance and Sensitivity

For a single fixed finger and its two neighboring moving fingers. There are two capacitances associated with each finger pair, one is the left-side of the finger, denoted as C_l , and the other is the right-side of the finger, denoted as C_r . When the tool is not vibrating, the values of these two capacitance is the same, i.e.:

$$C_l = C_r = \frac{\varepsilon_0 lt}{d}, \tag{1}$$

where ε_0 is the permittivity of the vacuum, l is the engaged overlapping distance of the fingers, t is the thickness of the fingers, d is the distance between a fixed-comb finger and its neighboring movable finger.

3.1. Movement Along y Direction

When the tool accidently hits the fixture, the tool will vibrate, the free finger will move by a distance, say x, and then the capacitance values of these two capacitors become the following:

$$C_l = \frac{\varepsilon_0 lt}{d-x} \tag{2}$$

and

$$C_r = \frac{\varepsilon_0 lt}{d+x} \tag{3}$$

The total value of capacitance is:

$$C = C_l + C_r = \frac{\varepsilon_0 lt}{d-x} + \frac{\varepsilon_0 lt}{d+x} = \frac{2d\varepsilon_0 lt}{d^2-x^2} \tag{4}$$

For a case study, suppose there are 13 fingers, which means there are 12 capacitors, so the 12 capacitors will contribute the total capacitance of the device. So the above can be rewritten as follows:

$$C = 12\frac{2d\varepsilon_0 lt}{d^2-x^2} \tag{5}$$

This change can be transferred to the electrical signal, and under a certain value, then it means the machine tool is in the process of manufacturing, even though there is small vibrations, the capacitance change is under that value, the capacitance will not trigger the electrical controller to stop the machine, but when the capacitance change is very large, then the capacitor will trigger the controller to stop the machine immediately. This is under the condition that when the pieces are softer than fixture. When the pieces are stiffer than fixture, then we need to set the condition that when the capacitance under that value, then the capacitor needs to trigger the controller to stop the machine, and when the vibration is above that value, then let the capacitor not trigger the controller to stop the machine. It can also be put as this way, under certain value range, the capacitance change is not sensitive (big) enough to trigger the controller to stop the machine, which is under the condition that the piece is softer than fixture. And also that certain value needs to be determined by experimentation.

If: C= 12 $\frac{2d\varepsilon_0 lt}{d^2-x^2}$ < Value 1

Value 1 needs to be determined by experiment.

The capacitor will not trigger the controller to stop the machine

If: C= 12 $\frac{2d\varepsilon_0 lt}{d^2-x^2}$ > Value 1

The capacitor will trigger the controller to stop the machine.

Above certain value range, the capacitance change is not sensitive (small) enough to trigger the controller to stop the machine, which is under the condition that the piece is stiffer than fixture. And also that certain value needs to be determined by experimentation.

$$\text{If: } |C = 12\frac{2d\varepsilon_0 lt}{d^2 - x^2}| < |\text{Value } 1|$$

The capacitor will not trigger the controller to stop the machine.

$$\text{If: } |C = 12\frac{2d\varepsilon_0 lt}{d^2 - x^2}| > |\text{Value } 1|$$

The capacitor will trigger the controller to stop the machine.

Set the decision logic to certain value, decision logic will receive a signal from the capacitor/sensor to determine if it is actually manufacturing or collision. We can set the logic to negative value when the pieces are stiffer than fixture, it is like a mathematic logic. The sensor will not decide if the contact is the beginning of a collision or simply defines the manufacturing pieces. This is the function of the decision logic [6], and set certain value to the logic, if the value larger or smaller than certain value that was given to the logic, then the detector/sensor will trigger the machine to stop or not to stop, it is related to the decision logic module design, which has been out of author's research scope, and can be done as a future work. This report is mainly proposes the idea that use the capacitive principle based method to design the collision sensor.

In terms of when the cutting tool breaks the moment it hits the fixture, this must be the condition that the fixture is harder than the piece, if the piece is harder than the fixture, then the tool will also break when manufacturing pieces, so it is not realistic at all, so the pieces must be softer than fixture at than case. If it is in that case, as being said above, i.e. under certain value range, the capacitance change is not sensitive (big) enough to trigger the controller to stop the machine when the tool is in the process of manufacturing. And also that certain value needs to be determined by experiment. Ideally, when the tool hit the fixture, the detector/sensor will trigger the machine to stop immediately, so the tool will not break. Say a worst case scenario, the tool breaks, the capacitance will also change, so it will trigger the machine to stop. Either way, no matter the tool breaks or not, if the capacitance change is above that value, then it will trigger the machine to stop.

However during motions, the rate of capacitance change can be measured, this rate of change can also be called the displacement sensitivity, it is obtained by taking the derivative of C with respect to x, and we can have the following,

$$S(x) = \frac{\partial C}{\partial x} = \frac{48d\varepsilon_0 ltx}{(d^2 - x^2)^2} \tag{6}$$

The above is under the movement along the y direction (transverse). Transverse comb drive devices are frequently used for sensing for the sensitivity and they are ease of fabrication.

3.2. Movement Along x Direction

When the movement is along the x direction, we have the following, please note that the movement along z direction is very small or none because the suspension beam is along the z direction which blocks the movement along z direction. There are 13 fingers, which means there are 12 capacitors, so the 12 capacitors will contribute the total capacitance of the device. At rest, the total capacitance is:

$$C = 12\frac{\varepsilon_0 lt}{d} \tag{7}$$

When there is force in x direction, which will make the fingers move in the x direction, and therefore will cause the effective thickness t' to change. Suppose the change value is x, under the above changed condition, the capacitance will change to the following:

$$C = 12\frac{\varepsilon_0 l(t - x)}{d} \tag{8}$$

The relative change of capacitance w.r.t. displacement x (i.e. displacement sensitivity, or the change of capacitance as a function of applied displacement) can be expressed as follows:

$$\frac{\partial C}{\partial x} = -\frac{12\varepsilon_0 l}{d} \tag{9}$$

4. Frequency Response

The device can be seen as a fixed-free cantilever beam, and the resonant frequency can be expressed as:

$$f_1 = \frac{1.732}{2\pi}\sqrt{\frac{EIg}{Fl_1^3}} \tag{10}$$

$$I = \frac{\mathrm{w}t^3}{12} \tag{11}$$

There are two suspension beams, so the force/spring constant can be expressed as follows [1]:

$$F = k \cdot x \tag{12}$$

$$k = 2 \times \frac{Ewt^3}{4l_1^3} \tag{13}$$

Plug in the above F and I, resonant frequency can be finally derived as follows:

$$f_1 = \frac{1.732}{2\pi}\sqrt{\frac{EIg}{Fl_1^3}} = \frac{1.732}{2\pi}\sqrt{\frac{g}{6x}}, \tag{14}$$

where l_1 is the suspension beam length. E is the Young's modulus. w is the width of the finger, t is the thickness of the finger. The resonant frequency value is depend on the above parameters, different parameter will result different values.

5. Fabrication

Silicon bulk micromachining is the process that involve partial removal of bulk material in order to create three dimensional structures or free suspended devices. Etching a subtractive process that remove materials. Etching can be divided into two categories, one is wet etching and the other is dry etching. For the wet etching, the liquid etchants can be acids and hydroxides; for the dry etching, we have the physical etching (impact of atoms/ions), reactive ions and enhanced by RF energy. And also isotropic etching can give rounded profiles and anisotropic etching can yield flat surfaces.

Prototyping and fabrication processes are illustrated in the Fig.3-7. If we draw a vertical line that cuts across both sets of fingers in Fig. 3, we will get the cross section as shown in Fig. 6. Here we only drew two of the 13 fingers in the cross section for the purpose of clearly illustrating the fabrication process. These are the two floating rectangles in final step.

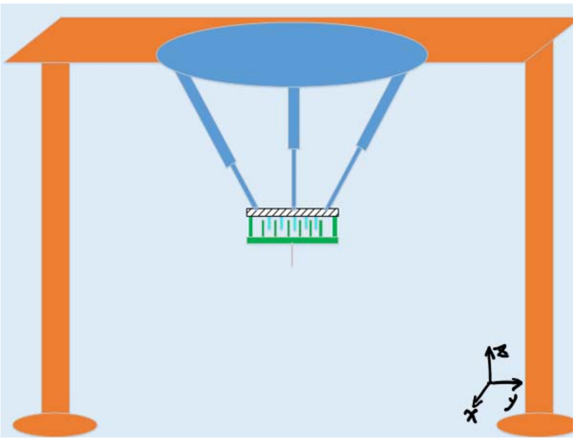


Fig. 3. Vibration detector/sensor used in 3-DOF hybrid robotic manipulator.

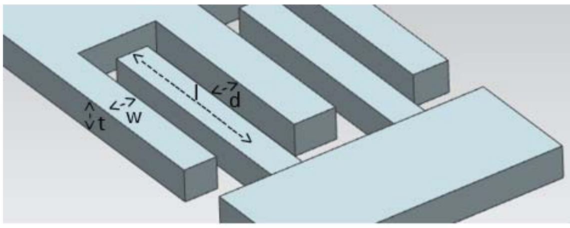


Fig. 4. Dimensions of the detector.

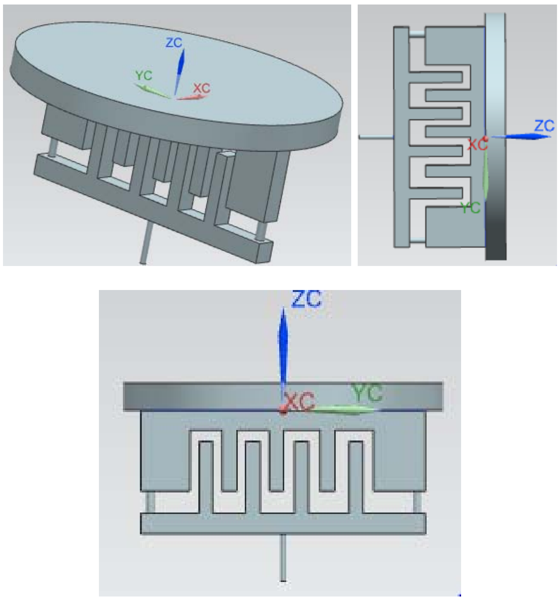


Fig. 5. Capacitance based collision detector.

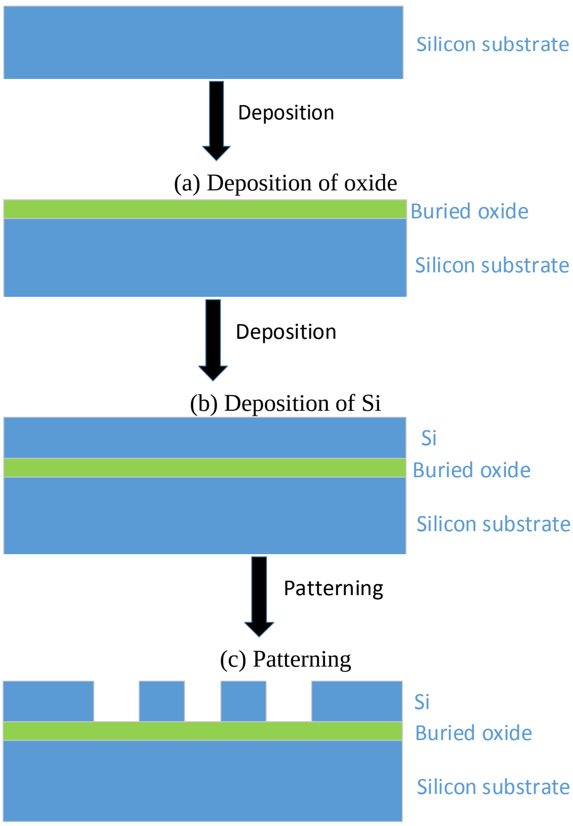


Fig. 6. Fabrication process.

And

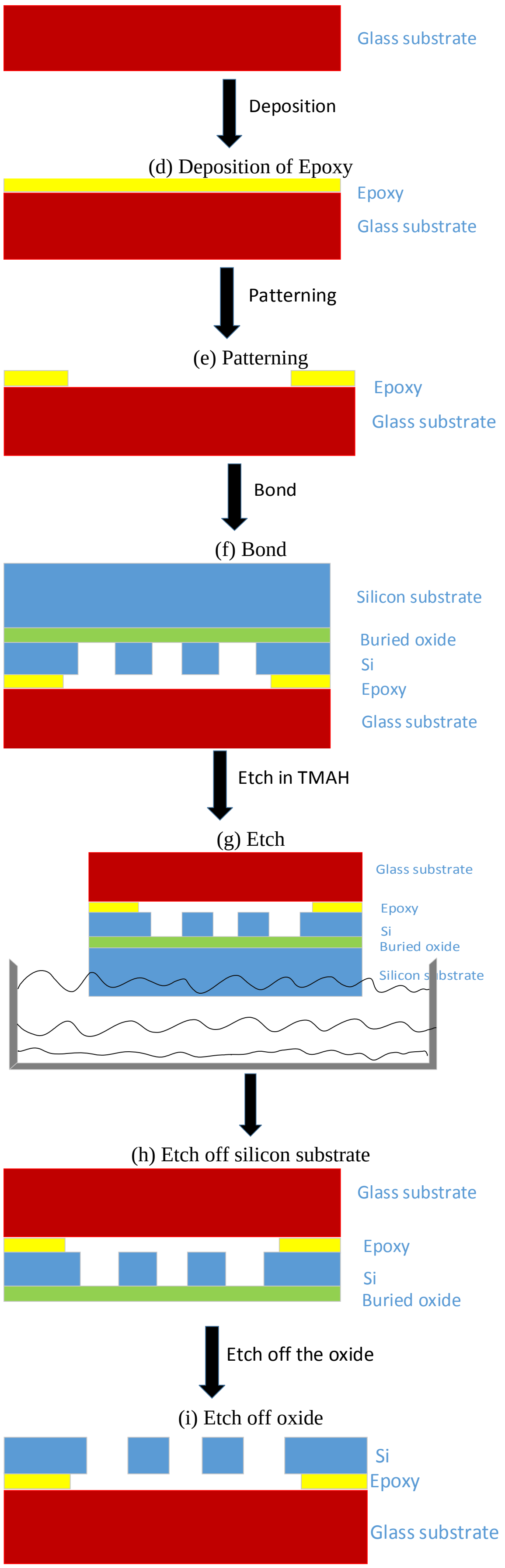
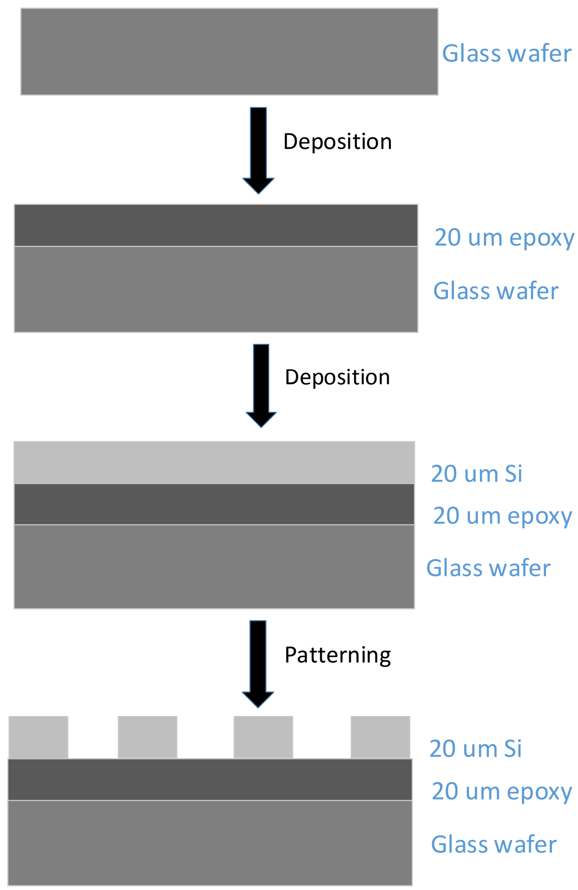


Fig. 6. Fabrication process (Continued).

Fabrication method 2:



The epoxy is etched in an oxygen plasma (dry etching), which undercuts the silicon to free the moving parts;

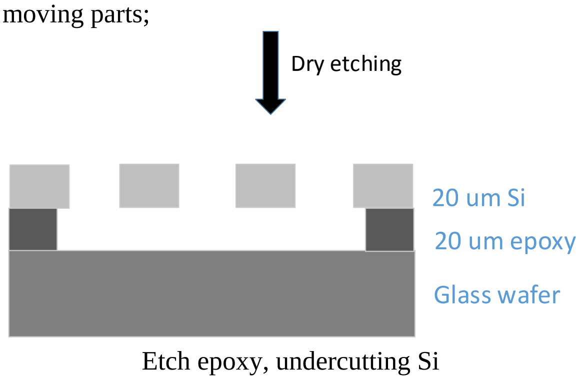


Fig. 7. Fabrication process.

Compared with parallel-plate capacitors, the capacitance between two neighboring set of fingers are relatively small. However, one can achieve large capacitance and force by increasing the number of comb pairs. The proposed collision detector can also be used in other machine tools.

7. Conclusions

In this paper, a capacitance based collision detector is proposed and designed for the purpose of detecting any collision between tool and peripheral equipment (e.g. fixture). One side of the finger-like capacitor is attached to the moving platform of the hybrid robotic manipulator and the other side of the finger-like capacitor is attached to the tool. When the tool accidently hits the peripheral equipment, the vibration will make the distance of the capacitor change and therefore trigger the machine to stop. The new design is illustrated and modelled. The capacitance, sensitivity and frequency response are analyzed in details, and finally the fabrication process are presented. The proposed collision detector can also be applied to other machine tools. Future work will build the prototype to test the proposed detector in the real application scenarios.

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References

[1]. Chang Liu, Foundation of MEMS, *Pearson Prentice Hall*, 2006.

[2]. L. E. B. Ribeiro, F. Fruett, Analysis of the Planar Electrode Morphology for Capacitive Chemical Sensors, in *Proceedings of the 6th International Conference on Sensor Device Technologies and Applications (SENSORDEVICES'15)*, Venice, Italy, 23-28 August 2015, pp. 179-182.

[3]. Tsai L. W., Joshi S., Kinematic analysis of 3-DOF position mechanisms for use in hybrid kinematic machines, *Journal of Mechanical Design*, Vol. 124, No. 2, 2002, pp. 245-253.

[4]. D. Zhang, Kinetostatic analysis and optimization of parallel and hybrid architecture for machine tools, Ph.D. thesis, *Laval University*, Canada, 2000.

[5]. Dan Zhang, B. Wei, Design, Analysis and Modelling of a Capacitive-Based Collision Detector for 3-DOF Hybrid Robotic Manipulator, in *Proceedings of the 6th International Conference on Sensor Device Technologies and Applications (SENSORDEVICES'15)*, Venice, Italy, 23-28 August 2015, pp. 31-36.

[6]. http://www.marposs.com/technology.php/eng/sensors_grinders_monitoring

[7]. Dong-Hoon Kim, Jun-Yeob Song, Suk-Keun Cha, etc., Real-Time Compensation of Chatter Vibration in Machine Tools, *International Journal of Intelligent Systems and Applications*, Vol. 5, No. 6, 2013, pp. 34-40.

[8]. Chia-Jung Chen, Rong-Shine Lin, Rong-Guey Chang, Efficient Web-Learning Collision Detection Tool on Five-Axis Machine, *World Academy of Science, Engineering and Technology*, Vol. 7 No. 7, 2013, pp.1053-1057.

[9]. Ebrahim Mohammadiasl, Vibration Detection and Backlash Suppression in Machine Tools, in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, St. Louis, USA, October 2009, pp. 972-977.

[10]. T. Rudolf, C. Brecher, F. Possel-Dölken, Contact-based Collision Detection – A New Approach to Avoid Hard Collisions in Machine Tools. A. Donmez, L. Deshayes (Eds.), in *Proceedings of the International Conference on Smart Machining Systems*, 2007, pp. 1-4.

[11]. Qiaokang Liang, Dan Zhang, Quanjun Song, etc., Design and fabrication of a six-dimensional wrist force/torque sensor based on E-type membranes compared to cross beams, *Measurement*, Vol. 43, Issue 10, December 2010, pp. 1702-1719.