Design, Analysis and Modelling of a Capacitive-Based Collision Detector for 3-DOF Hybrid Robotic Manipulator

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***Abstract*—A capacitive based collision detector 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 manipulator when it is in operation. 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.**

Keywords- collision detection; sensor; capacitance; robotic manipulator; modelling.

I. 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 are required. The sensing principle is easy to implement, requiring only two conducting surfaces. Secondly, it has the characteristic of a 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]. 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, such as machine tools as shown in Figure 1. When machine tools are in operation, it is sometimes unavoidable to hit the peripheral equipment (e.g., fixture) by the tool, which can damage cutting tools, clamps and fixtures as shown in Figure 2, or cause damage to the machine itself, which undermines the performance of the whole parallel robotic system, and delays the productions. Therefore, how to prevent the collisions during machining is very important for the machining process. When the end-effector/tool of parallel robotic machine tool accidently hits the peripheral equipment, e.g., fixture, an operator usually finds it, and hits the emergency stop button, but there is always a time delay. The machine tool should ideally stop immediately when the tool hits the peripheral equipment so that it does not cause further damage. Based on this need and motivation, a sensor should be developed to address this goal. Some computer aided manufacturing software has 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 are not aware of the surrounding environment. The end effector just follows the code and it is totally dependent on an operator to detect if a crash occurs.

Imagine the following scenario: when the tool hits the fixture, there should be a vibration produced. So, the question is how to 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 triggers the bag to deploy. Inspired by this idea, a capacitance-based collision detector/sensor is designed that can sense the vibration and convert the vibration to an electrical signal.

In [2], vibration on a rotating spindle is generated by the sum of the variations in weight distribution. The

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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 scenario mainly measures the amount of vibration that the rotating spindle produced and it is not appropriate to use here as a collision detector. In [3], the chatter vibration is detected by using three different acceleration sensors that are attached to three different axis of the machine tool. In [4], a web learning tool with 3D simulation for axial table collision detection was proposed, but no device has been designed. In [5], a vibration detection algorithm was proposed and a speed regulator was designed for the backlash vibration of a machine tool. In [6], 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 [7], 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. The 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 an object, 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.

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

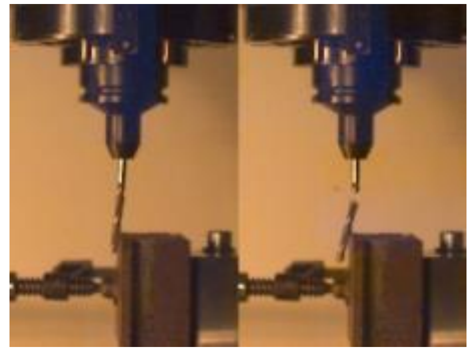

Figure 2. Collision occurred during machining [6]

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.

II. 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.

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 as shown in Figure 3. The details and its dimensions are shown in Figures 4 and 5. When the tool accidently hits the ground or an object, it will vibrate and the distance between the fingers will change and therefore, the capacitance will change and trigger the machine to stop.

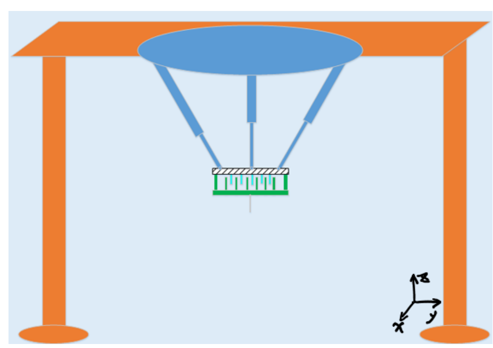

Figure 3. Vibration detector/sensor used in 3-DOF hybrid robotic manipulator

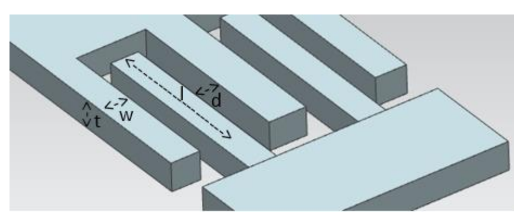

Figure 4. Dimensions of the detector

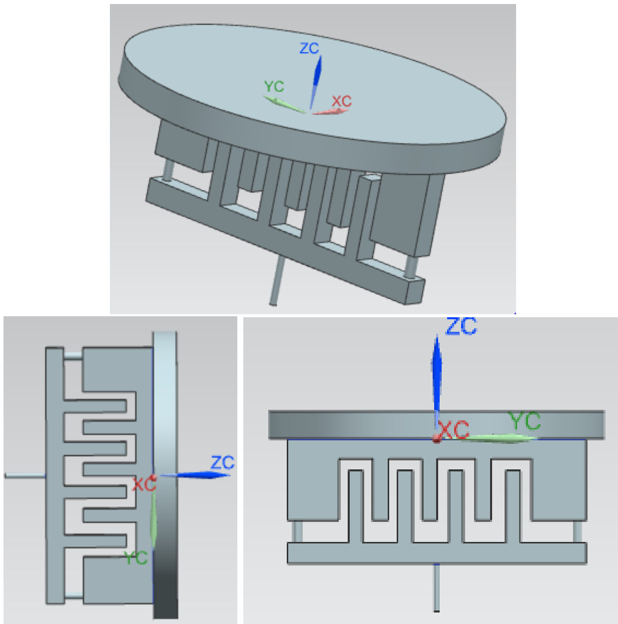

Figure 5. Capacitance based collision detector

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.

III. 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.,:

$$C_l = C_r = \frac{\varepsilon_0 lt}{d} \quad (1)$$

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.

A. 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:

$$C_l = \frac{\varepsilon_0 lt}{d - x} \quad (2)$$

and

$$C_r = \frac{\varepsilon_0 lt}{d + x} \quad (3)$$

The total value of capacitance is:

$$C = \frac{\varepsilon_0 lt}{d - x} + \frac{\varepsilon_0 lt}{d + x} = \frac{2d\varepsilon_0 lt}{d^2 - x^2} \quad (4)$$

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:

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

This change can be transferred to the electrical signal, and under a certain value, it means the machine tool is in the process of manufacturing. Even though there are small vibrations, the capacitance change is under that value, and the capacitance will not trigger the electrical controller to stop the machine. When, however, the capacitance change is very large, then the capacitor will trigger the controller to stop the machine immediately. This takes place if the condition of the pieces is softer than the fixture. When the pieces are stiffer than the fixture, we need to set the condition so that when the capacitance is under that value, the capacitor needs to trigger the controller to stop the machine. When the vibration is above that value, the capacitor will not trigger the controller to stop the machine. In other words, under a 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. Also, that certain value needs to be determined by experimentation.

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

Value 1 needs to be determined by experiment

The capacitor will not trigger the controller to stop the machine

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

The capacitor will trigger the controller to stop the machine

Above a 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. Also, that certain value needs to be determined by experimentation.

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

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The capacitor will not trigger the controller to stop the machine

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

The capacitor will trigger the controller to stop the machine

Set the decision logic to a certain value, the decision logic will receive a signal from the capacitor/sensor to determine if it is actually manufacturing or a collision. We can set the logic to negative value when the pieces are stiffer than fixture. 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]. If the value is larger or smaller than a 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 the authors' research scope, and can be done as a future work. The main purpose of this paper is the idea of using 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 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. Also, that certain value needs to be determined by experimentation. Ideally, when the tool hits the fixture, the detector/sensor will trigger the machine to stop immediately, so the tool will not break. The worst case scenario is when the tool breaks, at which point the capacitance will also change, so it will trigger the machine to stop. Either way, no matter if 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,

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

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

B. Movement along x direction

When the movement is along the x direction, we have the following, (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:

$$C = 12\frac{\varepsilon_0 lt}{d} \quad (7)$$

When there is force in x direction, which will make the fingers move in the x direction, this 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:

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

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:

$$\frac{\partial C}{\partial x} = -\frac{12\varepsilon_0 l}{d} \quad (9)$$

IV. FREQUENCY RESPONSE

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

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

$$I = \frac{\mathrm{w}t^3}{12} \quad (11)$$

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

$$F = k \cdot x \quad (12)$$

$$k = 2\times\frac{E\mathrm{w}t^3}{4l_1^3} \quad (13)$$

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

$$f_1 = \frac{1.732}{2\pi}\sqrt{\frac{EIg}{Fl_1^3}} = \frac{1.732}{2\pi}\sqrt{\frac{g}{6x}} \quad (14)$$

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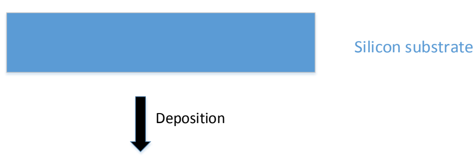
Where l_1 is the suspension beam length, E is the Young's modulus, w is the width of the finger, t is the thickness of the finger, the resonant frequency value is dependent on the above parameters, a different parameter will result in different values.

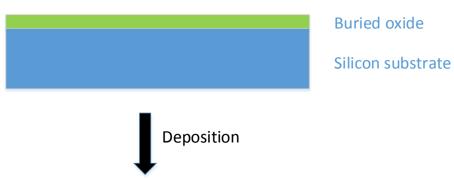
V. FABRICATION

Silicon bulk micromachining is the process that involves partial removal of bulk material in order to create three dimensional structures or free suspended devices. Etching is a subtractive process that removes 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. Isotropic etching can give rounded profiles and anisotropic etching can yield flat surfaces.

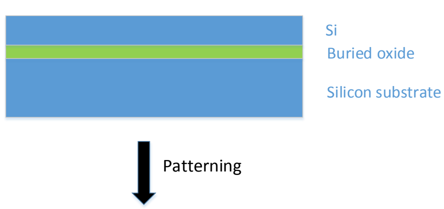
A process for prototyping is illustrated in the following Figure. If we draw a vertical line that cuts across both sets of fingers in Figure 3, we will get the cross section as shown in Figure 6. Here we only drew two of the 13 fingers in the cross section for the purpose of clearly illustrating the fabrication process. These are the two floating rectangles in the final step.



(a) Deposition of oxide

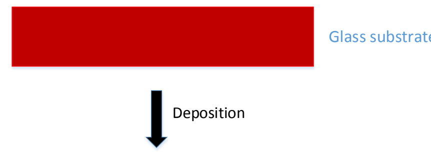


(b) Deposition of Si

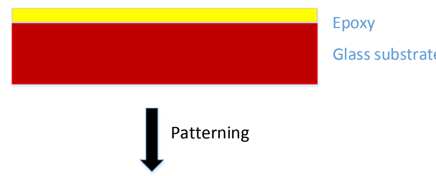


(c) Patterning

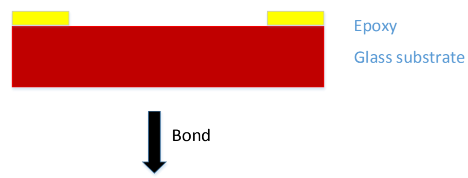
And



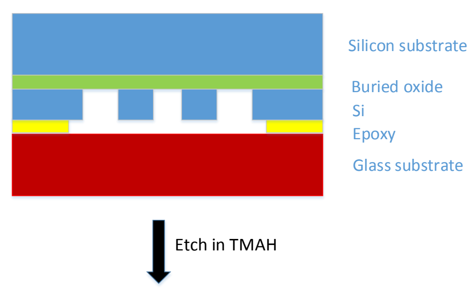
(d) Deposition of Epoxy



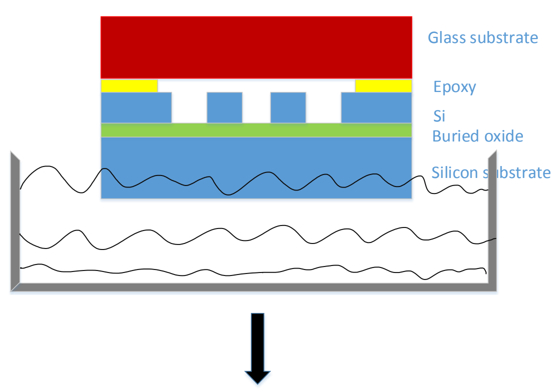
(e) Patterning



(f) Bond



(g) Etch



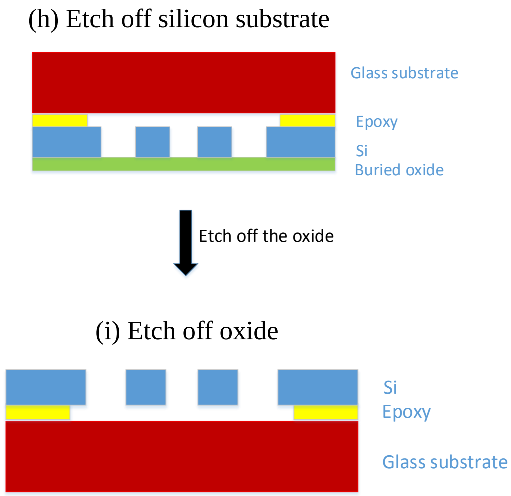


Figure 6. Fabrication process

Compared with parallel-plate capacitors, the capacitance between two neighboring sets 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.

VI. CONCLUSION

In this paper, a capacitance based collision detector is designed in order to detect any collisions between tool and peripheral equipment to prevent further damage to the machines. The new design is illustrated and modelled. The capacitance, sensitivity, and frequency response of the detector are analyzed in detail, and the fabrication process is finally 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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