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CAPACIFLECTOR-BASED VIRTUAL FORCE CONTROL AND CENTERING

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SUMMARY

This reports presents a novel concept in force control, called *virtual force control.* The virtual force concept avoids sudden step transition of position control to contact force control resulting in contact force disturbance when a robot end-effector makes contact with the environment. A virtual force/position control scheme consists of two loops, the force control loop and the position control loop. While the position control loop regulates the free motion, the force control loop regulates the contact force after making contact with the environment and the virtual force measured by a range sensor called capaciflector in the virtual environment. After presenting the concept of virtual force control, the report introduces a centering scheme in which the virtual force controller is employed to measure three points on a cone so that its center can be located. Experimental results of a one-degree-of-freedom virtual force control scheme applied in berthing an orbital replaceable unit are reported and compared with those of conventional pure contact force control cases.

1 INTRODUCTION

A robotic assembly task such as mating the male and female parts of an electrical connector or inserting an orbital replacement unit (ORU) into its fixture is generally carried out in two modes, the non-compliant mode and the compliant mode. In the non-compliant mode, since the robot end-effector is moving in free space and is not in contact with its working environment, only pure position control is necessary. On the other hand, in the compliant mode, since the robot end-effector is in contact with the environment, not only position but also contact force control is employed in order to avoid damages to the end-effector and the workpiece. Numerous control schemes such as accommodation, joint compliance, impedance control, and hybrid position/force control have been developed for the compliant mode [1,2]. Most developed force control schemes assume that some degrees of freedom (DOF) are lost when the non-compliant mode is transferred to the compliant mode. And through proper modification of a selection matrix [2], certain DOFs are selected to be force-controlled and the remaining DOFs to be position-controlled. As a result, at the instance the robot end-effector makes contact with the environment, a sudden step transition from position control to force control occurs in those DOFs selected to be force-controlled. The contact force impulse caused by this sudden control mode transition excites the robot structural resonances. These in turn produce unwanted contact chattering and consequently damages to the contact surface especially when the end-effector touches a very stiff object and is controlled by a high-gain force control system [3]. One obvious solution to the above problem is to perform the assembly task at a very slow speed so that the impact of force at contact is minimized. A main drawback of this method is the unnecessarily long operation time which is very critical for some tasks especially when performed in space. The above drawback of conventional force control has motivated researchers to search for ways of making a smooth transition of position into force control. This report introduces a novel contact force control concept called *virtual force control* which enables the force controller to be activated even before the robot end-effector workpiece touches the environment. In particular, the virtual force control is developed for a six DOF parallel manipulator whose mechanism have attracted many researchers because of the ability to perform fine and precise motion [8,9]. The report is organized as follows. It first briefly reviews the properties and operation principle of the capaciflector. Then using a special case of one DOF berthing of an ORU, the report introduces the concept and a control scheme of the virtual force control. After that, it develops three supporting processes of the virtual force control scheme, the prefiltering, the off-line calibration and modeling and the on-line distance determination. Then the development of a centering scheme based upon the virtual force is presented. Finally results of an experiment in which the proposed control scheme is used to berth an ORU to its fixture are presented and compared to those of two conventional pure contact force control cases.

2 THE CAPACIFLECTOR PROPERTIES

A *capacitive sensor* is a sensor possessing the ability to sense the capacitance of the capacitor between the sensor plate and a grounded object. The total capacitance c_t that the sensor senses is the sum of the capacitance of the capacitor between the sensor and ground c_{sg} and the capacitance of the capacitor between the sensor and the object c_{so}. Therefore the range and the sensitivity of the sensor can be increased by decreasing c_{sg}. This can be done by using insulation materials to increase the ***stand off*** distance between the sensor plate and ground. However the added insulation introduces many problems such as causing the robot arm on which the sensor is mounted to be bulkier than necessary or impeding the heat flow of the robot arm to outside environment. Consequently, in order to resolve the above problem, the *capaciflector* (*capaci*tive re*flector*) which is a capacitive sensor backed a reflector element (shield) was developed [4]. The reflector prevents field lines from the sensor plate to return directly to ground and thereby increases the number field lines from the sensor plate to the object. In order to make the capaciflector useful such as for control applications, a circuit should be designed to convert the measured capacitance into the corresponding DC voltage. Figure 1 shows the block diagram of a circuit currently used for the capaciflector. As seen from the figure, the measured capacitance serves as the input capacitance of an oscillator whose frequency depends on the capacitance. Via a converter, the frequency of the oscillator is then converted to a corresponding DC voltage which then filtered and amplified. Finally from the fact that the distance between the sensor plate and the object is inversely proportional to the capacitance of the capacitor between the plate and the object, the output of the above capaciflector circuit is a measure of the distance. As a result, the capaciflector can be used to measure the distance from a grounded object to the sensor plate. Since its development, the capaciflector has been found in several applications such as docking [5] and imaging [6].

3 VIRTUAL FORCE CONTROL

Figure 3 depicts an experiment arrangement which is used to explain the concept of virtual force control. As shown in the figure, a six DOF parallel manipulator consisting of a base platform, a payload platform and six linear actuators is used to berth an ORU into its fixture. Contact is measured by a six DOF force sensor mounted between the ORU and the manipulator. To enable the reader to follow the explanation easily, one DOF berthing is considered. Assuming that the ORU is perfectly aligned with its fixture, if a conventional force control scheme is employed, the manipulator is controlled by a pure position control scheme to move the ORU down onto the fixture at a desired speed and to stop the motion when a contact is established by a force sensor reading along the vertical axis. At the instance of making contact, a sudden stepwise transition of position into force control takes place. The force control scheme then takes over and controls the manipulator to push the ORU onto its fixture until a desired contact force is applied. The sudden stepwise transition of position into force control often creates contact force disturbances which may damage the contact surface.

If a capaciflector is mounted at the bottom of the ORU and used to measure the capacitance between the ORU bottom plate and the fixture upper plate, then a *virtual environment* can be defined as the zone bounded by $d_v \leq d \leq 0$. The corresponding capacitance range for the virtual environment is given by $c_v \leq c \leq \infty$. Since the capaciflector circuit is driven by a power supply with finite voltage, its output voltage will reach a maximum value which is usually the power supply voltage when the capacitance reaches ∞. Consequently the output voltage of the capaciflector circuit is equal to its maximum value when the ORU bottom plate touches the fixture upper plate. In addition, the capaciflector capability of continuously monitoring the capacitance change as the ORU approaches the fixture enables a velocity control system to regulate the ORU velocity to be zero at contact. Through proper transformation, the capacitance can be transformed into a *virtual force* which pulls or pushes the ORU as it enters the virtual environment.

Figure 2 illustrates a general force/position control system composed of two loops, the lower position loop controlling the ORU motion outside the virtual environment and the upper force loop controlling the virtual force inside the virtual environment and the contact force $f_{c,des}$. In the position loop, actual manipulator joint displacements measured by joint position sensors are transformed into the corresponding Cartesian motion via the manipulator forward kinematic transformation. The difference between the actual and desired motion is then used to drive a pure position controller whose operation is controlled by a switching variable β. The force loop has two subloops, the virtual force subloop utilizing a capaciflector to regulate the motion of the ORU inside the virtual environment in order to achieve a desired trajectory of the virtual force and the contact force subloop utilizing a wrist force sensor to apply a desired force on the fixture after the ORU makes contact with the fixture. The combination of the actual virtual force f_v and the actual contact force f_c is then compared with the desired contact force. The difference between the combined force and the desired contact force is then used to drive a force controller whose operation is controlled by a switching variable α.

For this particular one DOF berthing case, the switching variables α and β assume the following properties:

$$\alpha = \begin{cases} 0 & \text{if } d > d_v \\ 1 & \text{if } d \leq d_v \end{cases} \qquad \beta = \begin{cases} 1 & \text{if } d > d_v \\ 0 & \text{if } d \leq d_v \end{cases} \tag{1}$$

where d denotes the distance of the ORU bottom plate to the upper plate of the fixture and d_v the upper boundary of the virtual environment. The transformation converting actual capacitance c_{act} to virtual force f_v is given by $f_v = c_{act} - c_{max}$. According to (1), the position control loop is the only loop which is activated for $d > d_v$ and is turned off as soon as the ORU enters the virtual environment. At the same instance, the force control loop is activated. In the virtual environment, since no contact has been made resulting in no contact force measured by the wrist force sensor, only the virtual force subloop is activated. Inside the virtual environment the virtual force is negative and is acting like a force pulling the ORU into the fixture upper plate. The subtraction of the desired contact force from the virtual force is bigger than the desired force. Thus the force controller should control the ORU to move into the direction of the pulling virtual force (toward the fixture upper plate) so that the resulting virtual contact force is reduced. As the pulling virtual force decreases to zero, the ORU velocity should decrease proportionally. When the ORU makes contact with the fixture, the virtual force is equal to zero yielding full control to the contact force subloop. In other words, the virtual force subloop is fully activated in the virtual environment and is switched off as soon as the ORU bottom plate touches the fixture upper plate. If the ORU velocity is controlled so that it is zero when the virtual force is zero then a soft landing of the ORU bottom plate on the fixture upper plate is secured and no contact force disturbance is produced.

4 SUPPORTING PROCESSES

This section presents the developments of three processes required in the implementation of the proposed control scheme, namely the prefiltering, the off-line calibration and modeling and the on-line distance determination.

4.1 The Capaciflector Prefiltering

According to Figure 1, while Switch S in the ON position, the capaciflector is being prefiltered. Capaciflector prefiltering is to set the capacitance value to zero at a vertical position. This is done by feeding back the capacitance value to a computer via an Analog/Digital converter board, processing it and sending an off-set voltage out to the frequency-to-voltage converter via a Digital/Analog converter board until the capaciflector output voltage is equal to zero. Prefiltering can be performed *off-line* for calibration and modeling and *on-line* for distance determination.

4.2 The Off-Line Calibration and Modeling

This section presents a method of obtaining *off-line* a modeling equation of the distance d_{cal} between the ORU bottom plate and the fixture upper plate as a function of the capacitance c_{cal}. First, the capaciflector is prefiltered at a vertical location about 10 inches above the fixture upper plate. Then the parallel manipulator is controlled to move the ORU down onto the fixture with an increment of 0.05 inch and the capacitance value is measured and recorded at each increment. Using the recorded data, orthogonal functions are used to derive the coefficients a_0, a_1,...,a_6 of the following 6-th order polynomial

$$d_{cal} = f_1(c_{cal}) = a_0 + a_1 c_{cal} + a_2 c_{cal}^2 + a_3 c_{cal}^3 + a_4 c_{cal}^4 + a_5 c_{cal}^5 + a_6 c_{cal}^6 \tag{2}$$

A typical plot of the above polynomial is given in Figure 4.

4.3 The On-Line Distance Determination

Before moving the boundary of the virtual environment, the distance between the current vertical location of the ORU to the fixture must be determined. Recalling that the modeling function is obtained for the region 10 inches $\leq d \leq 0$, prefiltering at an unknown vertical location $d_0 \leq$ 10inches is equivalent to shifting the vertical axis in the positive direction of c_{cal} an amount of c_0 (see Figure 4). In other words, if the capacitance value c_0 at d_0 can be determined, then the calibration function $d_{cal} = f_1(c_{cal})$ can be modified to obtain a function f_2 relating c_{act} to d_{act}, namely $d_{act} = f_2(c_{act})$. Thus substituting $d_{cal} = d_{act}$ and $c_{cal} = c_{act} + c_0$ into $d_{cal} = f_1(c_{cal})$ yields

$$d_{act} = f_1(c_{cal}) = f_1(c_{act} + c_0) = f_2(c_{act}) = a_0 + a_1(c_{act} + c_0) + \ldots + a_6(c_{act} + c_0)^6 \tag{3}$$

Consequently in order to obtain c_0, first the capaciflector is prefiltered at the unknown vertical position d_0 and the ORU is controlled to move a small known distance Δ_d and the capacitance change Δ_c caused by the movement is measured and recorded. The slope $\frac{\Delta_d}{\Delta_c}$ is then computed and substituted into the derivative of $f_2(c_{act})$ with respect to c_{act} and evaluated at $c_{act} = 0$, to obtain

$$\frac{\Delta_d}{\Delta_c} = a_1 + 2a_2c_0 + 3a_3c_0^2 + 4a_4c_0^3 + 5a_5c_0^4 + 6a_6c_0^5 \tag{4}$$

The roots of (4) are then solved using a computer subroutine and c_0 is selected to be the smallest positive root. Finally c_0 is substituted into $d_{cal} = f_1(c_{cal})$ to calculate d_0.

5 VIRTUAL FORCE-BASED CENTERING

This section presents the development of a centering scheme for a cone using the developed virtual force control scheme. Figure 5 depicts the cross section of a cone to which the tip of a tool is to be centered. Under the assumption that the tool plate is parallel to the cone (or the tool is perpendicular to the cone), the tool is moved in the cone plane to touch three points on the inside of the cone under virtual force control so that the touching is performed without any force impact. Using the joint sensors on the robot, the coordinates of the touching point can be calculated with respect to the robot base coordinate system. Considering the two-dimensional coordinate system x and y as shown in Figure 5, the cone cross section which is a circle having a center at (x_0,y_0) can be described by

$$(x - x_0)^2 + (y - y_0)^2 = r^2 \tag{5}$$

or

$$x^2 + y^2 - 2xx_0 + x_0{}^2 + x_0{}^2 - 2yy_0 + y_0{}^2 \tag{6}$$

where r is the radius of the cone at the current vertical position of the tool tip.

Supposing that the coordinates of the three touching points are (x_1,y_1), (x_2,y_2), and (x_3,y_3), and substituting them into Equation (6), we obtain

$$x_1{}^2 + y_1{}^2 - 2x_1x_0 + x_0{}^2 - 2y_1y_0 + y_0{}^2 = r^2 \quad (7)$$

$$x_2{}^2 + y_2{}^2 - 2x_2x_0 + x_0{}^2 - 2y_2y_0 + y_0{}^2 = r^2 \quad (8)$$

$$x_3{}^2 + y_3{}^2 - 2x_3x_0 + x_0{}^2 - 2y_3y_0 + y_0{}^2 = r^2 \quad (9)$$

From (7-9), we get

$$f_1(x_0, y_0, r) = x_1{}^2 + y_1{}^2 - 2x_1x_0 + x_0{}^2 - 2y_1y_0 + y_0{}^2 - r^2 \quad (10)$$

$$f_2(x_0, y_0, r) = x_2{}^2 + y_2{}^2 - 2x_2x_0 + x_0{}^2 - 2y_2y_0 + y_0{}^2 - r^2 \quad (11)$$

$$f_3(x_0, y_0, r) = x_3{}^2 + y_3{}^2 - 2x_3x_0 + x_0{}^2 - 2y_3y_0 + y_0{}^2 - r^2 \quad (12)$$

The above equations represent a system of three nonlinear equations with three unknowns, x_0, y_0 and r. Newtons's Raphson iterative method can be used to solve for the unknowns. The Jacobian matrix of this method is computed as follows:

$$\mathbf{J} = \begin{bmatrix} \frac{\partial f_1}{\partial x_0} & \frac{\partial f_1}{\partial y_0} & \frac{\partial f_1}{\partial r} \\ \frac{\partial f_2}{\partial x_0} & \frac{\partial f_2}{\partial y_0} & \frac{\partial f_2}{\partial r} \\ \frac{\partial f_3}{\partial x_0} & \frac{\partial f_3}{\partial y_0} & \frac{\partial f_3}{\partial r} \end{bmatrix} = \begin{bmatrix} -2x_1 + 2x_0 & -2y_1 + 2y_0 & -2r \\ -2x_2 + 2x_0 & -2y_2 + 2y_0 & -2r \\ -2x_3 + 2x_0 & -2y_3 + 2y_0 & -2r \end{bmatrix} \quad (13)$$

The procedure of computing x_0, y_0 and r is presented in the following algorithm:

Algorithm 1: Virtual Force-Based Centering

- **Step 1:** Select an initial guess $x_0{}^{(1)}$, $y_0{}^{(1)}$, and $r^{(1)}$.
- **Step 2:** Compute $f_i(x_0{}^{(1)}, y_0{}^{(1)}, r^{(1)})$ for i=1,2,3 using (12).
- **Step 3:** Compute $\mathbf{J}(x_0{}^{(1)}, y_0{}^{(1)}, r^{(1)})$ using (13).
- **Step 4:** compute

$$\begin{bmatrix} x_0{}^{(2)} \\ y_0{}^{(2)} \\ r^{(2)} \end{bmatrix} = \begin{bmatrix} x_0{}^{(1)} \\ y_0{}^{(1)} \\ r^{(1)} \end{bmatrix} - \mathbf{J}^{-1}(x_0{}^{(1)}, y_0{}^{(1)}, r^{(1)}) \begin{bmatrix} f_1(x_0{}^{(1)}, y_0{}^{(1)}, r^{(1)}) \\ f_2(x_0{}^{(1)}, y_0{}^{(1)}, r^{(1)}) \\ f_3(x_0{}^{(1)}, y_0{}^{(1)}, r^{(1)}) \end{bmatrix} \quad (14)$$

- **Step 5:** Compute

$$\begin{bmatrix} x_0{}^{(2)} \\ y_0{}^{(2)} \\ r^{(2)} \end{bmatrix} - \begin{bmatrix} x_0{}^{(1)} \\ y_0{}^{(1)} \\ r^{(1)} \end{bmatrix} \quad (15)$$

- **Step 6:** Repeat Steps 1-5 until an acceptable difference in Step 5 is achieved.

It is noted that the radius r computed in the above algorithm can be used to determine the distance between the tool tip the end of the cone if the geometry of the cone is available. Consequently, if the centering scheme is employed, then the on-line distance determination process of the virtual force control scheme as presented in the previous section can be avoided.

6 EXPERIMENTAL RESULTS

This section is devoted to report results of an experiment in which the one DOF virtual force control scheme is applied to berth the ORU onto its fixture. The experiment is carried out in four phases: the distance determination phase, the pure position control phase, the virtual force control phase and the contact force control phase, which are described below:

- **The Distance Determination Phase:** Starting at an unknown vertical location $d_0 \leq 10$ in, using the approach in Section 4.3, the distance of the ORU bottom plate to the fixture upper plate is determined.

- **The Pure Position Control Phase:** Based upon the distance d_0 determined in the above phase, the parallel manipulator is controlled to move the ORU with full speed down to the fixture and the motion is stopped as the ORU reaches a distance d_v of about 0.5 in. above the fixture upper plate.

- **The Virtual Force Control Phase:** As soon as the ORU reaches d_v, the virtual force control scheme is fully activated and the pure position control is switched off via the variables α and β, respectively. The capacitance c_{act} which is measured by an X-shaped capaciflector mounted in the center of the ORU bottom plate and is in the range from 0 Volt (at d_0) to 10 Volts (at contact) is converted to the corresponding virtual force by the transformation $f_v = c_{act} - 10$. Thus the virtual force has a value of -10 lb (at d_0) and a value of 0 lb (at contact). Being pulled by the negative virtual force to the fixture plate, the ORU is controlled by the virtual force control scheme so that its motion causes the virtual force to decrease from -10lb to 0lb smoothly without any overshoot, ensuring a soft landing of the ORU bottom plate on the fixture upper plate with almost zero contact force.

- **The Contact Force Control Phase:** As soon as the contact between the ORU and the fixture is established by the capaciflector reading of zero virtual force, the contact force control scheme is activated and the virtual control scheme is switched off. A constant gain force controller is employed to keep pushing the ORU on the fixture plate until a desired contact force $f_{c,des}$ is exerted.

Figure 6 shows the time histories of the virtual force and the contact force of the above experiment. To compare the performance of the virtual force control with pure contact force control, two additional experiments with a pure contact force control scheme are conducted, one with a velocity of 0.3 in/sec and another with a velocity of 0.062 in/sec starting at the same distance d_0 as in the virtual force control scheme. Figure 7 shows the time history of the contact force of the three experiments and Table 1 summarizes their performance in terms of maximum overshoot, time to contact, and settling time. As seen from the table, the pure contact force control scheme with high velocity has short operation time but suffers from high maximum overshoot and one with low velocity has low maximum overshoot but long operation time. The virtual force control scheme achieves both short operation time and negligible maximum overshoot.

Control Scheme	Velocity	Max. Overshoot	Time to Contact	Settling Time
Pure Contact	0.3 in/sec	77 lbs	9 sec	15 sec
Pure Contact	0.062 in/sec	7 lbs	43 sec	50 sec
Virtual	0.3 in/sec	0.5 lbs	9 sec	28 sec

Table 1 Experiment results of ORU berthing

7 CONCLUSION

This report has presented the novel concept of virtual force control whose development was based on a range sensor, called capaciflector. The basic properties of the capaciflector were discussed. Results experiments conducted to evaluate the performance of the proposed virtual force control scheme for berthing an ORU with its fixture confirmed that the virtual force control scheme provides superior performance as compares to pure contact force control scheme. Current activities focus on developing a three DOF virtual force control scheme which will be integrated with a capaciflector-based scanner system for pose determination [6]

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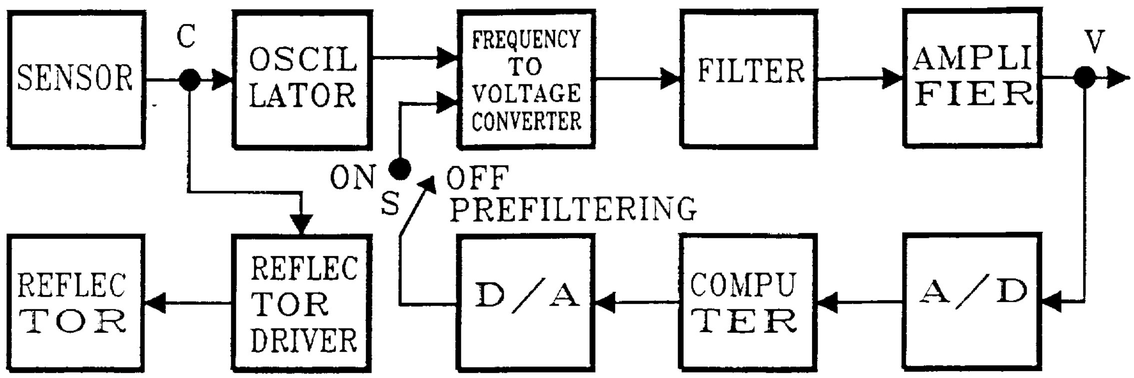

Figure 1 Block diagram of the Capaciflector

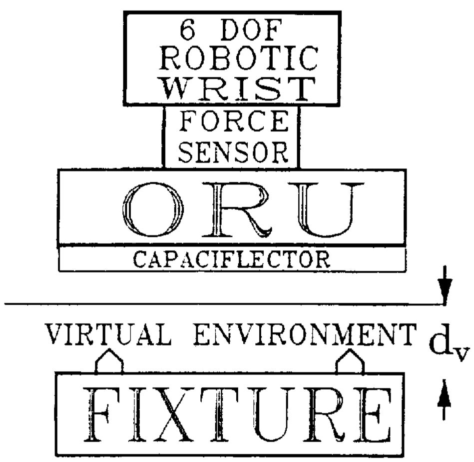

Figure 2 The virtual force concept

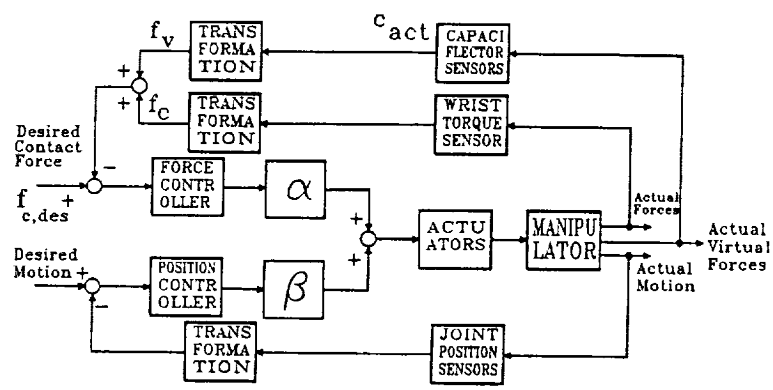

Figure 3 The virtual force/position control scheme

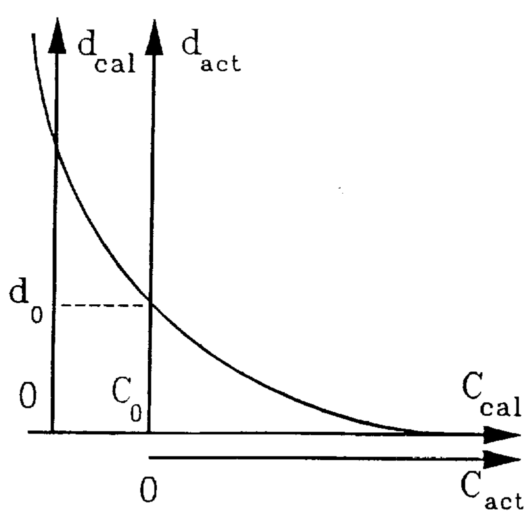

Figure 4 The calibration curve

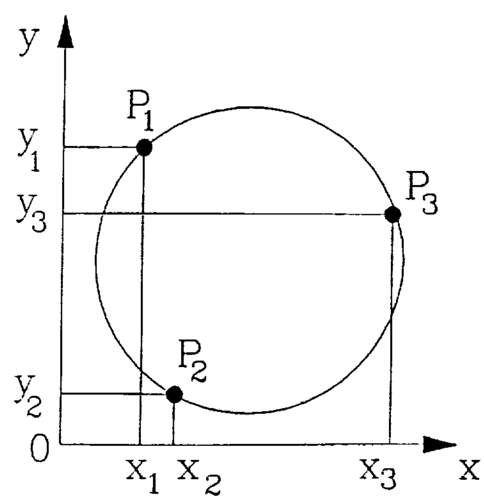

Figure 5 Cross section of the cone to be centered

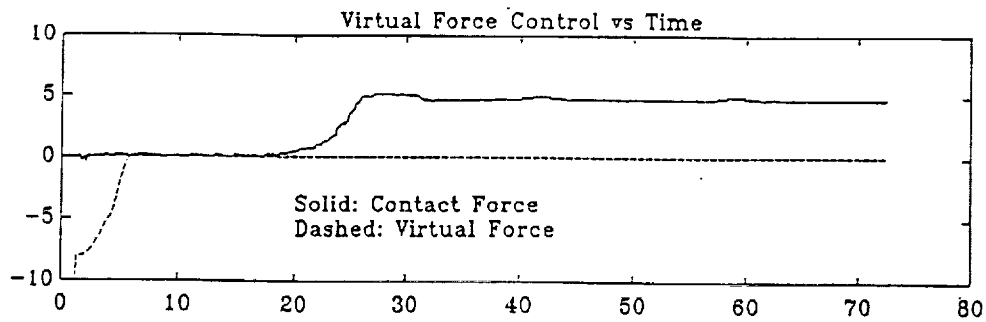

Figure 6 Time responses of the virtual and contact forces

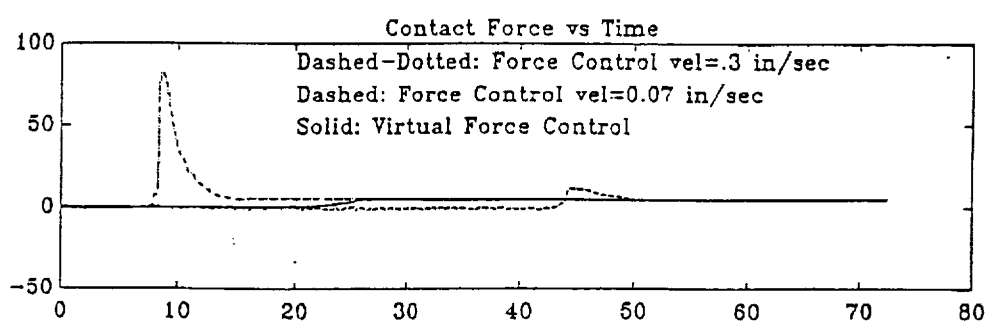

Figure 7 Comparative evaluation of time responses of contact forces