Force/Position Control of 3 DOF Delta Manipulator with Voice Coil Actuator

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ABSTRACT

Parallel manipulators are widely used in the industries for several applications. Due to its precision in motion as well as its robustness, parallel manipulators have proved its advantage over serial manipulators. In this paper, a 3DOF parallel manipulator is presented and force control of the manipulator is demonstrated. The proposed manipulator uses a direct drive voice coil arc actuators to achieve compliance required for human-robot interaction or soft mechanical manipulations. Its implementation in the proposed delta manipulator is discussed in the paper. The paper has discussed a unique method of controlling position as well as the force at the end-effector of the delta manipulator. The method used in making the manipulator compliant does not need an explicit force sensor and is convenient to implement. The method is inexpensive and works satisfactorily in a human interactive environment which is demonstrated through experiments discussed in the paper. The proposed design finds its application in robot-assisted assembly, surface finishing, cooperative manipulation, haptics etc.

KEYWORDS

Delta manipulator, voice coil actuator (VCA), force control, passive compliance

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1 INTRODUCTION

Compliant robotic manipulators have tremendous scope in industrial application such as assembly line operation, welding, pick and place to sophisticated medical and space applications. In some of these applications, the manipulator has to work in shared workspaces with humans. Human robot interaction (HRI) provide several benefits with regard to human and robot capabilities due to their technical feasibility, high productivity gains and safety.

The parallel manipulators are widely used in industrial applications due to its advantage in load supporting capability. A parallel manipulator can be identified as a closed loop kinematic chain whose end effector is connected with the base through several kinematic chains that are independent from each other [1]. Parallel manipulators have stability and higher precision compared to serial manipulators [1], so they can be considered ideal for Human Robot Interaction applications. Various designs of parallel manipulators have been proposed by researchers in the past after the first industrial parallel manipulator that was reported by W. L. Pollard [2] in 1942. The universal tyre testing machine designed by Gough and Whitehall [3] used a six-linear jack system to achieve 6-DOF in a parallel manipulator. The well known Stewart platform was first introduced by Stewart [4] for a flight simulator, where limited manipulators were used to achieve the precision and stability of a parallel platform frugally. Delta manipulator is an example of one such manipulator. A Delta manipulator is a 3 DOF parallel mechanism with all the linear degrees of freedom. The concept of Delta manipulator has been realized in many forms like the Orthoglide parallel robot with pure translational DOF [5].

The primary objective of robot manipulator is to satisfy specific position or perform a specified task through its end effector. The robotic manipulator comes in constant interaction with the physical environment while operating a given task. In human interactions, the performance of the robot's system depends on its stability, reliability and more importantly the overall safety of the robot and its environment. Compliance is introduced in manipulators to meet this requirement. Adding compliance to the robot makes it safer to use in human-robot shared workspace. A compliant manipulator gives freedom of deviating the manipulator from its own desired position when an external force is applied. Due to this feature the peak force attained during a collision or during human interaction is reduced which ensures the safety of the system and its environment. Adding compliance affects the precision and time of operation of the robot. However, compliance in manipulators limits the stiffness of joints and thus the resulting manipulator with compliance proves to be a a compromise between safety and performance. Compliance has been achieved in various serial manipulators such as KUKA KR5 [6] and many others in the past, however, compliance in 3 DOF delta

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manipulator or more generally in parallel robots is sparsely reported in the literature.

The paper introduces a compliant 3 DOF Delta manipulator using a unique drive system known as voice coil actuator (VCA). The proposed mechanism with the controller discussed in the paper is able to achieve a precise position with an added advantage of being compliant to any stiff environmental interactions. This mechanism can be used in operations where human interaction is expected and safety is of prime concern. The paper discusses about the mechanical structure of the delta manipulator and presents an analysis of the proposed control scheme.

Section 2 discusses the mechanical aspects of the Delta manipulator which includes the detailed structure of the mechanism, details of the actuator of the mechanism, inverse kinematics and analysis of the torque requirements of the springs used in the design. This section also discusses about the passive compliance and its implementation on the delta manipulator, which is a primary objective of the proposed work. In section 3, the control scheme of the system and its behavior depending on the solution of inverse kinematics is discussed. In the later part, the force control of the manipulator and method used for making it compliant has been discussed at length. The results of the work presented and the conclusions are mentioned in section 4.

2 MECHANICAL DESIGN

2.1 Mechanical structure

The proposed Delta manipulator with its retrofitting is shown in Fig. 1. The three limbs of the manipulator are connected to the base platform as well as to the top platform. Describing the ith limb, the first link that is connected to the actuator is labeled as l_{1i}. The second link that connects the first link to the top platform is labeled as l_{2i}. This link is a planar four-bar parallelogram and has two degree of freedom. The angles defined are θ_{1i}, θ_{2i} and θ_{3i}. θ_{1i} is the angle of the first link with respect to the horizontal. θ_{2i} is the angle between l_{2i} and the extension of l_{1i}. θ_{3i} is the angle made by the second link with the XZ plane. All the links and angles of the proposed Delta manipulator are shown in the schematic Fig. 2.

There are two spherical joints T_i and M_i and a revolute joint B_i as shown in Fig. 2. The spherical joint T_i connects the second link with the top platform and the joint M_i is the connection between l_{1i} and l_{2i}. The revolute joint B_i is the coupling of the link l_{1i} with the arc-segment voice coil actuator.

The world frame XYZ was taken with it's origin as the vertex of base platform. The XZ plane passes through the vertex of top platform and the base platform as shown in Fig. 2 and Fig. 3. The second link has 2-degrees of freedom due to the spherical joint and are shown in XZ and YZ plane. The YZ plane shows the third degree of the manipulator. Two relative frames $U_2V_2W_2$ and $U_3V_3W_3$ were chosen such that their origin coincides with the other two vertices of the base platform as shown in Fig. 3

2.2 Selection of Actuator

Rotary Voice Coil Actuators (VCA) or arc-segment type were used as to precisely actuate the rotary joint moving the first link of each leg. The actuator in the presented work is BEIKIMCO RA60-10-001A. As the design of the VCA is versatile regarding capacity, shape, size and configuration, they can be used in many precise motion mechanisms [7, 8]. Voice coil actuators can be used with a single phase power and are of direct drive nature which eliminates the backlash and non-linearity associated with gearboxes. Accurate position can be achieved due to its cog free mechanism. The input current to the voice coil actuator directly corresponds to force/torque output. VCAs have many advantages over other forms of actuation in the HRI and force controlled applications [9, 10]. A directly-driven VCA if pushed against the direction of travel, continues to apply a force proportional to its current, and gets back driven if the force exceeds the limit of VCA [11]. VCA has to be actively controlled for any external force being applied. This feature was used to identify any extrinsic disturbance. Optical position encoders were used to obtain the position feedback.

As Voice coil actuators are two position actuators, in order to achieve any intermediate position between the two extremes, a varying resisting torque was required. To fulfill this, a linear spring was attached as shown in Fig. 1 to the links l_{1i} to apply a torque against the VCA. The spring applies a force proportional to its extension at the point of attachment. The force was reflected as resisting torque at the actuator. This allowed the voice coil actuator to maintain any intermediate position for a given current flowing through its armature. Any position thus obtained is a balance of torque generated due to the coil current and the torque generated due to the extended spring and mass of links and end effector.

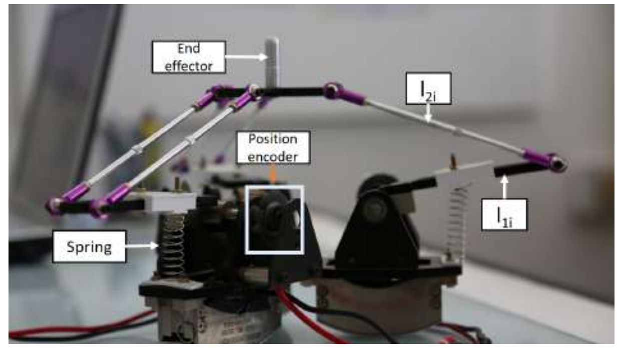

Figure 1: The proposed Delta mechanism with VCA

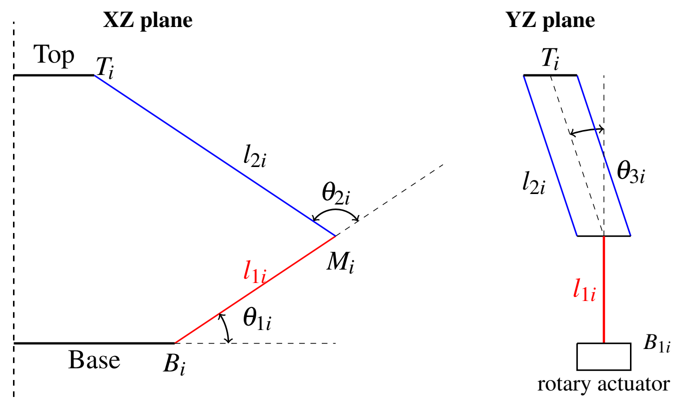

Figure 2: Schematic diagram of suggested Delta mechanism

2.3 Passive Compliance

The use of passive compliance has been reported for force control mechanisms since last four decades. In the recent, though active compliance has been proved to have advantage due to variable stiffness it is an arduous task to design an active compliant mechanism. The advantage of passive compliance lies with its simplicity. Though passive compliance in its simplest form works with a constant stiffness, if coupled with a robust controller scheme it can perform tasks satisfactorily. Use of passive compliance in the robot structure can possibly achieve the required adaptation without the need of an active compliance control [12].
A given mechanism can be made passively compliant in three ways: by having a compliant robot base, by having a compliant end-effector (eg: RCC), or by having compliant limbs [13] or joints in the manipulator. In the mechanism discussed in the paper, the compliance was achieved by having compliant links driven by a direct drive VCA. Linear springs were attached to the links of the manipulator which performed dual task of maintaining any intermediate position of the manipulator as well as contributing to the compliance of the manipulator. The springs used had stiffness value such that the actuator attained full deflection at 60% of the stall torque of the actuator. The springs were mounted between the base and link l_{1i} as shown in Fig. 1. A constant torque was applied by the actuator to maintain a particular position of the manipulator with the help of springs. This allows any external force to deviate the link from the balanced position after use of suitable control scheme.

2.4 Inverse Kinematics

The inverse kinematics of suggested Delta Mechanism is shown below:

Structure definition:

l_{1i} ←length of the link coupled with actuator
l_{2i} ←length of the link connected to first link and top platform
t ←length of the edge of the top platform
b ←length of the edge of the base platform

Base platform:
The base platform is an equilateral triangle of length b,
B_1, B_2, B_3 are the three vertices of the base platform such that:

$$\begin{bmatrix} B_{1x} & B_{1y} & B_{1z} \\ B_{2x} & B_{2y} & B_{2z} \\ B_{3x} & B_{3y} & B_{3z} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ -cos\psi & sin\psi & 0 \\ -cos\psi & -sin\psi & 0 \end{bmatrix} \begin{bmatrix} b & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Top platform:
P_x, P_y and P_z are the x,y and z co-ordinates of end effector. T_1, T_2, T_3 are the three vertices of the top platform

$$\begin{bmatrix} T_{1x} & T_{1y} & T_{1z} \\ T_{2x} & T_{2y} & T_{2z} \\ T_{3x} & T_{3y} & T_{3z} \end{bmatrix} = \begin{bmatrix} 1 & \frac{2}{3} & 0 \\ 1 & \frac{-1}{3} & sin\psi \\ 1 & \frac{-1}{3} & -sin\psi \end{bmatrix} \begin{bmatrix} P_x & P_y & P_z \\ t & 0 & 0 \\ 0 & t & 0 \end{bmatrix}$$

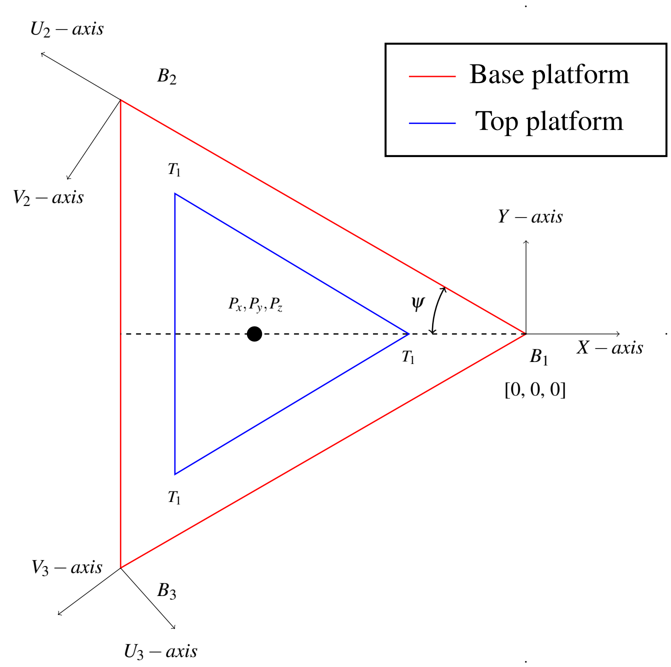

Figure 3: Top view of the base platform

Here, ψ is equal to 30 degrees. After the inverse kinematics on one leg shown in appendix, we get the point M_1, i.e the point where the link l_{1i} and link l_{2i} are connected.
The transformation matrix for transforming the frame $U_nV_nW_n$ to XYZ is given as:

$$\mathbf{T^x_{u_n}} = \begin{bmatrix} cos\phi & -sin\phi & 0 & 0 \\ sin\phi & cos\phi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -B_{nx} \\ 0 & 1 & 0 & -B_{ny} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where, ϕ is the angle between the planes U_nV_n and XY.
Here, $\mathbf{T_n}$, $\mathbf{M_n}$ and $\mathbf{B_n}$ are defined as:

$$\left[\mathbf{T_n}\right] = \left[T_{nx} \quad T_{ny} \quad T_{nz}\right]^T \quad \left[\mathbf{M_n}\right] = \left[M_{nx} \quad M_{ny} \quad M_{nz}\right]^T \quad \left[\mathbf{B_n}\right] = \left[B_{nx} \quad B_{ny} \quad B_{nz}\right]^T$$

Multiplying the transformation matrix, $\mathbf{T^x_{u_n}}$, the point $\mathbf{T_n}$ and $\mathbf{B_n}$ will be transformed to base frame.

$$\begin{bmatrix} \mathbf{T_{new}} \\ 1 \end{bmatrix} = \left[\mathbf{T^x_{u_n}}\right] \begin{bmatrix} \mathbf{T_n} \\ 1 \end{bmatrix} \qquad \begin{bmatrix} \mathbf{B_{new}} \\ 1 \end{bmatrix} = \left[\mathbf{T^x_{u_n}}\right] \begin{bmatrix} \mathbf{B_n} \\ 1 \end{bmatrix}$$

Substituting $[\mathbf{B}_{new}]$ and $[\mathbf{T}_{new}]$ as $[\mathbf{B}_1]$ and $[\mathbf{T}_1]$, $[\mathbf{M}_{new}]$ can be obtained by using inverse kinematics as explained in appendix. Using this $[\mathbf{B}_n]$, $[\mathbf{M}_n]$ and $[\mathbf{T}_n]$ was obtained in the rotated frame. The obtained points were retransformed from base frame to $U_nV_nW_n$,

$$\mathbf{T_x^{u_n}} = \begin{bmatrix} 1 & 0 & 0 & B_{nx} \\ 0 & 1 & 0 & B_{ny} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} cos\phi & -sin\phi & 0 & 0 \\ sin\phi & cos\phi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T \tag{2}$$

$$\begin{bmatrix} \mathbf{T_n} & \mathbf{M_n} & \mathbf{B_n} \\ 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} \mathbf{T_x^{u_n}} \end{bmatrix} \begin{bmatrix} \mathbf{T_{new}} & \mathbf{M_{new}} & \mathbf{B_{new}} \\ 1 & 1 & 1 \end{bmatrix} \tag{3}$$

The end-effector as well as all the joints are defined in the XYZ frame by using (3).

2.5 External Torques

To achieve a desirable position in the proposed mechanism, the opposing torques by the mass of the links, end effector and the extension of the spring were balanced by the actuator torque.

In order to implement compliance, we had to model the torque requirement of the actuator with respect to the position of end effector. This was done by expressing the torque as a function of angles made by the links. As following a given trajectory was not the main focus, a static analysis of the delta manipulator was sufficient to calculate the torque required by the actuator to maintain a particular pose. The torque required at the actuator can be understood from the static balance shown in Fig 4,

The torque applied due to the position of the links is

$$\tau_l = \left[m_1 g \frac{l_1}{2} cos\left(\theta_1\right) + m_2 g \left(l_1 cos\theta_1 + \frac{l_2 cos\theta_3}{2} cos\left(\theta_1 + \theta_2\right) \right) \right] .\hat{\mathbf{k}} \tag{4}$$

Here, θ_3 is the angle made by link 2 in **yz** plane

k = stiffness of the spring in N/mm (in the proposed system it was

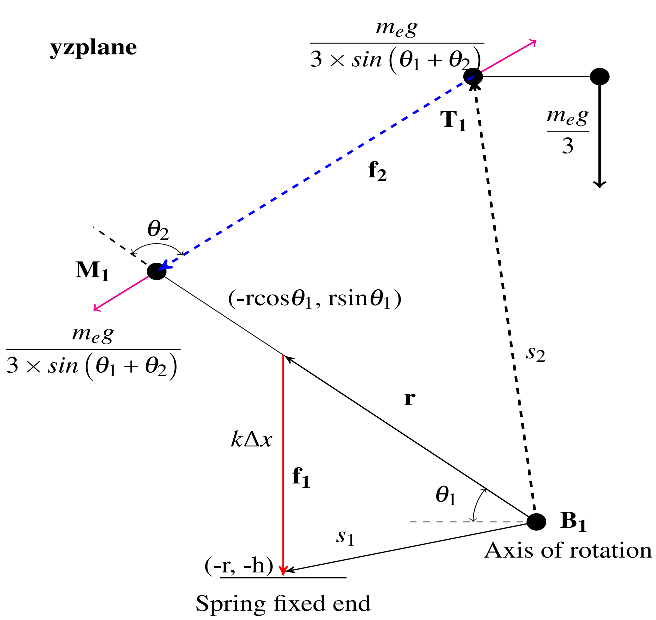

Figure 4: Static force balance for one leg of the manipulator

0.25 N/mm)

Δx = Extension of the spring in mm

The direction vector of the force due to the extension of the spring is

$$\mathbf{f_1} = \frac{\mathbf{s_1} - \mathbf{r}}{|\mathbf{s_1} - \mathbf{r}|} \tag{5}$$

The direction vector of the link l_2 is,

$$\mathbf{f_2} = \frac{\mathbf{r} - \mathbf{s_2}}{|\mathbf{r} - \mathbf{s_2}|} \tag{6}$$

Here, $\mathbf{s_1}$ is the vector from the axis of the actuator to the spring mount on the base and $\mathbf{s_2}$ is the vector from the axis of the actuator to the point T_1, on the top platform and $\mathbf{r}$ is the vector from the axis of the actuator to the spring mount on the link l_1 The force applied by the spring is,

$$\mathbf{F} = k\Delta x.\mathbf{f_1}$$

The torque applied by the spring therefore is,

$$\tau_s = \left(\mathbf{r} \times \mathbf{F}\right).\hat{\mathbf{k}}; \tag{7}$$

The force due to the mass of end-effector when the mass of end effector is m_e,

$$\mathbf{F_m} = \frac{m_e g}{3sin\left(\theta_1 + \theta_2\right)}.\mathbf{f_2};$$

The torque reflected due the mass of end effector is

$$\tau_m = \left(\mathbf{r} \times \mathbf{F_m}\right).\hat{\mathbf{k}}; \tag{8}$$

Therefore, the torque required to balance the leg at a particular position can be given as summation of $\tau_\mathbf{l}, \tau_\mathbf{s} and \tau_\mathbf{m}$,

$$\tau_e q = \tau_l + \tau_s + \tau_m \tag{9}$$

The motor constant (M) is a parameter of the actuator that relates torque and current linearly as,

$$\tau_{eq} = Mi$$
$$i = \frac{\tau eq}{M} \tag{10}$$

3 CONTROLLER

3.1 Controller Scheme

The proposed controller scheme provides a method to control the position as well as torque of the delta manipulator. To achieve accurate position, PID (Proportional, Integral, Derivative) Controller was implemented with certain modification. Current limiting based approach was applied to control the torque applied by the Delta Manipulator. The proposed control scheme takes care of non-linearity of the system satisfactorily and also provides a passive compliance. In the proposed design for attaining any given equilibrium position the torque provided by the Voice Coil Actuator balanced the resisting torque provided by the spring. As the spring was kept vertical initially, the linear springs provided a torque proportional to sin(θ_{1i}), more torque has to be provided by the Voice Coil Actuator to traverse a greater angle. The range of the the arc actuator used was 15^0. To provide torque to the Voice Coil Actuator a DC voltage was provided which is proportional to the required torque. Thus as the voltage increased, the Voice Coil Actuator traversed from one extreme position to a point where the resisting torque became equal to the torque applied by the Voice Coil Actuator. This results in attaining any intermediate angular position. The desired angular

position of the delta links (l_{1i}) was determined by using the inverse kinematic relations derived in appendix A. The control scheme consists of PID control with two closed loops- encoder based feedback for precise angle($\theta_{\mathbf{1i}}$) control and current based feedback for limiting the torque provided by the Voice Coil Actuator as shown in Fig. 5. The desired angle was mapped into encoder counts and provided to the controller. This count behaved as the set point for the PID control scheme and the current quadrature phase encoder counts from the feedback loop were taken in as the input to the system, thereby error signal was determined. This error signal was fed to the PID control eq. (11) and eq. (12) which produced a control signal that was a sum of three terms. The first term was proportional to the error(ε_p), the second term was proportional to the integral (ε_i) of the error, which in the discrete time case resulted in summation of previous errors and present error and the third was proportional to the derivative (ε_d) of the error which was the difference in the present and the previous value of the error. This control signal drove the voltage of the voice coil actuator. Thus the desired angle was achieved by incrementing the voltage provided to the voice coil actuators at a rate determined by the PID control till the desired angles were achieved.
The PID control is determined as follows:

$$\varepsilon_p = \theta_{des} - \theta_{current}$$
$$\varepsilon_v = \varepsilon_i - \varepsilon_{i-1}$$
$$\varepsilon_s = \Sigma_i^n \varepsilon_p$$
$$\mathrm{PWM}_i = \mathrm{PWM}_{i-1} + \mathrm{K}_p\varepsilon_p + \mathrm{K}_i\varepsilon_s + \mathrm{K}_d\varepsilon_v \tag{11}$$

if $\varepsilon_p <$ threshold,

$$\mathrm{PWM}_{i+1} = \mathrm{PWM}_i \tag{12}$$

The threshold condition in eq. (11) and eq. (12) was put to account for the limitation in the minimum angle measured by the encoders. Since the manipulator had three different links and PID control scheme is Single Input Single Output system (SISO), three separate PID control loops were used to control the delta manipulator, each one controlling the position of a link. The essential parameter of the PID scheme was the gain (K_p,K_i, K_d) terms which were tuned using Ziegler Nichols rule for optimal performances. The K_p was gradually increased from zero, until oscillatory motion was observed. K_i was then increased analytically till the maximum value of Kp to reduce the steady state error term. The Kd term was tuned, thereafter to reduce the oscillation by the same method till optimum motion was achieved. Thus to achieve any given position, the control scheme maintained a sufficient PWM or in a way, torque to balance the resisting torque establishing an equilibrium condition. The control scheme was extended to achieve a given path.
When the enjoined motion of the robot was hindered, or cramped by the surroundings, the robot forcefully tried to overcome the restriction in order to attain the requisite position. Under these conditions the actuator drew large amount of current which failed the purpose of compliance. Thus, an external current loop was employed to control the amount of torque provided by each link of the voice coil actuator. At each position the current required was calculated from (10) and the PID control loop was limited by measuring the current flowing through each link. To implement compliance, the torque should be limited at each point i.e delta manipulator must not provide an extra torque to compensate the external disturbance. The current was measured through the current sensor and at any particular position if the actual value increased from the calculated value, the PID loop was paused until the current flowing through the links was reduced below the threshold value, following which the PID position control loop was resumed. Hence, through our unique scheme we were able to control the position and torque of the delta manipulator.

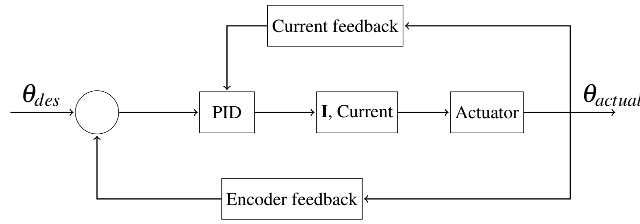

Figure 5: Controller scheme

3.2 Development of controller

3.2.1 Microcontroller. The microcontroller used in the application board was ATmega 2560, which is a low power, high performance 8-bit microcontroller. It has 48 programmable input/output pins which could easily serve the demand for the pins required for current sensing, voice coil actuator direction and the pins required by the encoder used. Its advanced RISC architecture runs at 16 Mhz clock and has 128 Kb of flash memory which was sufficient for the purpose. It has 8-channels of 10-bit ADC which gave a very fine resolution in case of current sensing. Also, two way handshaking based serial communication was established between PC and board for debugging and real time control.

3.2.2 Motor driver. The voice coil actuators were driven using Hercules lite 6A, 16V, 8 Ampere motor drivers. It consists of two direction pins which can be logically turned high or low to change the direction of actuation and a pulse width modulation pin using which the speed of actuation can be controlled.

3.2.3 Optical encoder. The position feedback of the voice coil actuators (VCA) were achieved using optical encoders mounted on the shafts of actuator. Optical encoders with quadrature outputs were chosen for this purpose, in order to attain high resolution along with direction perception. The optical encoder used generates 2000 pulse per rotation thus providing a resolution of 0.18 degree. As the encoder has quadrature outputs, it consist of two channels namely Channel A and Channel B that give pulses which are 90^0 out of phase. These two channels help in determining the direction in which the VCA was moving as shown in the Fig. 6
The output of both the channels was connected to the interrupt pins of the microcontroller.
This was done for achieving accurate position control so that whenever pulse is generated due motion of VCA, the program flow goes to the interrupt service routine where a counter can be incremented or decremented on the basis of direction of motion of the actuator. Depending on the state (i.e. logical HIGH or LOW) of both the channels of the encoder, when the interrupt arrives, the direction of motion can be easily determined.

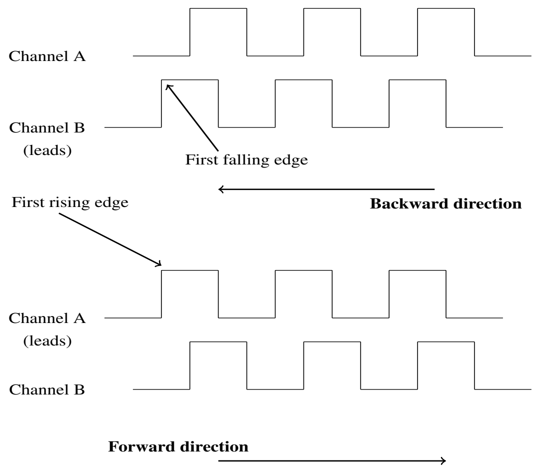

Figure 6: Determination of direction using two channels

Another advantage of using a quadrature encoder is that the resolution can further be increased. Resolution gets doubled (x2) when the value of the counter changes with the rising as well as falling edge of one channel and it gets quadrupled (x4) when the value of the counter changes with the rising and falling edges of both the channels.

3.2.4 Current sensor. For achieving passive compliance of the robot with physical environment, Allergo ACS712 current sensor has been used. It is Hall Effect based current sensor IC in which the current flowing through the wire produces a magnetic field, which the hall IC converts into an equivalent voltage. The maximum current that can be sensed using ACS712 is 5A with a sensitivity of 185 mV/A which was optimum for the proposed work.

4 RESULTS AND DISCUSSION

The results obtained by the experimental setup are discussed in the following section. The theoretical and experimental plots are compared in this section followed by subsequent explanation.

The theoretical torque required to be produced by the actuator was compared with the actual torque applied. It was observed that the torque required showed a linear behaviour within the operating range of the actuator i.e 15 degrees. The plots of expected vs actual torque are shown in Fig. 7. The assumption of linearity may not hold true for higher angles and then an empirical method should be used to derive a relation between current and torque.

The real time analysis of path followed by the delta was performed. The top view of the delta was recorded and a marker was placed on the end effector. A planar circular path of radius 4mm was fed and the movement of the delta following the path was recorded. The plot of desired and actual path is shown in Fig. 8. It was observed that the delta manipulator followed the path using position control with a decent accuracy.

The torque required by the actuator to maintain a position of end effector was calculated through static balance of moments. Compliance was introduced in the system by spring and torque limit based control. The compliance is shown in the Fig. 9. In the plot without torque limit, the actuator continues to provide excess torque required

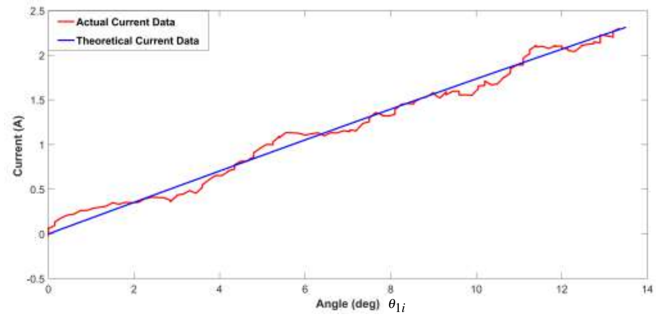

Figure 7: The torque required by a link with respect to θ_{1i}

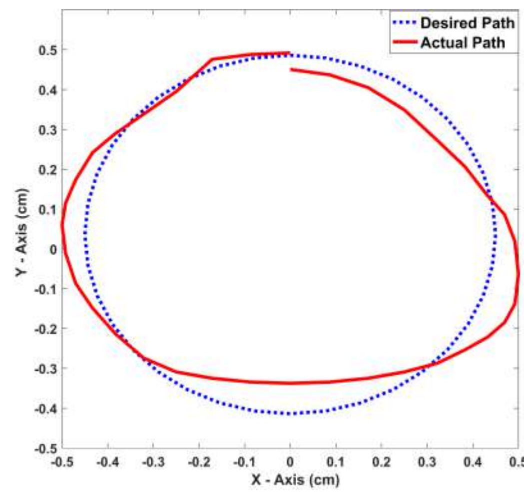

Figure 8: Delta following the given circular path of radius 4mm

to maintain the position thereby failing the purpose of compliance. Whereas, when the torque is limited, the actuator does not provide any excess torque and thus becomes compliant in nature.

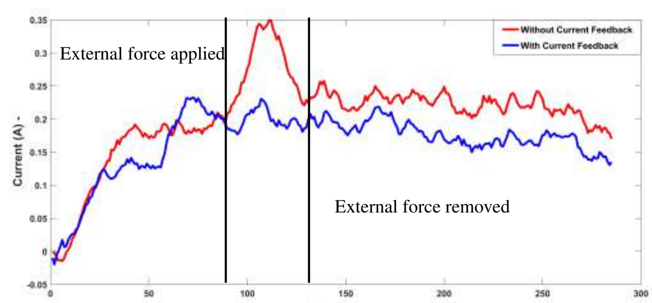

Figure 9: Current provided by VCA for external force with and without current limit.

5 CONCLUSIONS

In this paper the position/force control of delta manipulator with a low torque direct drive voice coil actuator is proposed. The driving

system with the controller proposed has an added advantage of compliance in the manipulator. The paper compares the desired and actual torque required to move the links. It also demonstrates following a desired path using the proposed delta manipulator.
The proposed manipulator can be used in applications where human robot interaction is involved and is not controlled solely by a stiff position-time controller. As passive compliance does not require a sophisticated control algorithm. Such robots are inexpensive and are equally safe as a active force compliant system and do not affect the precision of end operation. For high torque applications, active force compliance should be preferred over passive compliance.

A APPENDIX

Inverse Kinematics of one leg

$l_1 \leftarrow$ length of the link attached to an actuator
$l_2 \leftarrow$ length of the link attached to the top platform
$\theta_{11} \leftarrow$ Angle of the link1 with respect to the horizontal
$\theta_{21} \leftarrow$ angle of link$_{21}$ with respect to the link$_{11}$
$\theta_{31} \leftarrow$ Angle between the link$_{21}$ and it's projection on the **XZ** plane as shown in Fig. 2

The known position of the end-point of the second link, link$_{21}$, is given by **x**, **y** and **z**,
from geometry:

$$\theta_{\mathbf{31}} = sin^{-1}\left(\frac{y}{l_{21}}\right)$$

$$\theta_{\mathbf{21}} = cos^{-1}\left(\frac{x^2+z^2-l_{11}^2+l_{21}cos\theta_{31}{}^2}{2l_{11}l_{21}cos\theta_{31}}\right)$$

by taking intermediate values m and ϕ such that:
$\mathrm{m}\cos\phi = \mathrm{l}_{11} + \mathrm{l}_{21}\cos\theta_{21}$
$\mathrm{m}\sin\phi = \mathrm{l}_{21}\sin\theta_{21}$
m=$\sqrt{l_{11}^2+l_{21}cos\theta_{31}{}^2+2l_{11}l_{21}cos\theta_{21}cos\theta_{31}}$
$\phi = \mathrm{atan2}(\sin(\phi), \cos(\phi))$
$\theta_{\mathbf{11}} = cos^{-1}\left(\frac{x}{m}-\phi\right)$

$M_{1x} = B_{1x} + l_{11}cos\theta_{11}$
$M_{1y} = B_{1y} + l_{11}sin\theta_{11}$
$M_{1z} = B_{1z}$

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