Biologically inspired control for artificial muscles

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ABSTRACT

New actuator technologies are moving closer towards the creation of artificial muscles. For these muscles to behave in synergy with natural human muscle then they must be controlled in a similar manner. It has been postulated that the control of human motion is achieved through a force and position control strategy termed impedance control.

An impedance controller has been developed for implementation on an ionic polymer-metal composite (IPMC actuator). The basis for this controller is a PID position controller that is demonstrated to accurately control the position response of the IPMC actuator. This position controller is extended to form an impedance controller with a force control loop and impedance filter. Inspite of identified non-linearities in the polymer force output during motion, the impedance controller has been successfully implemented demonstrating the controller design process and good performance of the control strategy.

Keywords: EAP, IPMC, Impedance control, Artificial muscle, PID

1. INTRODUCTION

Conventional actuators such as electric motors, pneumatic and hydraulic cylinders are not viable artificial muscles for in vitro use within the human body due to their size and shape. Over the last decade the development of artificial muscles has gained momentum resulting in new actuators with greater potential to assist human muscle. These alternative actuators vary from pneumatic muscle actuators (PMA) [1], piezo electric actuators [2] to electroactive polymers [3]. Of these recent advances, a type of electroactive polymer called ionic polymer-metal composite (IPMC) offers great potential due to its relatively large displacement, great force to weight ratio and the ease at which it can be shaped and manipulated. IPMC actuators are created by chemically plating a sheet of Nafion® polymer with platinum [4]. When voltages are applied to the platinum electrodes, stress is generated within the membrane causing bending motion. A simplified model of the mechanism that causes bending has been produced by [5]. Research is ongoing to improve the performance of these actuators by methods such as increasing the thickness of the polymer [6] and an additional coating of metal [7], however at their present state of development these actuators exhibit excellent power to weight ratio combined with large relative displacement.

The force output and bandwidth of modern actuators have been evaluated against that of human muscle [8]. However, if these artificial muscles are to be compared against human muscles, comparable control methods must also be considered. Indeed if controlled appropriately, artificial muscles may not be required to exhibit physical properties similar to human muscle. To understand the control requirements for artificial muscles it is useful to consider the manner in which the central nervous system utilises human muscles. Control of human motion is not yet fully understood, however the theory postulated by Hogan [9] decomposes human motion into an a task planning stage and a motor application stage. The human consciousness plans global movement tasks, which are then broken down into movement stages and then implemented by the subconscious.

To illustrate this, consider an example of arm movement (figure 1). The movement that the arm is to undergo is specified by the human consciousness (A). This movement is then broken down into discrete points (virtual reference points) (B). The human arm moves to each new virtual point, altering its position if any external forces are encountered. The position alters as if the arm behaved as an ideal stiffness and damping (C,D). This results in the arm's position and the external forces applied to the arm effecting forces applied by the muscles to move the arm (i.e muscles within the arm implement a force and position strategy resolved through the kinematic links (bones) of the arm). This ensures stability of movement in the presence of an unknown external environment. By varying the stiffness and damping parameters the amount the human effects the environment can be changed. Low stiffness causes the human to exert little force on objects interfering with motion, conversely high stiffness causes large forces to be exerted to objects interfering with motion. It is interesting to note that the separation of movement into distinct points (B) is apparent in the motion of humans suffering illnesses such as stroke where damage to the brain causes jerky, segmented motion [10].

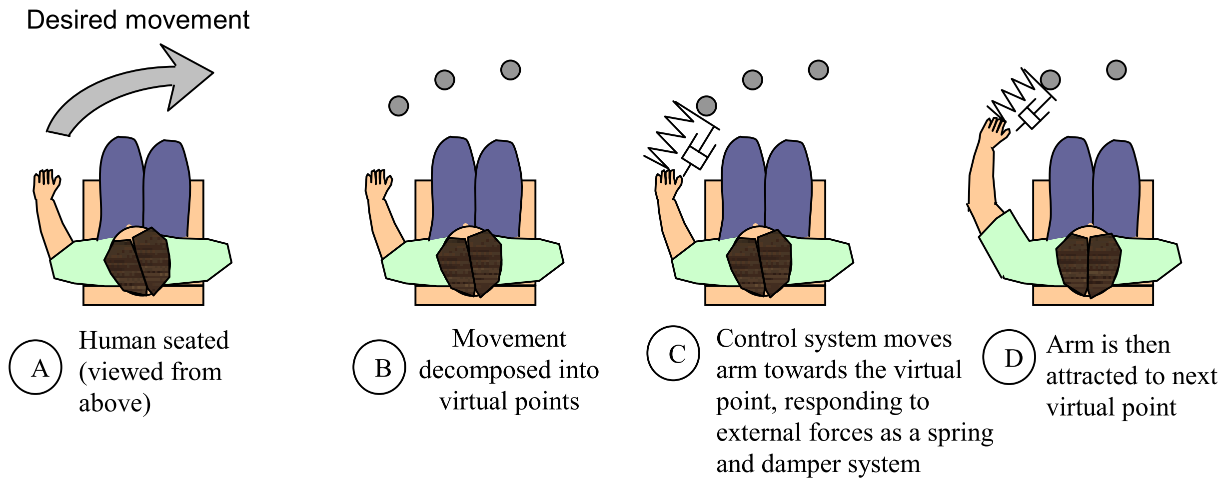


Figure 1 *Example of arm movement*

Over the last decade this force and position strategy 'termed impedance control' has begun to be applied to robotic systems to enable them to function more successfully in unpredictable environments. Note that full implementation of impedance control includes an inertial element so robots can mimic the physical properties of objects for applications such as haptic interfaces [11]. For movement purposes the inertial element is not used, with the controller is required to mask the physical inertia of links and joints.

2. IMPEDANCE CONTROLLER DESIGN

The free body diagram of the impedance controller is shown in figure 2 (where M is the inertia, K is the stiffness, C is the damping).

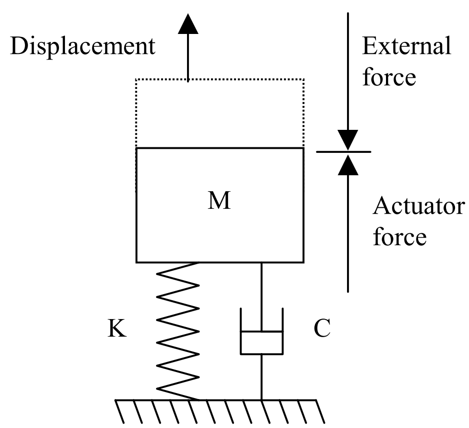


Figure 2 *Impedance control free body diagram*

Due to impedance control being a force and position control strategy the controller design can either consider position the input (x_i) and force (F_x) the output (equation 1) or force as the input and position the output (equation 2). This result is known as the duality of impedance control.

$$\frac{F_x}{x_i} = Ms^2 + Cs + K \qquad (1)$$

Force is controlled whilst monitoring and responding to changes in position

$$\frac{x_i}{F_x} = \frac{1}{Ms^2 + Cs + K} \qquad (2)$$

Position is controlled whilst monitoring and responding to external forces

The majority of researchers have opted to use a force based impedance controller when implementing the controller on robots due to the ease at which motor output torque (hence force) can be controlled [12]. However the majority of advanced modern actuators exhibit non-linearities in their force output and as such force based impedance control is not appropriate.

Force output of IPMC

Research has been performed to analyse the force output of IPMC actuators at varying voltages and distances from its clamp [13]. The output force of IPMC actuators also varies with movement of the actuator. To demonstrate this the output force of a piece of IPMC (Nafion ® 117, cut to 5mm x 20mm) at 15mm from its clamp for 5V applied voltage has been measured at various endpoint displacements (figure 3) when 5V is applied. The output force is shown to be a non-linear function of endpoint position.

The change in output force can be easily explained by examining the basic working's of the actuator. As the IPMC bends it acts against the natural elastic properties of the material. At the limits of motion the elastic properties of the actuator cancel out the internal bending stress caused by the applied voltage. Therefore the force that can be asserted is zero in the direction of the motion is zero. Throughout the movement the same effect alters the actuator force output.

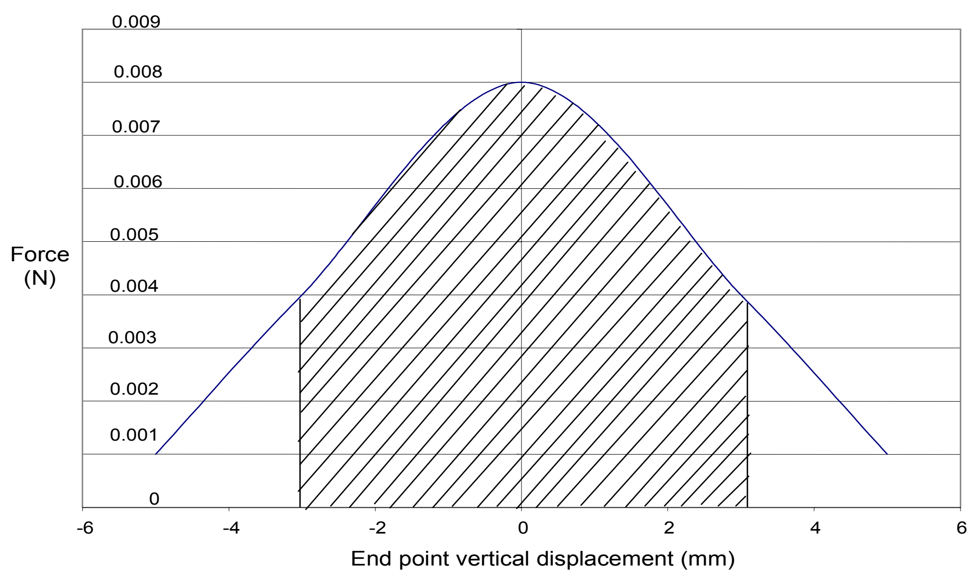


Figure 3 *IPMC force output against endpoint displacement*

This results in a non-linear force output characteristic during motion and, more importantly, results in tailing off of actuator force close to the limits of motion. An end-point movement range of ±3mm enables the IPMC to apply bi-directional force.

Position controller

The controller is to be position based so the position controller is the dominant element. A simple PID controller controls the actuator position (figure 4). This approach does not require a mathematical model of the actuator response, which can be difficult to obtain. The IPMC position was measured at 15mm from the clamp using a laser sensor. The PID controller gains were selected using the ultimate frequency method [14]. The gains for the PID controller are listed in table 1.

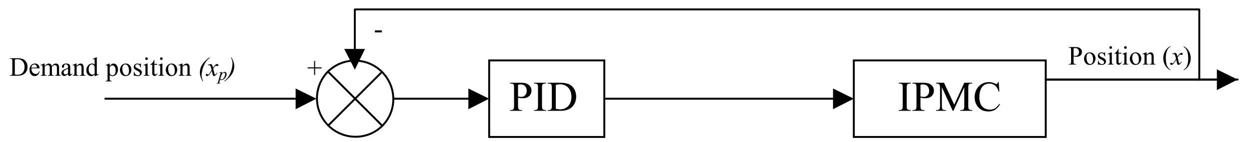


Figure 4 *PID controller*

	Proportional	*Derivative*	*Integral*
Gain	5.4	0.065	0.26

Table 1 *PID controller gains*

The position response of the PID controller is shown in figure 5 when tracking a sine wave and figure 6 when tracking a square wave while the voltages are restricted to below 5V to prevent damage to the actuator. This is larger than the low voltages applied by some researchers [15] to improve the controller response and enable larger forces to be applied when the impedance controller is implemented. The square wave response exhibits slight overshoot and quick response time. The sine wave is accurately tracked with slight phase lag.

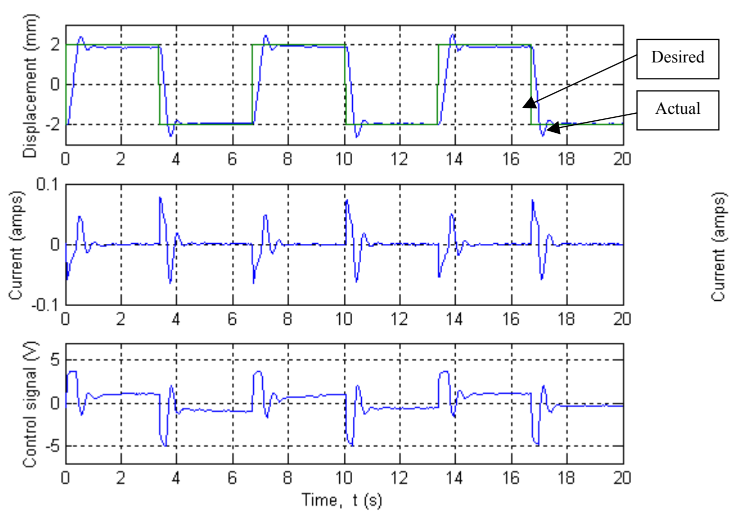


Figure 5 *IPMC square wave response*

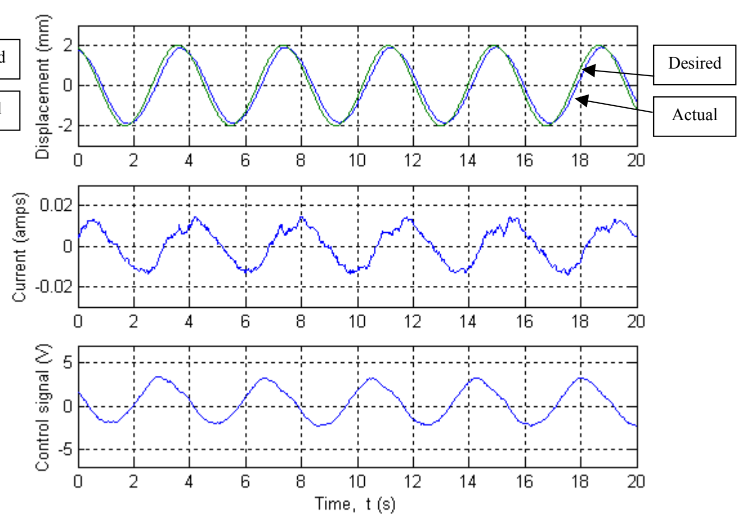


Figure 6 *IPMC sine wave response*

Impedance control

The position controller can be augmented to form an impedance controller. Equation 2 mathematically describes how the external forces effect the position response. The block diagram of the impedance controller is shown in figure 7 where the contact force is measured and fed into an impedance filter. The demand position is modified by the output of the impedance filter. The impedance controller allows for a force to be specified, the desired force. However this is only useful if a weight of an object to be picked up is known or where a known force is to be applied to the environment. In this situation the desired force is zero, so any force encountered is force error.

To implement the impedance controller an experimental set-up was used as shown in figure 8. The position controller using the laser position sensor remains the same. A force sensor and spring are introduced to apply external forces to the IPMC. The force sensor measures the forces applied to the IPMC through the spring. Ideally the actuator would have force sensors mounted upon it so that it could interact freely with any environment. Due to size limitations and low force output the force sensor has been mounted externally.

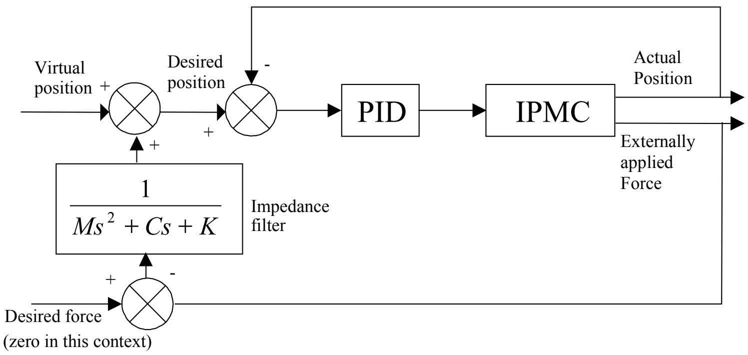


Figure 7 *Impedance controller block diagram*

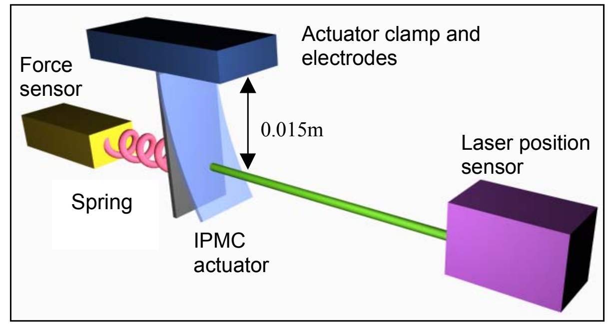


Figure 8 *Experimental layout*

When the IPMC moves into contact with the spring a force is exerted upon it with the impedance controller determining whether the IPMC moves into the spring or whether the spring restricts IPMC motion. So to put the controller in context with the earlier example of arm motion. The desired motion is split into a virtual point (figure 9 A,B). The polymer is then desired to move to the virtual point whilst responding to any external forces as if it were a spring and damper system. If external forces are encountered the virtual point will not be reached, instead a compromise position will be reached between the two conflicting demands of zero externally applied force and the virtual position (D).

It is important to understand there are now three position traces:

1 ***The virtual position*** (demand position (x_p) - an arbitrary point of desired motion, which is unaffected by IPMC movement or externally applied forces.

2 ***The desired position*** (x_d) – The virtual position modified by external forces (this would be the virtual position if no external forces were encountered).

3 ***The IPMC position*** (x) – The position of the IPMC measured by the laser sensor (if the position controller was ideal this would be equal to the controller desired position).

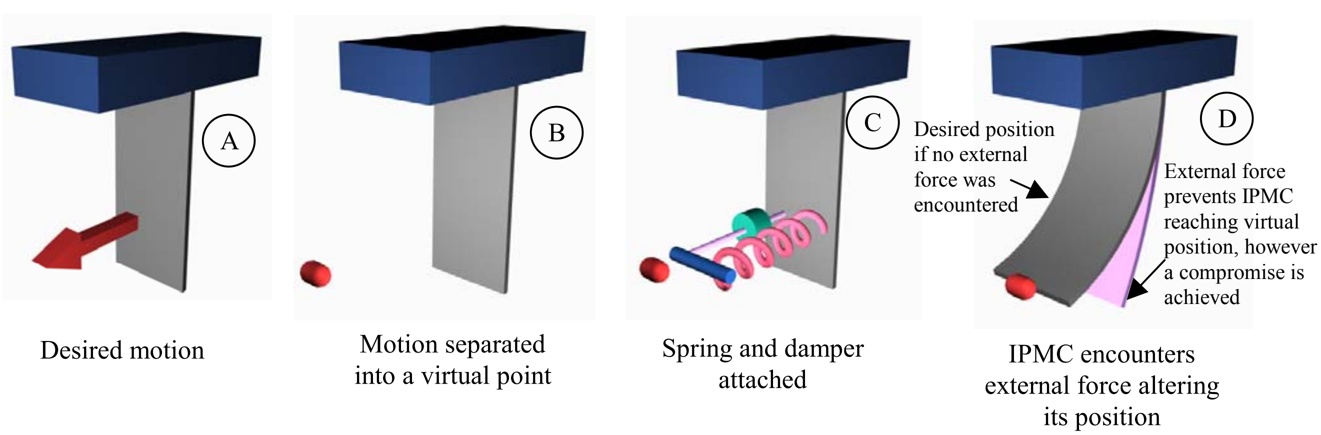


Figure 9 *IPMC impedance controller behavior*

2 Impedance controller results

Results were obtained for a selection of damping and stiffness parameters. The first response implemented a damping coefficient of 0.1 and a stiffness of 50. As a result of the relatively high stiffness the virtual position and desired are almost identical (i.e the external forces encountered are too small to noticeably compress the impedance filter spring and damping arrangement). This

requires the IPMC to exert sufficient force to move through the spring. Figure 10 is the IPMC response with the above mentioned damping and stiffness parameters.
After 15s the spring and force sensor are placed in the line of motion of the polymer. The response time of the polymer is effected and a larger potential difference has been applied across the polymer to produce the additional force to act against the spring. However the IPMC achieved the steady state position.

Decreasing the stiffness of the impedance controller causes external forces to have a greater influence. The controller response (K=5 C=0.1) is shown in figure 11. The external force causes the desired position to change significantly. The desired position is tracked, however there are delays in response. Finally the spring is brought into permanent contact with the actuator (figure 12). Inspite of the presence of external forces the actuator still moves, however the controller behaviour is effected. The output voltage approaches saturation when these forces are applied.

The PID controller behaves well and offers some robustness to external forces (i.e the IPMC actuator almost follows the desired trajectory inspite of the external forces). It possible to include a feed-forward force element to reduce some of the burden on the position controller due to these external forces [16]. However an approximate model of the actuator force output would be required.

3. CONCLUSIONS

The control of artificial muscles from a biological perspective has been discussed and been demonstrated by implementation on IPMC actuator. In its current form the IPMC actuator would have limited practical applications due to the small force output obtainable. However it has been demonstrated that advanced force and position controllers can be effectively implemented on the polymer actuator. Including a feed-forward force element would improve the position controller's robustness to external forces. Increasing the force output of these actuators through improved fabrication would increase the potential applications. It is vital that for any actuator to behave as an artificial muscles it must be controlled by a force and position control strategy to ensure stability and safe function. For practical applications force

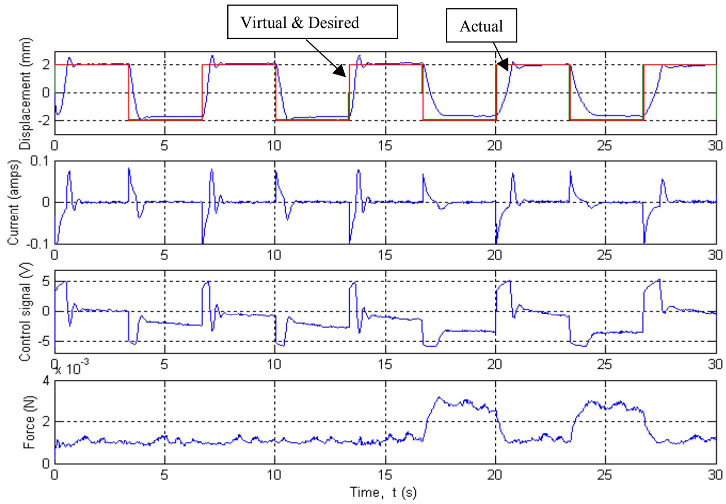


Figure 10 IPMC impedance response (K=50 C=0.1)

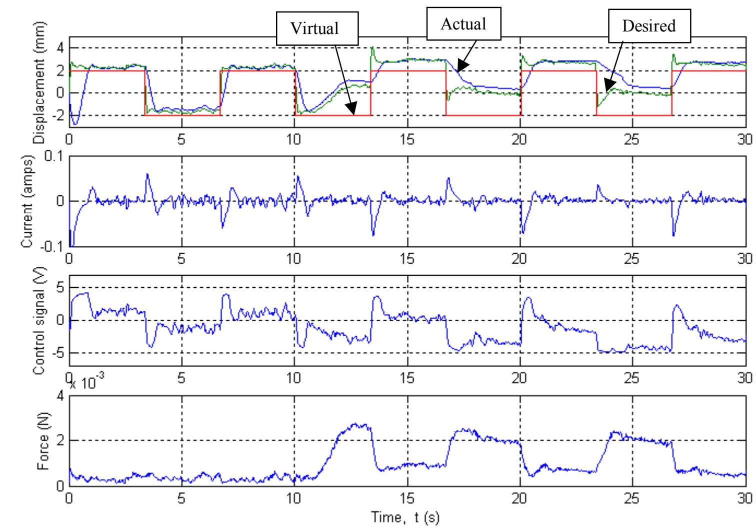
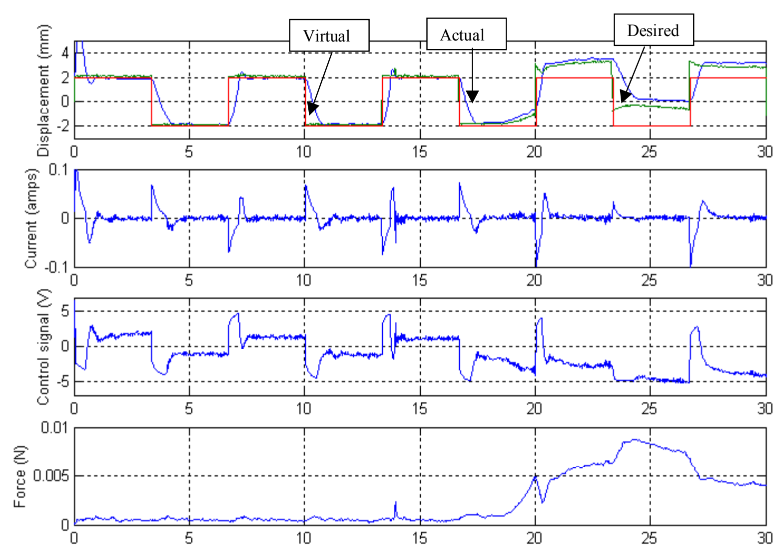


Figure 11 IPMC impedance response (K=5 C=0.1)



sensing must be mounted on the actuator itself so that it is capable interacting autonomously in any environment. Further work will investigate improving the force output of the IPMC and improving the controller strategy.

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