ADAPTIVE CONTROLLER DESIGN OF PNEUMATIC TELEOPERATION SYSTEM

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ABSTRACT

This paper presents an adaptive control design of a pneumatic teleoperation system that could be useful for applications like MRI-guided surgery. The system under study is special because of its reduced number of components compared to other bilateral teleoperation systems, which reduces cost and complexity. The direct fluidic connection and the force feedback that is transferred to the human operator allow the operator to feel as if s/he were having physical contact with the environment without the need for a force sensor on the slave actuator. A simulation model that allows stability and transparency assessment is presented in detail. A linear controller is optimized for various operating remote environments via transparency assessment. The linear controller leads to good results for certain operating environments, but its tuning is dependent on the impedance characteristic of the environments both on the master and slave sides. Since the system must perform under parametric uncertainties on both sides of the teleoperator, an adaptive control scheme is developed. A self-tuning regulator is designed to allow the teleoperator to cope with a variable environment. The control design is validated in simulation and yielded satisfactory performance under multiple environment settings.

Keywords: Teleoperation system, adaptive control, pneumatic actuator, self tuning regulator, pipeline dynamics

NOMENCLATURE

A Cross sectional area of the pneumatic line
A_p Piston area
b Critical pressure ratio given by the valve manufacturer
B_{h,e} Damping constant of the operator hand and environment
c Sonic conductance given by the valve manufacturer
D Tube diameter
F_h Hand force
k_{h,e} Spring constant of the operator hand and of the environment
K_v Electromechanical valve gain
L Pneumatic line length
l_{cyl} Total cylinder length
m_h Modeled mass of the hand
\dot{m}_{m1} Mass flow rate in chamber 1
\dot{m}_{L1} Mass flow rate into line 1
m_p Mass of the piston
m_{v1,2} Mass flow rate out of valve 1 and 2
P_{m1,2} Pressures across chambers 1,2 of the master cylinder
P_{1,2} Pressure across chambers 1,2 of the slave cylinder
P_{u1,2} Upstream pressure of valve 1,2
P_{d1,2} Downstream pressure of valve 1,2
P_c Pressure supply to the valves
P_T Atmospheric pressure
R Ideal gas constant
T Gas temperature
T_0 Temperature of air at reference conditions

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Teleoperators are used in situations where the human operator cannot have physical interaction with the remote environment, so they allow the human operator to control an actuator remotely.

Teleoperation systems are generally composed of a master and a slave, as shown in Figure (1), and use a specific communication scheme between these two to achieve the required goal of allowing the operator to interact with the physical environment remotely [1].

In some situations, the human operator cannot have direct contact with the task environment due to several reasons: geometric and physical constraints, danger on human life, human operator and environment location, etc.

![Figure 1: General teleoperation system composition](image)

If the slave reflects force from the task environment to the human operator, the teleoperator is said to be controlled bilaterally [2]. Advances were done in this field using different actuation techniques and different communication protocols like mechanical, electrical, wireless or fluidic, for different applications such as medical, nuclear or marine. These advances tend to improve two important criteria that define the performance of the teleoperator, stability and transparency.

In network theory, an n-port system is characterized by the relationship between effort and flow [3]. The effort $f$ can be the force output of a mechanical system, or the voltage output of an electrical system; the flow $v$ can be the velocity input of a mechanical system or the current input of an electrical system. For a linear time-invariant, lumped one port network, the relationship is denoted as impedance $Z(s)$, which is the ratio between effort $f$ and flow $v$:

$$Z(s) = \frac{f(s)}{v(s)}$$

where $f(s)$ and $v(s)$ are the Laplace transforms of $f$ and $v$ respectively. Figure (2) shows the different parameters communicated between the master and slave actuators, where $V_m$ is the velocity of the human operator hand and $F_h$ is the force transferred from the teleoperator. $V_s$ and $F_e$ are the velocity of the slave actuator and force reflected by the environment, respectively.

Transparency is defined as the impedance ratio between the master and the slave:

$$\text{Transparency} = \frac{Z_t}{Z_e}$$

$Z_t$ is the impedance of the teleoperator system including the environment impedance, and $Z_e$ is the environment impedance, and they are given by:

$$Z_t = \frac{F_h}{V_m} \quad Z_e = \frac{F_e}{V_s}$$

The goal of a teleoperator is to make the impedance felt by the operator $Z_t$ equal to the actual environment impedance $Z_e$. The system stability is influenced by both operator and environment dynamics [4]. Stability and transparency are two conflicting design issues [5]. A good teleoperator design is the one that can accomplish the best tradeoff between stability and transparency. This tradeoff is based on many assumptions: application, accuracy needed, environment and operator behavior, etc.

Dale A. Lawrence presented in [5] a general multivariable architecture that can be used in bilateral teleoperation systems.
as shown in Figure (3), where $F_h$ and $F_e$ are the forces acting on the slave and master actuators. The reflection of force $F_h$ by the hand caused from motion $V_h$ of the slave actuator is characterized by the hand-arm impedance $Z_h$. An additional exogenous force $F_{\epsilon}^*$ can be exerted by the operator to move the master cylinder to its desired position. Similarly, the reflection of force from the environment caused from slave actuator motion is characterized by the environment impedance $Z_e$. Also the environment may have an active component that causes an exogenous force $F_{\epsilon}^*$. $C_1, C_2, C_3, C_4, C_i$ and $C_m$ are communication links defined in [5]. The architecture is transmitting four variables, force and velocity in both directions (master and slave). This architecture was the source of many papers published in the last two decades, where researchers optimized design for better teleoperators behavior. Building teleoperation systems that are under rate control or more generalized master-slave correspondence laws was done in [3], such as mixed position-rate mode. The paper started from Lawrence’s architecture [5], and built a more general structure that can be used in bilateral teleoperators which provides better force feedback to the operator. General analysis of performance and stability robustness of impedance-impedance 3-channel architectures was presented in [6]. The analysis was targeted for tele-surgery applications on soft tissue, where relatively low frequencies are used, negligible time delay and low impedances exist. The paper recommended using the Position, Position-Force architecture based on analysis of simulation evaluation results. Literature shows that using kinesthetic force feedback in passive teleoperator systems, which enhances the operator feeling in the environment force, had good transparency, so the human operator feels exactly as if s/he is having physical contact with the environment. Stability is not guaranteed under all conditions. On the other hand, using cutaneous force feedback (which helps identifying the properties and features of the environment) leads to good stability but less transparent systems [7]. Combining cutaneous and kinesthetic force feedback in teleoperators was presented in [7], where force feedback is computed on the master side and is actuated via a kinesthetic device, as long as the passivity condition is not violated. When the passivity layer detects a violation and the kinesthetic device is unable to provide the required feedback, a cutaneous actuator conveys a suitable tactile sensation according to the amount of force, while recovering transparency. Environment parameter estimation architecture was presented in [8] where nonlinear stiffness and damping of the physical environment are estimated using indirect adaptive control approach, which improved transparency, gave realistic results, and allowed the controller to provide the necessary information from the remote environment to the human operator.

As a summary of what was presented in literature, optimizing transparency was done in different ways:

1. Improving the architecture, i.e changing communication lines and transferred variables [5, 3, 6].
2. Choice of sensors, and improving sensors design [7].
3. Proper choice of controller type [8].

Pneumatic actuators are widely used in teleoperation systems due to a variety of benefits over other types of actuation: low cost, backdrivability, ease of implementation, precision sensing and high force to weight ratio. In this paper our purpose is to assess and control a 1 degree of freedom pneumatic actuator with force feedback to be implemented and used under real-time MRI imaging. The teleoperation system was first presented in [9]. Initial testing of the system identified the challenge of optimizing transparency while maintaining stability.

The purpose of this research is approached by first analyzing what has been done in literature regarding pneumatic teleoperator systems, establishing architecture of our system in comparison to Lawrence [5], assessing transparency and stability, and linear control design.

Section 2 states the governing equations of the model, section 3 introduces the linear controller with transparency assessment analysis, section 4 presents the adaptive control design, section 5 shows the simulation results, and section 6 concludes the work.
2 GOVERNING EQUATIONS

This section introduces the governing equations of the model. Figure (4) shows the different physical components of the system, and how they are connected. Master and slave actuators are connected with a physical connection, i.e. pneumatic lines. Two position sensors are connected to the pistons, and two pressure sensors are connected to the tubes. The valves are placed near the master actuator and are used by the controller to adjust the pressures in the lines connecting master and slave cylinders.

The model equations are divided into four main parts: actuators motion, cylinder chamber pressure drop, valve dynamics and tube models.

2.1 Actuator Motion

The force transmitted to the human operator is given by:

\[ F_h = (P_{m1} - P_{m2})A_p - m_p \dot{x}_m - \beta \ddot{x}_m \]  \hfill (3)

where \( A_p \) is the cross sectional area of the piston, \( x_m \) is the master piston position, \( \beta \) is the viscous friction coefficient of the pistons and \( m_p \) is the mass of the piston. The slave piston equation of motion is given by:

\[ m_p \ddot{x}_s + \beta \dot{x}_s = (P_{s1} - P_{s2})A_p - B_e \dot{x}_s - K_e x_s \]  \hfill (4)

where \( x_s \) is the slave piston position, \( B_e \) is the damping coefficient and \( K_e \) is the spring constant of the environment model.

2.2 Cylinder Chamber Pressure Drop

Assuming isothermal conditions because we don’t expect fast movements in the teleoperation application, the rate of change of the pressure in chamber 1 of each cylinder is given by:

\[ \dot{P}_{i1} = \frac{RT}{V_{i1}} \dot{m}_{i1} - \frac{P_{i1}}{V_{i1}} V_{i1} \]  \hfill (5)

where \( i = m \) or \( s \) refers to either master or slave respectively, \( P_{i1} \) is the pressure in chamber 1 in each cylinder, \( V_{i1} \) is the volume of chamber 1 in each cylinder.

With the volume of chamber 1 written in terms of cylinder position:

\[ V_{i1} = V_{id} + x_i A_p \]  \hfill (6)

where \( V_{id} \) is the dead volume of the chamber. Substituting Eq. (6), Eq. (5) becomes,

\[ \dot{P}_{i1} = \frac{RT}{V_{i1}} \dot{m}_{i1} - \frac{P_{i1}}{V_{i1}} V_{i1} \]  \hfill (7)

Similarly, the change in pressure in chamber 2 is expressed as,

\[ P_{i2} = \frac{RT}{V_{i2}} \dot{m}_{i2} - \frac{P_{i2}}{V_{i2}} V_{i2} \]

\[ = \frac{RT}{V_{id} + (l_{cyl} - x_i)A_p} \dot{m}_{i2} + \frac{P_{i2}}{V_{id} + (l_{cyl} - x_i)A_p} \dot{x}_i A_p \]  \hfill (8)

2.3 Valve Dynamics

The valve is connected to the pressure supply and to the atmospheric pressure as shown in Figure (5), where the spool position \( x_v \) is controlled with the control input \( u \). The mass influx

\[ \dot{m}_{vn} \]

of the valve \( \dot{m}_{vn} \), related to the control input \( u \), is given by ISO
6358 technical nozzles and orifices [10] as:

\[
\dot{m}_{vn} = \begin{cases} 
uc \rho_0 P_{un} \sqrt{\frac{T_0}{T_{1n}}} \left[ 1 - \left( \frac{P_{un}}{P_{dn}} \right)^{\frac{n}{2}} \right] & \text{for } \frac{P_{dn}}{P_{un}} > b \\
uc \rho_0 P_{un} \sqrt{\frac{T_0}{T_{1n}}} & \text{for } \frac{P_{dn}}{P_{un}} \leq b 
\end{cases}
\]

Where \( n = 1 \) or 2 refers to valve 1 or 2, \( c \) is the sonic conductance given by the valve manufacturer, \( \rho_0 \) is the density of air at reference conditions, \( P_{un} \) is the upstream pressure, \( T_0 \) is the temperature of air at reference conditions, \( T_{1n} \) is the upstream temperature of air, \( P_{dn} \) is the downstream pressure, and \( b \) is the critical pressure ratio given by the valve manufacturer.

The natural frequency of the valve spool position control is 400 Hz. Since this is fast compared to other dynamics in the system, it can be neglected for the purpose of control design.

### 2.4 Tube Modeling

Applying the conservation of mass and continuity equations for the lines, we get:

\[
\dot{m}_{vn} = \dot{m}_{mn} + \dot{m}_{Ln}
\]

Tube dynamics are modeled by a simplified equation, assuming the temperature change in and out of the lines is minimal, which is valid if the highest frequency \( f \) in rad/s follows the condition [10]:

\[
f \leq \frac{4v}{A}
\]

where \( v \) is the kinematic viscosity, and \( A \) is the cross sectional area of the lines. If this condition is satisfied, the tubes can be modeled with one or more elements with simple resistance, capacitance and inertance characteristic [11], as shown in Figure (6).

The pressure gradient in the first line is given by:

\[
\dot{P}_{L1} = \frac{RT}{AL} (\dot{m}_{L1} - \dot{m}_{s2})
\]

Finally, since the capacitance of the line is connected to the chamber of the cylinder, the following condition holds:

\[
P_{L1} = P_{s2}
\]

The model architecture is presented in Figure (7). The human operator hand force is considered as input to the master cylinder, which returns force feedback to the operator. The pressure drop caused by master cylinder movement is transferred through the pneumatic lines from the master to the slave actuator to cause slave piston movement. On the other side, the environment force acting on the slave actuator is represented as the product of the environment impedance multiplied by the slave cylinder’s velocity. What makes this architecture different than
The previous work is that the whole teleoperation system is one physical unit (master - lines - slave). It does not consist of two physically independent master and slave actuators that are only connected through control signals, compare Figure (3). This results in the fact that only one control signal (the valve spool position at master side) exists, while the architecture of Lawrence [5] has two control channels between master and slave.

3 TRANSPARENCY ASSESSMENT AND LINEAR CONTROL DESIGN

Transparency assessment is done by comparing the impedance of the teleoperator $Z_e$, which is the impedance transmitted to the human operator, to the impedance of the environment $Z_t$ as shown in Figure (2).

The impedance of the teleoperator $Z_e$ is given by equation (3), where velocity of the operator master, assumed to be equal to hand velocity, is the input to the master and the resulting force transmitted to the operator is the output, and the environment impedance $Z_t$ is given by equation (4). The environment can be modeled as a simple spring-damper system as shown in Figure (4). Ideally, the transparency ratio should be equal to unity. In other words, the impedance transmitted to the human operator should be made equal to the impedance of the environment, so the human operator feels exactly the environment impedance, see Figure (2).

Linearizing nonlinear model equations is helpful in assessing how design parameters, such as cylinder or tube diameters and lengths, affect transparency and stability margin. The impedance is frequency dependent, thus the transparency ratio can also be represented in a bode plot. The aim of a control design is to get a transparency ratio of 0 dB for low operating frequencies, and have a high cutoff frequency while maintaining stability.

Proportional position control with cascaded pressure feedback was applied to the system in [9], position difference of the master and slave cylinders is fed back to the controller that controls the valve spool positions as shown in Figure (8). This controller yielded good results regarding transparency while maintaining stability for a low stiffness environment. The control parameters that ensure tracking of master and slave with guaranteed stability were found to be: $K_p = 2.9V$/bar and $K_s = 2.4N$/mm. Using a lead compensator can increase the bandwidth of a system without loss of phase margin [12]. Therefore, a lead compensator with cascaded pressure feedback is designed to improve the system performance, i.e. to control the slave piston to follow the master piston and supply the required force feedback to the human operator. It is desired to maintain a phase margin of $\gamma \approx 50^\circ$ at a gain cross-over frequency of $\omega_{gc} = 50rad/s$. The following compensator transfer function is used:

$$T(s) = \frac{0.052s + 1}{0.0076s + 1}$$

(15)

The open loop frequency response that reveals the stability margin is plotted in Figure (9) for both, the plant with proportional control and with lead compensator. The environment is modeled as a simple spring and damper system as shown in Figure (4), with spring stiffness $K_e = 0.1N$/mm and damping $B_e = 0.5N$.s/mm.

In Laplace domain, the environment impedance is written as:

$$Z_e = \frac{0.5s + 0.1}{s}$$

(16)

Referring to Figure (4), the input of the open loop frequency response is the valve input $u$ and the output is the error signal $x_m - x_s$. One can see how with the lead compensator the new gain crossover frequency is shifted to the right, $\omega_{gc} = 50rad/s$, and the phase margin is maintained. Therefore, for the transparency ratio $T(Z_e/Z_t)$, we may expect a higher bandwidth for the lead compensated system. Figure (10) shows the transparency ratio of the system with the two different linear control laws. The ideal 0 dB transparency ratio magnitude is achieved at low frequencies, with a phase of $0^\circ$ for both controllers. At higher frequencies, the teleoperator starts losing transparency as the magnitude of $Z_e/Z_t$ moves away from 0 dB. It is seen that the lead compensator control improves transparency for higher frequencies.

To illustrate the fact that a change in the environment parameters directly affect the transparency, Figure (11) compares the transparency achieved with the lead compensator for the original and a 5 times stiffer system.

It can be seen that the lead compensator does not maintain the same level of transparency. As the remote environment gets stiffer, the relatively low stiffness of the teleoperator becomes more apparent. This is expressed by the fact that the transparency magnitude and phase is dropping from the 0 dB and $0^\circ$ line starting at lower frequencies.
FIGURE 9: Open loop frequency response comparison between plant with proportional position control and lead compensator, input is dimensionless valve input signal $u$ ($u = 1$ is valve fully opened), output is position error between master and slave cylinders.

FIGURE 10: Bode plot of transparency ratio for system with proportional position feedback and system with lead compensator feedback, input is the velocity of the human operator hand and output is the force reflected to the operator.

4 ADAPTIVE CONTROL DESIGN

The control purpose can be described as a tracking problem. The purpose is to make the slave piston position $x_s$ to track the master piston position $x_m$. An indirect self-tuning regulator (STR) without zero cancellation is chosen to address this problem, because the system is non-minimum phase. This control paradigm uses a recursive least squares (RLS) algorithm to estimate the plant parameters [13]. The controller parameters are in turn updated based on the estimation of the system parameters. A block diagram of the adaptive controller is shown in Figure (12). The adaptive controller is designed so that the system output $x_s(t)$, the slave piston position, tracks the reference input $x_m(t)$, the master piston position. The parameter estimation block estimates the system parameters based on the system output $x_s(t)$ and the control input $u(t)$. The “Controller Design” block supplies the “Controller” block with updated parameters to compute the control signal $u(t)$, based on the estimated system parameters, and on the desired model output. The “Controller” block generates the actual system input, the valve input signal $u$, based on the system output $x_s$ and the desired system output (the reference input) $x_m$, the position of the master piston.
4.1 Parameter Estimation

The teleoperator transfer function in discretized form $G(z)$ taking the input and output as stated above, is given by:

$$G(z) = \frac{B(z)}{A(z)} = \frac{b_0 z^5 + b_1 z^4 + b_2 z^3 + b_3 z^2 + b_4 z + b_5}{a_0 z^6 + a_1 z^5 + a_2 z^4 + a_3 z^3 + a_4 z^2 + a_5 z + a_6}$$

(17)

Dividing both levels by $z^6$, we get:

$$A(z^{-1})y(t) = B(z^{-1})u(t)$$

(18)

$$(a_0 + a_1 z^{-1} + \ldots + a_6 z^{-6})y(t) = (b_0 z^{-1} + b_1 z^{-2} + \ldots + b_5 z^{-6})u(t)$$

(19)

The system expressed as a difference equation can be written as:

$$y(t) = -a_1 y(t-1) - \ldots - a_6 y(t-6) + b_0 u(t-1) + \ldots + b_5 u(t-6)$$

(20)

Thus, the parameters vector $\theta(t)$, and the regression vector $\varphi^T(t)$ are written as:

$$\theta(t) = [a_1, \ldots, a_6, b_0, b_1, \ldots, b_5]^T$$

$$\varphi^T(t) = [-y(t-1), -y(t-2), \ldots, -y(t-6), u(t-1), u(t-2), \ldots, u(t-6)]$$

And thus the output $y(t)$ is written as:

$$y(t) = \varphi^T(t) \theta$$

(21)

Recursive least square estimation is given by [13]:

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)(y(t) - \varphi^T(t) \hat{\theta}(t-1))$$

$$K(t) = P(t)\varphi(t) = P(t-1)\varphi(t)/(\lambda I + \varphi^T(t)P(t-1)\varphi(t))^{-1}$$

$$P(t) = (I - K(t)\varphi^T(t))P(t-1)/\lambda$$

where $P(t) = (\varphi^T(t)\varphi(t))^{-1}$, $K(t)$ is a vector of weighting factors that tell how the correction and the previous estimate should be combined, and $\lambda$ is a forgetting factor that introduces time-varying weighting of data such that $0 < \lambda \leq 1$. The parameters $\theta(t)$ are initialized with reasonable values that can represent the nominal system, and the $P(t)$ matrix is initialized with a 12x12 identity matrix multiplied by a large number to achieve asymptotic output tracking. When the filtered absolute error between the master and slave position $x_m - x_s$ is driven into a specified tolerance band ($0 - 15$ mm), the parameter adaptation is stopped. The plant parameters are held constant until the error increases again, which could be caused by changes in forces experienced from environment or operator or caused by parameter changes of the contact environments.

4.2 Controller Design

The desired performance specification are stipulated by the reference model which is given the following equation:

$$\frac{B_m(s)}{A_m(s)} = \frac{\omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2} (s + \psi)^4$$

(22)

where $\omega_n$ is the natural frequency of the second order polynomial, $\zeta$ is the damping ratio and $\psi$ is parameterized as a non-dominant pole far left from the second order model poles; these poles are necessary to increase the order of the model to $6^{th}$ order to respect the causality conditions: $\deg A_m(z) = \deg A(z) = 6$ and $\deg B_m(z) = \deg B(z) = 5$.

A control law that yields two degrees-of-freedom, feedforward and negative feedback, is given by:

$$Ru(t) = Tu_c(t) - Sy(t)$$

(23)

The control signal $u(t)$ which corresponds to the valve spool position, is obtained from eq (23) as:

$$u(t) = \frac{T}{R} u_c(t) - \frac{S}{R} y(t)$$

(24)

Polynomials $R$ and $S$ are computed using Diophantine equation:

$$AR + BS = A_0 A_m$$

(25)

Based on the causality conditions, $R$ and $T$ are fifth order polynomials and $S$ is a second order polynomial:

$$R(z) = r_0 z^5 + r_1 z^4 + r_2 z^3 + r_3 z^2 + r_4 z + r_5$$

$$S(z) = s_0 z^2 + s_1 z + s_2$$

Polynomial $T$ is computed using:

$$T = \frac{A_m(1)}{B(1)}$$

(26)

In discrete form, $T(z)$ is written as:

$$T(z) = t_0 z^5 + t_1 z^4 + t_2 z^3 + t_3 z^2 + t_4 z + t_5$$

(27)

The observer polynomial $A_0(z)$ is of $5^{th}$ order, it can be written as:

$$A_0(z) = (z + O0)(z + O1)^4$$

(28)
which can be expanded in the form:

\[ A_0(z) = z^5 + a_01z^4 + a_02z^3 + a_03z^2 + a_04z + a_05 \]  

(29)

The control signal \( u(t) \) is saturated between -1 and 1 because it corresponds to the valve spool position, thus a maximum \( u(t) = 1 \) corresponds to full opening of the valve, or 100%.

5 SIMULATION RESULTS

This section presents simulation results of the proposed teleoperation system and controller.

The implementation requires the definition of the desired response characteristics. The following results are achieved by setting the characteristic natural frequency \( \omega = 2\pi \text{rad/s} \), damping ratio to be unity and all other poles of the reference model to a very high value (\( \psi = 10^5 \text{rad/s} \)).

Regarding the recursive least squares block, the parameter vector \( \theta(t) \) is initialized with the approximate parameters of the system operating in different operating environments listed below, the \( P \) matrix is initialized with an identity matrix multiplied by \( 10^{17} \), which results in fast convergence.

The observer polynomial parameters are specified as: \( O0 = 0.8 \) and \( O1 = 0.99 \).

To show the ability of the system to adapt to various environments, it is tested with different operating environments: human skin, fat, and muscle. The values of stiffness and damping of each environment were presented in [14] as:

1. Skin: \( K = 0.331 \text{N/mm} \) and \( B = 3 \cdot 10^{-6} \text{N.s/mm}^2 \)
2. Fat: \( K = 0.083 \text{N/mm} \) and \( B = 10^{-6} \text{N.s/mm}^2 \)
3. Muscle: \( K = 0.497 \text{N/mm} \) and \( B = 3 \cdot 10^{-6} \text{N.s/mm}^2 \)

The system performance results are shown for two cases, when tested against human fat and muscle. Simulations are carried out with a 10N, 1 rad/s sinusoidal force excitation of the master piston rod. This excitation happens in the block “Teleoperator system” in Figure (12). The effect of the force excitation is a motion of the master piston. The STR control works to achieve a tracking of this master motion by the slave piston. Results for master and slave pistons positions are shown in figures (13) and (14), which show that adaptation is taking place. Asymptotic tracking, which is indicated by the decaying error, is achieved after 13.2s for the fat environment case, and after 5s for the muscle environment case.

It is worth noting that the implementation showed a high sensitivity to changes in initialization parameters. As such, the proposed control paradigm does not guarantee stability [13]. While the controller worked well for many different environment settings, unstable behavior was observed for some combinations of observer settings and initial estimation parameters. One thing that should be pointed out, is that the implementation of the self-tuning regulator in this paper is non-typical, in the sense that the output of the plant is used in a feedback fashion as the reference input for the control. The issue of potential instability will be further explained and addressed in future work.
6 CONCLUSION

Proportional and lead compensator controllers with pressure feedback were designed to control the proposed teleoperator. The slave actuator was capable of following the master when controller parameters are chosen correctly, and it was shown that lead compensator has advantage over the proportional controller. Since the teleoperator is to be implemented under live MRI imaging, where parameters of environment and human operator arm are varying, it was shown that both proportional and lead compensator were not capable of properly adapting to this change.

The proposed adaptive controller is tested in two different environment impedances, which resemble human fat and muscle, the system performed well in both cases. Adaptation takes place as expected and a small dynamic error (0 to 10 mm) between the master and slave cylinders is achieved. In future work the proposed control scheme will be implemented on the test rig and extensively tested.

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APPENDIX:

\[ x_{\text{mE}} = \frac{L_{\text{cyl}}}{A} \]

\[ P_{\text{atm}} = 1.013 \times 10^5 \]

\[ P_{\text{m1E}} = -\sqrt{\frac{P_{\text{atm}} b_1^2}{2(b_1-1)}} \]

\[ P_{\text{m2E}} = P_{\text{m1E}} \]

\[ P_{\text{m2E}} = P_{\text{m1E}} \]

\[ P_{\text{m2E}} = P_{\text{m1E}} \]

\[ c_1 = \frac{V_{\text{atm}} + sE}{10P_{\text{m1E}}A_p} \]

\[ c_2 = \frac{P_{\text{m1E}}A_p}{10P_{\text{m1E}}A_p} \]

\[ c_3 = \frac{RT}{V_{\text{atm}} + sE} \]

\[ c_4 = \frac{RT}{V_{\text{atm}} + sE} \]

\[ c_5 = \frac{RT}{V_{\text{atm}} + sE} \]

\[ c_6 = \frac{RT}{V_{\text{atm}} + sE} \]

\[ c_7 = \frac{RT}{V_{\text{atm}} + sE} \]

\[ c_8 = \frac{RT}{V_{\text{atm}} + sE} \]

\[ c_9 = \frac{1000A_p}{L_c} \]

\[ c_{10} = \frac{1000A_p}{L_c} \]

\[ c_{11} = \frac{1000A_p}{L_c} \]

\[ c_{12} = \frac{1000A_p}{L_c} \]