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Enhancement of Stability and Transparency in Teleoperated Robots Through Isotropy-Based Design

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ABSTRACT The primary challenge in implementing teleoperated master-slave robots is that both of its objectives – stability and transparency, are conflicting to each other. This trade-off is usually attributed to the time-delay in the communication channel, and state-of-the-art controllers are proposed primarily to counteract the effects of this time delay. Despite such controllers, it is observed that the system suffers from instability and inaccurate force feedback (loss of transparency), at least under certain conditions. This is because issues other than time delay which cause oscillations and inaccurate force feedback are rarely addressed in the literature. In this paper, such issues are clearly identified and it is shown here that controller design cannot counteract these issues. It is proposed in this paper that an isotropy based design of robots is necessary for recovering the additional stable and transparent behavior of the system, apart from what a controller can achieve. Another significant contribution of this paper is that because of the proposed design, the need for two signals from the traditional four-channel teleoperation architecture is eliminated, thus reducing the complexity of the system. Experimental validation is carried out by implementing a two-channel architecture on the designed robots.

INDEX TERMS Bilateral teleoperation, conditioning index, isotropy based design, stability, teleoperation architecture, transparency.

I. INTRODUCTION

Teleoperation is the art of manipulating objects from a distance. It is a partially autonomous operation where the human grasps and manipulates the objects while being remotely located from the object. This would be necessary while interacting with hazardous materials, performing undersea operations, surgeries, etc., since the distantly located human can have higher safety and comfort, than when he is at the operational environment. Several other applications of teleoperation in recent days can be seen in [1]–[5]. These include teleoperation applied in wide domains such as mobile robots, forest machines, laser surgeries etc.

The essential components of any teleoperation system include master robot(s), slave robot(s), communication channel, and controllers. The master robot is directly handled by the user, while the slave robot located in a remote environment is programmed to mimic the master and manipulate the objects. Furthermore, the environmental forces (reaction forces from the object) experienced by the slave are transmitted back to the master so that the user can experience the environment transparently. Thus, there is a transmission of both the position and force signals through the communication channel. Fig. 1 shows the typical control architecture of a teleoperation system with bilateral control having 4-channel communication.

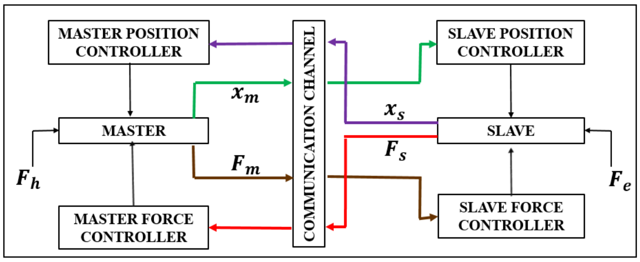

FIGURE 1. Traditional 4-channel control architecture of a teleoperation system.

Here, x_m and x_s are the positions of the master and slave manipulators while F_m and F_s are the master and slave forces

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respectively. The forces from the human and the environment are denoted by F_h and F_e respectively.

The two key performance objectives of a teleoperation system are stability and transparency. Meeting these two objectives demands simultaneous position tracking as well as force tracking. Thus, force feedback becomes mandatory for complete transparency. However, since feedback through a delayed channel (the communication channel) causes instability [6], stability and transparency are always at a trade-off in teleoperation systems.

Since it has been observed that the trade-off arises because of the time-delay in the communication channel, state-of-the-art provide solutions in two broad categories:

A. IMPLEMENTING CONTROL ALGORITHMS

The first breakthrough for solving this stability-transparency trade-off is considered to be the passivity based control technique presented in [7]. Here, it is identified that the communication channel is the only active component adding energy to the system, and a control law is proposed to keep the communication channel passive. Another well-accepted solution is presented in [8], where it is identified that position and force signals when passed through the communication channel would destabilize the system. So a transformation is proposed to convert these signals to wave variables and then transmit across the communication channel. A feed-forward control technique, whose gain depends on the time delay, is presented in [9] to retain the stability and transparency. Another delay-dependent control is presented in [10] to achieve the same end. Recently, a sliding mode controller, specific to surgical applications is shown in [11]. Adaptive control being implemented to teleoperation can be seen in [12] and [13]. In the more recent days, P-D control being applied to asymmetrically varying time-delays is also shown in [14] and [15]. An exhaustive list of all such control techniques is presented in [16]. Essentially, all these controllers are meant to counteract the effects of time-delay.

B. ALTERING THE COMMUNICATION CHANNEL

There is another class of state-of-art solutions, which alter the communication channel's internal architecture, to improve the system performance. [17] proposed that TCP (Transmission Control Protocol) induces the channel to wait until the previous signal is acknowledged, thereby increasing the time-delay. Hence a UDP (User Datagram Protocol) is preferred. A predictor based internet communication is proposed in [18] to improve the efficiency of the communication channel.

Each of these control techniques and communication protocols addresses only issues related to time delay. Consequently, implementation of even well acceptable controllers still leaves the system with unwanted oscillations and inaccurate force feedback [16]. This is because there are other reasons which onset oscillations in the robots.

The aim of this paper is to analyze the factors causing such oscillations and loss of accurate force feedback, and propose a solution for the same. It is shown in this paper that oscillations and loss of force feedback occur not only because of signal transmission between master and slave, but also because of improper signal transmission with each of the master / slave, i.e. from active joints to the end-effector. Such internal transmission issues need to be addressed at the robot design stage itself. Fig. 2 shows the factors affecting simultaneous achievement of stability and transparency.

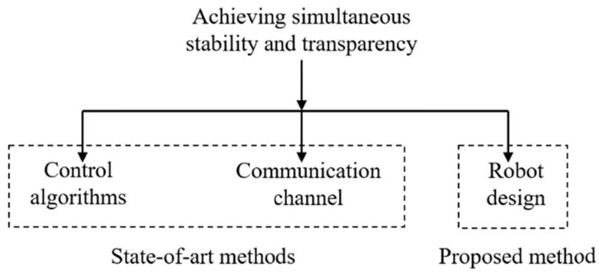


FIGURE 2. Factors affecting achieving simultaneous stability and transparency.

How the robots should be designed to overcome such issues is discussed in this paper. In addition, the consequences of such design on the overall teleoperation architecture itself are analyzed. *It is shown that with the help of the proposed design, the overall teleoperation architecture can be simplified from a traditional four-channel to a two-channel architecture.* Thus, the effect of the proposed design is two-fold:

(i) It ensures faithful internal transmission of signals within each robot and thus minimizes the oscillations and loss of force feedback, which the controller cannot do.
(ii) It facilitates minimization of number of communication channels.

The organization of this paper is as follows. Section II proposes that by improving the isotropy of the master and slave manipulators, stability and transparency can be further enhanced. It is also shown that the position feedback channel from the slave can be eliminated when such design is implemented. Section III explains the actual design procedure for improving the isotropy of the manipulators. The ratio of link lengths for the case study of a five-bar manipulator is determined by maximizing the isotropy index. Section IV shows the validation of the proposed design by analyzing the stability and quality of force feedback received from a virtual environment. Simulation results of Section V show that state-of-the art controllers still leave some oscillations under specific conditions, and incorporation of proposed method improves the situation. Section VI shows experimental results carried out when a two-channel architecture is implemented on the proposed design. Section VII gives the concluding remarks based on the results portrayed in sections V and VI.

II. EFFECT OF WELL-CONDITIONING THE MASTER AND SLAVE MANIPULATORS

This section demonstrates that an isotropy-based design of the master and slave manipulators enhances transparency and

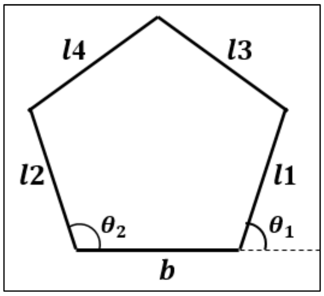


FIGURE 3. Symmetric 2-DOF five bar manipulator.

stability, consequently giving the freedom to eliminate the position feedback channel from slave to master.

The usual requirements while designing the master and slave manipulators are:

i. High rigidity: This enables the manipulator to withstand any impact from the environment, making it immune to oscillations.
ii. Low inertia: Helps the operator to feel the master be weightless, thus sensing environmental forces accurately.
iii. No backlash: Ensures accurate position sensing.
iv. Low gear ratio: Helps to minimize the errors in end-effector force estimation.

Commercial haptic devices (master manipulators) such as Phantom (by SensAble), Omega and Sigma (by Force Dimension), Virtuose (by Haption), Pantograph (a five-bar linkage), etc. satisfy all these requirements. These manipulators are of course designed for isotropy. However, explicit analytical study of its consequences on stability and transparency as presented in this paper is rarely found in the literature.

The case study of a five-bar linkage as a master/slave arm is taken herein to explain the effect of making it isotropic. The proposal is, however, valid for any manipulator.

A. CHOICE OF MECHANISM

A 2-DOF model is chosen for simplicity of analysis since it equally serves the same purpose of a 6-DOF manipulator while studying the stability and transparency of the system. A simple 2-R serial manipulator might fall short in functioning as a slave manipulator, due to its lacking rigidity. So a parallel mechanism is chosen here, in order to make the manipulator resistant to the vibrations when encountered by a stiff object. Bio-inspired model of human arms shows that five-bar linkage is the most apt design for achieving 2-DOF using a parallel mechanism (the forearm and arm connected at the elbow joint act as the links and the chest joining the two shoulders acts as the fixed base). In view of this, the case study of a symmetric five bar manipulator is chosen herein such that $l1 = l2$ and $l3 = l4$, as shown in Fig. 3.

B. EFFECT ON STABILITY AND TRANSPARENCY IN MASTER-SLAVE MANIPULATION

1) DEFINING STABILITY AND TRANSPARENCY

Throughout the rest of the discussion in this paper, the notion of stability is not merely limited to energy conservation, but to non-oscillatory behavior of robots. Such a viewpoint is more meaningful in the current context because of the following reason. To achieve the desired objective of position tracking, we not only need to ensure energy boundedness while passing through a communication channel, but also have to account for oscillations arising from improper internal transmission. Moreover, in applications such as surgeries, even oscillations (not just unbounded energy) are undesirable. For instance, a surgical tool tip undergoing even mild oscillations is undesirable in tele-surgical robots such as DaVinci. In [19], an attempt to minimize the unwanted vibrations at the tool tip of a minimally invasive tele-surgical robot can be found. This is in fact the reason why importance is paid to Modal analysis during the design of the slave arm of a surgical robot. Having understood the practical importance of the minimizing the oscillations, this paper aims at that end, rather than merely the conventional stability notion of bounded oscillations.

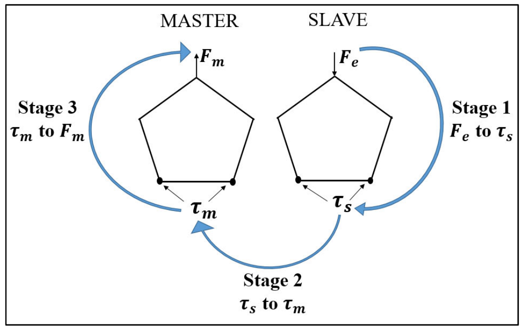


FIGURE 4. Transparency flow in a five-bar master-slave system.

Similarly, the notion of transparency indicates a sense of user feeling the environmental forces through the master robot. As mentioned in [20], transparency requires accurate force tracking along with position tracking. So, results of position tracking and force tracking are shown in this paper to establish both "stability" and transparency.

Consider two symmetric five-bar mechanisms used as master and slave manipulators, as shown in Fig. 4.

As seen in Fig. 4, when an environmental force F_e acts upon the end-effector of the slave, the corresponding joint torques τ_s of the slave are computed (stage 1 shown in Fig. 4), and transmitted to the master side where it is applied as τ_m at the joints (stage 2). These joint torques are then experienced by the user as F_m at the end-effector (stage 3). To meet the performance objectives, F_m should be as close as possible to F_e, without bringing "instability" at any of the three stages.

Improper signal transmission at any of these three stages can result in the robot's oscillations. It is already shown in sections IA and IB how state-of-the-art techniques [7]–[16] achieve proper signal transmission at stage 2. The still remaining oscillations are the ones arising from stages 1 and 3. This section analyses the root cause for oscillations at stages 1 and 3, and the design solution to counteract the same. It is important to note here that control techniques are not sufficient for counteracting oscillations at stages 1 and 3. This is because the controller's role is simply to supply appropriate joint torques at each robot, by taking information from other robot. The circumstances in which onset of oscillations occurs in stages 1 and 3 is explained below.

2) ENHANCING STABILITY AND Transparency IN STAGES 1 AND 3

During stage 1, the joint torques τ_s are computed as [21],

$$\tau_s = J_s^T F_e \quad (1)$$

where J_s is the Jacobian of the slave manipulator.

The slave torque τ_s is transmitted to the master end and supplied as joint torque τ_m to the master (in case of dynamically similar master and slave manipulators). Thus,

$$\tau_m = J_s^T F_e \quad (2)$$

In case the two manipulators are not dynamically identical, an additional transformation such as scaling would be necessary.

The force experienced by the human F_m is computed as

$$F_m = ({J_m}^T)^{-1} \tau_m,$$
$$F_m = ({J_m}^T)^{-1} J_s^T F_e \quad (3)$$

Now, if the master manipulator's Jacobian J_m is ill-conditioned, any small uncertainties in F_e are magnified in F_m. This leads to a loss of transparency. Thus, a portion of the transparency can be recovered by making the master's Jacobian well-conditioned. By making the Jacobian isotropic, its Eigen values become relatively equal [22]. An isotropic design of the master arm can ensure that the Eigen values of both J_m and J_m^T would be nearly equal, which will enhance the transparency of the system.

Furthermore, the stability of the system can also be improved by making the master and slave Jacobians well-conditioned. On the master side, the typical control law governing the joint torques is a function of F_e. Since in most cases, F_e is practically estimated from the slave joint torques (in order to avoid using an explicit force sensor), τ_m turns out to be a function of the slave's Jacobian as given in (4) [23].

$$\tau_m = f\,(F_e) = f((J_s^T)^{-1} \tau_s) \quad (4)$$

The torque produced by the joint motors can be expressed as a function of motor current as:

$$\tau = K_t i \quad (5)$$

where τ is the motor torque, i is the current drawn by the motor, and K_i is the torque constant of the motor.

It is understood by now that joint torques are already in a fluctuating condition. In addition, any inadvertent fluctuations in the motor current (which occurs very commonly) will lead to joint torque variations at the slave and cause oscillations.

Given the onset of minor fluctuations in the slave torque, it can be seen from (4) that an ill-conditioned slave's Jacobian J_s leads to larger uncertainties in the master joint torques. In turn, fluctuations in τ_m naturally brings oscillations in the master manipulator because of its dynamics as shown below [24].

$$\ddot{q}_m = M^{-1}[\tau_m - C\dot{q} - G] \quad (6)$$

Here, M, C and G refer to the Inertia, Coriolis and gravitational matrices respectively of the master manipulator.

It can be inferred from (6) that the fluctuations in τ_m lead to fluctuations in $\ddot{q}_m$. Consequently q_m(the master position) also fluctuates, resulting in ''instability'' at the master manipulator. Thus, making the slave's Jacobian well-conditioned can avoid this whole issue and enhance the stability at the master manipulator also.

On the slave side, the control law governing the joint torques is typically a function of q_m. Only then, there is a possibility of position tracking by the slave manipulator.

$$\tau_s = f(q_m) \quad (7)$$

Equation (7) shows that there would be fluctuations in τ_s due to the already existing variations in q_m (as evident from (6)). This, again, results in ''instability'' at the slave position (due to the slave dynamics shown in (8)) whenever its Jacobian is ill-conditioned.

$$\ddot{q}_s = M^{-1}[\tau_s - C\dot{q} - G] \quad (8)$$

Thus, by making both the master and slave isotropic, i.e., their Jacobian matrices becoming well-conditioned, both the stability and transparency of the system can be improved.

Apart from preliminary performance enhancement, isotropic design also help to enhance performance in another significant way. This is explained below.

C. REDUCING TO A 2-CHANNEL ARCHITECTURE

It is claimed almost 3 decades ago in [20] that a 4-channel architecture is mandatory for simultaneous achievement of both stability and transparency of the teleoperation system. On this basis, recent developments in architecture such as [25] and [26] adhere to a 4-channel architecture. Even the newly developed controllers are being tested on a 4-channel architecture [27]. An extension of the wave-variable method shown in [28] is still combined with a 4-channel architecture. But this sub-section shows that the traditional 4-channel architecture can be reduced to a 2-channel architecture using the proposed design.

In the typical 4-channel architecture shown in Fig. 1, the primary function of the master is to reproduce the environmental forces, and this is vividly achieved by transmitting slave's joint torques to master joints (F_s). This force feedback is also supposed to automatically stop the master's motion, when the slave encounters an obstacle. However, since it is usually observed that the master still undergoes oscillations despite force-feedback, an additional position feedback (x_s) is taken from the slave to lock the master's position in coherence with the slave. Now that the reason for such unwanted

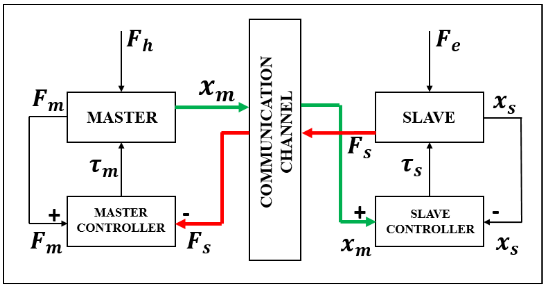


FIGURE 5. Proposed two channel control architecture of a teleoperation system.

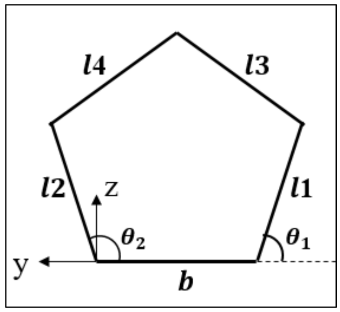


FIGURE 6. Symmetric five-bar manipulator.

oscillations are identified and addressed, this explicit position feedback from the slave (x_s) can be eliminated (without compromise in transparency also). On similar grounds, the signal F_m (in Fig. 1) can be eliminated since only x_m is now sufficient to achieve position tracking of the slave robot. Thus, the net effect of the proposed design is the two-channel architecture, with only x_m and F_s sent across the communication channel, as shown in Fig. 5.

Some of the existing two-channel architectures found in the literature are listed here. [29] proposed a two-channel architecture in its rudimentary form. [30] presents a transparency-optimized approach, but it requires switching between control laws. [31] utilizes impedance control as a tool for two-channel architecture, but demands the incorporation of acceleration control. [32] achieves a satisfactory balance between stability and transparency, introducing force reflection filters. [33] presents a two-channel architecture with the adaptive neural fuzzy controller. [34] proposes a position-position architecture, but is not sufficient for systems of high inertia. This is because when the inertia is high, the end-effector may not receive the intended forces corresponding to the joint torques. A more detailed reasoning for the same is provided in [35]. The two-channel architecture presented in this paper is unique, in the sense that it results from a design modification, accommodating higher levels of stability and transparency. It is also to be noted that the two-channel architecture presented in this paper is a position-force architecture, and thus there are no issues faced even with high inertia systems.

D. COMPARISON OF FOUR-CHANNEL AND TWO-CHANNEL ARCHITECTURES

This sub-section is aimed at showing the advantage of reducing the four-channel architecture to a two-channel architecture.

It is important to note that the traditional four-channel architecture, which is proposed for the purpose of simultaneously achieving transparency along with stability cannot perform so under all circumstances. This is true even in the case of one of the first and break through four-channel architectures mentioned in [20]. This method is valid only for the systems where there is no time delay [32]. In the presence of time delay, usually techniques like 3-channel with a local feedback etc. are implemented to counteract the trade-off effects [36]. The inefficacy of the four-channel architecture in the presence of time-delay can be informally understood in the following way.

In the case of 4-channel architecture, the master is also expected to track the slave's position. This implies that the master and slave are believed to be in the same position, only after the position controller on the master implements the slave position feedback. Assuming a constant time delay of T through each communication channel, position tracking is expected to be achieved after a delay of 2T ('T' for forward position transmission, another 'T' for backward position transmission). In the next cycle, the slave is expected to track the position of master which was the '2T' delayed position. On the contrary, in case of a 2-channel architecture, we can be sure that master and slave sync in their positions only after a total delay of 'T' (since there is no need for backward position transmission). Thus, after a delay of 'T', the slave can again start tracking the master's position. Thus, the effects of time delay are much less pronounced in case of a 2-channel architecture. This is also shown in [21]. The problem is even more exacerbated in case of varying time delays. Thus, saving on time delay essentially means saving on the stability, as explained in Section I.

Now that the advantages of an isotropy based design of robots are delineated, how such design could be done is demonstrated in the following section.

III. ISOTROPIC DESIGN OF FIVE BAR MECHANISM

This section shows the isotropic design of a five-bar master/slave by choosing optimal link lengths. To maintain a symmetric workspace, a symmetric five-bar mechanism is chosen such that $l1 = l2$ and $l3 = l4$ (shown in Fig. 6). However, this methodology is applicable for any manipulator.

A. ISOTROPY ANALYSIS

For quantitatively measuring the degree of isotropy of the mechanism, a conditioning index (CI) is chosen here as in (9) [37].

$$Conditioning\ Index = \frac{1}{\|J\| \left\|J^{-1}\right\|} \tag{9}$$

where J is the Jacobian of the manipulator and the norm operator $\|.\|$ is chosen as the Frobernius norm defined as,

$$\|A\| = \sqrt{Trace(AA^T)} \tag{10}$$

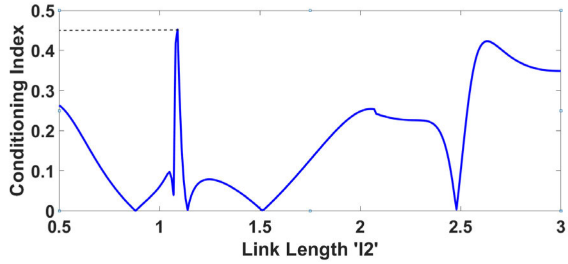


FIGURE 7. Variation in CI w.r.t. link length $l2$.

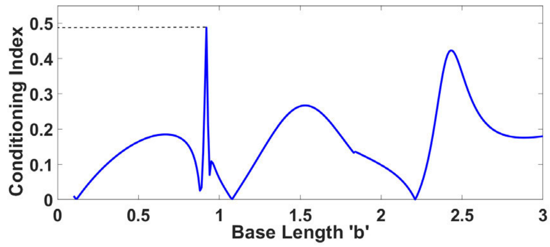


FIGURE 8. Variation in CI w.r.t. base length b.

An analysis is performed herein to identify the most appropriate link length $l2$ and base length b, which can maximize the above-mentioned conditioning index. While the value of conditioning index ranges from 0 to 1, a higher conditioning index denotes a higher degree of isotropy.

For a given configuration, the effect of each link length on the conditioning index is computed as follows. At first, the Cartesian position of the end-effector is written in terms of the joint angles in a matrix form. Then differentiating the relationship with respect to time leaves us with the relation between Cartesian velocity and the joint velocities. The relating matrix is nothing but the Jacobian J mentioned in (9). It is to be noted here that this Jacobian would be a function of $l2$, $l4$ as well as b. Thus, the conditioning index is readily obtained (from (9)) as a function of these three parameters.

For ease of analysis, the length $l4$ is normalized to unity, and the other lengths $l2$ and b which yield maximum CI are obtained. The consequence of individually varying the link length and base length is shown at first. The optimal link length $l2$ is obtained by analyzing the variation in CI, with base length as constant.

It can be observed from Fig. 7 that the CI is maximal for a length $l2 = 1.09$ with a conditioning index of 0.452. This analysis is performed with a constant base length b of 1unit and is thus the suggested design for applications such as telesurgery etc., where the rigidity of the manipulator is not the prime requirement. For applications where the manipulator requires to carry a payload, the choice of base length is also a key design aspect. Thus the effect of varying base length alone on the conditioning index is shown in Fig. 8, keeping the link length constant.

The highest conditioning index of 0.488 is seen at a base length of $b = 0.92$. This analysis, which is more suitable for military applications, is carried out for $l2 = 1$ unit, i.e. all four links being of equal length. The results closely match with other isotropy based designs of five bar linkages as in [38].

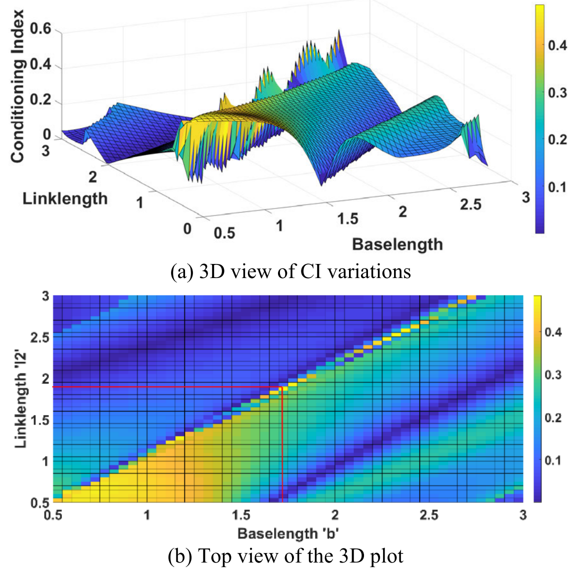


FIGURE 9. Variation in CI w.r.t. base length and link length.

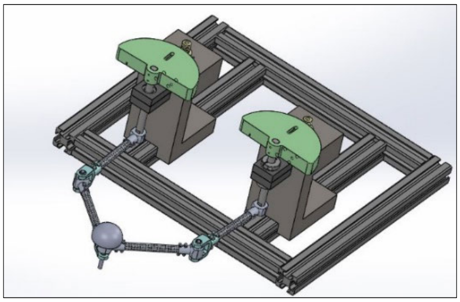
In most applications, the design cannot be restricted to a specific link length or base length. Hence the variation of CI while simultaneously varying both the link length and the base length is shown in Fig. 9. The joint positions chosen for this analysis is the position where the determinant $|J|$ is maximized [22]. This results in $\theta_1 = 116^0$ and $\theta_2 = 72^0$. Fig. 9(a) shows the 3D view of variations in CI w.r.t. base length and link length, while Fig. 9(b) shows the same plot in top view.

The highest conditioning index observed here is 0.486, which occurs at several combinations of link length and base lengths (all the yellow regions). With the above figure as a reference, the five-bar manipulator's links can be designed to maximize the conditioning index. Thus, the isotropy analysis presented here serves as a guideline for isotropy based design for any master and slave manipulator. Out of the multiple combinations, the link length of 1.9 units and base length of 1.7 units (shown with red lines in Fig. 9(b)) is taken forward for design. The CAD design and actual fabricated manipulator are shown in Fig. 10.

Both the master and slave robots are designed as shown in Fig. 10. The actual experimental setup is described later in Section VI.

B. PREFERRED ZONE OF OPERATION

An extended study also serves as a user guideline for determining the most isotropic workspace region. Once the manipulator is designed with the aforementioned lengths, it is possible to identify the zone of the reachable workspace where stability and transparency could be faithfully retained using a two-channel control architecture. Thus, with the above-chosen base length and link length, the variation of the conditioning index is studied w.r.t. the variation in joint


(a) CAD Model

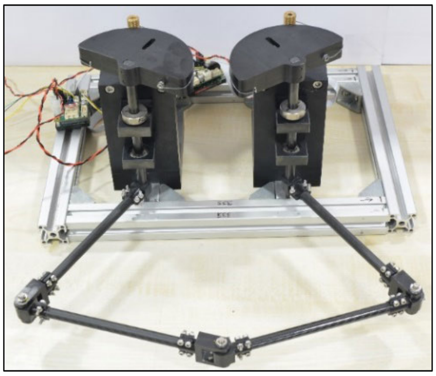

(b) Fabricated Setup

FIGURE 10. Five-bar manipulator.

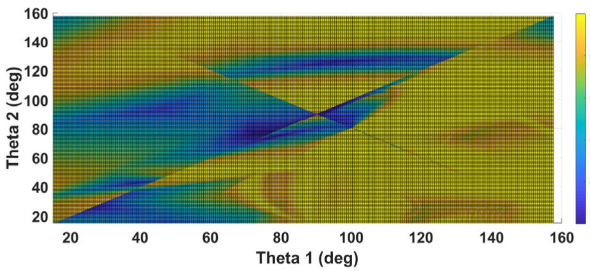


FIGURE 11. Variation of CI in the joint space.

positions. The conditioning index for each joint position is shown in Fig. 11.

This analysis helps in identifying the region of operation where maximal force-feedback can be experienced. This figure shows that the proportion of the isotropic region for the designed manipulator is significantly high. Further insight into improving the isotropic proportion of workspace is discussed in [39]. Interested readers are suggested to go through [40], [41] to get an elaborate discussion on the manipulator's singularity, workspace and dexterity analysis. Having performed an isotropy based design of the master and slave manipulators, its validity is tested by taking force-feedback from the environment.

IV. VALIDATION USING HAPTIC FEEDBACK

The utility of the proposed design as a haptic device can be ascertained if the user is able to transparently acquire force feedback from a virtual environment, without the onset of instabilities.

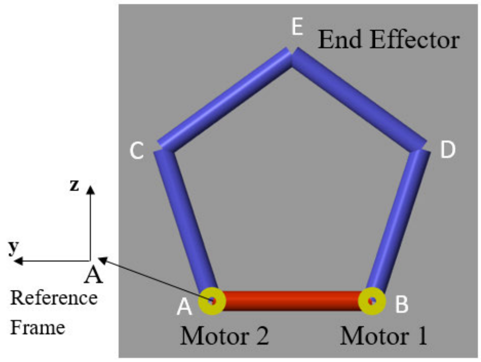


FIGURE 12. SimMechanics model of the 5 bar linkage.

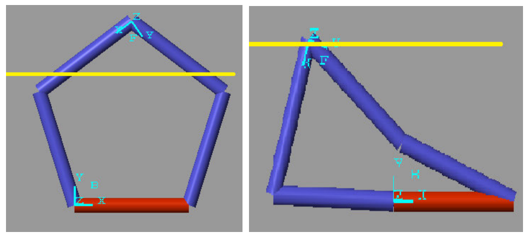

(a) Initial Position (b) End-effector hitting the wall

FIGURE 13. Methods End-effector stopping at a virtual wall.

In order to validate this, a rigid body dynamics tool of Simulink® – SimMechanics, is used. The five-bar linkage is modeled as shown in Fig. 12.

The following are the simulation parameters chosen.

Density of each link = 2.00g/cm3 (Carbon fibre rods)
Stall torque of motors = 342mN-m (Maxon® RE 30 DC)
Damping at the revolute joints = 0.001N-m/(deg/sec)
Range of motion for each active joint = 300 degrees
Step size = Auto
Solver = ode4
Sensing distances and angles through = Transform sensor

All the above values are chosen to best suit the real time experiments. It is shown later in Section VI that carbon fibre links and Maxon RE 30 motors are used in the experiments. The reasons for choosing them during the experiments is also described in Section VI.

Since all the links are placed in the same plane in the real model, the range of rotational motion is restricted.

A virtual wall, as shown in Fig. 13, was modeled to act as a stiff environment. As in the case of most haptic studies, the presence of the virtual wall is intended to be detected only by the end-effector.

The end-effector coordinates are measured from the reference frame (at point A of Fig. 12) and the position is recorded as shown below.

The position coordinates show that the end-effector reaches the virtual wall position (z=0.08m) at about 3.7 seconds and is unable to move further even though the motors continue to supply torques. As can be seen from

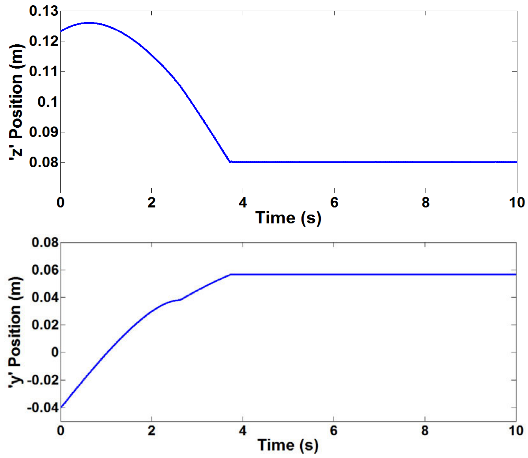


FIGURE 14. End-effector's vertical and horizontal positions.

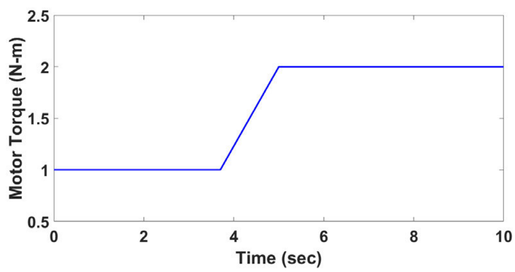


FIGURE 15. Motor stalling at wall position.

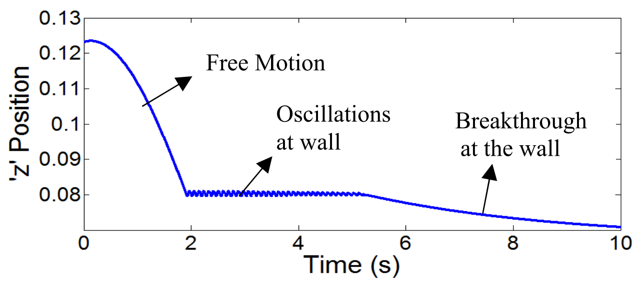


FIGURE 16. End-effector oscillating at the wall and finally breaking through.

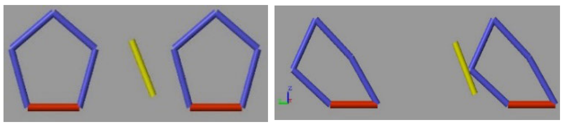
Fig. 15, the motor stalls when the end-effector hits the wall and starts drawing larger currents.

However, when the user applies larger forces to oppose the motor, the manipulator undergoes some vibrations at the wall position, and for still larger forces from the user, the manipulator can actually break-through the wall. This phenomenon as shown in Fig. 16, occurs due to the backdrivability of the motors.

The above results demonstrate that the designed haptic device can be operated in a teleoperation architecture.

V. SIMULATION RESULTS

This section demonstrates through simulation results that the isotropy based design shown in Section III is suitable to be implemented in a two-channel architecture, and enhance the performance objectives – stability and transparency.



(a) Initial Position (b) Collision Detection

FIGURE 17. Collision detection in teleoperation.

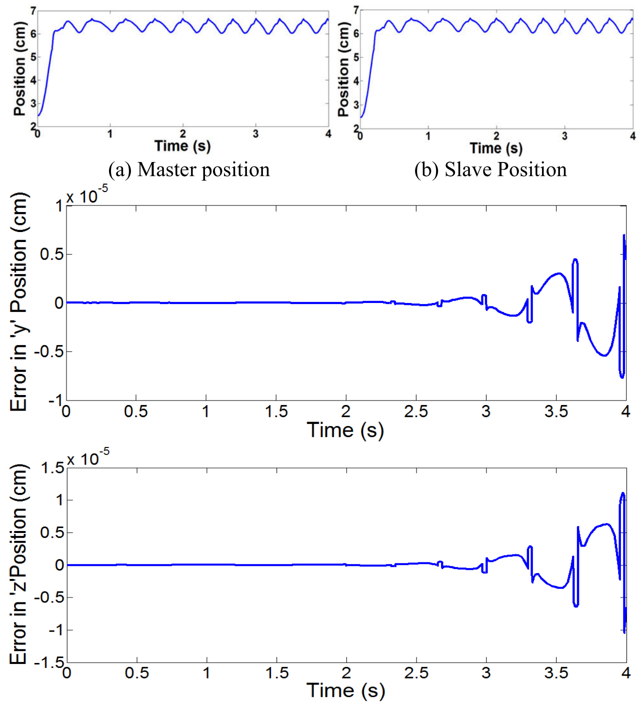


FIGURE 18. System becoming unstable in presence of time-delay.

A. INSTABILITY OCCURRING WITH ARBITRARY DESIGN

Teleoperation is first implemented using a non-isotropy based design of robot arms, thus not guaranteeing a two-channel architecture. A wall that exerts a force of 5N is placed in the path of the slave, at y-coordinate of 6cm and z-coordinate of 8cm. The SimMechanics visualization of the setup is shown in Fig. 17 below. The manipulator to the left represents the master, the manipulator towards the right represents the slave and the yellow bar denotes the obstacle (wall).

The simulation results of the teleoperation with four-channel architecture are shown in Fig. 18. The controller used is a typical PD controller. The positions of both the master and slave in y-coordinate are shown while the errors in position are shown for both y and z coordinates.

It can be seen that the error increases with time and could eventually lead to instability. This demonstrates the effect explained in Section I. State-of-the art mainly attempts to address this instability issue only by incorporating a controller to compensate the effects of time delay.

B. EFFECT OF STATE-OF-THE ART CONTROLLER

The case study of a fairly standard controller proposed in [9] is considered herein. It is shown in [9] that their

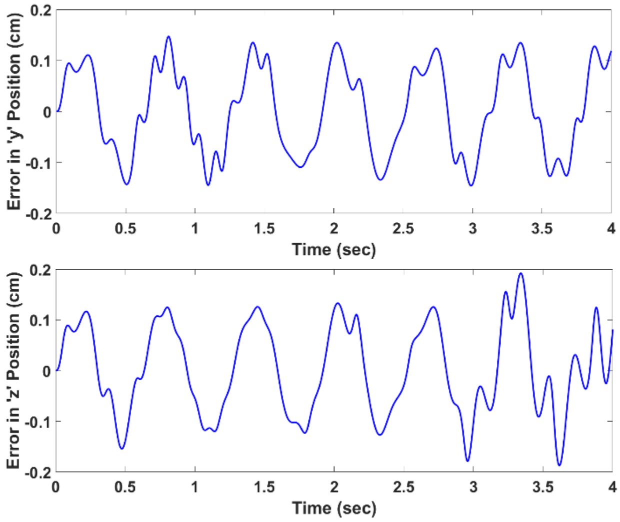


FIGURE 19. System retaining stability without zero convergence using state-of-art [9] controller.

feed-forward controller makes the position tracking error converge to zero. However, the same controller might not yield a zero convergence under different operating conditions. The result of implementing this controller on a non-isotropic design of robots is shown in Fig. 19. In this case, link lengths of $l2 = 1.5$ and $b = 1.5$ are chosen.

The system, however, remains stable because of the proven Lyapunov analysis. Since the feed-forward controller is already designed to address the issue of time delay, the oscillations left are due to another reason, i.e. ill-conditioned robot Jacobians, as explained in Section II.

C. EFFECT OF ISOTROPY BASED DESIGN

To further eliminate the unwanted oscillations, the isotropy based design proposed in Section III is implemented with the same controller and same operating conditions as above. The position tracking error is then observed as shown in Fig. 20.

It can be observed from Fig. 20 that the proposed design successfully eliminates the oscillations caused due to ill-conditioned robots, and makes the tracking error converge to zero. Since the proposed design also accommodates a two-channel architecture, the same is used for the above simulation. Table 1 summarizes the effect of the controller and the isotropy based design.

The following can be inferred from the series of simulations:

i. A teleoperated system becomes unstable in the presence of time-delay. (Fig. 18)
ii. A controller can make the system stable, but might still leave out some oscillations. (Fig. 19)
iii. An isotropy based design of robots can address these oscillations as well. (Fig. 20)
iv. A two-channel architecture is feasible for the proposed design.

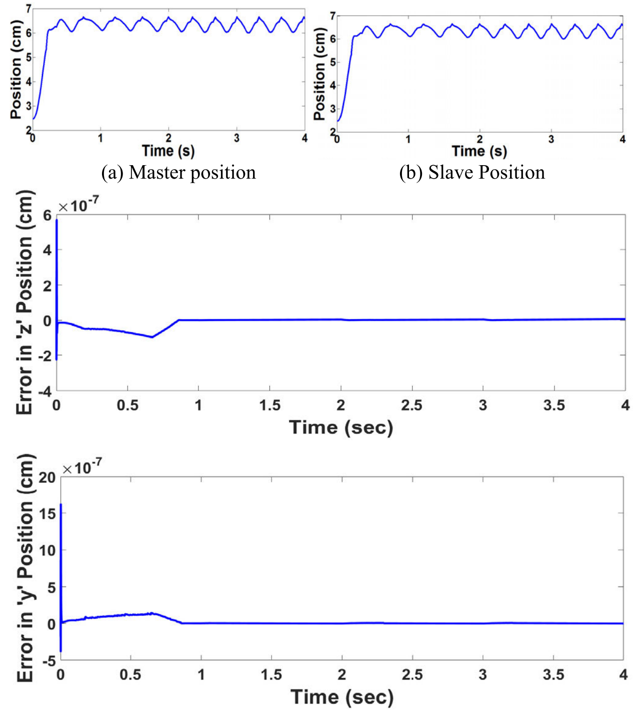


FIGURE 20. System retaining stability with zero-convergence using isotropy based design.

TABLE 1. Position Tracking error of various combinations.

	Ordinary controller	Capable controller
Non-isotropic design (4-channel)	Becomes unbounded with time	Oscillates within bounds
Isotropic design (2-channel)	Oscillates within bounds	Converges to zero

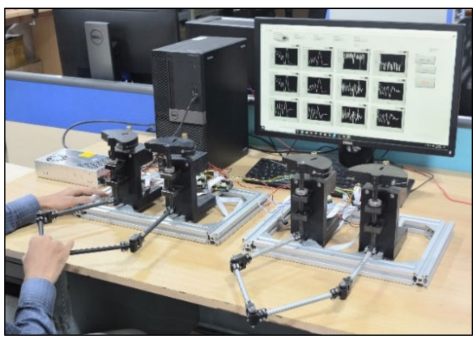


FIGURE 21. Experimental setup.

VI. EXPERIMENTAL RESULTS

Having obtained satisfactory simulation results, two of five-bar manipulators shown in Fig. 9 are used as master and slave robots. The human operating the master robot of the teleoperation system is shown in Fig. 21.

The salient design aspects of this device are the usage of:

i. Carbon fiber links – Carbon fiber having a high stiffness to weight ratio can simultaneously contribute to the rigidity of the manipulator and reduce its inertia.
ii. Maxon RE 30 motors – These motors having high stall torque allows the manipulator to interact with highly stiff environments and yet not damage the motor.
iii. Maxon EPOS 4 controllers – These high precision position controllers enable the slave to achieve accurate position tracking.
iv. Parallel mechanism – As already explained, it maintains rigidity for any given configuration.
v. Capstan driven mechanism – This torque amplification mechanism (ratio of 1:10) avoids backlash and simultaneously fulfills the purpose of gears.

Because of the above chosen physical components, the system possesses the characteristics of high rigidity, low inertia, no backlash, good backdrivability etc. The mathematical model of the master and slave sub-systems is represented by standard Lagrangian dynamics of the form [23],

$$\begin{aligned} M_m\ddot{q}_m(t) + C_m\dot{q}_m(t) + G_m &= \tau_h - \tau_m \\ M_s\ddot{q}_s(t) + C_s\dot{q}_s(t) + G_s &= \tau_s - \tau_e \end{aligned} \tag{11}$$

where M represents the Mass matrix, C represents the Coriolis matrix, G represents the gravitational vector, q_m and q_s represents the joint variables of the master and slave, τ_h represents the external torque on the master from the human, τ_e represents the external torque on the slave from the environment and τ_m and τ_s represent the joint torques of the master and slave robots, respectively.

It is to be noted that both the master and slave robots are fabricated with the lengths obtained in Section III. Now, this teleoperation setup is incorporated with a two-channel control architecture and the stability and transparency are analyzed.

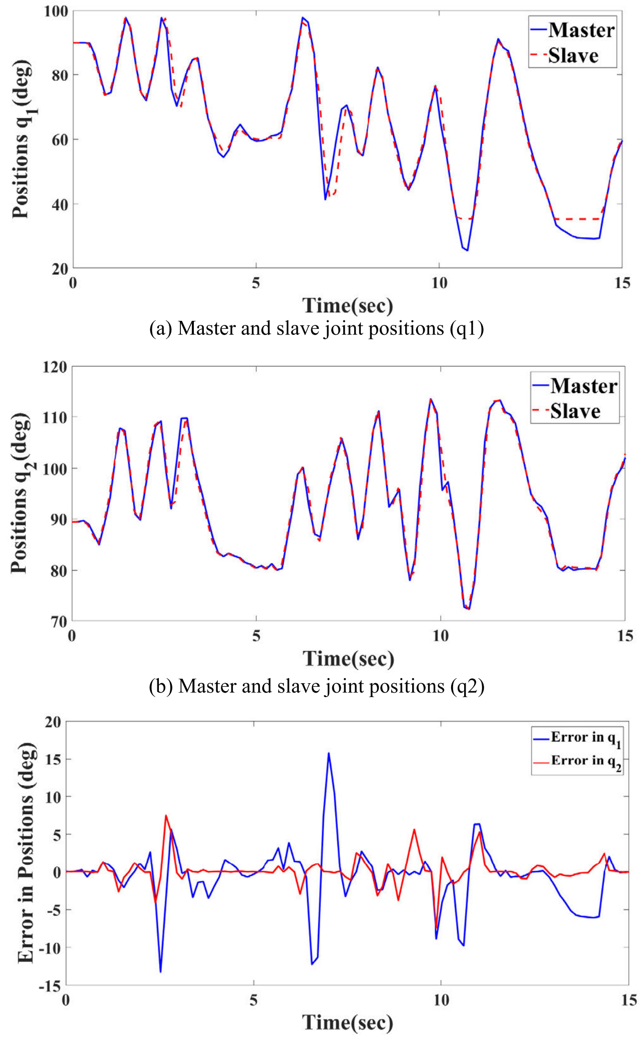
The same control law as mentioned in [9] is used to perform the experiments also. The controller is fundamentally a feed-forward controller. Thus it is capable of identifying any modelled external disturbances and make the system performance robust to these disturbances. The only restriction imposed over the controller is the nature of time delay. It is mandatory that the variations in time delay are less than unity, i.e. $\dot{T} \leq 1$. Furthermore, the feed-forward control gain is chosen as a function of the rate of change of delay.

$$f^2 \leq 1 - \frac{dT}{dt} \tag{12}$$

This controller is implemented on both the 4-channel as well as 2-channel architectures to test the efficacy of the proposed method.

A. EXPERIMENTS WITH 4-CHANNEL ARCHITECTURE

The operator is allowed to move the master manipulator freely while a silicone elastomer representing a tissue model is introduced in the path of the slave. The controller mentioned above is implemented on a non-isotropic design, with



(a) Master and slave joint positions (q1)

(b) Master and slave joint positions (q2)

(c) Error in joint positions

FIGURE 22. Position tracking with four-channel architecture.

a typical 4-channel architecture. The position tracking results are shown in Fig. 22.

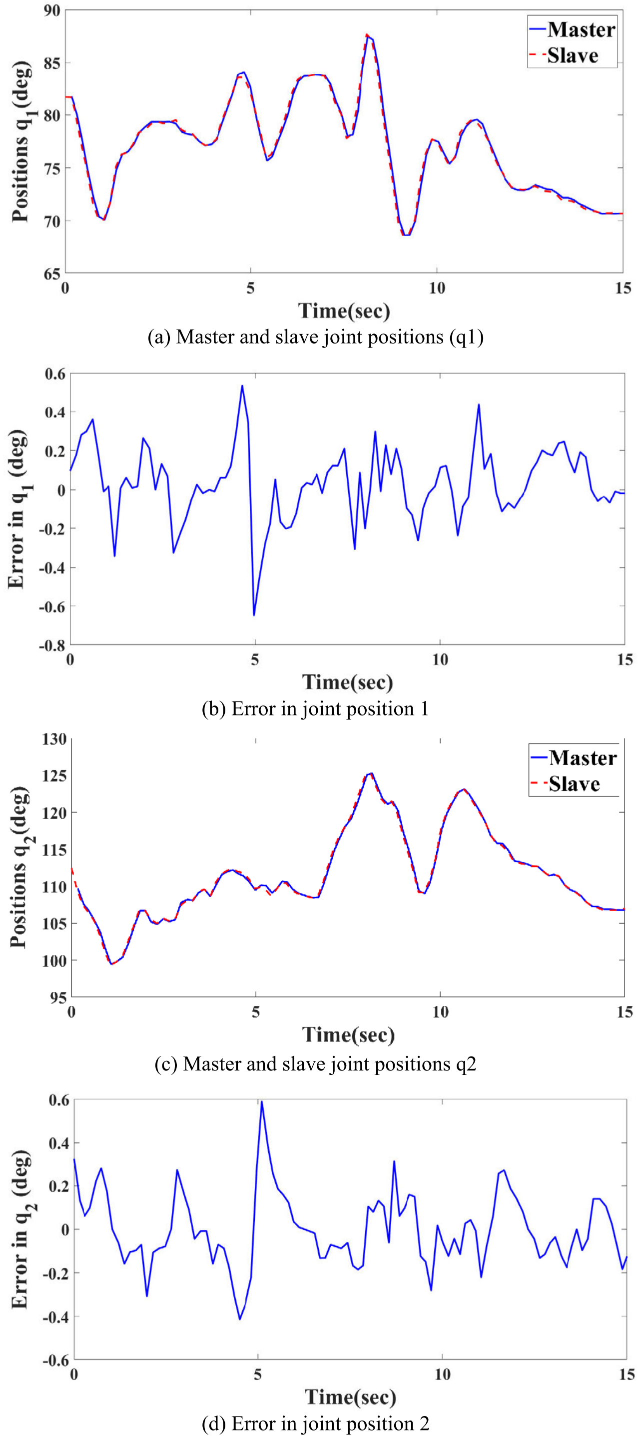
It can be seen that the position tracking error rises upto 10-15deg. in the case when a non-isotropy based design is implemented, leading to a 4-channel architecture. The error values can now be compared with the results obtained when the same controller is implemented on an isotropic design, leading to a two-channel architecture.

B. EXPERIMENTS WITH 2-CHANNEL ARCHITECTURE

A silicone elastomer representing a tissue model is introduced in the path of the slave at t=1.5sec as an obstacle and released at t=2.7 sec. This is also repeated at other time instants. The position tracking results are shown in Fig. 23.

The position tracking errors converging almost to zero (with a negligible error of <1deg.) demonstrates the system stability. The joint torques are shown in Fig. 24 to demonstrate force tracking.

It can be observed from Fig. 24(a) and 24(c) that as soon an obstacle is introduced in the path of the slave robot,



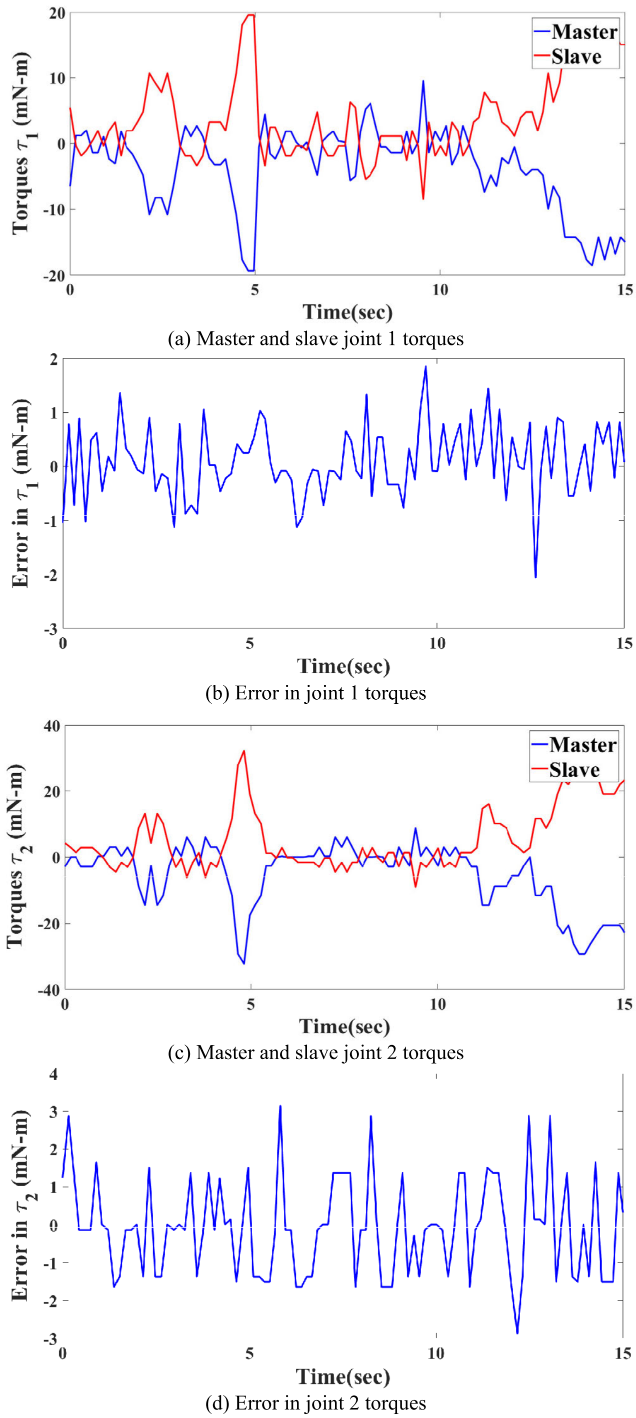
(a) Master and slave joint positions (q1)

(b) Error in joint position 1

(c) Master and slave joint positions q2

(d) Error in joint position 2

FIGURE 23. Position tracking with two-channel architecture.



(a) Master and slave joint 1 torques

(b) Error in joint 1 torques

(c) Master and slave joint 2 torques

(d) Error in joint 2 torques

FIGURE 24. Force tracking with two-channel architecture.

its joint torques shoot up (in magnitude). The master and slave torques being in opposite direction rightly indicate the resistive force felt by the user. Further, the force tracking error also converging to zero (with a negligible error in the order of 1mN-m), along with accurate position tracking, demonstrates the transparency of the system [20]. Thus, the isotropic design is experimentally proven to meet the performance objectives with a two-channel architecture itself. The root means square errors (RMSE) of both position tracking as well as force tracking are tabulated in Table 2.

It is important to compare these values with the errors obtained using a non-isotropic design. Such arbitrary design, with the need for a 4-channel architecture leads to position errors as high as 15 deg., with an RMSE of about 2 deg., which is almost 10 times the RMSE obtained using a 2-channel architecture (Table 1).

TABLE 2. RMSE of position tracking and force tracking (2-channel).

	Position Error (deg)	Force Error (mN-m)
Joint 1	0.20	0.65
Joint 2	0.18	0.76

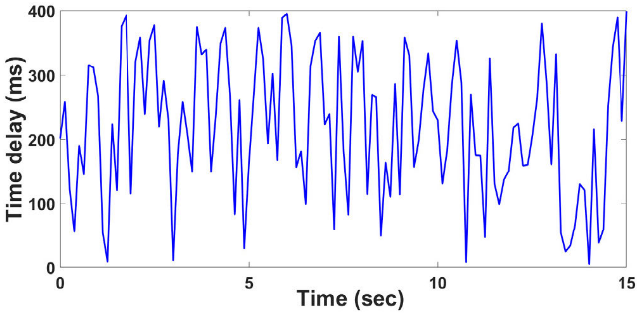


FIGURE 25. Time delay measured during teleoperation experiments.

Another crucial observation made during the simulations and experiments as well is the consequence of implementing a 2-channel architecture on a non-isotropic design. In this case, it is seen that without the position feedback from the slave, the master and slave position do not sync sufficiently. In fact, this is the prime reason for incorporating the traditional 4-channel architecture [20]. But this paper demonstrated how to design the system so as to obtain satisfactory results with 2-channel architecture itself.

C. SYSTEM BEHAVIOUR FOR DIFFERENT TIME DELAYS

Time delay is an important factor in any teleoperation system and the same was analyzed for the proposed architecture. The time-delay measured during the experiments is shown in Fig. 25. The effect of this delay has been compensated using control laws as in [9].

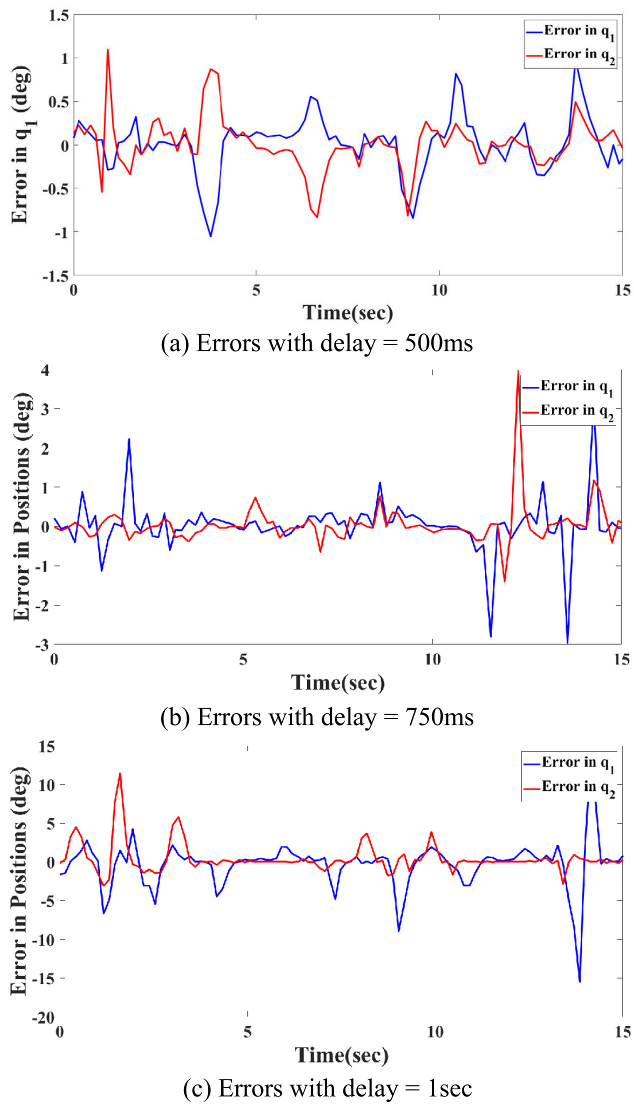
In order to further validate the proposed method, the same 2-channel architecture is subjected to increasing amounts of delays upto 1sec. A practically implementable communication protocol can hardly cause a delay greater than this. The position tracking errors measured in case of various delays is shown in Fig. 26.

It can be noted from Fig. 26 that the position tracking occurs for various time delays also. However, with increase in delay, the magnitude in error is observed to increase, which is natural.

As mentioned earlier, the commonly occurring fluctuations in motor current could possibly drive the system to unwanted oscillations. A sample of such *measured* motor current obtained experimentally when teleoperation is performed with a delay of 250ms is shown here for illustration.

These fluctuations, which are quite significant in the context of teleoperation, could only potentially be a cause for oscillation in the manipulator position. There could be other reasons as well as mentioned earlier in Section II.

The key contributions of this paper are summarized as follows:



(a) Errors with delay = 500ms

(b) Errors with delay = 750ms

(c) Errors with delay = 1sec

FIGURE 26. Position tracking errors with various delays.

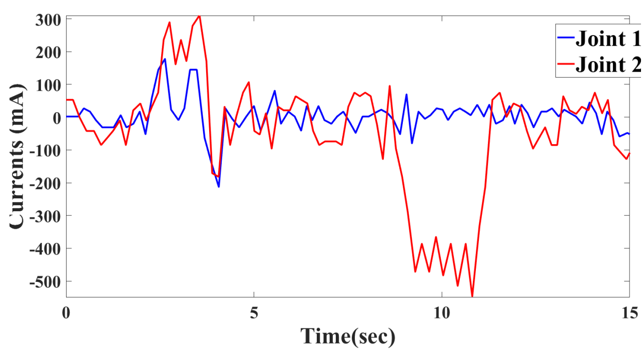


FIGURE 27. Fluctuations in motor currents.

i. An isotropy based design can address the instability issues arising due to torque/position variations in stages 1 and 3 of the teleoperation, where the controller design cannot make an impact.
ii. Such isotropy based design also helps to eliminate two channels from the traditional four-channel architecture.

iii. In comparison to a four-channel architecture, the two-channel architecture reduces the instability at stage 2 also, as the time delay occurring from two communication channels is eliminated.

VII. CONCLUSION

The issue of simultaneously enhancing the two conflicting objectives of teleoperation – stability and transparency, is discussed in this paper. This paper proposes that an isotropy based design of robots can add to the stability and transparency of the system, apart from using an efficient controller. The additional advantage of using this design is that the number of communication channels is halved, thus reducing the ill effects of time delay. It is demonstrated analytically, through simulations and also through experiments, that an isotropy-based design combined with a two-channel architecture can much better meet the performance objectives of a teleoperation system.

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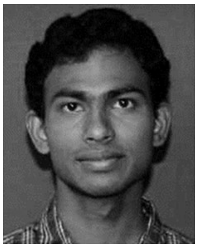

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