Teleoperated Hexapod Robot for Imitation Learning Task Training

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***Abstract*— To operate successfully in the unstructured environment of homes and small businesses, robots will be implemented by unskilled operators who cannot explicitly program their motions. Recently, deep imitation learning has been used to train robots that manipulate their environment based on pixel-to-action control. The robot actions are determined by camera inputs without programmed trajectories. Such training is often performed on robotic hardware which was not designed for imitation learning. This paper describes a new robot which is designed expressly to improve the training speed and ability of pixel-to-action policies. In particular, hexapod robot hardware is designed for teleoperation, thus improving correspondence and simplifying human control.**

I. Introduction

Robots need improved awareness to operate successfully in the unstructured environment of homes and small businesses. Absolute accuracy only improves the performance of robotic machines when their workspace is also accurate – modern commercial robots still cannot perform even simple table-top tasks that humans find easy and monotonous without significant cost in programming and workspace design. Recently, deep learning researchers have trained robots to manipulate their environment based on the imitation of the robot while under human control [1]. After training, the robots are able to watch their own work and control their motions directly to manipulate their environment with no explicitly programmed trajectories. This 'Pixel-To-Action' control has the potential to enable lower cost robotic hardware, trained by imitating the actions of unskilled operators, inexpensively, and without writing code. To expand these abilities, robotic hardware must allow unskilled operators to perform tasks robotically in order to create the data for training. By connecting people to robotic workspaces using teleoperation, this data will provide a stable basis for imitating the human control in the future. Issues to address in the design of this hardware include correspondence (the different kinematics of human and machine motions) and simplified control (human can use natural motions and receives position and force feedback cues) [2]. In this study, we describe the design of a tele-operated robot pair which allows humans to easily perform manipulation and assembly tasks with the same visual, position, and force feedback available to the robot. This tele-operated hexapod robot architecture can provide improved training data to advance the study of Imitation Learning for manipulation.

Imitation Learning in the field of robotics seeks to allow a robot to mimic a human's control of the machine autonomously [3, 4]. This concept has been very successful for autonomous vehicles especially [5]. When considering manipulation tasks, imitation learning seeks a policy whereby robot arms or humanoids are able to robustly replicate the motions of a human operator 'expert' performing the same task. Preferably, the robot is able to replicate the motions and results of the human without explicitly designing a 'reward' or 'objective function' that is to be achieved [6, 7]. Rather, the human operator should perform a task (such as tabletop assembly or sorting) by controlling the robot, and the robot should then robustly perform the task itself. Compared to other techniques such as reinforcement learning, imitation learning can be trained with less training data since the data is generated by an expert not by trial-and-error [1]. One defining feature of imitation learning is that the human controls the robot to perform the task initially, as opposed to a human performing the task while being monitored by external tracking devices [4]. However, this does lead to situations where some robots, especially robot arms, cannot be controlled naturally by humans for training data. Thus, it is important to study the mechanical and electrical arrangement of robotic arms which allow natural human motions to be monitored and replicated. As with most deep learning techniques, improved availability of training data improves robot performance [8]. Robotic arms are often costly, so training data cannot be easily gathered [7, 9]. Three topics must be addressed to improve the quality of data collected for imitation learning in robotic manipulation: correspondence, natural imitating control with feedback, and improved access for imitation learning researchers.

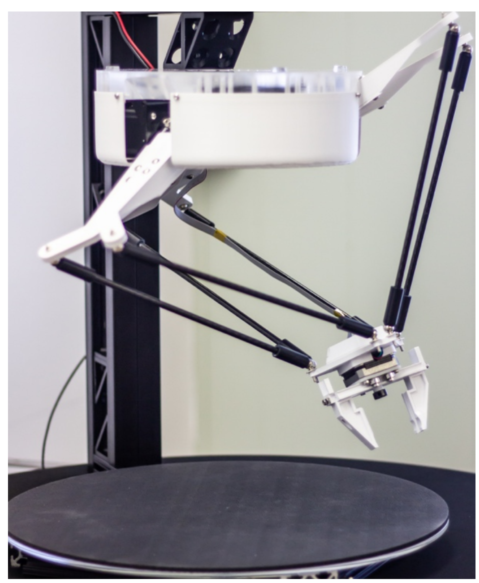

Figure 1 - The hexapod robot manipulator during teleoperation.

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Good correspondence in imitation learning is achieved when two conditions are met: (1) all information available to the human expert which guides their decisions is recorded, and (2) that same extent of information is available to the robot when executing the task autonomously [3]. An example of good correspondence would be a robot piloted by a human who uses a joystick for control input and a first-person-view video stream for feedback [10]. In general, such 'tele-operated' systems usually ensure good correspondence. The same is true for robotic arms. However, it is not common for robot arms to be equipped for teleoperation. For instance, sometimes the robot is operated by joystick (rate-control) where the human directly observes the scene in front of the machine while the robot is restricted to a camera view of the workspace, which violates condition (1) since the human has information available (things they see) that may not be recorded [11]. Others have guided the robotic arm with 'kinesthetic teaching' moving it by hand to move and grasp objects – this violates condition (1) again since the human has a sense of pressure and force that is not recorded by the machine [12, 13]. Another difficulty with kinesthetic teaching for pixel-to-action learning is occlusion. Occlusion is interference in the camera's view which limits the information available to the robot during operation. Some researchers however have successfully implemented robot arm teleoperation [1]. Teleoperation is a reliable method for data collection and ensures good correspondence, so it is implemented in this study.

Human dexterity is due in large part to our innate ability to combine position and force control. Human interfaces which aim to provide 'natural control and feedback' should attempt to imitate the motions, manipulation strategy, and haptic information which humans use in everyday tasks. Unfortunately it is usually difficult to achieve good natural control while maintaining good correspondence. For instance, motion capture and VR help immerse a human in the control environment, but require significant remapping of the human inputs in to robot controls [1]. Also, these systems rarely provide for force and torque feedback of the end effector itself. This study overcomes these problems by using hexapod robot hardware combined with bilateral teleoperation to provide both position and force control in the most natural manner possible.

Hexapod robots were studied in the early 1990s as an extension of delta robots to cover six degrees of freedom [14, 15]. Parallel robots such as hexapods have benefits for teleoperation because they allow for 6 DoF feedback control, because there is no chance of 'gimbal lock' between human motion and robot arm kinematics, and because the weight of the motors is stationary, simplifying compensations needed to remove unwanted feeling of the machine's self-mass [16]. This study employs two teleoperated hexapods of identical shape and size. It is important for the human operator to achieve both position control and force feedback. A reliable way to ensure that the master robot (provides feedback for the human) and slave (interacts with the real workspace) is by using bilateral teleoperation, in which identical commands are sent between the two machines such that it does not matter which is used as the master or the slave [17]. It is possible, though not trivial to attain this with 'transparency' – wherein the robot does not add additional dynamics beyond what the operator would experience if touching the workspace directly [18].

In this study, bilateral impedance control is used, augmented by feedforward torque compensation [19]. This combined position and force feedback provides stable and intuitive control for even unskilled operators [20]. An important consideration in teleoperation (as with all human-machine interactions) is the delay time between inputs and response [21]. This has been studied and solved in many ways, most solutions involve some method for adding damping until the system stabilizes [22]. The control laws used in this study can ensure stability with stable time-delays up to hundreds of milliseconds, allowing them to be operated over the internet as needed.

Finally, it is important to ensure that a system designed for Imitation Learning data collection will actually be useful in collecting large datasets that can contribute to future research. Accessibility due to upfront cost will unfortunately dominate the decisions of small labs and secondary schools that otherwise would contribute to robotics research. Due to the many open-source robotics projects such as ROS, and the wide availability of powerful and inexpensive electronic development platforms, the final obstacle to robot costs are in the mechanical hardware. For the hexapod-style robot studied here, the high cost of servo motors and gearing is the primary cost. For this study, we chose to implement NEMA 17 stepper motors. Torque-feedback control is developed, using quadrature, to operate these stepper motors as though they are fully functioning low-speed DC servos [23]. This is done using a combination of linearization techniques more commonly applied to brushless-DC motors [24, 25]. The workspace is small enough that these motors can be directly driven with no precision-gearing required – reducing the motor drive costs by an order of magnitude over commercial geared servos.

This report describes the development of a machine which achieves good correspondence and natural feedback using torque controlled stepper-motors. The remainder of the paper is organized as follows: First, The mechanical design of the hexapod is described, including the kinematic equations for both forward and inverse kinematics. The dimensions of the machine are selected based on creating a workspace which mimics the workspace of a human in a table-top task. Second, torque feedback servo motors are created from stepper-motors. The electronic hardware and linearizing equations which achieve this are described and validated. Third, bilateral teleoperation is implemented. The equations which achieve bilateral position-position control are presented and shown to allow natural force and position feedback by a novice operator.

II. Mechanical Design

The hexapod robot hardware is designed to allow free movement of the human expert's hand, and achieve six degree-of-freedom motion of the end-effector. The hexapod is similar to the much more prevalent 'delta' robot, however it provides rotation degrees of freedom since six motors drive the arms. There are many configurations of the six arms that can provide different workspaces for the machine. By grouping pairs of arms together in parallel, this machine achieves a large range of motion while sacrificing torque in some positions [26]. During teleoperation, a pair of robots are used which are identical except for the end effector. The 'master' robot which is touched by the human expert has a pressure sensing control handle. The 'slave' robot which mimics the human motions has a gripper which closes and opens in response to the expert's pressure on their handle. Since the two machines are identical in size and kinematics, most of the teleoperation laws can correspond directly between matching motors on the two machines. A kinematic solution is still valuable as it can be used to compensate for the weight of the end-effectors which are not identical. Designing hexapod mechanical hardware for teleoperation and imitation learning requires selecting the upper (L) and lower (l) arm lengths, solving kinematics for gravity compensation, and sizing the arms and base to achieve the desired workspace.

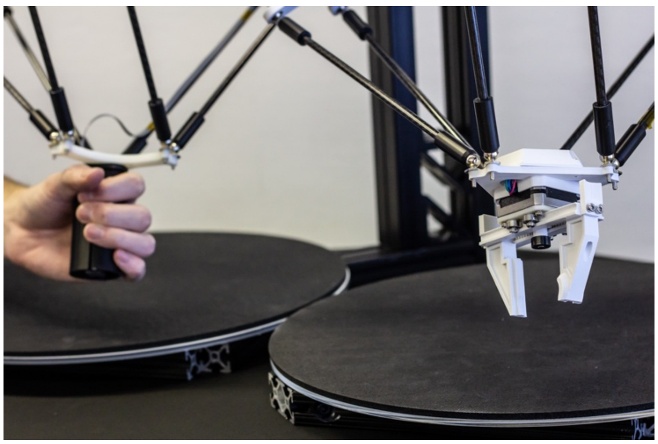

Figure 2 - The human operator controls a pressure-sensitive handle. The orientation and position of the handle are mimicked by the robot. The gripper closes with force proportional to the operators grip.

Similar to delta robots, hexapods have the interesting characteristic of allowing a direct inverse kinematics solution, but having an ambiguous forward kinematics solution. The Jacobian and forward kinematics can both be solved numerically to completely characterize the motion. The inverse kinematics can be solved analytically, determining the six motor angles θ based on the position (p_p) and rotation matrix (R) of the end-effector platform. The spherical joints on the rotated platform (p_i) can be found relative to their static displacement from platform center ($D_p, \pm A_p$):

$$\begin{aligned} p_{i_1} &= p_p + R\ \{D_p \quad A_p \quad 0\}^T \\ p_{i_2} &= p_p + R\ \{D_p \quad -A_p \quad 0\}^T \\ p_{i_3} &= p_p + R\, R_z(-2/3\,\pi)\ \{D_p \quad A_p \quad 0\}^T \\ p_{i_4} &= p_p + R\, R_z(-2/3\,\pi)\ \{D_p \quad -A_p \quad 0\}^T \\ p_{i_5} &= p_p + R\, R_z(2/3\,\pi)\ \{D_p \quad A_p \quad 0\}^T \\ p_{i_6} &= p_p + R\, R_z(2/3\,\pi)\ \{D_p \quad -A_p \quad 0\}^T \end{aligned} \tag{1}$$

The revolute joint positions on the base (p_s) are known and stationary. For each arm, the location of the universal joint at the elbow can be solved along with the angle of the revolute joint on the base (which is also the motor angle):

$$a = \frac{l^2 - L^2 - \left(p_{s_1} - p_{i_1}\right)^2|_{xyz}}{2L}$$
$$b = \left(p_{s_1} - p_{i_1}\right)|_x$$
$$c = -\left(p_{s_1} - p_{i_1}\right)|_z$$
$$\theta_1 = \Theta(a, b, c)$$
$$\Theta(\mathrm{a,b,c}) \equiv \mathrm{atan2}\left(\frac{\left(ac^2 - b\sqrt{-c^2(a^2 - b^2 - c^2)}\right)}{c(b^2 + c^2)}, \frac{\left(ab + \sqrt{-c^2(a^2 - b^2 - c^2)}\right)}{b^2 + c^2}\right) \tag{2}$$

This is solved similarly for the other joints, each with unique inputs for a, b and c. For notational simplicity henceforth, this entire procedure which returns six motor angles θ given platform position p_p and platform rotation matrix $R(r, p, y)$ - a function of platform roll r, pitch p, and yaw y - is combined into a single function:

$$\theta = HexaIK(p_p, R(r, p, y)) \tag{3}$$

For lack of an analytical solution, the Jacobian (J) for the hexapod robot is solved numerically. The forward kinematics is solved numerically as well, updating an iteration of the search at each update of the control law:

$$\begin{aligned} \hat{\theta} &= HexaIK(\hat{p}_p, \hat{R}) \\ \hat{p}_p &= \hat{p}_p + J^{-1}(\theta - \hat{\theta}) \end{aligned} \tag{4}$$

Finally, the Jacobian can be used to compensate for gravity to reduce or eliminate the static weight of the end-effectors during teleoperation. Using virtual work arguments, the instantaneous motor torque can be related to instantaneous platform loads [27]

$$\mathrm{T} = J^T F \tag{5}$$

To compensate for the effect of gravity on the platform mass m_p, each motor is fed-forward a torque to cancel the torque caused by gravity which is

$$\tau_i = J_{2,i} * m_p g \tag{6}$$

In addition, the torque of the upper arms m_L acting at radius r_L is not negligible. It can be compensated with

$$\tau_i = m_L r_L g \cos(\theta_i) \tag{7}$$

The motor current u to produce these torques is related to the motor torque constant (K_t)

$$u = t_i / K_t \tag{8}$$

Once the kinematics are obtained, they can be used to optimize the workspace of the machine. The 'workspace' for this study is considered to be any space the robot can reach where the Jacobian matrix 'local conditioning index' [28] is better than 0.01 and where the upper arms move no more than 90 degrees from the horizontal plane.

As the intention for this machine is to replicate the movements of a human performing tabletop tasks, the workspace is designed to achieve a span which does not limit the motions of the human. Also, the torque available from NEMA17 stepper motors is considered. For this first prototype, the workspace should provide approximately 400mm diametric reach and 300mm vertical reach, while allowing a 1 kg payload at any point. A comparison between this workspace and one which achieves nearly the full reach of a human over a table-top is shown in Figure 3.

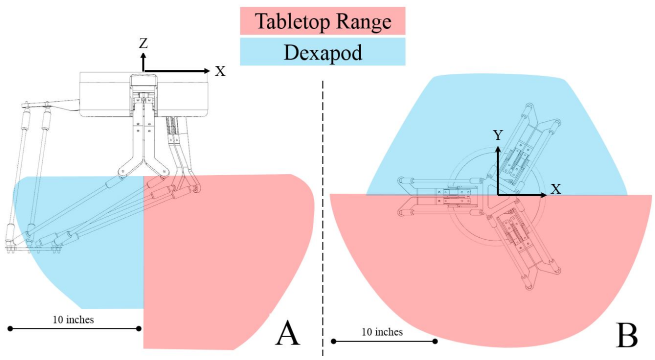

Figure 3 – Robot workspace design. The red area provides the range of a human arm over a table. The hexapod studied here reaches the blue region.

III. Servo-Motor Control

A teleoperation system cannot provide force feedback using traditional stepper motors, it requires the ability to smoothly control the torque of the motor as in DC servos. To attain torque control of a stepper motor, the motor equations of motions should be modeled and linearized so that the ticking/stepping behavior is hidden during closed loop control. Consider first the 'free-body' action on the rotor [24]. Assuming a rotor inertia J, rotor damping B, torque constant K_m, and rotor with N_r teeth, driven by input current in the coil-sets I_A and I_B

$$J\ddot{\theta} + B\dot{\theta} = -K_m\left(I_A - \frac{e_A}{R_m}\right)\sin(N_r\theta)$$
$$+K_m\left(I_B - \frac{e_B}{R_m}\right)\cos(N_r\theta) - T_D\sin(4Nr\,\theta) + T_{ext} \quad (9)$$

e_A and e_B are the back-EMF voltages generated by the spinning rotor, and R_m is the magnetization resistance, which is typically so large that e_X/R_m is negligible. Finally, T_D is the detent torque of the rotor which is felt when turning the motor by hand when unpowered and is generally considered to be a disturbance or friction that is not modeled. The current in the coils develops based on the applied voltage according to

$$L\dot{I}_A + RI_A = v_A - e_A$$
$$L\dot{I}_B + RI_B = v_B - e_B \quad (10)$$

Where

$$e_A = -K_m\dot{\theta}\sin(N_r\theta)$$
$$e_B = K_m\dot{\theta}\cos(N_r\theta) \quad (11)$$

These highly nonlinear equations are not a concern when using the motor to step, in fact the nonlinearity allows the stepping sequences to function. Essentially, even when running at a 'constant speed', stepper motors are usually pausing at each step. Torque control requires smooth motion.

Consider equation (9) where the coil currents are directly commanded (e.g. by chopping), the detent torque is small, and the magnetizing resistance is large:

$$J\ddot{\theta} + B\dot{\theta} = -K_mI_A\sin(N_r\theta) + K_mI_B\cos(N_r\theta) \quad (12)$$

It is fortunate (but not immediately apparent) that this system can be feedback-linearized by adopting an input using the Direct Quadrature transformation:

$$I_A = -u\sin(N_r\theta)$$
$$I_B = u\cos(N_r\theta) \quad (13)$$

In which case trigonometric identity cancels the nonlinearity without inversion (which would fail near $\pi/2$ anyway). This nonlinear mapping reduces the motor equation to

$$J\ddot{\theta} + B\dot{\theta} = K_m u \quad (14)$$

This feedback-linearizer, enabled by the current chopping, reduces the complexity of the stepper motor to the same form as a conventional DC motor. For stable operation, this requires several important physical characteristics in the real control system

- Current driver bandwidth is much higher than motor inertial bandwidth
- The output can be controlled with fine resolution to achieve $\sin(\theta)$ modulation
- The encoder has sufficient resolution and bandwidth to determine instantaneous $\sin(N_r\theta)$
- Detent torque is small compared to K_m

This linearizer allows feedback control to be designed as if the stepper is a linear system. It allows closed-loop control of position and speed (Figure 4).

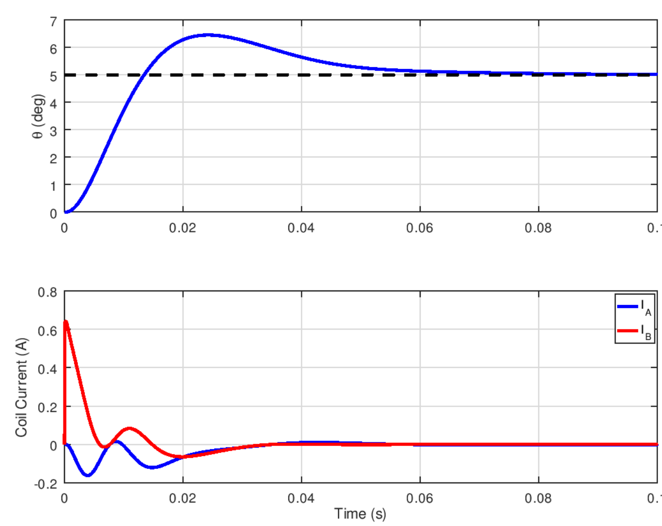

Figure 4 - Simulating closed-loop control of the stepper motor with feedback-linearized controller. Modulating coil currents leads to smooth torque control.

IV. Teleoperation

Since the robotic hardware is identical on the master and slave ends, the robot has parallel kinematics with lightweight arms, and end-effector weight was compensated independently in each machine, the teleoperation scheme for the robots reduces to six single degree-of-freedom controllers running in parallel. To enable four-channel teleoperation, load cells were initially fitted to each of the upper arms of the machine. However, it was determined in testing that using motor current as a proxy for torque provided better transparency in control than using load cell. The resulting teleoperation scheme uses position-position control using Proportional-Derivative or Lead dynamics along with feedforward of the motor currents (as a proxy for torque). It is known that this control scheme provide good transparency: the PD dominates when the machine is moving in free space, and the feedforward torque dominates during contact. Generally, the robot behaves like a motor with a single pole and an integral, but the effective mass can vary based on the position

$$M(x_m)\ddot{x}_m + B\dot{x}_m = u_m + f_h$$
$$M(x_s)\ddot{x}_s + B\dot{x}_s = u_s - f_e \tag{15}$$

The control law for teleoperation has three components: position tracking feedback, stabilizing damping, and force tracking feedback:

$$u = \frac{u}{e_x} + \frac{u}{x} + \frac{u}{e_f} \tag{16}$$

The position tracking is accomplished using proper PD (Lead) control:

$$\frac{u_m}{e_x} = K\frac{(s+\alpha)}{s+\beta}$$
$$e_m = x_s - x_m \tag{17}$$

And similarly for the slave. Each motor is given additional stabilizing damping

$$\frac{u_m}{x_m} = -K_d s \tag{18}$$

And finally, the force from the other end of teleoperation is fed-forward, potentially with force error feedback:

$$\frac{u_m}{e_f} = K_u f_s + K_p e_f$$
$$e_f = f_s - f_m \tag{19}$$

V. Results

The complete hexapod controller is compiled for Cortex M4F based microcontroller unit which handles the quadrature drive, communication, gravity compensation, and teleoperation data transfer. Due to the varying timescales of relevant information in these components, they each have unique sample rates (Table 1). The quadrature update runs in parallel with the main computations by using DMA both to read the encoders and to update the motor driver states. Communication between the machines is handled using TTL UART at 2MBAUD, leading to a typical round-trip latency below 4 ms. The controller was also tested using WiFi and socket layer communication through the internet, and was stable with a typical latency of 60 ms over 450 miles.

Table 1 - Sample rates for the four levels of control handled by the robot embedded control computer

Control Loop	**Sample Rate**
Quadrature	10 kHz
Servo Control	500 Hz
Communication	400 Hz
Logging	10 Hz

To assess the feedback and stability of teleoperation control, a test scenario was examined wherein small cubes of varying mass were arranged on the table, then picked and placed in a row by the operator. Tracking performance of one of the motors is shown in Figure 5. It is seen that the slave closely tracks the motions of the master while the cubes are lifted. In Figure 6, the operator lifts and holds each of the three cubes in order from heaviest to lightest. Since the teleoperation is effectively impedance control, position error is proportional to each block's mass, thus feedback force felt by the user is also proportional to each block's mass.

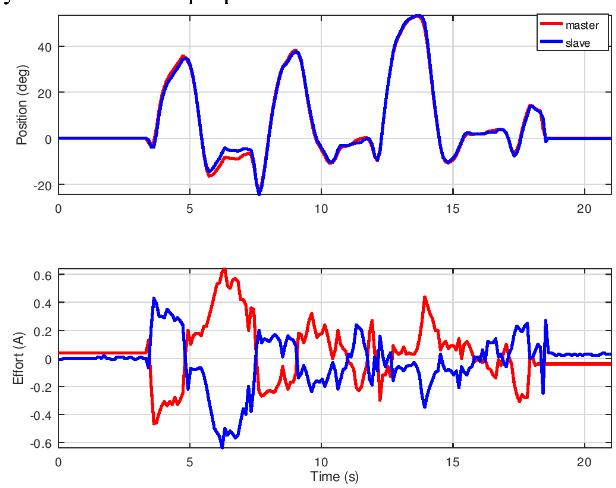

Figure 5 - Tele-operated control while moving and sorting three cubes of varying mass

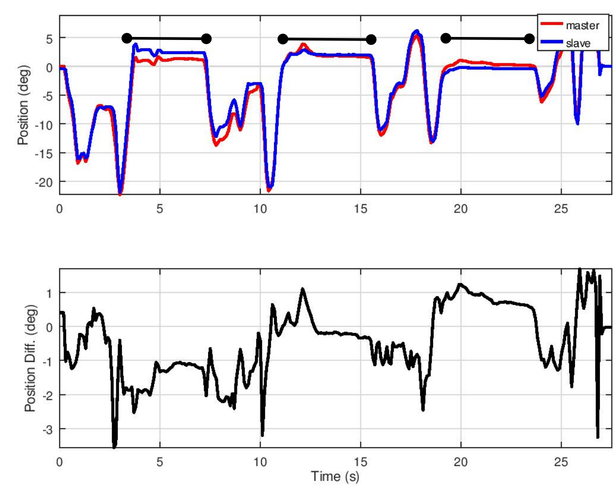

Figure 6 - Lifting and holding each of the three cubes demonstrates the force-feedback available to the operator. Bars denote stationary periods.

VI. Conclusion

This research studied the design of a robotic machine which allows high quality data to be recorded during task-training for imitation learning. The machine achieves good correspondence by implementing teleoperation over a video stream. This teleoperation improves natural control ability by a human operator since it replicates their motions directly (position) rather than being rate controlled or trying to map human kinematics onto dissimilar robot kinematic structures. The teleoperation control designed allows force feedback, also enhancing the operator's control. This data is recorded for use when training models for Imitation Learning or other forms of Programming by Demonstration. By using direct drive stepper motors, this machine is accessible to labs that could not afford traditional industry robots, increasing the access to training data for future intelligent robotics studies.

In future work, the interaction of the operator via a video stream over long distance, with communication over the internet, will be studied. Long term storage of the teleoperation sessions will be established to help create a databased of human operated robot control. This data will be used to improve Imitation Learning.

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