Admittance Controller for Physical Human-Robot Interaction Using One-DOF Assist Device

Hninn Wai Wai Hlaing, Aung Myo Thant Sin, Theingi

Abstract— This paper presents the admittance control scheme for improving physical human-robot interaction. For achieving the effective of assistance, and the human operator, in which the detection of the human inference is required, must achieve intuitive cooperation. The proposed controller considered for human intension, (i.e force increasing and force decreasing), depending on the applied force by monitoring the difference of the magnitude of the measured force during each sampling period. Then, virtual damping is adjusted to high value for fine positioning or low value for fast motion. Internal position controller is also adjusted to get the accurate and precise motion. The experiment validated by using a single degree of freedom device. These algorithms are is practically applicable to position-based admittance controller. The experimental data demonstrate that the position-based admittance controller approach outperforms the motion very well and the mechanism design was verified.

Index Terms— Admittance control, physical human-robot Interaction, robot control, one-DOF assist device, motion control.

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1 INTRODUCTION

In conventional industry, it is commonly used the conventional position controller for the purpose of robot's motion, which means to approach from actual position to desired position. Robot can be capable of many tasks that are difficult for human operator. They would certainly help the problems of people according to the program that is put in the controller. They can do instead for human in the repetitive works, the hazardous environment for human operator and the heavy tasks for human. However, there are many considerable issues of position controller in robotics devices. For example, oscillations (overshoots and undershoots), correspondence to set-point (desired) tracking which causes from discontinuous position commands, unexpected results from robot's movement which leads to the processing lag and the motion lag, and so on. Therefore, the robotics devices may cause harm to the human operator in industrial workspace. Moreover, in such situation, it is true that the portion of the position control on workspace will probably not to be avoided, especially in human–robot interaction.

Although robots have been used for many applications, robots are required to work in direct interaction with the environment or an external object. The main challenge for human-robot interaction system is to observe their environment and human intension, and to respond them adequately and safely. For safety reasons, the contact force between the robots and humans are infrequent, and appropriate controllers are needed. In several applications, admittance control is the reasonable controller for two main classes; there are used in human-robot interaction applications [1], [2], [3] and haptic devices [4]. Dimeas [5], and Campeau-Lecours [6] are demonstrated the admittance controller applied to reduce the human effort in lifting large payloads. Man-machine cooperation work system has been developed in [7], [8], [9], [10].

Dimeas in [11] also investigated for detecting unstable problems of the admittance controller and regulation of the admittance parameters to stabilize the system. Force control based admittance controllers are expressed in [12], [13]. Force sensor is normally used in human-robot cooperation applications to detect the human contact force that is attached the robot end-effector to control the motion of the device. Force is the desired input in admittance controller, which is measured and responds with the displacement [14] and virtual object dynamics and internal position controller are considered in this controller.

Several techniques have been developed in the literature to deal with the safety matters increased in the robot and human cooperation workplace. In this paper, admittance controllers are described such as internal position controller (PID controller) and admittance controller are considered in one-DOF system for physical human-robot interaction.

The proposed admittance controller employs the algorithm for inferring human intension by monitoring the magnitude of the measured force. Then, the virtual damping is adjusted for fine positioning and accurate motion. The algorithm is experimentally developed by using a single degree of freedom device, which has been demonstrated with the internal positional controller in admittance controller with constant-damping approach. This may be able to find that the proposed algorithm is better performance in position-based admittance control tests.

The rest of this paper is organized as follows. Section II discusses an overview of admittance controller. Section III presents prototype of one-DOF assist device and the position control experiment and the effectiveness of experimental impulse test are illustrated in Section IV. Section V concludes the paper.

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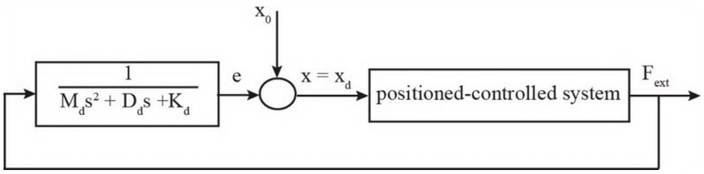

Fig. 1. The concept of admittance control [15]

2 ADMITTANCE CONTROLLER

There are two popular control methods, namely impedance and admittance control are widely used in haptic applications and physical human-robot interaction application. In impedance-type control [19], the measurement of the displacement used as an input and reciprocates with an adjustment of force as an output. The alternative method, admittance control acquires the force as an input and gives as an output is the displacement to control the position of devices. Two basic methods of impedance and admittance control interact with a virtual environment through the transmission force and motion to cooperate with robot. But, the impedance-controlled device is better suited for dynamic interaction with stiff environments. The admittance-controlled device enables the compliant motion of a precise position control of industrial robotic systems. When the human operator starts to be in contact with virtual environment, the inertia and friction would be too hard for a human operator to impart a movement to the devices even if the force sensor is used.

In the admittance control, the plant is position-controlled and not force-controlled. Let as consider the position-controlled system in which the motion of the mass follows a given desired trajectory x_d without any tracking error, i.e., $x = x_d$. The concepts of admittance control can be implemented by the control system as shown in Fig. 1. In the admittance control system, the device sense forces commanded by the user and controlled the motion (velocity or position). The position is accurate enough; the robot's response to external forces is close to that of the virtual object. Consider a single degree-of-freedom system in which the mass interacts with an environment. The controller is designed to be a mechanical admittance. The position control system is comprised of the plant dynamics and the position controller as shown in Fig. 2.

Let m and x be the generalized inertia and displacement of the mass respectively. *F* is the actual measured force and F_{ext} describes the external force of the environment when contacted with the robot. The equation can be written as follow:

$$m\ddot{x} = F + F_{ext} \tag{1}$$

The control objective for admittance control is to design the control force that will establish a given relationship between external force and the deviation error $e = (x - x_0)$ from a desired equilibrium trajectory x_0. Typically, the linear second order relationship as follow:

$$F = M_d\ddot{e} + D_d\dot{e} + K_d e \tag{2}$$

where, M_d, D_d and K_d are positive constants and represent the desired inertia, damping and stiffness, respectively. The error *e* is the difference from x_d to x. The desired position x_d and the measured position x are the inputs to the controller while *F* is the torque command to the actuator. Substituting (2) into (1) after replacing x with x_d, the complete system dynamics can be written as follows:

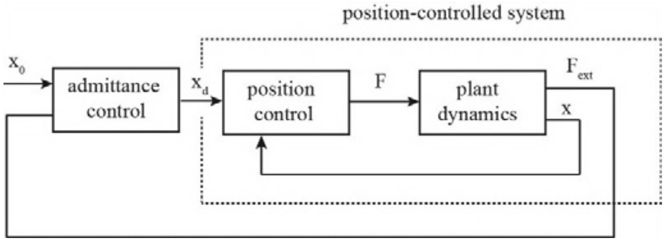

Fig. 2. Implementation of admittance control [15]

$$F_{ext} = M_d(\ddot{x}_d - \ddot{x}_0) + D_d(\dot{x}_d - \dot{x}_0) + K_d(x_d - x_0) \tag{3}$$

It should be noted that the impedance controller uses static feedback whereas the admittance control law in (3).

2.1 Internal Position Control in Admittance Controller

In admittance controller, internal position controller is essential need to drive the device. In the formulation of any practical control problem, there will always be a discrepancy between the actual plant and its mathematical model used for the controller design. These discrepancies (or mismatches) arise from unknown external disturbances, plant parameters, and unmodeled dynamics. Designing control laws that provide the desired performance to the closed-loop system in the presence of these disturbances or uncertainties is a very challenging task for a control engineer. This has led to intense interest in the development of the so-called robust control methods that are supposed to solve this problem.

The proportional-derivative (PD) and proportional-integral-derivative (PID) control schemes have been extensively used, especially for industrial robots. The nonlinear factors such as link inertia and joint frictions are usually influenced on most of the dynamics model. The stiff position controllers have not been matching for the realization of both slow response against large positional error and accurate position control in normal operation. Moreover, such factors and disturbances have been caused the degradation of control performance in the industrial-position controlled system [16], [17], [18]. It is certainly true that the stiff position controller are usually applied as the lowest level controller which is necessary for achieving improvement without overshoots and oscillations, although there still remains theoretical challenge concerning the stability and the convergence property of the PID control.

The basically block diagram of PID controller is shown in Fig. 3. As the general application of process control, the proportional-integral-derivative (PID) controller, defined by

Equation 4.2 $$u(t) = K_p e(t) + K_d e(t)dt + K_i \int e(t)dt \tag{4}$$

where, K_p, K_i, and K_d are the proportional gain, the integral

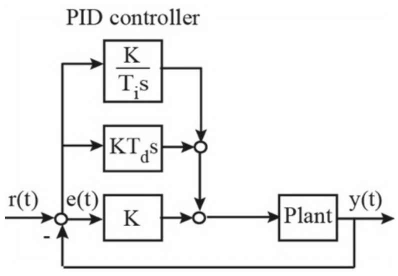

Fig. 3. Block diagram of PID controller

gain and the derivative gain time constant. Equation (4) has explicit physical meanings, that the current error *e*, and the accumulated error is ∫ *e*.

The three-term functionality offering treatment of both transient and steady state responses, proportional-integral-derivative (PID) control provides a generic and efficient solution to real world control problems. Its three-term functionality of PID parameter highlighted by the following.

The proportional term will be provided an overall control action proportional to the error signal through the all-pass gain factor. As the proportional gain adjustment is getting smaller, the larger the proportional contribution to the output. This can obtain a sensitive and rapid control reaction. However, when the proportional gain K_P is too small, it may cause oscillation and then it could increase the process reaction and reduce the steady state error.

The integral term will be reduced steady-state errors through low-frequency compensation by an integrator. In addition, the integral item may be used to eliminate the steady state error. When there is steady state error, adjust the integral time constant larger to decrease the error. The derivative term will be improved transient response through high-frequency compensation by a differentiator. Moreover, the derivative item may be used to make the system smoother and not too over shoot. By using the PID controller, which will improve the performance of the device, reduce the overshoot, eliminate steady state error and increase stability of the system.

3 PROTOTYPE OF ONE-DOF ASSIST DEVICE

The important characteristics of single degree of freedom devices include force that the actuators can exert, force/torque sensor, encoder, workspace, etc. Although the device is varying considerably in those parameters, the underlying physical design is generally the same. A single degree of device is shown in Fig. 4, which is usually includes the elements are described.

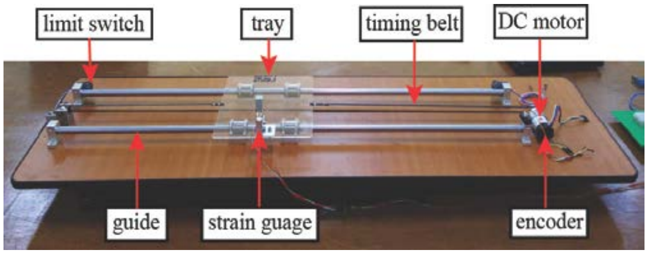

Fig. 4. Prototype of one-DOF assist device

The setup used for the experiment in the research, a prototype of one-DOF intelligent assist device, shown in Fig. 4, which is allowing the translations in only one direction. In this prototype, the device's usable range of motion is 730 mm. The powerful 12V brushed DC motor with 19:1 metal gearbox and the integrated quadrature encoder is fixed at the side of the device. The resolution of the encoder is 64 counts per revolution of the motor shaft, which corresponds to 1200 counts per revolution of the gearbox output shaft. An aluminum pole of force sensor was fixed on the base of moving tray. Limit switch was mounded at the end of the moving path.

The size of 5 mm timing belt drive was used in this device. The motor turns a set of pulleys and connects with timing belt employed on the shafts. Timing belt drive transforms the rotational motion to linear motion. Motion control requirements for such system are accurate velocity control, linear motion and high resolution. Using of belt for high precision applications has become appropriate because of rapid development of motor and drive technology as well as the implementation of timing belts in belt-driven systems. Belt drive systems provide high speed and acceleration, accurate and repeatable motion with high efficiency, long stroke lengths and low cost. Modeling of a linear belt-drive system and designing its position control are examined in this work. The strain guage 1 kg torque/force sensor mounted on the moving tray, which is used to how many contact forces on it and to move the device easily without many forces on it. Using the one-DOF device, which is composed of a DC servo gear motor, experimentally tested the proposed controller.

3.1 Discrete-time Algorithm of Position-based Admittance Controller

This section investigates the discrete-time algorithm of position-based admittance controller. The motivation of admittance control in contact with virtual environment is presented by one-DOF device. Single degree-of-free-body system is shown in Fig. 5. One-DOF admittance equation is written as

$$f = m\ddot{x} + b\dot{x} \tag{5}$$

where, f is the force applied by the human operator measured by the force sensor, m is the virtual mass parameter, b is the viscosity and $\ddot{x}$ and $\dot{x}$ are velocity and acceleration respectively. The trajectory to be followed by the moving tray can be prescribed as a position x_d or desired velocity. The combining of the virtual object dynamics and internal position controller could be created the desired force input f_d for forcing the robot to follow the virtual objects motion in the admittance controller. This controller can be described as follows:

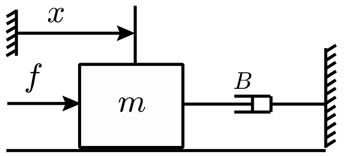

Fig. 5. One-degree of free-body system

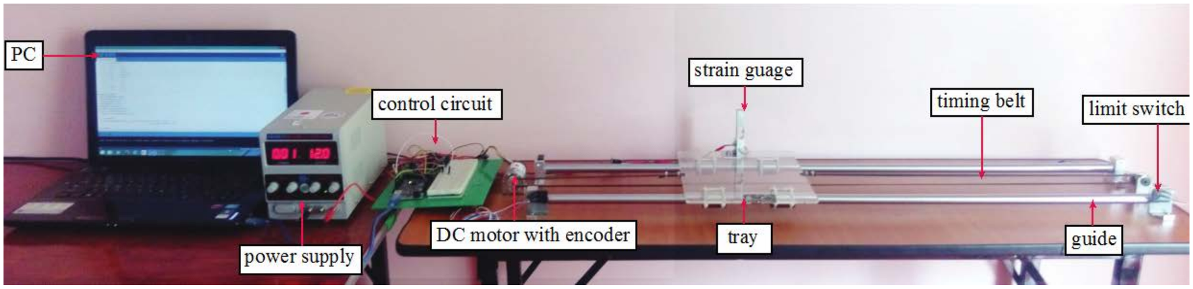

Fig. 6. Experimental Setup

$$\ddot{x}_d = \frac{-b\dot{x}_d - f + f_d}{m} \tag{6}$$

$$\tau = K(x_d - x) + B(\dot{x}_d - \dot{x}) + M(\ddot{x}_d - \ddot{x}) \tag{7}$$

K, *B*, *M*, *m*, and *b* are positive constants, and then the force *f* can be measured directly using the force sensor attached to the moving tray and the measurement distance *x*.

Desired force f_d is the input to the controller, when the torque sends command to the actuator. The robot respond by the external force depends on the selection of the gains parameters *m*, *b* and *k*. The higher viscosity *b* also needed the more external force to move the robot, particularly at high velocities. The robot resist in changes of the motion by increasing the inertia *m*. The stiffness term *k* is set to null when free motion of the robot is desired. Virtual object dynamic equation (6) (mass, $m > 0$ and viscosity, $b > 0$) interacts to the external force f and desired force f_d. The internal position controller (7) accepts the desired position input x_d, and *K*, *B*, and *M* are *P*-, *D*- and *I*- gains respectively.

The continuous time expression (6) cannot be directly integrated for numerical computation. The following relation is to be noted from (6):

$$m\ddot{x}_d = -b\dot{x}_d - f + f_d \tag{8}$$

The above relation is used to replace the backward (implicit) Euler discretization (i.e $v(k) = (x(k) - x(k-1))/T$), where *k* is the discrete time index and *T* is the sampling interval. By following the detailed derivation as shown in the following equations.

$$\dot{X}_d = \frac{X_d(k) - X_d(k-1)}{T} \tag{9}$$

$$\ddot{X}_d = \frac{X_d(k) - 2X_d(k-1) + X_d(k-2)}{T^2} \tag{10}$$

By substituting in (8)

$$m\left[\frac{X_d(k) - 2X_d(k-1) + X_d(k-2)}{T^2}\right] + b\left[\frac{X_d(k) - X_d(k-1)}{T}\right] = -f + f_d \tag{11}$$

Simplify the above equation; the equation will become the following,

$$\frac{mX_d(k) - 2mX_d(k-1) + mX_d(k-2)}{T^2} + \frac{bTX_d(k) - bTX_d(k-1)}{T^2} = -f + f_d \tag{12}$$

$$X_d(k)[m + bT] - X_d(k-1)[2m - bT] + mX_d(k-2) = T^2[-f + f_d] \tag{13}$$

The position-based discrete time algorithm becomes the following equation.

$$X_d(k) = \frac{X_d(k-1)[2m - bT] - mX_d(k-2) + T^2[-f + f_d]}{[m + bT]} \tag{14}$$

By using of this equation, the admittance control experiments are demonstrated.

4 EXPERIMENTS

4.1 Position Control Experiment

The experimental setup of one-DOF assist device as shown in Fig. 6, which device allows moving in only one direction for horizontal motion, that is used in the experiments. The force acting on the link was measured by strain guage to move the horizontal motion of the device that was controlled with the PC running window operating system. Arduino (MEGA) 2560 type micro-controller with 16-MHz clock frequency was connected with PC by using USB cable. The PC is used for data monitoring and off-line data processing.

The experiments were aimed to demonstrate the tracking performance of both PID controller when the parameters have been optimized, and whether there exists in mm scale. According to the principle of PID, the main purpose is to ensure safety, accurate and precise motion in interaction system. As previously mentioned, they are suited for against large positional errors and against small positional errors. For the performance of experiment, it refers to the positioning performance Fig. 7. The performance of PID controller was presented. To begin with, the desired position angle is chosen for step input control distance is 100 mm. When the program run, the robot wait for 2 seconds. After waiting the timer, the position will be move 10 mm in during 2 seconds. The distance will be added the next 10 mm until 100 mm in very 2 seconds. In this experiment, the parameters of PID gains were tuned by trial and error method. The parameter were selected as K_p= 8, K_i = 0.008 and K_d = 0.8 respectively.

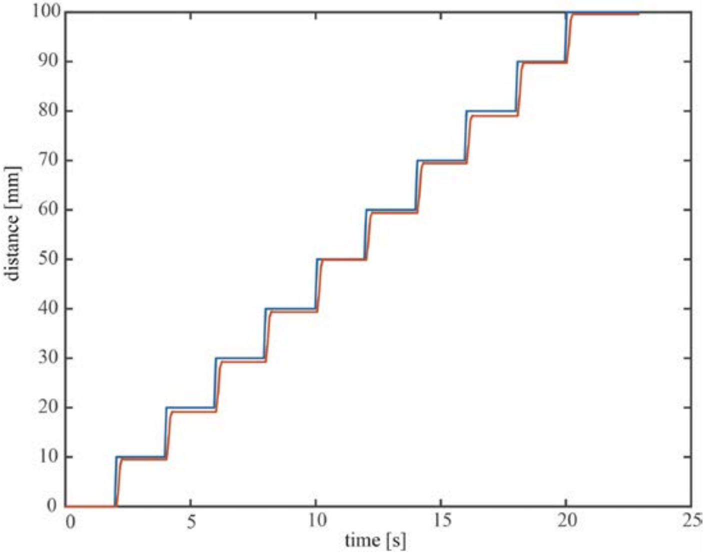

Fig. 7. Position control experimental result

It can be seen that the actual distance can followed the desired results. However, PID has been indicated that there exist steady-state errors which result in undershoots during the normal operation.

4.2 Admittance Control Experiment

In admittance model, when the human operator starts to be in contact with the virtual environment, the contact force is sensed; and this force will result in virtual motion deviation from the case of the absence of the applied contact force for the given physical properties of the virtual environment. A typical implementation of admittance control is illustrated in Fig. 8. The virtual object with simple dynamics is considered in the controller, and its motion is simulated according to the measured force and an input desired force.The robot is controlled to track the virtual object's motion. When the internal position controller is accurate enough, the response of the robot to external forces is close to that of the virtual object.

The admittance-controlled device enables the compliant motion of a precise position control of industrial robotic systems. When the human operator starts to be in contact with virtual environment, the inertia and friction would be too hard for a human operator to impart a movement to the devices even if a force sensor is used. The motivation of admittance control in contact with virtual environment is presented based on one- DOF device. The combining of the virtual object dynamics and internal position controller could be created the desired force input f_d for forcing the robot to follow the virtual objects motion in the admittance controller.

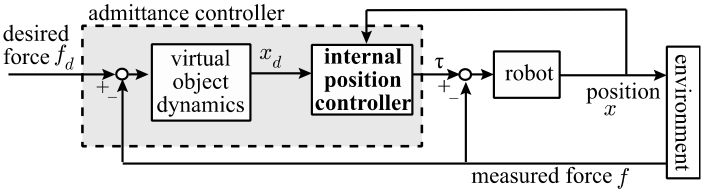

Fig. 8. Admittance control block diagram of robot in contact with environment

The conventional admittance experiment is designed with constant parameter of virtual damping and the virtual mass m in this case. It should be noted that when F_d is zero, there is no force acting on the force senor, the actuating force F will be zero too at that time and the object cannot be move. When the force acting the force sensor, the robot was easy to accelerate while the low force commented that for the low admittance case, but the robot harder to perform fine movement as shown in Fig. 9. There will be smooth velocity profile and there is no noisy signal along the motion.

On the other hand, when the parameters are set to high value, the large force is required to move the robot as shown in Fig.10. However, it is easier to perform the fine movements.

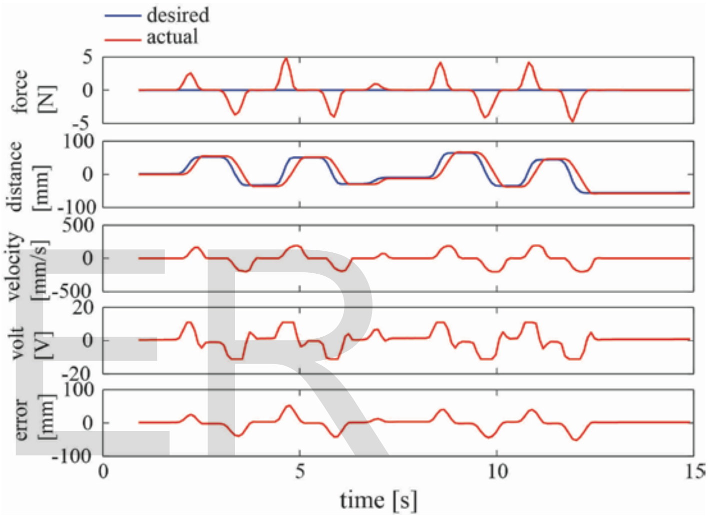

Fig. 9. Experimental result of low damping parameter in admittance controller

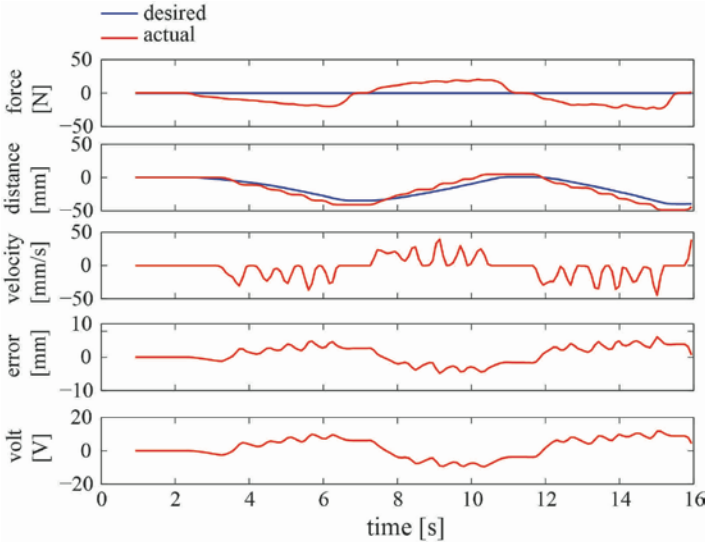

Fig .10. Experimental result high damping parameter in admittance controller

The damping parameter b has a greater effect at the effectiveness of the cooperation than the inertia m. The use of high values of admittance damping parameter generally demands for the large human force that can improve the accuracy of robot motion and fine movements. On the other hand, when the low admittance parameters are used, the human operator requires less force and they can perform the task quickly and easily, at the risk of the positioning accuracy. In the case of low damping case, it helps to move the robot more easily and quickly than the high damping case. The compromise between the force required moving the robot and the ability to perform fine movements is the main drawback of the fixed admittance control.

4.2 Position-based Admittance Controller with Impulse Experiment

In the proposed scheme, an admittance controller is integrated along with a position controller. The admittance controller, that is used to facilitate the interaction, receives the measured force and outputs the position. The desired relationship between the input force and output position should be established to achieve the power assisting movement.

In common implementations of admittance control, the external force is measured such that the typical linear second-order relationship (6). The parameter m and b represent the desired inertia and damping respectively. By tuning the parameters m and b, its can define the position, velocity and acceleration of the object respectively given as the human acting force. The model of the system is not necessary because of the internal position controller (PID) is integrated in the inner position controlled loop. The main control loop is described in (5), where the desired force is set equal to zero as a necessary condition for the object to remain still, when the force measured by the strain guage or force sensor is zero.

It should be ensure that when $F_d = 0$, the actuating force F will be zero too and the object will remain still. When the operator acts the applied force, the device will be moving depending on the virtual damping parameters. By using low damping parameter, it will react the quick response and the slow response appears in high damping case.

In this experiment, the performance of the conventional admittance controllers using constant damping parameter in the manipulation of an object by a human operator is presented. The purpose of the experiment is to demonstrate human robot interaction system by using the single degree of freedom device under real conditions including human factor. In the current work, admittance control is considered because it accepts force inputs and reacts the motion output and implements and automatic control system that impose the actuating force F indirectly to the plant through the position control loop. This procedure fits better to human robot interaction systems, where there is no contact with stiff environment and the tasks are performed with free motion. The accuracy of the admittance control is depends on that of the position control system.

Position-based admittance control experiments are reported in this section. The impulse test is performed with one-DOF device by applying an impulsive force in two cases: low and high damping parameter in admittance controller. Virtual mass is kept constant. As the identical impulses were not possible to repeatedly apply by the human operator in every experiment, impulse force profile was created in

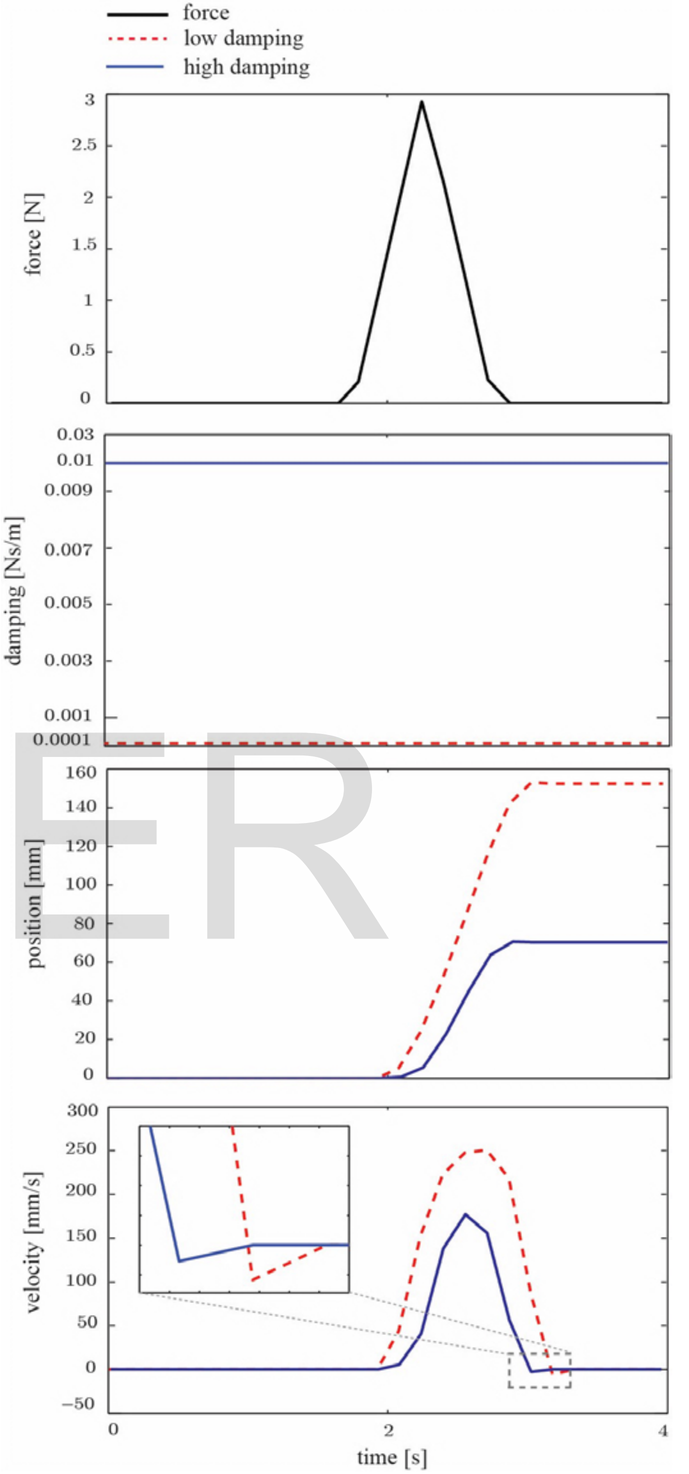

Fig .11. Impulse experiment for position-based fixed damping admittance program and then used as the desired force signal instead of the output of force sensor. The position-based admittance controller accepts the desired force and the input of internal controller x_d is the output of the admittance controller. The actual distance x gets from the motor with an encoder from the feedback loop and the error was calculated based on the position error, differences between the desired distance x_d and actual distance x.

In the first case, default damping was chosen for the admittance parameter. For the admittance controller, the mass should not be too low to obtain the smoother response. Therefore, the parameters are used m = 0.001kg and low damping parameter b = 0.0001 Ns/m and high damping parameter b = 0.01 Ns/m respectively. The internal controller parameters were performed chosen as K = 5 Nm, B = 0.5 Ns/m and M = 0.05 N/ms. These parameters are tuned by trial and error method. According to these values, the object will be moved the low and high speed depending on the damping parameter, when the force applied to the force sensor.

As the identical impulses were not possible to repeatedly apply by the human operator in every experiment, impulse force profile was created in program and then used as the desired force signal instead of the output of force sensor. The position-based admittance controller accepts the desired force and the input of internal controller x_d is the output of admittance. The actual distance x gets from the motor with an encoder from the feedback loop and the error was calculated based on the position error, differences between the desired distance x_d and actual distance x. The result of the impulse force and the result of the position and velocity are illustrated in Fig.11.

In accordance with this experiment, the impulse force commented that for the low admittance case represents with blue line, the robot was easy to accelerate but harder to perform fine movements. But, there exists overshoot in the velocity profile and the oscillation was appeared at the end point of the motion. On the other hand, the impulse force commented that for the high admittance case, while the higher force was required for the movement. It can be seen that using the high virtual damping results in smooth velocity profile without overshoots but it achieved the lowest velocity. In the case of low damping value, it helps to move the robot easily and quickly. On the cooperation of the object by impulse test, the position-based admittance controller performed the motion very well and the mechanism design was verified.

5 CONCLUSION

This research presents admittance control scheme for improving physical human-robot interaction. In admittance controller, the control performance for position-based admittance controller was studied by using single degree of freedom belt drive mechanism. For achieving effective of the performance, admittance control experiment was investigated by using impulsive force profile depending on virtual damping. The use of high values of admittance parameter (virtual mass and viscosity) generally demands for the large human force that can improve the accuracy of robot motion and fine movements. On the other hand, when the low admittance parameters are used, the human operator requires less force and they can perform the task quickly and easily, at the risk of the positioning accuracy. Thus, while the human operator is trying to carry out the desired task in cooperation with the robot, both high and low damping parameters are necessary to achieve both fast and fine motion. Therefore, the compromise between the achievement of accurate positioning and quick motion is to overcome the disadvantage of conventional admittance control.

Future work should investigate the approach that varies both virtual mass and viscosity. Theoretical and experimental investigation of the stability of the proposed technique is an open research.

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