Physical Human-Robot Interaction (pHRI) through Admittance Control of Dynamic Movement Primitives in Sit-to-Stand Assistance Robot

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***Abstract*—Physically assistance robots have been conceptualized to compensate or augment the human musculoskeletal function. However, due to the concerns of safety and effectiveness for physical human-robot interaction (pHRI) in such robots, compliant joints are preferred over the rigid joints. This paper illustrates the implementation of admittance control in a sit-to-stand (STS) assistance robot. The 3-degrees of freedom (dof) robot comprises of ball screw-based linear actuators that are arranged in a parallel configuration. While the actuation system is preferable for strength and performance, the non-backdrivable characteristic corroborates the rigidity of the joint, making it unfavorable for human-robot interaction operation. To enhance compliance, force sensor-based admittance control system is implemented. Regarding motion planning, the trajectory were modeled as Dynamic Movement Primitives (DMP), which facilitates the implementation of admittance control. The proposed model is implemented in the robot prototype and validated by illustrating the force input and the motion output.**

***Index Terms*—Assistant Robot, Admittance Control, Physical Human-Robot Interaction (pHRI), Movement Primitives**

I. INTRODUCTION

It was estimated that a staggering number of 30% male and 45% women of age above 55 years faced some difficulties with performing the sit-to-stand (STS) maneuver [1]. This impairment is directly related to mobility, which means that the independence in living and quality of life are hindered. The situation is further exacerbated by the surge in the percentage of elderly within the overall population. According to the World Bank Data, the population of elderly (aged above 65 years) was 8.8% in 2018 [2]. With an increase in health facilities, life expectancy has increased, while several high-income and middle-income countries are experiencing a decline in the fertility rate. The issue of mobility impairment, augmented by the population situation, has resulted in a major problem on a personal and societal level.

Consequently, the area of robotics has seemed keen to address the issue. With the advent of both wearable as well as non-wearable robots, the paradigm of physical human-robot interaction (pHRI) has been explored to provide adept solution. Some of the preliminary and prominent attempts involved the development of supporting plate [3] or supporting arm [4] and the determination of optimum kinematic parameters to provide necessary assistance force to the user. Although these systems primarily lend support to the upper body, some of the elementary research also actuated the seats to provide force through the buttocks [5], [6]. However, most of them could not be implemented for common use mainly due to the size and lack of mobility in the system.

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Fig. 1: Mobility assistance robot developed in BART LAB intended to assist sit-to-stand, stand-to-sit and walking

The lack of mobility was addressed by integrating the supporting element with the walking assistance system [7], [8]. This evidently was a turning point, as this form of robots attracted substantial attention, which could be inferred from the upsurge in the number of publications and product development. Most of the subsequent works incorporated a support system for upper body along with a mobile walker system [9]–[15]. Despite the fundamental functional similarity, the research objectives were considerably different. For example, the works illustrated in [9], [16], [17], utilized force and position control to ascertain optimum assistive force, encouraging the user to supplement the remaining force, which was deemed vital for preserving and fostering the muscular strength in the user [18]. While some works were concerned with the commercialization of the product [10], [11], [13], [15], several others targeted to determine an optimum trajectory for the supporting manipulator system. For instance, [12] aimed to determine optimal trajectory/strategy for STS transfer and finally illustrated the development of a sit, stand and walking assistance system. However regarding the trajectory of motion, [19]–[21] considered natural-like trajectory for the assistance system to be providing the most favorable results.

In spite of the variety of research objectives, most of the works have given limited attention towards the advanced control system. However, when considering pHRI, the contact forces generate errors and uncertainties for the system, making the system unstable. The system cannot solely rely on pure motion control but has to consider force control as well [22]. [9] introduced a system which automatically switched between position control and force control depending on the amount of force involved. The state variable(velocity) has been represented by a piece-wise function based on the force value, while the spring constant and the damping constant were manipulated to switch the mode of control. Another force control scheme has been implemented in [11]. Both the works rely entirely on the force sensor that is attached with the end-effector and does not mention any filtering technique for the force data or any advanced motion control scheme for precise force control. This direct method of force control demands proper structured model of environment, which is not generally pragmatic [23]. Indirect methods can be employed to achieve robust behaviour so that safety and precision can be maintained when interacting with humans [22].Besides, safety and precision are vital for the pHRI systems. All of the concerns and prerequisites can be addressed wholly by considering the problem as a motion planning problem.

Regarding the indirect force control schemes, admittance control has been used extensively in the area of pHRI. In the development of exoskeletons, the compliant behaviour offered by the admittance control system has been employed to perform the human intention prediction [24], [25]. The concept of human intention prediction through admittance control has also been executed in an interactive robotic arm through adaptive control system [26]. Parameter adaptation has also been used by [27] to ensure human-robot collaboration in the KUKA LWR 4+ robotic arm. In [28], admittance control has been used to implement virtual damping in conjunction with the electromyography-based system for improving the human-robot cooperation. Also, sensorless techniques have also been implemented effectively using motor current feedback to estimate the force through the calibrated current [29].

Similarly, [30] has used a model based approach, by considering frictional and inertial model, and switching between dynamic mode and quasi-static mode, to determine the interactive force between human and the robot without the use of any force sensors. Admittance control has been suitable for the application mainly because of the interactive force measurement, precise trajectory-following and relevance for a high-inertia system. Compared to admittance control, impedance control offers precise force actuation, which compels the system to be lightweight, low friction and low impedance [31]. Admittance control requires robotic system with a high power and high impedance [23], which is specially suitable for robots supporting human beings.

This paper describes the admittance control-based motion planning system in the Sit-to-Stand assistance robot developed in Center for Biomedical and Robotics Technology (BART LAB), Mahidol University. The motion planning system utilizes admittance control along with Dynamic Movement Primitive (DMP) that was introduced by [32], which encodes the motion trajectory as a spring-damper model. The DMP-based equations, modified for admittance control, is implemented to demonstrate the effectiveness of the control system for pHRI.

II. MATHEMATICAL MODELING

The compliant mode starts from the start of the initation of the motion and ends during the stabilization phase. This is because of the problems associated with elderly due to stability. The basic control equation can be written as:

$$m\ddot{\theta} + b\dot{\theta} + k\theta = \tau \quad (1)$$

where, θ is the generalized co-ordinate, m is the mass matrix, b is the damping matrix and k is the desired stiffness matrix, and τ is the exteral wrench. Taking Laplace transform,

$$(ms^2 + bs + k)\theta(s) = \tau(s) \quad (2)$$

Impedance is the ratio of force and position in the laplacian domain, which is why the impedance is frequency dependent. Admittance is the inverse of the impedance. A good force controller is signified by a small admittance because it means that the small motion perturbation produces small force perturbation. This behaviour can be achieved through either controlling impedance or controlling admittance. Regarding impedance control, the robot senses the endpoint $\theta(t)$ and commands the joints with $-\tau$. Admittance control senses τ from user through sensors and controls the motion response, which means that the transfer is from forces to motion. In this scenario, admittance control is more viable. ‘ The compliant admittance control has to be implemented in joint level as it involves a multiple degree of freedom which also means that the torque sensing has to be implemented in multiple joints. The trajectory data regarding the task space is converted into joint level data resulting in θ_d and $\dot{\theta}_d$ for each joint. A much detailed admittance control diagram is shown in figure 2.

For the Dynamic movement primitive(DMP), this approach models the system with comprehensible damped spring model, modulated by nonlinear terms, providing sufficient stability while achieving the required target. The system of DMP, adapted from [32] and written in the form prescribed by [33] as (3):

$$T_c\dot{z} = g^T(\Xi + \varepsilon) + f_{dmp} = \alpha_z(\beta_z(g^* - x) - z) + f_{dmp}, \quad (3)$$

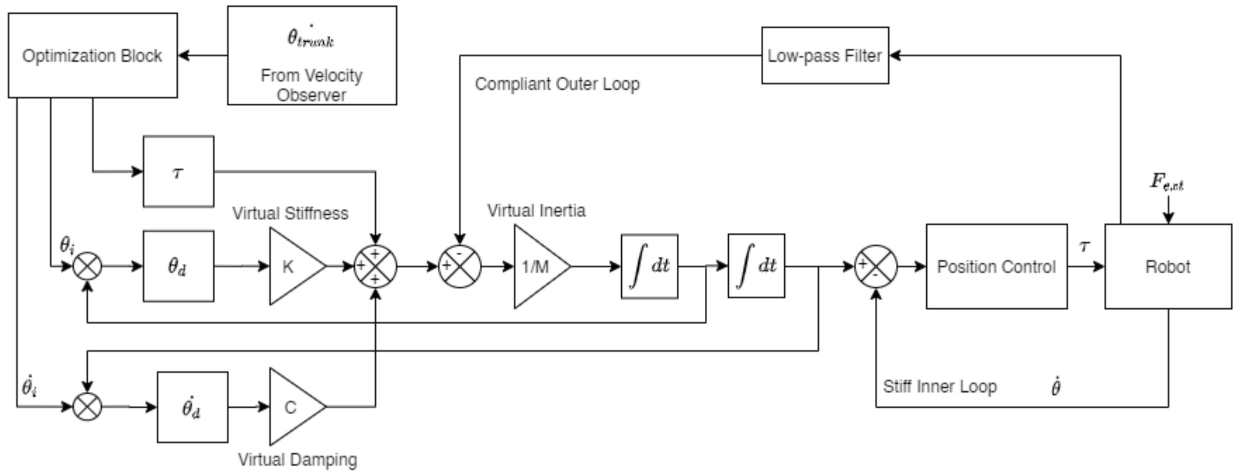


Fig. 2: Block diagram of the proposed admittance control system for the force control system

where,

$$f_{dmp} = \alpha_z \left(\beta_z \left(g^* - x\right) - z\right), \tag{4}$$

and,

$$T_c \dot{x} = z. \tag{5}$$

In (3), (4) and (5) , T_c is a time constant, α_z and β_z are positive constants responsible for critically dampening the system, x and z are the state vectors, $g*$ is the goal state vector and is a function of basis function as well as the row vector of the control transition matrix G. Since Ξ (with Gaussian noise ϵ) controls the shape of the trajectory connecting the initial state with the goal state, for further calculation, it is considered as the control. The term f_{dmp}, which is a time variant function, is a nonlinear forcing function that introduces nonlinearity in (3), and can be further expressed in terms of phase variable s, which is defined in such a way that:

$$T_C \dot{s} = -\alpha_s s. \tag{6}$$

The equation is also termed as a point attractor canonical system, where α_s is a constant. The significance of s is that the value converges from one to zero as the system state approaches g*, which signifies stability. Also, for STS modeling, f_{dmp} is bound to be phasic with respect to a phase variable s, resulting in a point attractor system such that:

$$f_{dmp}\left(s\right) = \frac{\sum_{i=1}^{N} \xi\left(s\right) w_i}{\sum_{i=1}^{N} \xi\left(s\right)} s \left(g^* - x_0\right). \tag{7}$$

Since $\xi\left(s\right)$ is a fixed basis function and w_i is the adjustable weight, (7) illustrates how the nonlinear function can be represented as a normalized linear combination of basis function, which can be written explicitly as (8):

$$\xi\left(s\right) = exp\left\{-\frac{1}{2h_n^2}\left(s - \mu_n\right)\right\}, \tag{8}$$

where, h_n^2 and μ_n determines bandwidth and the phasic activity level of the Gaussian kernel.

The concept of DMP can be modified for admittance control by modifying equation 3 and 8 as:

$$T_c \dot{z} = \alpha_z \left(\beta_z \left(g^* + A_a - x\right) - z\right) + f_{dmp}, \tag{9}$$

and

$$T_c \dot{x} = z + \dot{A}_a. \tag{10}$$

Based on [34], $\dot{A}_a = f(F_d - F_m)$ is the time-derivative of the admittance that modifies the position value of the DMP. Here, f is a scaling factor, F_d is the desired force and F_m is the measured force in the system. The equations 9 and 10 combine the notion of admittance control and that of DMP are implemented in the real robotic system.

III. MATERIALS & METHODS

While the proposed models have been implemented in the simulation and real robot, they have also been evaluated with appropriate methods. For the implementation, reference trajectory has been supplied to the system. In the absence of any human force, the robot follows the reference trajectory. Whereas, in the presence of any disturbance force, the system complies in the direction of the disturbing force, while preserving the boundary goals. This was simulated in Simulink within MATLAB 2019a. After simulation, this was implemented in the real system.

The robotic system which comprises of linear actuators for each degree of freedom (dof), is controlled by Pololu JRK G2 motor controllers which are connected to Robotic Operating System (ROS) server operating within Ubuntu Mate in Raspberry Pi 4. The proposed models were converted into algorithm and coded in Python language within the ROS framework.

The motion trajectories were obtained using Xsense MTw Awinda, which is a wireless human motion tracker system that relies on Inertial Measurement Unit (IMU) sensor placed on several parts of the body (Figure 3). The real-time tracking data can be captured through Xsense software suite. To monitor the end-effector twist, force/torque sensor F/T sensor Nano17 from ATI Industrial Automation has been incorporated.

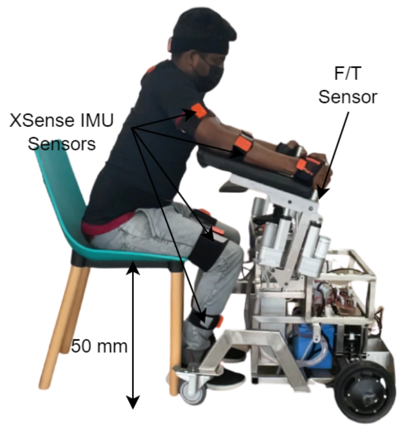
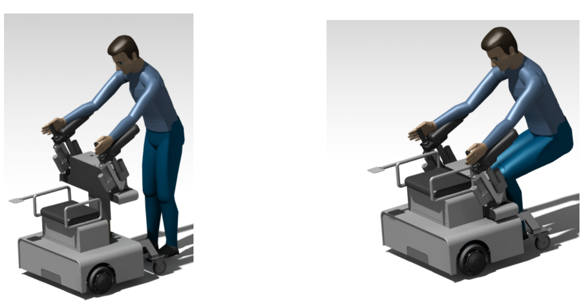


Fig. 3: Arrangement of experiemental setup along with the user. F/T Sensors are used for force acquisition in the force control loop while Xsense IMU Sensors are used for the motion tracking application

IV. RESULTS

For the motion trajectory, biomechanical trajectory optimization based on reinforcement learning was implemented. As trajectory optimization is not within the scope of this paper, only the implementation of the trajectory is mentioned in the paper. Based on the resultant trajectory, the user sequence of motion has been illustrated in figure 4.

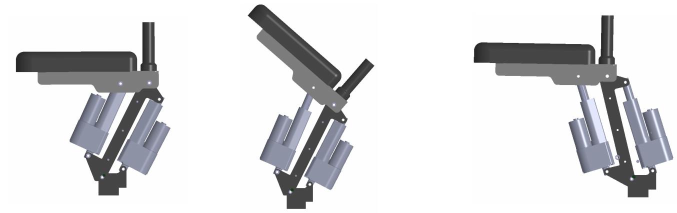


(a) (b)

Fig. 4: User Operation during STS motion

The sequence demonstrated in figure 4 can be seen in detail in figure 5. The trajectory data which is in the task space is converted into inverse kinematics equation in closed form solution. This operation resulted in linear actuator command which could be directly communicated to the linear actuators.

For the admittance control, simulation was conducted in Simulink based on the block diagram as illustrated in figure 2. As shown in figure 6, the system was simulated for the estimation of the actual torque. The Gaussian noise representing measurement noise was included with the reference arbitrary torque and the system was tested to resolve the actual torque.



(a) (b) (c)

Fig. 5: Sequence of operation of 2-dof parallel manipulator to achieve the target trajectory

Despite of the noisy torque (red line graph), the system could effectively identify the actual torque (blue line graph).

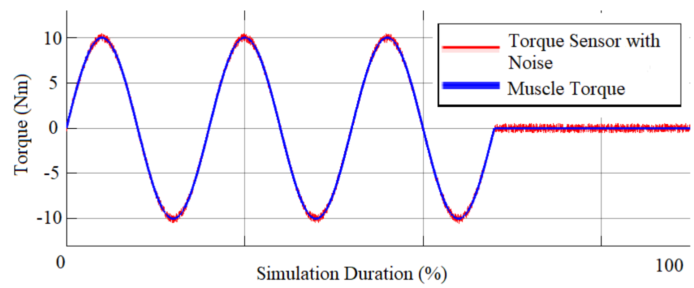


Fig. 6: Simulation result of torque estimation: Actual torque input and the estimated torque

Similarly, the change in trajectory in presence of external force disturbance has been simulated in figure 7. While the system follows red trajectory for decoupled motion (without the human force), the system follows a new trajectory (coupled motion) by considering the input force.

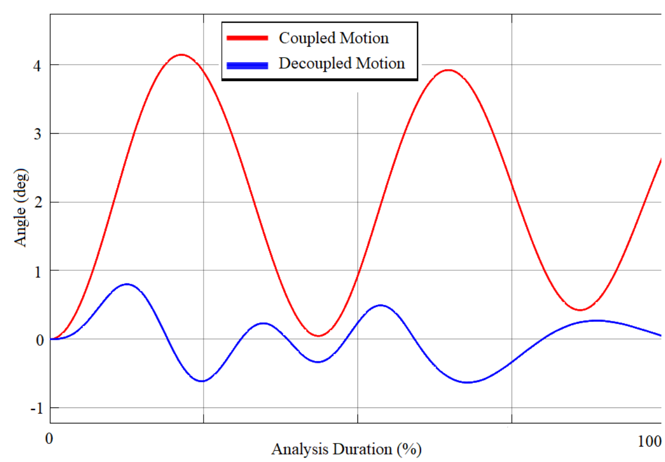


Fig. 7: Simulation of the implementation of admittance control: human-robot coupled motion vs decoupled motion of the robot

As per the motion planning, the reference trajectories were encoded as DMP and sent to the actuators within the real robotic system. The real sequence of operation has been demonstrated in figure 8. The sequence is started when the user places both the arms on the arm rest and initiates by pressing the switch on the control handle. As the control handle is pressed, the sequence initiates along with the admittance control loop which considers the position feedback and the force feedback to proceed with the motion. Finally, the system transports the user from sitting position to the standing position by considering the force disturbance from the user.

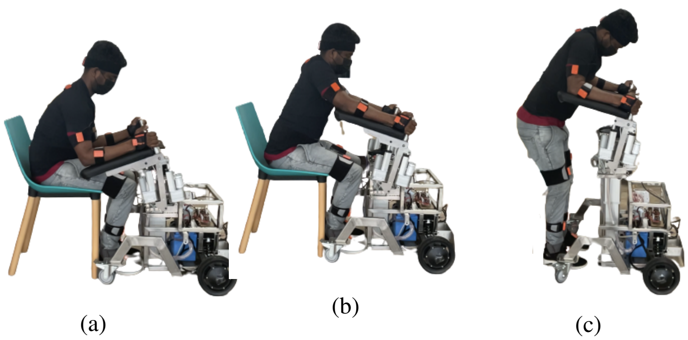


Fig. 8: Experimental demonstration of the user sequence of operation

The role of force feedback for the trajectory execution can be studied in detail by considering the recorded force data. However, force data can be extremely noisy irrespective of the quality of sensor. Therefore, filtering with sampling frequency of 2 Hz has been implemented to filter the noisy data. Also, since the robotic motion is planar in the human sagittal plane, the force data in x and z axis and torque data with respect to y-axis are used within the system.

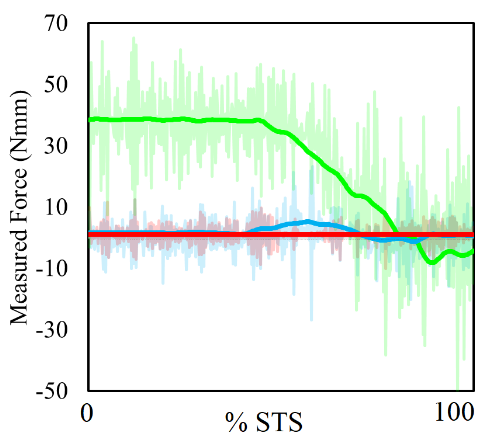


Fig. 9: Raw recorded force along with the filtered force trajectory in 3-dof

The filtered force data obtained in figure 9 has been encoded into DMP and the encoded DMP is illustrated in figure 10.

The external force disturbance, which is encoded as DMP, modifies the reference trajectory. This provides a degree of compliance to the system while preserving the goal setpoint. Finally the performance of the actual system can be summarized as of figure 11. The reference trajectory (red color) which was obtained from optimization changes the shape (blue color) due to the force feedback. While accuracy is maintained, the system provides compliant motion to the user.

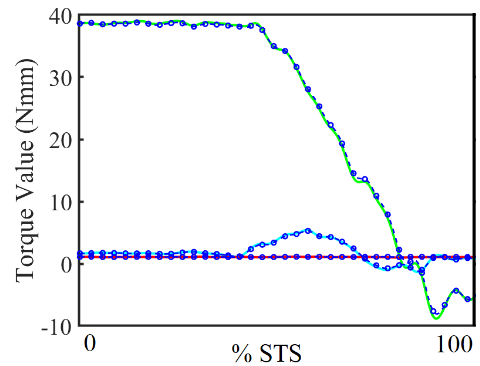


Fig. 10: Force DMP encoded from the filtered force trajectory

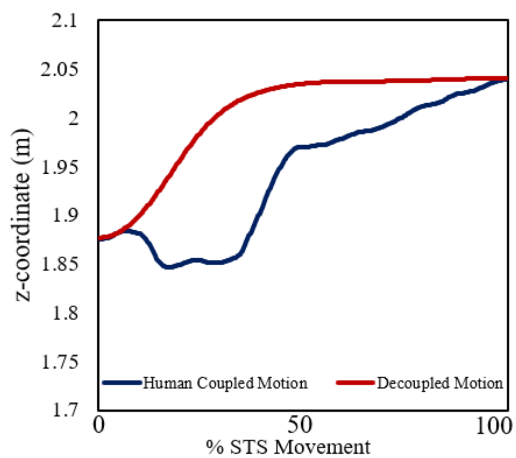


Fig. 11: Experimental Data: Comparison of reference trajectory (decoupled motion) with the actual human coupled trajectory

V. CONCLUSIONS

This paper illustrated the implementation of DMP-based admittance control of assistance robot. The simulation and the experimental data suggested that the proposed method provides effective solution for the motion planning in assistive robot. Since such robots rely on accuracy and safety, this paper shows that the implementation of DMP-based admittance control can successfully provide the required performance. Although the aspect of stability has not been studied within the paper, the use of non-backdrivable linear actuators certainly provide necessary stability for the implementation. Also, with low computational cost, online trajectory update can occur with high speed, which makes the method appropriate to be implemented in real robots. Further, this method can be extended to implement in other asssistive robots such as exoskeletons. When combined with the reinforcement learning-based trajectory optimization method that connects biomechanics with the assistive robotics, the overall system could provide general solution for the physically assistive robots. However, the effectiveness of the overall system to fulfill the objective can not be validated until the system biomechanical data has been analyzed. Further, the biomechanical validation involving actual user would be conducted and necessary modifications to the system would be performed. Regarding control system, the use of force sensor, which is increasing complexity as well as cost, would be eschewed by implementing sensorless force sensing system.

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