

Force Control of an Upper Limb Exoskeleton for Perceiving Reality and Supporting Human Movement Using Feed-forward Model

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Abstract: There is much attraction in developing the upper limb exoskeleton in many applications such as supporting human movement, rehabilitation and training. This paper presents the dynamics analysis and control of the three degree of freedom (DOF) upper limb exoskeleton using the feed-forward model (FFM). In the upper limb exoskeleton, the interaction force between the human operator's hand and the end effector is uncertain and nonlinear due to the disturbance effect of Coriolis force, centrifugal force, gravitational force and friction force; it can be sensed by using a 3-axis force sensor placed at the end effector. In the feed-forward model, the interaction force is considered as an error or disturbance. The force control will reduce the error by using proportional integral derivative (PID) weight gains FFM. For stability, the derivative portion of the PID weight gains FFM is filtered by the low pass filter (LPF). The application of LPF-PID weight gains FFM in control of the 1 DOF upper limb exoskeleton is shown in an experiment.

Keywords: 3 DOF upper limb exoskeleton, Proportional Integral Derivative (PID) weight gains FFM, feed-forward model (FFM), human machine interaction force, force sensor, servo motor, perceiving reality, and rehabilitation.

I. INTRODUCTION

The research aims to research and develop a three degree of freedom (3-DOF) upper limb exoskeleton. The 3-DOF upper limb exoskeleton is an external structure in the shape of human upper limb and is directly attached to human upper limb. It is equipped with force sensors for sensing the vector of forces exerted by the human operator at the end effector, and actuators for exerting necessary torques in revolute joints at wrist, elbow and shoulder. The controller regulates the interaction force to be a desired force reflection on the human operator. The control program is force feed-forward model. Kazerooni H. ([1], 1990) proposed an 1-DOF extender of upper extremity which used one set of piezoelectric load cell placed at the elbow link to sense the forces imposed by the human operator. The human operator is the center of controller, can receive physical feedback force from the extender; perceive a smaller amount of the force imposed by the environment and control the movement of the extender. Following this technique, Jing Tang et al. (2018), [2], proposed the direct force control of a 2-DOF upper limb exoskeleton for supporting human movement. In

that direct force control model, there are two sets of force and torque sensors. The force sensor placed at the end effector measure the interaction force which is the force exerted by the human operator. The torque sensors placed at the joints measure the torque generated by the electrical motors. The measured forces and torques are utilized by a three closed-loop controller to control the 2 DOF upper limb exoskeleton. In the closed loop 1 (core loop), the human exerts force at the end effector to control the upper limb exoskeleton. The closed loop 2 is Proportional Derivative (PD) weight gains feed-forward controller and the closed-loop 3 is a Proportional Integral (PI) weight gains feed-back controller. In feed-forward model, the physical interaction force is considered as a force error or disturbance force. The target of the controller is to reduce the force exerted by the human operator at the end effector. In feed-back model, the torque generated by electrical motor is compared with the desired torque, thus the control voltage of electrical motor is controlled by the torque error. In [2], the force error can be sensed by a force sensor or is approximately considered by a spring model. In the spring model, the interaction force is modeled by the position error between the desired motion

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and current motion of the end effector. Developing this technique, Nguyen Cao Thang et al. (2019), [3], [4] have developed the Proportional Integral Derivative (PID) weight gains feed-forward model for a 3 DOF systems. In [3], the PI feed-forward model was proposed to control the torque of a 3-DOF upper limb exoskeleton. In [4], a three closed-loop controller including the human control model, PD weight gains feed-forward model and the PI weight gains feed-back model which was proposed in [2] was applied to control a 3-DOF upper limb exoskeleton to support human movement. However, in [4] the constant interaction force is not realistic. P.V.B. Ngoc et al. [5] promoted the PI weight gains feed-forward model to control a 3-DOF lower limb rehabilitation robot.

In this paper, the authors research and develop the PID weight gains feed-forward model for a 3 DOF upper limb exoskeleton to support human movement. The authors suggest that the novel PID weight gains feed-forward model will reduce the force exerted by the human operator at the end effector. This paper presents the modeling and simulation of a 3-DOF upper limb exoskeleton, and an experiment of a real 1-DOF upper limb exoskeleton. The aim of the controller is perceiving the vector of forces exerted by human operator and reducing them. In the paper, a scenario is considered in which there are two loops. Loop 1: the human operator exerts force at the end effector and can feel the external load or perceiving reality. The controller can track the orientation and magnitude of the physical interaction force between the human operator's hand and the end effector. The generalize moments exerted by the human operator at joints are derived by using transposed Jacobian matrix. In Loop 2, the PID weight gains FFM will utilize the human torque to control three motors located at joints to assist human operator to perform some tasks: moving freely and lifting some objects vertically and horizontally. By simulation and experiment, we can investigate the performance, stability, and smoothness of proposed controller. We can guarantee the stability of the system base on the low pass filters (LPF) for derivative control, and adjust the control torque to avoid the chattering phenomenon. As the result, the human operator will naturally feel the external load first, after that he can be supported in a desired loading motion.

II. MODEL OF 3 DOF UPPER LIMB EXOSKELETON

The model of a 3 DOF upper limb exoskeleton is shown in figure 1.

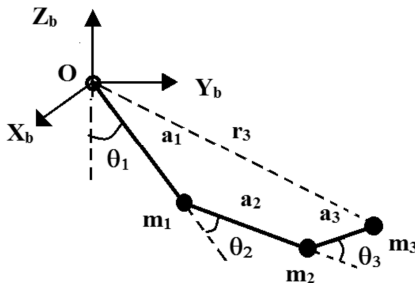


Fig.1. A three DOF upper limb exoskeleton

The upper limb exoskeleton system is a popular serial robotic chain including a joint at the shoulder (θ_1), a joint at the elbow (θ_2), and a joint at the wrist (θ_3), with 3 links namely: shoulder a_1 , elbow a_2 , and the wrist a_3 . The length

and masses of three links are a_1 , a_2 , a_3 and m_1 , m_2 , m_3 respectively.

Three geared servo motors are installed to power three links. In each servo motor, there is a position sensor used to measure rotation angle. At the end effector, a 3-axis force sensor is used to measure force exerted by the human operator's hand.

Denavite - Hartenberge (D-H) table is shown in Table 1.

TABLE 1. DENAVITE - HARTENBERGE (D-H) PARAMETERS FOR 3 DOF UPPER LIMB EXOSKELETON

Joint	a	α	d	θ
	0	$\pi/2$	0	$\pi/2$
1	a_1	0	0	$\theta_1 - \pi/2$
2	a_2	0	0	θ_2
3	a_3	$-\pi/2$	0	θ_3
	0	0	0	$-\pi/2$

In Table 1, the parameters a_i are constant. Only the variables θ_i ($i=1, 2, 3$) vary by rotation around z_{i-1} axis. From D-H table, the homogeneous transformation matrices are obtained using equation (1), Spong MW, Hutchinson S, and Vidyasagar M. (2004) [6].

$$\mathbf{A}_i^{i-1} = Rot(z, \theta_i) Trans(0, 0, d_i) Rot(x, \alpha_i) Trans(a_i, 0, 0) = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i & a_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i & a_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The homogeneous transformation matrix that transforms the reference coordinate $\{3\}$, which is at the end effector to the reference coordinate $\{b\}$, or the fixed base, can be calculated by multiplying individual transformation matrices as follows.

$$\mathbf{A}_3^b = \mathbf{A}_1^b \mathbf{A}_2^1 \mathbf{A}_3^2 \quad (2)$$

III. CONTROLLER DESIGN

The dynamics equation of motion is presented as the following equation. It can be conveniently constructed in matrix form, which is suitable for MDOF system (Do Sanh et al. [7]).

$$\mathbf{M}(\theta)\ddot{\xi} + \mathbf{C}(\theta, \dot{\theta})\dot{\xi} + \mathbf{K}\theta + \mathbf{G}(\theta) + \mathbf{F}(\dot{\theta}) = \mathbf{u}_s + \mathbf{J}(\theta)^T \mathbf{F}_{h_global} \quad (3)$$

Where,

$\theta = [\theta_1 \ \theta_2 \ \theta_3]^T$ - Vector of angles of rotation in joints 1, 2, 3.

$\dot{\theta} = [\dot{\theta}_1 \ \dot{\theta}_2 \ \dot{\theta}_3]^T = \left[\frac{d\theta_1}{dt} \ \frac{d\theta_2}{dt} \ \frac{d\theta_3}{dt} \right]^T$ - Vector of angular velocities in joints 1, 2, 3.

$\ddot{\xi} = [\ddot{\xi}_1 \ \ddot{\xi}_2 \ \ddot{\xi}_3]^T = \left[\frac{d^2\theta_1}{dt^2} \ \frac{d^2\theta_2}{dt^2} \ \frac{d^2\theta_3}{dt^2} \right]^T$ - Vector of angular accelerations in joints 1, 2, 3.

$\mathbf{u}_s = [u_{s1} \ u_{s2} \ u_{s3}]^T$ - Vector of supporting torques exerted by servo motors in joints 1, 2, 3.

$\mathbf{F}_{h_global} = [F_{x_b}, F_{y_b}, F_{z_b}]^T$ - Vector of forces exerted by human operator at the end effector in the reference coordinate $\{b\}$, or the fixed base.

$\mathbf{A}_3^b$ - The homogeneous transformation matrix;

${}^{(b)}\mathbf{r}_3 = [x_3 \ y_3 \ z_3]^T = \mathbf{A}_3^b(1:3,4)$ - The end effector's position vector is defined by the first three rows and the last column of the homogeneous transformation matrix, given in equation (2);

$\mathbf{J}(\theta)$ - The Jacobian matrix.

The symbol (T) denotes the transpose of a matrix.

$\mathbf{M}(\theta)$, $\mathbf{C}(\theta, \omega)$, $\mathbf{G}(\theta)$, $\mathbf{K}\theta$ are matrix of inertia masses, vector of Coriolis and centrifugal forces, vector of gravity forces, and vector of elastic force, respectively, which are derived using Lagrange equation.

$\mathbf{F}(\omega)$ - Joint Friction force Vector

Friction modeling: The joint friction is modeled as the combination of both Coulomb and viscosity friction. The joint friction of joint i ($i=1,2,3$) can be expressed as follows.

$$F_i(\omega_i) = \tau_{ci} \operatorname{sgn}(\omega_i) + b_i \omega_i \quad (4)$$

$$\operatorname{sgn}(\omega_i) = \begin{cases} 1 & \omega_i > 0 \\ 0 & \omega_i = 0 \\ -1 & \omega_i < 0 \end{cases} \quad (5)$$

In this paper, we consider a scenario:

Loop 1: At the beginning, a human operator moves the robot by exerting force at the end effector to guide the robot to follow a desired loading motion. At this stage, the human operator can feel the external load and the robot's weight. The angular sensors (encoders) installed at joints can measure the joints angles and the force sensor installed in the end effector can measure the forces exerted by the human operator.

Loop 2: After a delayed time, the human operator can feel a smaller amount of the external load and the robot's weight because the robot has been activated to support the movement of the joints.

The block scheme of controller system is shown in figure 2. In the loop 1, the human operator exerts the interaction force at the end effector to control the upper limb exoskeleton himself. The interaction force is considered as force error or a disturbance force. In this loop 1 of control process, the interaction force and the current positions of joints are sent to the Controller. In the Loop 2, the Controller will control torques in joints of the Exoskeleton. The target of the Feed-Forward Controller is to reduce the disturbance force.

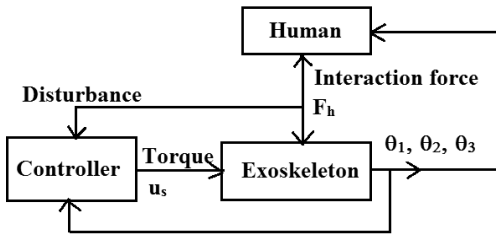


Fig. 2. Block scheme of feed-forward model system.

The interaction force is vector of forces exerted by the human operator at the end effector; it can be measured by using a 3 axis force sensor. For realistic simulation, the simulated interaction force $\mathbf{F}_{h_global}$ that is exerted by the human operator at the end effector is approximately modeled by a spring model. It is proportional to the position

error between the desired and current loading motion of the exoskeleton's end effector.

$$\mathbf{F}_{h_global} = K_f(\mathbf{r}_{3ds} - \mathbf{r}_3) \quad (6)$$

Where, ${}^{(b)}\mathbf{r}_{3ds} = [x_{3ds} \ y_{3ds} \ z_{3ds}]^T$ is the desired position of the exoskeleton's end effector.

${}^{(b)}\mathbf{r}_3 = [x_3 \ y_3 \ z_3]^T$ is the current position of the exoskeleton's end effector,

K_f is the stiffness weight gain matrix of the interaction model.

The forces and torques exerted by the human operator is also proportional to the stiffness weight gain matrix.

In Loop 1: the human operator applies some force to move the end effector in a desired loading motion using his own hand. The forces exerted by the human operator are directly transformed to the generalized torques at joints using transposed Jacobian matrix. At this stage, the human operator can feel the external load and the robot's weight.

$$\mathbf{u}_H = \mathbf{J}^T(\theta) \mathbf{F}_{h_global} \quad (7)$$

Where, θ - Vector of angles,

$\mathbf{F}_{h_global}$ - Vector of global interaction forces.

In Loop 2: the upper limb exoskeleton (the robot) can supply the power in order to support the human operator's movement. At this stage, the human operator can still feel the smaller amount of the external load and the robot's weight.

In order to deal with this scenario, the proportional - integral - derivative (PID) weight gains FFM control will follow formula (8).

$$\mathbf{u}_{PID} = \mathbf{w}_P \cdot \mathbf{u}_H + \mathbf{w}_I \cdot \int_0^t \mathbf{u}_H d\tau + \mathbf{w}_D \cdot \mathbf{u}_K \quad (8)$$

Where, $\mathbf{u}_H = [u_{H1} \ u_{H2} \ u_{H3}]^T$ is the vector of generalized torques exerted by the human operator at joints (the human operator's torque).

$\mathbf{u}_K = [u_{K1} \ u_{K2} \ u_{K3}]^T$ is the vector of derivative respect to time of human operator's generalized torque after the low pass filter.

$\mathbf{w}_P, \mathbf{w}_I, \mathbf{w}_D$ are the proportional - integral - derivative weight gains matrices.

In order to create the smoothness for the controlling process, we use a first order low pass filter (LPF) for controlling the derivative portion of PID formula (derivative control). The derivative respect to time of the human operator's generalized torques $d(u_{Hi})/dt$ ($i=1,2,3$) will be filtered by LPF leading to the smoothing derivative respect to time of generalized torques: u_{Ki} ($i=1,2,3$) following equation (9) or (10).

$$\tau_i \frac{d}{dt}(u_{Ki}) + u_{Ki} = \frac{d}{dt}(u_{Hi}) \quad (9)$$

Where, τ_i ($i=1,2,3$) are time constant of LPF i .

u_{Ki} ($i=1,2,3$) are smoothing derivative respect to time of the human operator's generalized torques after LPF.

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$\frac{d}{dt}(u_{Hi})$ ($i=1,2,3$) are derivative respect to time of the human operator's generalized torques before LPF.

Or one can use the Discrete Low Pass Filter (DLPF) for Derivative Control as follows.

$$u_{Ki}(t_k) = (1-r_i) * u_{Ki}(t_{k-1}) + r_i * \frac{d}{dt}(u_{Hi}(t_k)) \quad (10)$$

$$\frac{d}{dt}(u_{Hi}(t_k)) \approx u_{Hi}(t_k) - u_{Hi}(t_{k-1})$$

Where, $u_{Hi}(t_k)$ – Human torque at joint i ($i=1,2,3$)

$\frac{d}{dt}(u_{Hi}(t_k))$ – Derivative of human torque (approximated by current and previous human torque)

$u_{Ki}(t_k)$ - Derivative of human torque after LPF.

r_i – Smoothing factor.

For stably controlling of joint torques, the control torques at joints i ($i=1, 2, 3$) are adjusted as follows.

$$\begin{aligned} \text{if } u_{PIDi} < -p_i \text{ then } u_{Si} &= -s_i \\ \text{elseif } u_{PIDi} > p_i \text{ then } u_{Si} &= s_i \\ \text{else } u_{Si} &= 0 \end{aligned} \quad (11)$$

Where, p_i , ($i=1,2,3$), (Nm) are perceiving parameters.

s_i , ($i=1,2,3$), (Nm) are supporting parameters.

The perceiving parameters can delay the control torques to avoid chattering problem for the stability of proposed control system. The supporting parameters can create different levels of support.

IV. SIMULATION AND RESULTS

In this simulation of force control using Matlab software [8], the parameters of the mechanical system are:

$a_1 = 0.25$, $a_2 = 0.30$, $a_3 = 0.1$ (m): length of links 1, 2, 3, respectively. $m_1 = 0.5$, $m_2 = 0.5$, $m_3 = 0.5$ (kg): the mass of links 1, 2, 3, respectively. $g = 9.81$ (m/s^2)

Using the Proportional - Integral - Derivative weight gains FFM controller, The PID torques are the scale up versions of the human operator's torques. The weight gains matrices w_p , w_I , w_D and time constants of LPF are:

$$\begin{aligned} w_p &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, w_I = \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 0.1 & 0 \\ 0 & 0 & 0.1 \end{bmatrix}, \\ w_D &= \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 0.1 & 0 \\ 0 & 0 & 0.1 \end{bmatrix}, \tau_i = \begin{bmatrix} 0.1 \\ 0.1 \\ 0.1 \end{bmatrix} \quad (s) \end{aligned} \quad (13)$$

The interaction force and the stiffness weight gains matrix of the interaction model is set as follows.

$$\begin{aligned} F_{h_global} &= K_f(r_{3d} - r_3) \\ K_f &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 100 & 0 \\ 0 & 0 & 100 \end{bmatrix} \quad (N/m) \end{aligned} \quad (14)$$

The desired end effector's position vector is definitely following the three desired angles of joints. The desired angles of joints are below:

$$\begin{bmatrix} \theta_{1ds} \\ \theta_{2ds} \\ \theta_{3ds} \end{bmatrix} = \begin{bmatrix} \sin(t) \\ \sin(t) \\ 0.2 * \sin(t) \end{bmatrix} \quad (\text{rad}) \quad (15)$$

The initial position and speed of the joints are below:

$$\theta_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (\text{rad}); \quad \dot{\theta}_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (\text{rad/s}) \quad (16)$$

The joint friction coefficients are set as follows.

$$\tau_{Ci} = 0.1, b_i = 0.1, (i = 1, 2, 3) \quad (17)$$

The joint stiffness coefficients matrix is set as follows.

$$K = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 100 \end{bmatrix} \quad (\text{Nm/rad}) \quad (18)$$

The perceiving parameters and supporting parameters of control torques are:

$$p_1 = 4, p_2 = 2, p_3 = 1, s_1 = 3, s_2 = 1.5, s_3 = 0.75 \quad (\text{Nm}) \quad (19)$$

In the time axis, the duration of simulation is 10 seconds.

In the simulation program, the following equations (4) to (19) are simultaneously solved with the equation (3) by using ode solver ode45 in Matlab software.

In the simulation, the movement of the end effector in Y_bZ_b plane is shown in figure 3.

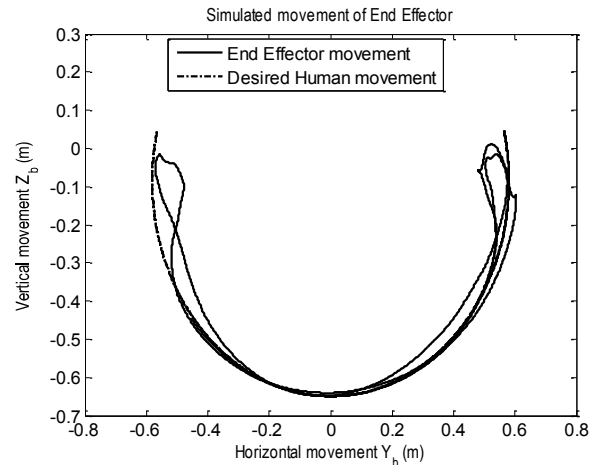


Fig. 3. Movement of end effector in Y_bZ_b plane

The interaction force exerted by human at the end effector is shown in figure 4.

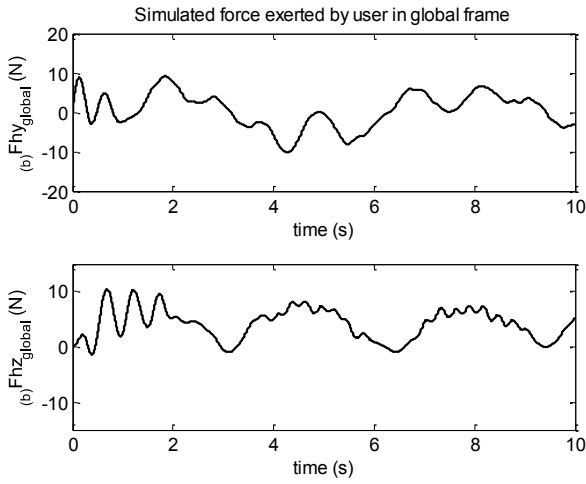


Fig. 4. Force exerted by human operator at the end effector in global frame {b} (attached to base)

The human torques, PID torques and Control torques at joint 1, 2, and 3 are shown in figures 5, 6, and 7.

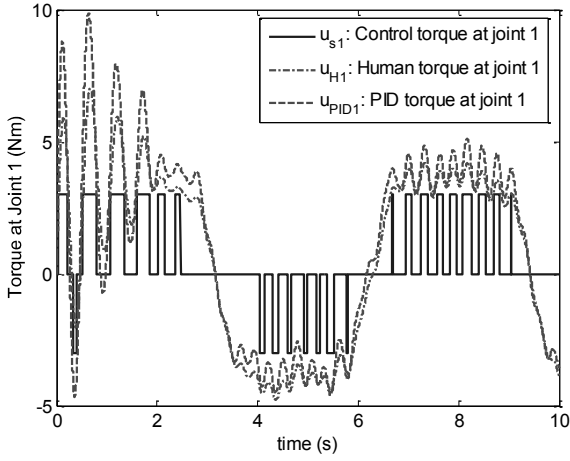


Fig. 5. Torque exerted by Human operator, and Controller in Joint 1

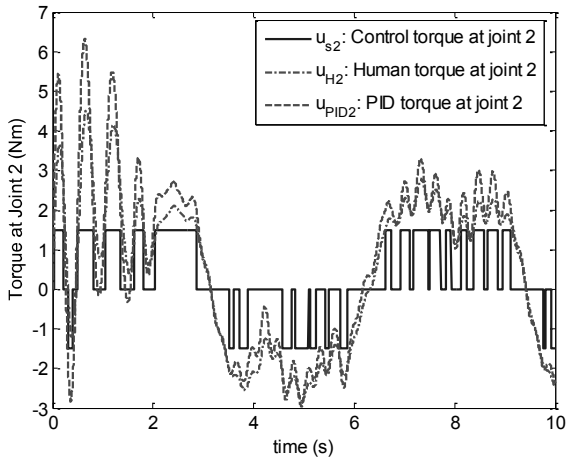


Fig. 6. Torque exerted by Human operator, and Controller in Joint 2

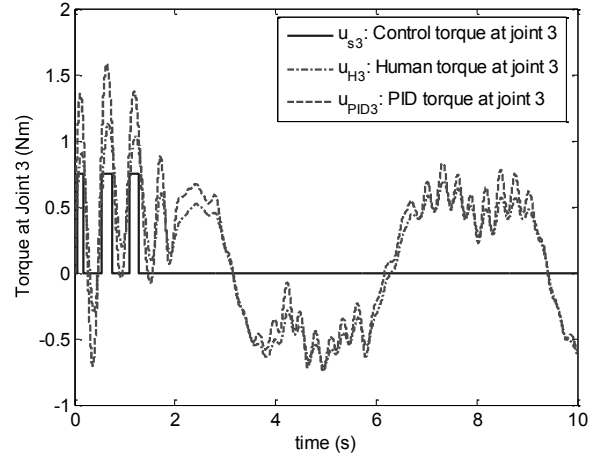


Fig. 7. Torque exerted by Human operator, and Controller in Joint 3

Since the supporting parameters s_1, s_2, s_3 can adjust the control torques, the strength of support depends on the supporting parameters. The control torques at joints can jointly support the human.

V. EXPERIMENT AND RESULTS

The experiment of PID weight gains feed-forward model to control a 1 DOF upper limb exoskeleton to support human operator's movement is shown in figure 8.

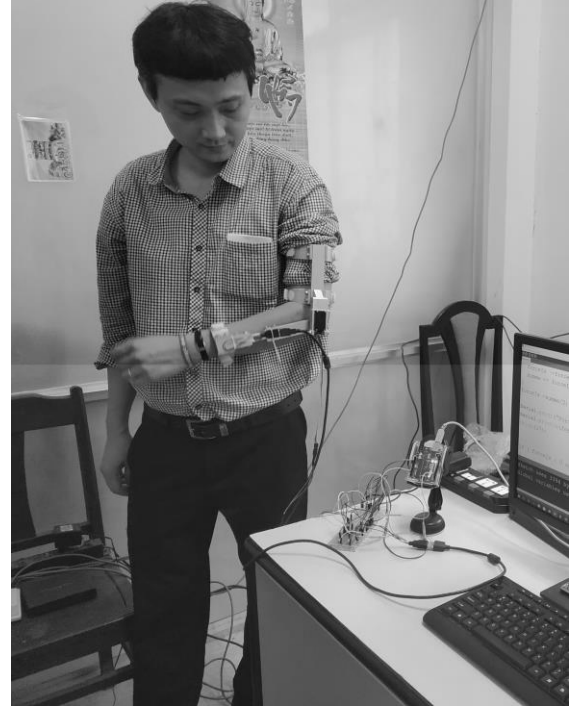


Fig. 8. An 1 DOF upper limb exoskeleton developed at Institute of Mechanics (VAST)

The 1 DOF exoskeleton has two links and one joint called elbow joint. The lengths of link 1 (shoulder link) and link 2 (elbow link) are $l_1 = 0.16$ (m) and $l_2 = 0.2$ (m), respectively. The single axis load cell whose max load is 9.8 (N) has very weak output voltage 0.001 (V), is placed at the link 2 to detect the physical interaction force. There is one servo motor whose max torque is approximately 1 (Nm), with very high gear ratio 280:1, in the elbow position of the exoskeleton.

In this experiment, we consider a scenario:

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Loop 1: When the human operator moves his arm in flexion and in extension movement, the load cell will measure the interaction force between the human operator's arm and the elbow link of the exoskeleton.

Loop 2: The FFM will control the torque of the servo motor to support the user's elbow rotation and reduce the physical interaction force of the human operator.

The force control system is shown in figure 9.

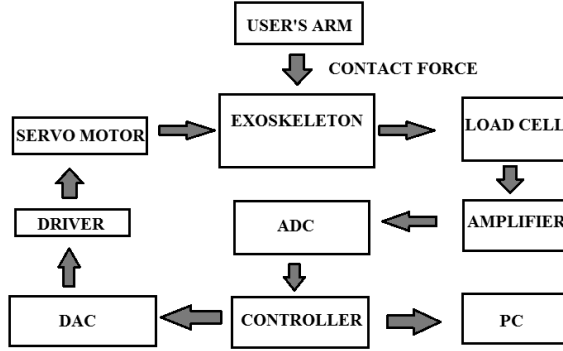


Fig. 9. Set up of the experiment

In figure 9, when the human hand moves, the interaction force F_{h_local} will be measured by the load-cell. The very weak measured voltage of the load-cell is amplified by the Operational Amplifier (OpAm). That amplified voltage will be high enough so that the controller can input through the Analog to Digital Converter (ADC) channel. The controller will output the Pulse Width Modulation (PWM) signal through the Digital to Analog (DAC) channel to control a motor driver circuit (Driver) placed inside the Servo Motor. Since the control torque of the Servo Motor is geared up, the exoskeleton will support human movement. The PC is used for building source code and uploading the machine code to the controller; and displaying the results of the experiment.

When applying the FFM to control the motor mounted on Upper limb Exoskeleton's elbow, we use the PID weight gains with discrete LPF for derivative control as follows.

$$u_{PID}(t_k) = w_p * F_{h_local}(t_k) * l_2 + w_i * \left[\sum_{k=1}^n F_{h_local}(t_k) * l_2 \right] + w_d * F_K(t_k) * l_2 \quad (20)$$

$$F_K(t_k) = (1-r) * F_K(t_{k-1}) + r \frac{d}{dt}(F_{h_local}(t_k))$$

$$\frac{d}{dt}(F_{h_local}(t_k)) \approx F_{h_local}(t_k) - F_{h_local}(t_{k-1})$$

Where,

$F_{h_local}(t_k)$ – The human force, measured by load cell at time t_k ($k=1,2,3, \dots, n$).

$\frac{d}{dt}(F_{h_local}(t_k))$ – Derivative of human force (approximated by current and previous human force)

$F_K(t_k)$ - Derivative of human force after LPF.

$w_p = 1, w_i = 1, w_d = 1$ - Constant PID weight gains.

$r = 1$ - smoothing factor

$l_2 = 0.2$ (m) - Length of link 2 (elbow link) .

u_{PID} - The filtered PID torque control.

In Equation (21), in order to avoid the chattering problem, we adjust the control torques as follows.

$$\begin{aligned} \text{if } u_{PID}(t_k) < -p \text{ then } u_s(t_k) &= -s \\ \text{else if } u_{PID}(t_k) > p \text{ then } u_s(t_k) &= s \\ \text{else } u_s(t_k) &= 0 \end{aligned} \quad (21)$$

Where, $p=0.75, s=0.1$.

The human torque, PID torque, Control torque are displayed in Figure 10.

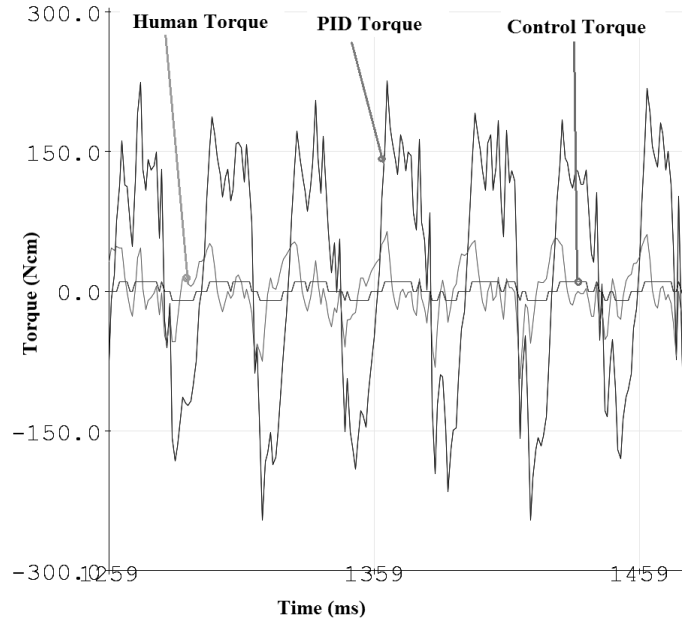


Fig. 10. The measurement of Human torque and control torque

Figure 10 shows the human torque, PID torque and the Control torque of servo motor which are controlled by Arduino UNO Single Board Computer (SBC). The control torque at elbow joint can support to fulfill the human movement.

VI. CONCLUSIONS

In this paper, we present kinematic and dynamic analysis of a 3-DOF upper limb exoskeleton using model force feed-forward model. In our experiment, the FFM is applied to control the real 1-DOF upper limb exoskeleton. We use a single axis load cell placed at the elbow link to measure the human machine physical interaction force. The force feed-forward model is applied to support human's torque by using the PID weight gains. In addition, we also have a LPF or a discrete LPF for derivative control. The proposed upper limb exoskeleton can smoothly and stably support human movement from the results of the simulation and experiment.

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