Dynamic Analysis and State Estimation of Wearable Extra Robotic Limbs for Physical Assistance and Load Reduction in Missile-mouting

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Abstract. In order to fully exploit the potential in the field of human augmentation, to help the wearer fulfill the task of physical assistance and load reduction, a new type of wearable robot that can perform tasks in close coordination with the wearer and assist the wearer with extra arms and legs secured around the body is presented. The system, named extra auxiliary robotic upper limbs-lower extremity exoskeleton (EARUL-LEE), consists of two additional robotic arms worn through a backpack around the upper body and two exoskeleton legs attached to the lower body tightly. The EARUL-LEE can assist the wearer by holding objects, lifting weights and streamlining the execution of a task. If the EARUL-LEE performs movements closely coordinated with the wearer and exhibits human-like dynamics, it might be incorporated into the body representation and perceived as parts of the wearer’s body. The EARUL-LEE can work closely with the soldier by supporting and securing the human body when lifting a missile, and more. Although the EARUL-LEE control performance is hindered by unpredictable disturbances due to involuntary motions of the soldier, which include postural sway and physiological tremor, the dynamic analysis the human-EARUL-LEE hybrid system include the models of human-induced disturbance based on biomechanics literature, extra auxiliary robotic upper limbs and lower extremity exoskeleton and state estimation method based on an orthogonal least squares for the EARUL-LEE, aimed to perform the missile-mounting for aircrafts on the ground or decks in tight coordination with the soldier as a close co-worker are presented here. Via the current study, the orthogonal least squares (OLS) filter is constructed to estimate the state and its performance is evaluated in terms of error covariance. The simulation results show that the orthogonal least squares filter can tracking desired trajectory and its convergence is better than without any filters. The results can be used to control the EARUL-LEE accordingly with the used end effectors and provide a method for improving the accuracy and stabilizing the human body and the EARUL-LEE.

1. Introduction

Although people's lives and work have become easier and easier with the invention of robots, multiple people need to complete the task together in some work scenarios. It is necessary to fully exploit the potential in the field of human augmentation, to help human fulfill the task of physical assistance and
load reduction. In recent years, wearable robot has been developed to assist human and augment the ability of human, such as exoskeleton. Though the exoskeleton is used to support human body and save energy, it is hard to apply in co-work scenarios. In order to solve these problems that exoskeleton and other wearable robots are hard to work, a new type wearable robot called wearable external limbs has been developed. The robot performs movements closely coordinated with the wearer and exhibits human-like dynamics. It can incorporate into the body representation and perceived as a part of the wearer’s body and assist the wearer by holding objects, lifting weights and streamlining the execution of different tasks. It can be used in service maintenance, battlefield rescue, individual combat and defence in military applications. It can be used in industrial manufacturing, medical escort, rescue and disaster relief, fine operations and other fields in civilian as well. The wearable external limbs possess significant social and economic value in future. This paper is aiming to demonstrate the application of the wearable external limbs in missile-mounting for physical assistance and load reduction.

Missile-mounting is a complex and hard process, for example, to mount a missile weights 160 kg needs 6 persons, requires stronger soldiers working together. Missile-mounting crew is challenged by several factors. First, the continuous increasing of the missile weight. Second, the increasing complexity of mounting tasks. Third, the fatiguing nature of many operations. Fourth, the operating hours is getting shorter. Fifth, the increasing cost of missiles per aircraft. China’s army construction has been characterized by a particularly sharp decrease in the number of soldiers and increase in the number of high-tech military equipment and talents, while the global security situation is unstable. Moreover, the missile-mounting efficiency is limited by several mount operations requiring the coordination of multiple soldiers. In most instances, a single soldier executes the main task (such as fastening the screws), with one or more comrades acting as assistants (simply lifting the missile). Therefore, multiple trained soldiers must execute trivial or repetitive actions. Another limiting factor is represented by fatiguing or dangerous situations. Almost everyone has injuries among ground service soldiers, and joint or skin injuries represent the most common nonfatal injury.

Robotic limbs can easily execute repetitive or heavy tasks, and they are not affected by fatigue or comfort issues. In addition, they are characterized by high positioning accuracy and high efficiency. Lower extremity exoskeleton could be used to support the total weight which caused by the missile loading on the human body. It can also assist soldiers move quickly and smooth on the floor or deck. On the other hand, robots can hardly replicate soldiers’ adaptability to unforeseen situations, or capacity to quickly learn and execute new tasks. Soldiers are also able to move in narrow space and flexibly modify their ground service plans in accordance with specific situations. Apparently, machines and human possess two unique and complementary skill sets, both are essential to the efficient execution of missile-mounting. In this context, it is beneficial to provide soldiers with additional robot-like skills able to help with the most physical strength demanding tasks, while leaving humans in complete control of the missile-mounting process. If these additional robot-like skills are wearable, they can reach an unprecedented level of coordination with the soldiers, eventually becoming functional extensions of their bodies. M. Y. Saraiji and T. Sasaki et al from the Keio University Graduate School designed the robotic limbs called MetaLimbs to help them re-imagine what the human body could do [1,2]. H. Asada et al from the Massachusetts Institute of Technology designed the robotic limbs called Supernumerary Robotic Limbs (SRL) which can hold objects, clamp them to a fixture, guide and support human hands, and assist the wearer [3]-[9]. R. Khodambashi et al from the Georgia Institute of Technology also designed the Supernumerary Robotic Limbs (SRLs) to hit the drum [10]. But all the robotic limbs have no lower limbs, the human body supports total loads and it may be harmful to human body. To realize this vision and provide the soldiers with additional robot-like skills, by means of wearable robotic limbs and lower extremity exoskeleton designed and built the extra auxiliary robotic upper limbs-lower extremity exoskeleton (EARUL-LEE), a wearable robot which augments its wearer by providing two additional robotic arms and two exoskeleton legs. The objective of the EARUL-LEE is to augment the soldiers’ skills and provide them with robot-like capabilities and relieve them from the most tedious or fatiguing tasks. The development of wearable
robotic limbs poses unique challenges, such as achieving accurate state estimation despite the unpredictability of the motion of soldiers.

Figure 1 illustrates the basic design concept of extra auxiliary robotic upper limbs-lower extremity exoskeleton (EARUL-LEE). The EARUL-LEE shows three main advantages of wearable, independent, and multifunctional. Being wearable can allow the external limbs to closely assist the soldier at all time. They perform tasks together with the user, becoming almost an extension of the human body. Unlike a traditional full-body exoskeleton, which all external limbs are attached directly to the human limbs, EARUL-LEE is separated from the upper limbs, it is fastened to the upper body and lower limbs. The EARUL-LEE is incompletely constrained to follow the movements of the human. The external limbs are free to move independently and can therefore assume the posture that best helps the wearer. On the other hand, the exoskeleton legs move together with the human legs, this unique characteristic of lower extremity exoskeleton is exploited in order to support and augment user during missile-mounting. The EARUL-LEE can exploit its large workspace to perform every action requires high working accuracy. Furthermore, it can also make use of interchangeable end effectors. In consequence, the EARUL-LEE is continuously disturbed by human motions and interactions with the environment. This means that the robotic system must be capable of compensating for unpredictable disturbances. It is required to estimate its own state and attenuate the disturbances, providing the wearer with robotlike accuracy.

![Figure 1](image1.png)  
**Figure 1.** The scenario assumptions and basic concept of EARUL-LEE.

![Figure 2](image2.png)  
**Figure 2.** The degrees of freedom.

This paper is organized as follows. Section 2 briefly describes the first prototype of the wearable external limbs, and this part is the base of the dynamic analysis and simulation. Section 3 presents a dynamic model for the study of the EARUL-LEE properties. The human disturbances have been considered. Section 4 presents an orthogonal least squares (OLS) filter approach to state estimation and analyzes the effects of end interference torque and the human disturbances caused by the robot’s posture changing on the accuracy of state estimation. Section 5 discusses and extends the estimate results. Finally, Section 6 summarizes the most important contributions of this study and several directions of future investigation.

2. Wearable external limbs

The wearable external limbs must work alongside the human, assist to the soldier and augment the soldier’s skills. The EARUL-LEE consists of two additional robotic arms wear through a backpack around the upper body and two exoskeleton legs attach to the lower body tightly. The EARUL-LEE base contains all the actuators and the main electronic components, and is located at the middle back, used shoulder straps and a waist belt fixed the EARUL-LEE to the human-machine system center of gravity that provides the most stable base for the wearable robot. The EARUL-LEE consists of a pair of additional robotic arms and a pair of exoskeleton legs that can intuitively and safely assist the
human to augment soldier’s skills. Each of two additional robotic arms is attached to a side of the base structure, each of two exoskeleton legs is secured to the legs. All the wearable external limbs can interact with the environment around the wearer. The robot’s weight is borne to the back bracket through the exoskeleton legs and finally passed to the ground. The ground support the mainly loads of the human-machine system, without burdening the limbs or the back. Power is provided through a piece of battery, to minimize the robotic limbs moment of inertia and to reduce power consumption, the battery is fixed immediately to the back bracket as a counterweight. The specifications of the wearable external limbs have been inspired by the properties of the human body in terms of joint torque, degrees of freedom and series elasticity, limbs weight, etc.

As figure 2 shows, the wearable external limbs have 12 degrees of freedom, two for each additional robotic arm there are one in the shoulder and two in the elbow. The shoulder flexion/extension joint has a 360 degrees range of active motion and a maximum torque of 100N⋅m which is the most powerful and provides the torque necessary to mount missiles on the aircraft. The elbow flexion/extension joint has a 240 degrees range of active motion and provides a maximum torque of 80N⋅m to coordinate with the shoulder joint. Four for each exoskeleton leg they are two in the hip, one in the knee, one at the ankle. The hip flexion/extension joint has a 140 degrees range of active motion and provides a maximum torque of 80N⋅m to reduce swing resistance of the thigh, while the adduction/abduction joint has a 30 degrees range of passive motion ensure the stability by following the center of gravity excursion in walking. The knee flexion/extension joint has a 120 degrees range of active motion and provides a maximum torque of 60N⋅m to assist the shank raising up. The ankle flexion/extension joint has a 120 degrees range of passive motion ensure the external limbs does not hinder the wearer’s motion. The height of the exoskeleton legs and length of the additional arms are adjusted to the wearer’s size. The range of the robot joints allows the end effectors to reach the majority of workspace while mounting operation in order to provide assists. The wearable external limbs can be equipped with various end effectors, tailored for different tasks.

3. Dynamic models

3.1. Equations of Motion of the Human-EARUL-LEE System

The EARUL-LEE is worn by a soldier and thereby disturbed by involuntary movements of the wearer as well as by physical interactions with the environment. The reference scenario for this study is that a soldier standing under the wing of an aircraft, where some mounting operations requiring high power and accuracy must be completed. The soldier is standing still with the feet in contact with the ground. The soldier wears the EARUL-LEE, whose goal is to augment the power and enhance the precision of the user. To achieve this goal, the wearable external limbs make contact with the environment in a missile-mounting scenario, this could be achieved by extra auxiliary robotic upper limbs and lower extremity exoskeleton in tight coordination with the soldier as a close co-worker in order to attenuate the human-induced disturbances and improve the accuracy of state estimation. When mounting, the lower extremity exoskeleton supports human body by contacting the environment, the extra auxiliary robotic upper limbs support their end effectors on the aircraft to better position the missile.

In order to create a complete but analytically tractable dynamic model of the reference scenario, it is necessary to make three main simplifying assumptions. First, the human-EARUL-LEE system will be studied in 2D, considering the sagittal plane (see Figure 3). Although mounting operations require 3D actions, movements in the sagittal plane capture important aspects of the class of tasks considered in missile-mounting. Missile-mounting have a very strict workflow and most of its main operations have completed in the sagittal plane. It is also difficult to perform an accurate task when working in uncomfortable postures. Furthermore, the human postural sway, which represents the major source of human involuntary disturbances, is more marked in the anterior/posterior direction (i.e. within the sagittal plane) [6]. The second assumption simplifies the modeling of the exoskeleton legs and of the additional arms. Instead of describing in detail the deformable mechanism, treat all robotic limbs as homogeneous rigid bodies and assuming the waist link and back bracket are a whole. In this case,
selected the feet as the basic point to construct the kinematic chain. The third assumption simplifies human-EARUL-LEE system interactions, the largest interactive force is located at the back bracket, so all interactive forces focused on the back bracket. In this case, the force caused by end effector only acts on the EARUL and is not affected on the LEE.

The model has 5 generalized coordinates \( (C_1x_1y_1, C_2x_2y_2, C_3x_3y_3, C_4x_4y_4, C_5x_5y_5) \) as figure 3 (c) shows. The inputs are the motor torques of five joints \( (\tau_1, \tau_2, \tau_3, \tau_4, \tau_5) \), the external forces at the end effector \( (F_{x_5}, F_{y_5}, \tau_e) \) and the human induced disturbance force and moment at the robot base \( (F_y, \tau_y) \) as figure 3 (b) shows. The outputs are the joint angles \( (\theta_1, \theta_2, \theta_3, \theta_4, \theta_5) \), they can see in figure 3 (d). According to the Spiral theory defined the center of mass, distances and length of five links respectively are \( C_1, C_2, C_3, C_4, C_5, r_{11}, r_{12}, r_{23}, r_{34}, r_{45}, l_1, l_2, l_3, l_4, l_5 \). Lagrange equations of motion can be linearized as follows,

\[
A(\theta)T = D(\theta)\dot{\theta} + C(\theta, \dot{\theta}) + G(\theta)
\]

\[
A(\theta) =  
\begin{pmatrix}
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\
A_{50} & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & A_{47} & A_{48} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & A_{57} & A_{58} & 1
\end{pmatrix}
\]
\[
T = \begin{pmatrix}
F_b \\
\tau_b \\
\tau_1 \\
\tau_2 \\
\tau_3 \\
\tau_4 \\
\tau_5 \\
F_{ey} \\
F_{ex}
\end{pmatrix}, \quad D(\theta) \ddot{\theta} = \begin{pmatrix}
D_{11} & D_{12} & D_{13} & D_{14} & D_{15} \\
D_{21} & D_{22} & D_{23} & D_{24} & D_{25} \\
D_{31} & D_{32} & D_{33} & D_{34} & D_{35} \\
D_{41} & D_{42} & D_{43} & D_{44} & D_{45} \\
D_{51} & D_{52} & D_{53} & D_{54} & D_{55}
\end{pmatrix} \begin{pmatrix}
\dot{\theta}_1 \\
\dot{\theta}_2 \\
\dot{\theta}_3 \\
\dot{\theta}_4 \\
\dot{\theta}_5
\end{pmatrix}
\]

\[
C(\theta, \dot{\theta}) = \begin{pmatrix}
C_{11} & C_{12} & C_{13} & C_{14} & C_{15} \\
C_{21} & C_{22} & C_{23} & C_{24} & C_{25} \\
C_{31} & C_{32} & C_{33} & C_{34} & C_{35} \\
C_{41} & C_{42} & C_{43} & C_{44} & C_{45} \\
C_{51} & C_{52} & C_{53} & C_{54} & C_{55}
\end{pmatrix} \begin{pmatrix}
\dot{\theta}_1 \\
\dot{\theta}_2 \\
\dot{\theta}_3 \\
\dot{\theta}_4 \\
\dot{\theta}_5
\end{pmatrix}, \quad G(\theta) = \begin{pmatrix}
G_1 \\
G_2 \\
G_3 \\
G_4 \\
G_5
\end{pmatrix}
\]

The Generalized inertia matrix is \( D(\theta) \), the Coriolis matrix is \( C(\theta, \dot{\theta}) \) and the Gravity matrix is \( G(\theta) \), there are constant matrices which calculated from the mass, joint angles and geometric parameters of links. Among the system inputs, only the motor torques \( (\tau_1, \tau_2, \tau_3, \tau_4, \tau_5) \) are actuated. The other inputs are exogenous disturbances.

### 3.2. Human Disturbances Model

Although the EARUL-LEE is worn by a soldier, the control strategy must take into account the disturbances which caused by involuntary human motions [11]. When the soldier is standing still during the execution of a missile-mounting, these motions usually belong to postural sway and physiological tremor. Postural sway resulting in the interactive forces raising at the shoulders, waist, thighs and shanks to maintain balance of human-EARUL-LEE system, the neuromuscular system exerts a restoring force \( \Delta F_b \) to keep balance, which is related to human oscillation acceleration. The total interactive force includes the shoulders and waist interaction, the thighs interaction, the shanks interaction and the interactive force caused by the end effector. Therefore, the human-induced disturbances acting on the EARUL-LEE can be modelled as figure 3 (c) shows.

- The human oscillation acceleration is \( a_b = \omega^2 \Delta \theta_b \), so the restoring force is shown as follows,

\[
\Delta F_b = \sum_{i=1}^{n} m_i a_b
\]

- Defined the interactive forces are the shanks interaction \( F_{e1} \), the thighs interaction \( F_{e2} \), and the upper body interaction \( F_{e3} \), the gravity components of end effector are \( G_{e1} \) and \( G_{e2} \), the
ground reaction of load is $F_h$, the distance between the end effector to shoulder is $d_s$, the distance between the feet to the back bracket is $d_L$, So, the force caused by human disturbances is shown as follows,

$$
\begin{align*}
F_b &= F_{E1} + F_{E2} + F_{E3} + \Delta F_b - G_{E2} \\
\tau_b &= F_h d_L + G_{E2} d_s
\end{align*}
$$

(7)

4. Orthogonal least squares filter

4.1. Method of orthogonal least squares filter

The developed dynamic model will be used for constructing the orthogonal least squares (OLS) filter for estimating the state of the human-EARUL-LEE system disturbed by the human and the environment. It will be shown that the state estimation accuracy depends on the EARUL-LEE posture, so that the disturbances can be estimated in real time. The orthogonal prediction criterion of the orthogonal least square method is "the minimum sum of the squares of the orthogonal distances of all points to the curve" [12], [13]. The state-space model will be considered to describe the EARUL-LEE when contacting with the operating ambient, and the errors of the independent variables are considered. The random errors of $\theta_i$ and $\omega_i$ are represented by $v_{yi}$ and $v_{y2i}$, the joint angle is $\theta_i$, the joint angular velocity is $\omega_i$. Thereby, the state vector $(\theta, \omega)^T$ is established by used the angles of 5 joints as the observation values and the joint angular acceleration $\phi_i$ as the interference term. At the beginning of analysis, the supposed system equation is shown as follows,

$$
\ddot{\dot{Y}} = A\dot{X} + B\phi,
$$

(8)

$$
\ddot{\dot{Y}} = \begin{pmatrix}
\ddot{\theta}_1 \\
\ddot{\theta}_2 \\
\ddot{\theta}_3 \\
\ddot{\theta}_4 \\
\ddot{\theta}_5
\end{pmatrix},
\ddot{X} = \begin{pmatrix}
\ddot{\omega}_1 \\
\ddot{\omega}_2 \\
\ddot{\omega}_3 \\
\ddot{\omega}_4 \\
\ddot{\omega}_5
\end{pmatrix},
$$

(9)

$$
Y = \begin{pmatrix}
Y_1 \\
Y_2
\end{pmatrix},
\dot{Y} = \begin{pmatrix}
\dot{\theta}_1 \\
\dot{\theta}_2 \\
\dot{\theta}_3 \\
\dot{\theta}_4 \\
\dot{\theta}_5
\end{pmatrix},
\ddot{Y} = \begin{pmatrix}
\ddot{\theta}_1 \\
\ddot{\theta}_2 \\
\ddot{\theta}_3 \\
\ddot{\theta}_4 \\
\ddot{\theta}_5
\end{pmatrix},
$$

(10)

$$
\begin{align*}
\ddot{\dot{Y}} &= Y + V_{y1} \\
\ddot{\dot{Y}}_2 &= Y_2 + V_{y2}
\end{align*}
$$

(11)

$$
V = \begin{pmatrix}
V_{y1} \\
V_{y2}
\end{pmatrix} = \begin{pmatrix}
\ddot{\dot{Y}} - \ddot{Y}_1 \\
\ddot{\dot{Y}}_2 - \ddot{Y}_2 - \ddot{Y}_2
\end{pmatrix} = \ddot{\dot{Y}} - Y = A\dot{X} + B\phi - Y, \ i = 1, 2, 3, 4, 5
$$

(12)

In this form, $\ddot{\dot{Y}}$ is the state prediction matrix at the next time $(t + 1)$, $\dot{X}$ is the gain matrix of the filter, $Y$ is the state prediction matrix at the time $(t)$, $V_{y1}$ and $V_{y2}$ are the error matrixes, $\phi_i$ is the interference matrix.

The orthogonal prediction criterion is described in mathematical form can be shown as follows,
\[
V^\dagger V = \text{min}
\]  

Then it can solve above equation by using indirect adjustment and obtain the result is shown as follows,

\[
\hat{X} = (A^T A)^{-1} A^T (Y - B \varphi) \quad (14)
\]

In this form, \( A \) is 10×10 order matrix, \( B \) is 10×5 order matrix, \( \varphi \) is 5×1 order matrix, \( T \) is the sampling time.

4.2. Robust fuzzy adaptive compensation control method based on friction

Supposed \( D(q) \), \( C(q, \dot{q}) \), \( G(q) \) are known and all the state variables can be measured. Because the joint friction is the mainly external interference during mounting operations, the fuzzy approximation consider friction. Since the friction is only related to the speed signal, the fuzzy system used to approximate the friction can be expressed as \( \hat{F}(\dot{q} | \theta) \), the robust fuzzy adaptive control law is shown as follows,

\[
\tau = D(q)\dot{q} + C(q, \dot{q})\dot{q} + G(q) + \tilde{F}(\dot{q} | \theta) - K_\theta \dot{s} - W \text{sgn} (s) \quad (16)
\]

The adaptive control law is shown as follows,

\[
\dot{\theta}_i = -\Gamma^{-1} s_i \tilde{\xi}_i (\dot{q}), i = 1, 2, \ldots, n \quad (17)
\]

The fuzzy system is shown as follows,

\[
\hat{F}(\dot{q} | \theta) = \begin{bmatrix}
\tilde{F}_1(\dot{q}_1) \\
\tilde{F}_2(\dot{q}_2) \\
\vdots \\
\tilde{F}_n(\dot{q}_n)
\end{bmatrix} = \begin{bmatrix}
\theta_1^T \tilde{\xi}_1(\dot{q}_1) \\
\theta_2^T \tilde{\xi}_2(\dot{q}_2) \\
\vdots \\
\theta_n^T \tilde{\xi}_n(\dot{q}_n)
\end{bmatrix} \quad (18)
\]

The membership function degree is shown as follows,

\[
\mu_i(x_i) = \exp \left( -\left( \frac{x_i - \bar{x}_i}{\pi} \right)^2 \right) \quad (19)
\]

In this form, \( \bar{x}_i \) are respectively \(-\pi/6\), \(-\pi/12\), \(0\), \(\pi/6\), \(\pi/12\) and \(i = 1, 2, 3, 4, 5\). \( A_i \) are NB, NS, ZO, PS, PB, respectively.

Finally, a simulation was set based the control flow shown in figure 4, the purpose is to make the actual motion of the joint follow the desired motion.

![Figure 4. The control flow of EURAL-LEE.](image-url)
4.3. Simulation parameters setting

Figure 5 shows the curve of membership function degree, the initial value of each element in the weight of the fuzzy system is taken as 0.1 and set the fuzzy controller parameters are $\lambda_1 = 10$, $\lambda_2 = 10$, $\Gamma_1 = \Gamma_2 = 0.01$, $K_p = 100I$, $W = diag[2, 2, 2, 2]$, respectively. The desired trajectories of the five joints come from the sine-cosine curve, they are showed in format 20.

$$
\begin{align*}
q_1(t) &= \sin(3t + 0.125) \\
q_2(t) &= \cos(3t + 0.225) \\
q_3(t) &= \sin(5t + 0.015) \\
q_4(t) &= \cos(t + 0.325) \\
q_5(t) &= \cos(2t + 0.33)
\end{align*}
$$

(20)

In the simulation, the physical parameters used in the ERUAL-LEE are given in Table 1.

| Parameters  | Value | Unit | Parameters  | Value | Unit |
|-------------|-------|------|-------------|-------|------|
| $M_1$       | 0.05  | kg   | $L_1$       | 0.17  | m    |
| $M_2$       | 0.33  | kg   | $L_2$       | 0.49  | m    |
| $M_3$       | 0.3   | kg   | $L_3$       | 0.43  | m    |
| $M_4$       | 1     | kg   | $L_4$       | 0.7   | m    |
| $M_5$       | 0.5   | kg   | $L_5$       | 0.5   | m    |

5. Simulation results and discussion

The simulation results are shown in figure 6 to 9, respectively. The black line means the desired trajectory, the red line means the estimated trajectory without OLS filter and the blue line means the OLS filter estimated trajectory in figure 6 to 9. The comparison between with OLS filter and without OLS filter of angle tracking among five joints shows in figure 6, figure 7 expresses the comparison of angular speed tracking among five joints, figure 8 and figure 9 are respectively expressed the angle tracking error and the angular speed tracking error between the original trajectory without OLS filter and the OLS filter estimated trajectory. Figure 6 and figure 7 show the outputs after OLS filtered can better tracking the desired trajectory than the original trajectory without OLS filter, the OLS filter can realize real-time tracking joint motion. The absolute errors of angle tracking with OLS filter are between 0.001 to 0.005 while the curves are smoothing and the absolute errors of angular speed tracking with OLS filter are between 0.001 to 0.05, there is a little tracking error by using OLS filter in figure 8 and figure 9, but the original trajectory without OLS filter has large error. The convergence is worse than the trajectory after OLS filtered, it can realize the tracking accuracy. At the start moment,
the tracking errors have some fluctuations, these may be caused by the change of swing. The tracking errors of joint 2, joint 4 and joint 5 are bigger than joint 1 and joint 3, because the joint 1 and joint 3 are attached to the ground and human body, the change of swing in joint 1 and joint 3 are smaller than other joints. Curves have no peaks in figure 6 to 9 and they are smooth, it shows that the OLS filter can eliminate bad poles. The results show that the estimated effect is good, and it can achieve a desired result by using OLS filter.

6. Conclusion and future work
This paper presented the extra auxiliary robotic upper limbs-lower extremity exoskeleton (EARUL-LEE), a wearable robot designed to assist soldiers in missile-mounting, aimed to perform the missile-mounting task for aircrafts on the ground or decks in tight coordination with the soldier as a close co-worker. It developed a dynamic model of the human-EARUL-LEE hybrid system include the models of human-induced disturbance based on biomechanics literature in order to study its behaviour. Through the current study, the dynamic model is used to construct the control system, and the orthogonal least squares (OLS) filter is constructed to estimate the state of the EARUL-LEE. The simulation results show that the OLS filter can track desired trajectory and its convergence is better than those without any filters. So, the OLS filter can estimate the trajectory and obtain smooth curves.
It can achieve desired results by using OLS filter. The main contributions of this study are the dynamic model of the human-EARUL-LEE hybrid system includes the models of human-induced disturbance and additional state equations. The OLS filter is used to estimate the motion and obtain better results. The results can be used to control the EARUL-LEE accordingly with the used end effectors and provide a method for improving the accuracy and stabilizing the human body and the EARUL-LEE.

Future research directions include the optimization of the dynamic model based on the actual missile-mounting trajectory and compare the OLS filter with other filters. To design a better control strategy for EARUL-LEE and to construct a sensing network includes multiple signals to describing the motion of human-machine system. In terms of practical implementation and testing, the next step will be represented by the completion of the EARUL-LEE prototype. This will allow to test control strategies, applying them to the actual working scenario.

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