Modeling and Balance Control of Supernumerary Robotic Limb for Overhead Tasks

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Abstract—Overhead manipulation tasks often require collaborations between two operators, which becomes challenging in confined spaces such as in a compartment. Supernumerary Robotic Limb (SuperLimb), as a promising wearable robotic solution, can provide assistance in terms of broader workspace, wider manipulation functionalities and safer working conditions. However, the safety concerns of human-centered SuperLimb interaction mechanisms are rarely studied to date, particularly regarding human standing balance. This study proposes a balance controller by which one individual operator can accomplish overhead tasks with the assistance of SuperLimb via tunable interaction force and supporting force regulation. The SuperLimb-human interaction is modeled and a dynamics control method based on OR decomposition (also known as QR factorization, in which a matrix is factorized into an orthogonal matrix and an upper triangular matrix) is adopted to decouple joint torques of the SuperLimb and the interaction forces. Therefore, the supporting forces can be regulated independently to guarantee the operator-SuperLimb interaction forces in a safe region. Force plate is used for measuring the CoP position as an evaluation method of the standing balance. The critical horizontal push force is learned through experiment to guide the balance controller. This method is implemented on

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a SuperLimb prototype worn on the operator's back, to provide necessary supporting forces on overhead object while allowing the operator to move freely underneath.

Index Terms—Balance, overhead tasks, supernumerary robotic limb, wearable robots.

I. INTRODUCTION

S UPERLIMB, i.e., Supernumerary Robotic Limb, as a pivotal branch of wearable robots, is an extension to exoskeletons and prostheses [1]–[3]. SuperLimb has the merit of extending the operator's workspace, augmenting human strength and allowing diverse postures beyond the human limb movement. Specifically, SuperLimb is capable of assisting overhead tasks, especially those in constrained workspaces [4]. These tasks include a series of operations with intensive workload and flexibility requirements in industrial set-ups, such as the compartment in the aircraft [5]–[7]. The working space limitation impedes the participation of large-size robots or coexisted multi-operator collaboration.

Overhead task assistance is one important branch among SuperLimb applications. In [8] a wearable robot mounted on the shoulder was designed to assist with tasks in the overhead workspace. Demonstration-based control allows the robot to take a proactive and preemptive action while confirming a successful transition. [7] explored a method to maintain free movements of the operator while exerting a constant supporting force from the SuperLimb to the ceiling. Admittance control strategy was proposed to map the errors between the desired and the measured supporting forces to the desired joint velocities. However, it is yet an open question on how to regulate the supporting force while maintaining the safety of operator-SuperLimb interaction forces, which is essential for human-centered wearable robotics. Compared to admittance controlled systems, the torque-based interaction mechanism in the fully dynamic model allows compliant interaction with the environment and human residing in the workspace of the robot [9], [10].

When the supporting force exceeds a certain threshold, the interaction forces, especially in the horizontal direction, will degrade the stance balance. To address this problem, this study proposes a dynamics control based on the modeling of operator-SuperLimb interaction. This method is able to regulate the interaction and supporting forces. We define a stability criterion with center-of-pressure (CoP) to evaluate the performance of the proposed method. The SuperLimb works in the task space where the human body is braced through a coupling impedance. QR decomposition is adopted to decouple the dynamic models of SuperLimb and human such that the supporting forces and joint torques can be controlled independently. The QR decomposition

2377-3766 © 2021 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information. is able to factorize a matrix into an orthogonal matrix and an upper triangular matrix [11]. A handy SuperLimb prototype is built for experimental validation. Within our best knowledge, it is the first study on standing balance issue of SuperLimb for the overhead tasks. The contributions of this letter lie in the following twofold:

(i) An operator-SuperLimb model is established which decouples SuperLimb joint torques and operator-SuperLimb interaction forces;

(ii) A balance controller based on the established model is proposed to regulate the interaction forces. CoP is selected as the evaluation index for balance.

The rest of the letter is organized as follows. We review related work in Section II, and presents the model of SuperLimb and human in Section III. Section IV proposes a balance control method based on the model of Section III. Section V demonstrates the experiment results. This line of research is concluded in Section VI.

II. RELATED WORK

SuperLimb is an emerging field where some researchers explored applications in augmenting, assisting and restoring human functions, and attracts accumulating attentions during recent years.

One of the major applications of SuperLimb is supporting assistance. A SuperLimb prototype is designed in [12] to assist in the preliminary supporting tasks such as holding objects, lifting weights, etc. Data-driven and intuitive approach is adopted for SuperLimb control. Compared with the data-driven method, dynamic analysis and state estimation of the SuperLimb supporting model are studied in [13] to attenuate disturbances. To enhance the capability for supporting, an optimization method is adopted in [14] to minimize human load under detailed SuperLimb model. In [15] a SuperLimb acts as an additional supporting leg to improve the human's standing and walking balance. However, only static balance is considered and supporting polygon is used for balance optimization. These supporting tasks are summarized in [16], which analyzes the quasi-static stability and compliance with which the body is supported. Null-space technique and joint stiffness are adopted to stabilize the body supporting system. For near-ground supporting works, [17] designs a SuperLimb with impedance control to stably support the wearer's body. [18] demonstrates a near-ground supporting capability that assists the operator in carrying a heavy payload on Extra Robotic Legs (XRL). Kinematics and dynamics are analyzed for joint torque optimization. However, experiment is yet conducted for verification. Only a passive quadrupedal model inspired from XRL is experimentally validated in [19]. A novel non-singular linkage mechanism is designed to provide adjustment of both the worker's distance to the ground and their torso tilt [20]. No control is analyzed for such a mechanism. [21] designs a supernumerary leg powered by the novel magnetorheological actuators to assist walking. Impedance control is adopted to achieve the compliance contact with the ground. [22] proposes an ambient SuperLimb that involves a pneumatically-driven robotic cane for at-home supporting assistance. A depth sensor is adopted for the ambient intention detection. However, this method is only applicable within a limited space.



Fig. 1. A single operator is manipulating on the overhead ceiling with the SuperLimb assisting in supporting it. Visual odometry device and F/T sensor are mounted on SuperLimb for estimating the pose of the float base of SuperLimb and the interaction force between operator and SuperLimb.

In the aforementioned works, researchers conduct inspiring explorations mainly in near-ground supporting tasks. With the equipment of SuperLimb, human's capability of handling versatile tasks is greatly leveraged. As another critical aspect, this letter mainly focuses on the balance in the overhead tasks.

III. MODELING OF SUPERLIMB

The SuperLimb configuration is shown in Fig. 1, with its base mounted on the back of the operator via a shoulder belt. The total weight of our SuperLimb prototype is 5 kg with joint-level torque control capability. The SuperLimb on the operator is inherently modeled as a manipulator with a floating base. A visual odometry device mounted on the base of SuperLimb measures the pose of the float base, and a F/T sensor mounted between SuperLimb and operator measures the interaction forces.

Our objective is to design an automatic control mechanism in which the SuperLimb is able to guarantee human balance, provide sufficient supporting force, and regulate the interaction forces between the operator and SuperLimb to maintain human body stability. This mechanism considers the operator and SuperLimb dynamics and computes desired SuperLimb torque inputs based on the operator, SuperLimb and environment states. These states are coupled in the dynamic model.

A full dynamic model is developed to include the states from operator, SuperLimb and the environment. Operator states include interaction forces between the operator and SuperLimb, linear and rotational accelerations, linear and rotational velocities. The SuperLimb states include joint position, velocity and torque. Environment states include the supporting force from SuperLimb. The states and inputs of operator and SuperLimb is integrated in this model to take into account the coupled operator-SuperLimb loop.

In this section, we will introduce the model in two levels: kinematic and dynamic models. In the kinematic model, the coupling of operator and SuperLimb movement is analyzed in two different cases, and their relationship in motion is given.



Fig. 2. The general model of SuperLimb and operator. In this model, the operator is modeled as part of the manipulator, however, the joint positions and torques of the operator are not controllable. It is noteworthy that the SuperLimb for overhead tasks is modeled in three dimensions in our study.

In the dynamic model, an analytical solution for SuperLimb torques is given to track certain movement of human body and the derivation of related supporting force is also provided.

A. Kinematic Model

The kinematic model studies the coupling of operator and SuperLimb motion. Here $q_h \in \Re^{h \times 1}$ and $\tau_h \in \Re^{h \times 1}$ represent human joint position and torque states, respectively; $q_s \in \Re^{s \times 1}$ and $\tau_s \in \Re^{s \times 1}$ represent SuperLimb joint position and torque states, respectively; s and h are the number of DoFs of Super-Limb and human, respectively. Note that, τ_h is treated as a state in this model rather than an input. Our objective is to track q_h and regulate τ_h through control of the SuperLimb. Our model only considers the condition s > h since in general manipulator has more DoFs than that of human body to provide the capacity of accomplishing multi-tasks simultaneously. As shown in the frame O_{SL} of Fig. 2, q_h depends on q_s and components of q_h . Therefore, q_s and q_h obey:

$$q_h = f(q_{h2}, q_s),\tag{1}$$

where $q_h = [q_{h1}, q_{h2}]^T$ and q_{h2} are coupled states. A closedkinematic chain exists in the model of Fig. 2, which also imposes an algebraic constraint. In this study, the kinematic model is categorized into two cases: 1) s = h and 2) s > h.

Case 1 (s = h): in this case, q_h and q_s are decomposed into two components, $q_h = [q_{h1}, q_{h2}]^T$, $q_s = [q_{s1}, q_{s2}]^T$. We design q_{s2} to track q_{h2} , i.e. $q_{h2} = Kq_{s2}$, where K is selected as a constant coefficient matrix. If q_{h2} includes rotational DoFs, correspondingly q_{s2} is selected from rotation DoFs. Likewise, if q_{h2} includes translation DoFs, correspondingly q_{s2} is selected from translation DoFs. We can select K to cancel q_{h2} in (1) so that (1) can be simplified to $q_{h1} = f(q_{s1})$. Therefore, the derivative of that equation is,

$$\dot{q}_{h1} = \hat{J}_{hs} \dot{q}_{s1},$$
 (2)

where \hat{J}_{hs} is the Jacobian with respect to frame O_{SL} as shown in Fig. 2. Combined with $q_{h2} = Kq_{s2}$, we have a relationship between q_h and q_s depicted as:

$$\dot{q}_h = J_{hs} \dot{q}_s = \begin{bmatrix} \hat{J}_{hs} & O\\ O & K \end{bmatrix} \dot{q}_s, \tag{3}$$

where J_{hs} and \hat{J}_{hs} are square and invertible except at singularity. The definition of singularity can be referred in [23]. In this study, singularity may occur if the manipulator is fully stretched and such a configuration is not allowed to happen in our implementation and thus singularity case is not within the scope of this study. From (3), \dot{q}_s^d and q_s^d can be computed as:

$$\begin{cases} \dot{q}_{s}^{d} = J_{hs}^{-1} \dot{q}_{h}, \\ q_{s}^{d} - q_{s}^{a} = \Delta q_{s} = J_{hs}^{-1} \dot{q}_{h}, \end{cases}$$
(4)

where q_s^d and q_s^a are the desired and actual states respectively.

Case 2 (s > h): in the same way as case 1, we still decompose q_s and q_h into $[q_{s1}, q_{s2}]^T$ and $[q_{h1}, q_{h2}]^T$. And q_{h2} is set to be equal to $q_{h2} = Kq_{s2}$ with K being a constant coefficient matrix. We have the similar form:

$$\dot{q}_h = J_{hs} \dot{q}_s = \begin{bmatrix} \hat{J}_{hs} & O\\ O & K \end{bmatrix} \dot{q}_s, \tag{5}$$

where $\hat{J}_{hs} \in \Re^{h1 \times s1}$ and $h_1 < s_1$. With svd-based pseudo inverse, we have the inverse of J_{hs} as:

$$\dot{q}_s = J_{hs}^+ \dot{q}_h = \begin{bmatrix} \hat{J}_{hs}^+ & O \\ O & K^{-1} \end{bmatrix} \dot{q}_h.$$
 (6)

Thus \dot{q}_s^d and q_s^d are computed in the same way as case 1:

$$\begin{cases} \dot{q}_{s}^{d} = J_{hs}^{+} \dot{q}_{h}, \\ q_{s}^{d} - q_{s}^{a} = \Delta q_{s} = J_{hs}^{+} \dot{q}_{h}. \end{cases}$$
(7)

In this design, SuperLimb can spare some DoFs to compensate for the operator's posture. In the simplest way, SuperLimb is designed such that all types of DoFs (translational and rotational) correspond to the motion DoFs of operator. However, translational DoFs usually spare large space and most manipulator configuration only includes rotational DoFs. Therefore, it is necessary to discuss the above method.

In this kinematic model, motion relationship between the operator and SuperLimb is discussed with the two aforementioned cases. The decoupling method is adopted to track the motion of the operator.

B. Dynamic Model

A dynamic system is normally formulated as $\dot{x} = g(x, u)$, where x is the system states and u is the input. In this study, the dynamics with human in the loop is considered and the interaction forces between operator and SuperLimb as well as the operator's motion states are taken into account. The dynamics is formulated as:

$$\dot{x} = g(x, u_s, u_h),\tag{8}$$

where u_s and u_h are inputs of SuperLimb and human respectively. $x = [x_s, x_h]^T$ is the system states, including SuperLimb sates x_s and human states x_h . Operator is modeled as a part of the manipulator and includes 3 rotation DoFs and 3 translation DoFs as shown in Fig. 2. The complete dynamics equation is as:

$$A\ddot{q} + h = \tau + J_c^T \lambda, \tag{9}$$

where A is the inertia matrix, h includes Coriolis force and gravity. τ is the joint torques of SuperLimb and operator. λ is the supporting force. $J_c \in \Re^{k \times n}$ is the Jacobian of support point with respect to global frame O as shown in Fig. 2. k is the number of DoFs of contact constraint. Since it is assumed that the operator is equivalent to a manipulator with 6 DoFs, of which 3 DoFs are rotational and 3 DoFs are translational, q and τ are defined as:

$$\begin{cases} q = [q_s, q_h]^T, \\ \tau = [\tau_s, \tau_h]^T, \end{cases}$$
(10)

where the subscription s and h represent SuperLimb and human respectively. Then $q_s \in \Re^{s \times 1}$ and $q_h \in \Re^{h \times 1}$. In this study, the condition $s \ge h$ is considered. Therefore, QR decomposition of J_c^T has the form as:

$$J_c^T = Q \begin{bmatrix} R\\0 \end{bmatrix},\tag{11}$$

where Q is an orthogonal matrix and $Q^T Q = I$, $R \in \Re^{k \times k}$ is an upper triangular matrix with rank of k. Therefore, we have:

$$A\ddot{q} + h = \tau + Q \begin{bmatrix} R\\0 \end{bmatrix} \lambda.$$
 (12)

The above equation is decomposed into two parts with λ extracted:

$$\begin{cases} S_k Q^T (A\ddot{q} + h - \tau) = R\lambda, \\ S_{kc} Q^T (A\ddot{q} + h) = S_{kc} Q^T \tau, \end{cases}$$
(13)

where the selection matrices S_k and S_{kc} are:

$$\begin{cases} S_k = [I_k, O_{k \times (n-k)}], \\ S_{kc} = [O_{(n-k) \times k}, I_{(n-k) \times (n-k)}]. \end{cases}$$
(14)

Therefore, the contact constraint is canceled from (14) and we have:

$$\begin{cases} \tau = (S_{kc}Q^T)^{\dagger}S_{kc}Q^T(A\ddot{q}+h), \\ \lambda = R^{-1}S_kQ^TN_{kc}(A\ddot{q}+h), \end{cases}$$
(15)

where $(\cdot)^{\dagger}$ is dynamically consistent pseudo-inverse [24], i.e. $W^{\dagger} = A^{-1}W^T (WA^{-1}W^T)^{-1}$. $N_{kc} = I - (S_{kc}Q^T)^{\dagger}S_{kc}Q^T$ is the null projection of $S_{kc}Q^T$. $\tau = [\tau_s, \tau_h]^T$, where τ_s is the joint torque of SuperLimb and τ_h is the joint torque of human. $\ddot{q} = [\ddot{q}_s, \ddot{q}_h]^T$ includes the joint accelerations of SuperLimb and human.

The task space above is defined in frame O_{SL} as shown in Fig. 2. Due to the pseudo inverse, the analytical solution given by (15) is not unique. In this dynamic model, joint torques of SuperLimb and human τ are decoupled with the contact force λ , which is the supporting force for overhead tasks. Using (15), we can compute τ and λ using joint acceleration.

This letter aims to regulate the interaction forces and contact forces, which corresponds to τ_h and λ . (15) is able to provide an

efficient solution for joint torque and supporting force. However, this solution does not take human body stability into consideration. To ensure the CoP stability of the operator, a balance control problem is formulated in the next section.

IV. BALANCE CONTROL

A. Full-Body Dynamics Control

Section III demonstrates a solution to τ and λ using joint acceleration of SuperLimb and human. Given a desired joint acceleration, a feasible τ and λ can be computed. The desired acceleration is :

$$\ddot{q}_s = J_{hs}^{\dagger} (\ddot{q}_h - \dot{J}_{hs} \dot{q}_s), \tag{16}$$

where \ddot{q}_h is the actual acceleration of human and J_{hs} is the Jacobian from frame O_{hs} to q_h . Thus the desired acceleration $\ddot{q}^d = [\ddot{q}_s^d, \ddot{q}_h^d]^T$.

The solution for supporting force in (15) is the optimal result under kinetic energy as cost function. It is the force that compensates all gravity of SuperLimb. We use λ_b as the basic force:

$$\lambda_b = R(A\ddot{q} + h),\tag{17}$$

where λ_b is the force for supporting gravity of SuperLimb itself. $\bar{R} = R^{-1}S_kQ^T N_{kc}$. $J_c^T \lambda_b$ is the joint torque for compensation of gravity and dynamics terms. If desired supporting force is λ_s , then the aggregated joint torque and corresponding supporting force is:

$$\begin{cases} \tau = J_c^T (\lambda_b - \lambda_s), \\ \lambda = \bar{R} (A\ddot{q} + h - \tau). \end{cases}$$
(18)

In this section we formulate the balance control of human body as a torque regulation problem and propose a balance controller which is able to calculate the desired torque inputs for SuperLimb to regulate the interaction force between the operator and SuperLimb. And combining with the basic solution we derived in Section III, this whole automatic control mechanism is shown in Fig 3.

To better investigate the relationship of τ_s and τ_h , and design a controller for τ_s to track the desired interaction torque $\bar{\tau}_h$, we can rewrite (18) into the following form.

$$\begin{bmatrix} Aqh_{s1} \\ Aqh_{h1} \end{bmatrix} = \begin{bmatrix} \tau_{s1} \\ \tau_{h1} \end{bmatrix} + \begin{bmatrix} J_{cs1}^T \\ J_{ch1}^T \end{bmatrix} \lambda,$$
(19)

where τ_{s1} and τ_{h1} correspond to q_{s1} and q_{h1} respectively, $Aqh = A\ddot{q} + h$, $\lambda \in \Re^{l \times 1}$, $J_{cs1} \in \Re^{l \times s1}$, $J_{ch1} \in \Re^{l \times h1}$. The motion of q_{h2} is compensated by q_{s2} as designed in the kinematics model in Section III, such as yaw or pitch DoF of human body. Obviously, revolute DoFs of human are able to be compensated by the revolute DoFs of SuperLimb. In the planar case, e.g. Sagittal plane, a human has x, z and pitch DoFs. The pitch DoF is compensated and thus h1 = 2, Supporting force $\lambda = [\lambda_x, \lambda_z]^T$ and thus l = 2. In spatial case, the yaw, pitch and roll DoFs are also able to be compensated by the revolute DoFs of SuperLimb and thus h1 = 3. $\lambda = [\lambda_x, \lambda_y, \lambda_z]^T$ and thus l = 3. Therefore, it is reasonable to assume that s1 = h1 = l both in planar and spatial case. J_{ch1} and J_{cs1} are square matrices. The above



Fig. 3. Automatic control mechanism of proposed balance controller for overhead task. The detailed communication mechanism is demonstrated in the dashed box to show the workflow proposed in this letter. Red lines are commands and black lines are states.

Algorithm 1: Balance Control Algorithm. 1: **Input:** $q_h, \dot{q}_h, \ddot{q}_h, (\lambda_s, \bar{\tau}_h)$ constant 2: **Output:** $\tau_{regulate}$ Initialize: $S_k \leftarrow [I_k, O_{k \times (n-k)}]$ 3: $S_{kc} \leftarrow [O_{(n-k)\times k}, I_{(n-k)\times (n-k)}]$ $\alpha \leftarrow \beta^{-n}$ 4: 5: while $x_{CoP} > \bar{x}_{CoP}$ do 6: $\begin{array}{l} q_s^d \Leftarrow \textbf{Kinematics model} \left(q_h^d \right) \\ q^d \Leftarrow [q_s^d, q_h^d]^T \end{array}$ 7: 8: 9: $A, h, J_c, J_{hs}, J_{hs} \Leftarrow \text{Dynamics model } (q, \dot{q})$ $\begin{aligned} \dot{q}_s^d &\leftarrow J_{hs}^{-1} \dot{q}_h^d, \\ \dot{q}_s^d &\leftarrow [\dot{q}_s^d, \dot{q}_h^d]^T, \\ \dot{q}^d &\leftarrow [\dot{q}_s^d, \dot{q}_h^d]^T, \\ \dot{q}^d &\leftarrow [\ddot{q}_s^d, \dot{q}_h^d]^T \end{aligned}$ 10: 11: 12: $Q, R \leftarrow QR$ decomposition of J_c $Aqh \Leftarrow A\ddot{q}^d + h$ 13: $\tau_b \Leftarrow (S_{kc}Q^T)^{\dagger}S_{kc}Q^TAqh$ 14: 15: $\lambda_b \Leftarrow R^{-1} S_k Q^T N_{kc} A q h$ $\tau \Leftarrow Aqh - J_c^T (\lambda_b - \lambda_s),$ $\tau_{h1} \Leftarrow \tau (s1 + 1 : s1 + h1)$ 16: $Aqh_{s1} \leftarrow Aqh(1:s1,:),$ 17: $Aqh_{h1} \Leftarrow Aqh(s1+1:s1+h1,:)$ 18: 19: $J_{cs1} \Leftarrow J_c(1:s1,1:s1)$ 20: $J_{ch1} \Leftarrow J_c(1:s1,s1+1:s1+h1)$ $W_1 \Leftarrow J_{cs1}^T (J_{ch1}^T)^{-1}$ 21: $W_1 \leftarrow \mathcal{I}_{cs1}(\mathcal{I}_{ch1}) \\ W_2 \Leftarrow Aqh_{s1} - \mathcal{I}_{cs1}^T (\mathcal{I}_{ch1}^T)^{-1} Aqh_{h1} \\ \tau_{s1}^a \leftarrow \alpha W_1(\bar{\tau}_{h1} - \tau_{h1}) + W_2 \\ \tau_{s1}^d \leftarrow PI(\tau_{s1}^a) \\ \lambda \Leftarrow (\mathcal{I}_{cs1}^T)^{-1} (Aqh_{s1} - \tau_{s1}^d) \\ \lambda \leftarrow \mathcal{I}_{cs1}^T + \mathcal{I}_{s1}^T \\ \lambda = \mathcal{I}_{cs1}^T + \mathcal{I}_{s1}^T + \mathcal{I}_{s1}^T \\ \lambda = \mathcal{I}_{cs1}^T + \mathcal{I}_{s1}^T + \mathcal{I}_{s1}^T \\ \lambda = \mathcal{I}_{cs1}^T + \mathcal{I}_{s1}^T + \mathcal$ 22: 23: 24: 25: $\tau_{\text{regulate}} \Leftarrow Aqh - J_c^T \lambda$ 26: 27: end while

equation is able to be decoupled as below:

$$\begin{cases} \lambda = (J_{cs1}^T)^{-1} (Aqh_{s1} - \tau_{s1}), \\ \lambda = (J_{ch1}^T)^{-1} (Aqh_{h1} - \tau_{h1}). \end{cases}$$
(20)

Within the scope of this study, the singularity of J_{cs1} and J_{ch1} is not considered, which never exists in the current configuration of the human and SuperLimb. Therefore, J_{cs1} and J_{ch1} are always taken as invertible. Therefore, we have:

$$\tau_{s1} = W_1 \tau_{h1} + W_2, \tag{21}$$

where $W_1 = J_{cs1}^T (J_{ch1}^T)^{-1}$ and $W_2 = Aqh_{s1} - J_{cs1}^T (J_{ch1}^T)^{-1}$ Aqh_{h1} . (21) represents the coupling relationship between interaction forces τ_{h1} and SuperLimb joint torques τ_{s1} .

 τ_{s1}^{a} represents desired value of τ_{s1} , and it is designed as below:

$$\tau_{s1}^a = \alpha W_1 (\bar{\tau}_{h1} - \tau_{h1}) + W_2, \qquad (22)$$

where $\bar{\tau}_{h1}$ is the desired interaction force. α is named as the convergence coefficients and set as below:

$$\alpha = \beta^{-n}.$$
 (23)

A PI controller is adopted to track τ_{s1}^a . And the PI control law is as below:

$$\tau_{s1}^d = K_p e + K_i \int_0^t e\delta t, \qquad (24)$$

where $e = \tau_{s1}^d - \tau_{s1}^a$. After plugging back τ_{s1}^d into (20) and combining with (18) we can have the expression of regulated torque command τ_{regulate} , which is the feed forward signal for SuperLimb joints to track.

$$\tau_{\text{regulate}} = Aqh - J_c^T \lambda. \tag{25}$$

In this subsection, a balance control based on the dynamics model of human-SuperLimb is proposed. Human is modeled as the part of the manipulation where the DoFs of human movement is uncontrollable. DoFs of human and the DoFs of the SuperLimb are coupled in the dynamics model. This study analyzed the relationship between the human movement and the SuperLimb and proposed a balance controller aiming at attenuating the disturbance of the horizontal interaction force so as to keep human's standing balance. Eqs. (21) and (22) imply that each component of τ_{h1} is guaranteed to converge due to α and the PI controller even if W_1 and W_2 include coupled factors. Therefore, the regulation of the interaction forces in x, y and zdirections is independent.

The algorithm of the proposed controller is shown in Algorithm 1. x_{CoP} is the position of CoP within the foot coordinate. \bar{x}_{CoP} is the safe threshold in which case human is able to keep standing balance.

B. Simulation

In this subsection, an example is demonstrated using the method proposed in the previous section. Due to the hardware condition in our study, a SuperLimb with three DoFs is worn on the operator. A human moves in the Sagittal plane, i.e. x - z plane in Fig. 2. In this case, human has three DoFs, i.e. x_h , z_h , and θ_h , where θ_h is the pitch angle of human body. The SuperLimb has three DoFs $q_s = [\theta_1, \theta_2, \theta_3]^T$ in Sagittal plane. Supporting force $\lambda = [\lambda_x, \lambda_z]^T$.

In this example, s = h = 3, $q_s = [\theta_1, \theta_2, \theta_3]^T$, $q_h = [x_h, z_h, \theta_h]^T$. We select $q_{s1} = [\theta_2, \theta_3]^T$, $q_{s2} = \theta_1$. $q_h = [q_{h1}, q_{h2}]^T$ where $q_{h1} = [x_h, z_h]^T$ and $q_{h2} = \theta_h$, as shown in Fig. 8. Based on the discussion in previous section, we set



Fig. 4. Push force (in percentage normalized by subject weight) versus CoP position within the supporting feet in the Sagittal (a) and frontal (b) planes, respectively. The deep blue line denotes the average push force trajectory and the light blue region represents the distribution of the push force. The human starts to fall when CoP moves beyond 110 mm within the frame of O for the Sagittal plane and 230 mm for the frontal plane. The average ratios of critical push force and subject and SuperLimb's total weight are 1.92% and 3.71% for the Sagittal and frontal planes, respectively.



Fig. 5. Joint torques of SuperLimb and interaction forces. τ_{s1} and τ_{s2} are the joint torques of SuperLimb. τ_x and τ_z are the horizontal (x direction) and vertical (z direction) interaction forces. The blue lines are the basic forces to compensate the gravity of SuperLimb itself. The red lines are the forces after disturbance. The black lines converge due to the balance control.

 $\theta_h = c - \theta_1$ to keep the posture of the first SuperLimb link relatively static in the global frame.

$$\begin{bmatrix} \dot{x}_h \\ \dot{z}_h \\ \dot{\theta}_h \end{bmatrix} = \begin{bmatrix} l_2 s_{2c} + l_3 s_{23c} & l_3 s_{23c} & 0 \\ -l_2 c_{2c} - l_3 c_{23c} & -l_3 c_{23c} & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_1 \end{bmatrix}, \quad (26)$$

where s_{ijc} stands for $sin(q_i + q_j + c)$ and c_{ijc} stands for $cos(q_i + q_j + c)$. l_i , (i = 1, 2, 3) is the length of the first, second



Fig. 6. Supporting forces converge due to the balance controller. The red lines are the supporting forces after disturbance. Black lines represents the convergence of the horizontal force under the balance controller. λ_x and λ_z represent the supporting forces in the x and z directions, respectively.



Fig. 7. The torque tracking of the SuperLimb. The red lines are the desired torques and the black lines are the actual tracking torques.



Fig. 8. The experiment scenario for overhead task. To evaluate the balance performance, subject stands on a force plate which is able to measure the CoP position. The DoFs in the figure correspond to those defined in (26) and (27).

and third SuperLimb links, respectively. c is the constant angle.

$$J_{hs} = \begin{vmatrix} l_2 s_{2c} + l_3 s_{23c} & l_3 s_{23c} & 0 \\ -l_2 c_{2c} - l_3 c_{23c} & -l_3 c_{23c} & 0 \\ 0 & 0 & -1 \end{vmatrix} .$$
(27)

The CoP data is measured when human stand statically. The subject is required to stand on a force plate which is able to measure the CoP position. Push force is exerted on the operator's back where SuperLimb's base is attached. The relationship between CoP's relative position within the supporting profile of the feet and the pushing force in both x and y directions is visualized in Fig. 4. There appears a threshold for the safe pushing force where the pushing force lower than the threshold will be safe to the human standing balance. Based on the standing

habit, the threshold in y direction is larger than x direction and therefore the balance in the Sagittal plane is more vulnerable to the push disturbances. Base on the statistic result, a balance controller with the CoP-related pushing force as performance evaluation is proposed. Considering the interaction force can be controlled independently and balance in the Sagittal plane is prone to disturbances, without loss of generality, our study will focus on the Sagittal plane to demonstrate the effectiveness of the proposed method.

In the simulation, the initial states of the SuperLimb and the operator are in statically stable state and the operator stands without horizontal interaction force. When the operator's movement incurs the increasing of the horizontal interaction force, balance controller attenuates both the horizontal interaction force and vertical supporting force. For the overhead task, vertical supporting force is necessary while horizontal supporting force is correlated to the horizontal interaction force which human stance balance is sensitive to. Fig. 5 and Fig. 6 show the evolution of the joint torques and the interaction forces when horizontal interaction force appears.

In Fig. 5, the two figures in the first row show the joint torques of SuperLimb and the two figures in the second row show the horizontal and vertical interaction forces respectively. The blue lines represent the forces that compensate the gravity of SuperLimb. The red lines represents the forces when horizontal forces' disturbance appear. The black lines represent how the forces converge under the balance controller.

From τ_x and τ_z in Fig. 5 it is demonstrated that the horizontal and vertical interaction forces are able to be regulated independently. With the balance controller, the horizontal interaction force is attenuated and converge back to around zero force. Fig. 6 demonstrates that the supporting forces are decoupled where λ_x and λ_z are the supporting forces in x and z directions, respectively. Horizontal supporting force converges back to around zero while vertical supporting force stays constant.

Fig. 7 shows the tracking of τ_s where the red lines are τ_s^a and the blue lines are the tracking torques τ_s^a . The noises are added in the desired torque commands. Supporting forces are two dimensional and therefore in this case only two DoFs of SuperLimb are needed to control the supporting forces. The first and second joints are selected which correspond to τ_{s1} and τ_{s2} . The model of SuperLimb and human is nonlinear and consistent for overhead tasks. The balance controller is based on PI control which is stable and extensively verified in many theories and experiments.

V. EXPERIMENT

In this section, experiment is conducted to verify the balance controller proposed in this study. The operator's movement is constrained in Sagittal plane. The vertical movement does not affect the standing balance. Therefore, we focus on the horizontal movement in the experiment.

A. Experiment Configuration

Fig. 8 demonstrates the experiment scenario. A off-the-shelf manipulator Interbotix VX300 was selected as the main mechanism, which weights around 4 kg and is suitable for a normal adult both in weight and size. There are five DoFs on VX300



Fig. 9. (a) The position trajectories of the base of the SuperLimb from four subjects.(b) The position, velocity and acceleration of the operator's movement in slow and fast conditions, respectively.

manipulator except for the gripper while only three revolute joints are along y axis in the Sagittal plane. There is one DoF at the wrist (along z axis in Fig. 2) and one DoF at the base of the manipulator (along x axis in Fig. 2). A 6-axis force sensor is mounted between the base of VX300 manipulator and a rectangle-shaped acrylic board, which is embedded and tightly attached in a backpack. The force sensor is able to measure the interaction force between the operator and SuperLimb. Intel RealSense T265 is adopted as the visual odometry and mounted on VX300 base to measure the operator's movement. A host PC with linux system runs the controller codes. ROS is adopted for running the controller of SuperLimb and collecting the sensing data from the force sensor and the visual odometry. Interbotix manipulator is set as current mode. The serial communication cable connects the SuperLimb and the host PC. The force plate measures the CoP of the operator. The data are synchronized during the experiment. It is noteworthy that the force plate is for evaluation purpose in the experiment rather than in the reality application due to the inconvenience of portability. Based on the results in Fig. 4, critical push force which incurs the falling of human in stance state is statistically learned and normalized taking human weight into account.

In experiment, four subjects were invited to participate as the operator. The heights of the subjects are 162 cm, 169 cm, 169 cm, and 173 cm respectively. The weights of the subjects are 50.3 kg, 64.5 kg, 80 kg and 77 kg respectively. Balance controller regulates the SuperLimb's joint torques to attenuate the horizontal interaction force to keep the operator's standing balance. Visual odometry measures the position of the operator's upper body, which is almost equivalent to the CoM of the human body [25]. Velocity and acceleration are differentiated from the position with filtering.

B. Experiment Results

Fig. 9 shows the position, velocity and acceleration of the operator's movement under slow and fast conditions, respectively. The red lines in Fig. 9 represent the fastest movement as possible as the subjects can in the stance state under the largest magnitude of horizontal motion in which CoP moves to the edge of the polygon of the supporting feet.

Fig. 10 demonstrates the performance of the balance controller under slow and fast conditions. CoP position measured by force plate is used for performance evaluation. At the beginning, the disturbing horizontal interaction force increases and push the



Fig. 10. Horizontal interaction force and CoP position (x direction). The left figure is for the fast condition in which a human moves relatively fast while the right figure is for the slow condition in which a human moves relatively slowly. The black and red lines are the horizontal interaction force and CoP position, respectively. The lines present the statistical average results and the red and blue regions are the distributions of the experiment results.

CoP away from the center of supporting feet. Balance controller attenuates the horizontal interaction force through regulating the SuperLimb's joint torques. When the horizontal interaction force converge back to around 5 N and CoP position returns to the initial location where the operator stands in balance. The CoP returns within around 0.8 s for the fast condition and around 2 s for the slow condition. The horizontal interaction force in the fast condition is relatively larger than that in the slow condition due to the inertia effects.

VI. CONCLUSION

This study proposed a model of the SuperLimb and human for overhead tasks and designed a balance controller to avoid potential falling danger. QR decomposition is used to decouple the supporting forces and the joint torques to control the interaction forces independently. To quantitatively evaluate the balance, CoP position is used as the balance index. Four subjects are invited to test the variability across the subjects. From the experimental results, the four subjects present different interaction forces due to variations of the inertia parameters, movement characteristics and etc. The variability is shown in the statistics results in Fig. 9 and 10. Overall, the proposed controller based on the operator-SuperLimb model is effective. We admit that there may be potential greater variability for more subjects cases. Theoretically, with accurate model parameters of both operator and SuperLimb, the controller is supposed to be consistently effective since both the models of the operator and the SuperLimb are taken into account. Within our best knowledge, it is the first time to study the standing balance issue of SuperLimb control for overhead tasks. The future work will include the comprehensive discussion about the controllability and the mechanical configuration of the SuperLimb.

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