Carrying Lower Extreme Exoskeleton Rapid Terminal Sliding-Mode Robust Control

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***Abstract*—For the carrying lower extreme exoskeleton system is non-linear and have variable parameters, which is usually subject to external dusturbances. The virtual torque control method is a well-established carrying system control technique, which needs no sensors between the pilot and the human-machine interface, instead, the controller estimates, based on measurements from the exoskeleton suits only, how to move so the pilot feels very little force. However, its main disadvantage lies on solveing the inverse dynamic model that is not easily obtained, which also need an exactly known dynamic model that is not realizable in practice. To overcome this issue, we propose building a virtual prototype model of the lower extremetry exoskeleton in SimMechanics. Using torque input and joint angle output data of the the virtual prototype model, the wavelet neural network is trained to building the inverse dynamics model which take the joint angle data as input and the torque data as output. In cases where some of the parameters of the plant undergo a change or the system is disturbed, poor performance may result. To cope with this drawback, based on Lyapunov stability principle, the rapid terminal sliding-mode robust adaptive controller is designed to control the serious nonlinear lower extreme exoskeleton system, and the convergence performance of the controller is analysed. Theoretical analyse and simulation results test the feasibility and validity of this control method.**

***Index Terms*—Carrying Lower Extreme Exoskeleton ; Inverse Dynamics Control; Virtual Prototype Model; Wavelet Neural Network; Rapid Terminal Sliding-Mode Robust Control**

I. Introduction

Different to the traditional robot, lower extremity exoskeleton intelligent carrying system is a new concept human-machine intelligent robot system, which task is keeping the mechanical leg coordinate with the operator while the interaction is less. The unique human-machine integral system has cause widely attention of international scholars[1]. Slave-master control[2,3], preprogramming control, force feedback control[4,5], ZMP control, myoelectric signal control, virtual joint torque control have all be used to the lower extreme exoskeleton control.

The aim of the slave-master control is acquiring information of the joint angle, which is used to the reference input signal and control the joint angle of the exoskeleton tracking the human's joint angle. The slave-master control method is used in the Hardiman exoskeleton[6], the inner exoskeleton is master, which is controlled by the operator and provide the command for the external slave exoskeleton. The exoskeleton also has the slave-master control structure, where the human joint should be measured and the machine can't block the human's movement, which need two exoskeleton and the system design is complex.

In the preprogramming control, exoskeleton devices are ran by pre-programmed procedure, the operator only can take some limited operation, such as "stop" or "start". These devices are such rehabilitation apparatus which are generally designed for patients with lower extreme disabilities, such as of the Ruthenberg active gait correction means [3]; Colombo gait correction, etc. [5]. All the rehabilitation-correction controlled by pre-programmed procedure require the patients to use a cane or additional auxiliary frame to keep the operator walking stability and the form of exercise achieved is also very limited.

The feedback information gotten from the force sensor can be used in the control system of HMI to keep the force between the machine and its surrounding environment at a pre-defined level [7]. In [8], Kyoungchul Kong and Hyosang Moon use the impedance

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compensation method to control the lower extremity exoskeleton, the force between the operator and the exoskeleton can be controlled, so that the operator does not feel the presence of the exoskeleton. In the force feedback control, the interaction force in the HMI should be measured, although in theory the establishment of such a control law is possible, but the actual hardware realization is very difficult.

Nanyang Technological University Xiaopeng Liu et al take lower limb trajectory tracking and zero moment point (ZMP: Zero Moment Point) control method to control its lower extremity energy and enhance the exoskeleton [4,9,10]. The disadvantage of this method is that the angle sensor must be installed on the body, which is as the reference input of the exoskeleton's location and is inconvenient to be used.

At present the most successful exoskeleton system come from the University of Tsukuba, Japan (Tsukuba) HAL series of lower extremity exoskeleton and the U.S. Berkeley University of weight-bearing exoskeleton system (BLEEX). HAL use EMG signals to identify the person's movement intent, it takes into account the viscous properties and elastic characteristics of human legs, the control of the viscous properties is studied based on the impedance control method, and the viscous properties of the muscle is analysed in-depth, so put the the HAL operator feel very comfortable [11,12]. But EMG control has its inherent disadvantages. It can not be mapped one-to-one relationship between joint torque and specific muscle EMG signal.

Virtual joint torque control selects the generalized moment vector control, the control law is in the joint space of the machine but is not at one point the human body. This method does not require any measurement device (such as a force sensor) installed between the human and machine, the controller can estimate how to move the exoskeleton to make the minimum force felt by the operator only through the measurement mounted on the exoskeleton. This control method has never been used in other robot system. For the system that the contact position between the exoskeleton suit and the operator is not fixed and difficult to be predicted, this control method can effectively control the movement of the exoskeleton suit. In paper[3,13,14], the research made by Berkeley University in the virtual torque control is given, which rely heavily on the accurate dynamic characteristics of the system model, such as the quality attributes, gravity properties and so on, and need to solve the inverse model of the system's dynamic equations, while the system is serious nonlinear and the inverse model of the dynamic equation is not easily obtained; the simple PD control method in paper[3,13,14] is used, but it doesn't appropiate for the lower extremity exoskeleton which contains friction and other non-linear factors, and the nonlinear robust control method should be used to control the lower extremity exoskeleton.

In this paper, the improved virtual joint torque control on the carrying robot is presented. In order to overcome the deficiencies of the virtual torque control, this passage take in-depth analysis of the human behavior characteristics and the control mechanism of carrying exoskeleton system virtual joint torque control, the virtual prototyping technology is introduced to model the exoskeleton. Using the prototype model, the wavelet neural network is applied to dynamic exoskeleton dynamics model study. Based on the principle of lyapunov stability, rapid terminal sliding-mode robust controller of the lower extreme exoskeleton system is designed. The convergence performance of the controller is analyzed, which is used to control lower extreme exoskeleton.

II. Lower Extreme Exoskeleton Virtual Torque Control

Fig. 1 shows a control block diagram of the virtual torque control, where G_a stands for the controlled object-the exoskeleton, $G_a^{'}$ stands for the inverse model of the exoskeleton, $K(s)$ is the controller.

From Fig. 1, we can get each joint angle q of the exoskeleton, calculated by the dynamics equation $G_a^{'}$ (Laplace equation), each of the joint torque which should be applied can be obtained. Compared with the actual output torque of the motor T_a, the virtual human-machine interference force can be gotten, which is used as the input of the controller. With the controller $K(s)$ added, the exoskeleton can be controlled. Meanwhile, if there exists angle error between man and machine when walking, i.e $q \neq q_h$, the man-machine interaction forces T_{hm} exists, which will also be applied to the

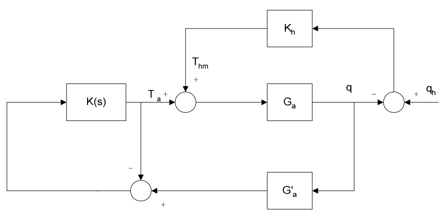

Figure 1. A simplified block diagram of the virtual torque control law.

exoskeleton. Pure torque of the machine exterted on the human can be considered as the result of the angular position error between human and machine[15]:

$$T_{hm} = K_h(q - q_h) \quad (1)$$

K_h is the equivalent impedance on the different point of the man-machine contact.

The man-machine torque model sometimes can be replaced by the spring - damping model:

$$T_{hm} = K_{p1}e + K_{d1}\dot{e} \quad (2)$$

Where $e = q_d - q$

From equation (1) and (2) we can see, the torque between the human and the machine is closely related to the location of the exoskeleton, the control target $T_{hm} \to 0$ is the same to the tracking objective $q \to q_h$, therefore, the stabilize of the T_{hm} / q_h can be guaranteed as long as the stabilize of the q / q_h is guaranteed.

For the exoskeleton systems using Lagrange equation to establish the dynamic model of the system $G_a^{'}$:

$$T = J\left(q\right)\ddot{q} + B(q,\dot{q}) + G\left(q\right) . \quad (3)$$

J stands for the moment of inertia, which is function of q; B stands for the centrifugal and Kerry Orie matrix, which is function of q and $\dot{q}$; G stands for gravity torque vector, which is function of q. The corresponding joint torque vector is $T = [T_1 \quad \ldots \quad T_n]^T$.

Ignoring the influence of friction, the joint torque of the human extered to the exoskeleton

$$T_{hm} = J\left(q\right)\ddot{q} + B\left(q,\dot{q}\right) + G\left(q\right) - T_a . \quad (4)$$

T is the output torque of the motor, G_a' is the estimation of the exoskeleton forward dynamic, if the model is very accurate, then $G_a G_a' = 1$

The control method presented in Fig. 1 is heavily dependent on the dynamic model $G_a^{'}$, and the precise mathematical model must be established.

In practical, it is often very difficult, such as in equation (4) the parameters of J, B, G, are not easy to accurately obtain . In this article the virtual prototype model is bulit using the SimMechanics in Matlab, and based on the input and output data of the virtual prototype model, the wavelet network (WNN) model of the dynamics model $G_a^{'}$ is built and avoid the complex mathematical model establishment of the exoskeleton nonlinear, strong coupling system. In order to overcome the friction, load disturbance, model uncertainty and other nonlinear factors of the lower extremity exoskeleton, rapid terminal sliding-mode robust adaptive nonlinear controller is designed to control the carrying robot. The improved system control block diagram is shown in Fig. 2, where $F(e,\dot{e})$ is the nonlinear controller.

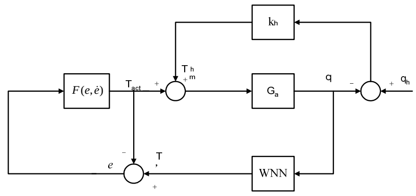

Figure 2. Lower extreme exoskeleton rapid terminal sliding-mode robust control diagram based on wavelet neural network.

III. Exoskeleton Virtual Prototype Model Building in SimMechanics

Using SimMechanics toolbox in Matlab, a lower extremity exoskeleton seven link virtual prototype model is established. In Fig. 3 the SimMechanics model is shown, where the inputs are three joint torque signals, the outputs are three joint angular signal, three joint angular velocity signals and three joint angular acceleration signals. The SimMechanics toolbox has a set of visual tools, which can be used to display the simulation result dynamically.

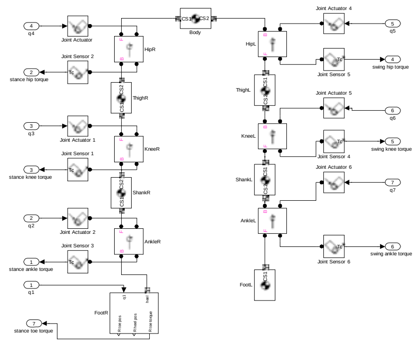

Figure 3. Virtual prototype model of lower extreme exoskeleton buit in SimMechanics

IV. Exoskeleton Inverse Dynamics Model Identification Using Wavelet Neural Network

Multilayer feedforward neural networks can approximate any nonlinear mapping with arbitrary precision, and bring a new, non-traditional expression tools for the modeling of complex systems. The lower extreme exoskeleton system inverse dynamic model $G_a^{'}$ can be made according to the input and output data of the virtual prototype model of the exoskeleton to complete the neural network modeling, and avoid the complexity modeling process of this non-linear, strong coupling system. In recent years, with the depth of the wavelet research and applications , people construct the wavelet network based on the idea of neural network. This network is a local basis function network, which has the adjustable distinguish scale, so that the network has a stronger nonlinear learning function, considering the compactly supported set of the wavelet basis function and small interaction between neurons, the learning speed is more faster .

Based on the input and output data of the virtual prototype model, the wavelet network (WNN) is trained to build the inverse dynamics model which take the exoskeleton joint angle, joint angular, joint angle velocity and joint angle acceleration of the virtual prototype model as input and the torque data as output.

In this study, the Morlet wavelet $\psi(\mathrm{t})$ is chosen as the mother wavelet, which has good finity support both in time-domain and frequency-domain:

$$\psi(x) = -xe^{-\frac{1}{2}x^2} . \quad (5)$$

The input vector is $\mathrm{x} = [\mathrm{x}_1, \mathrm{x}_2, \cdots, \mathrm{x}_\mathrm{n}]$, the wavelet has N nodes, w_{ij} is coefficient of the jth wavelet node to the kth output variable, and the kth output variable is

$$y_k \approx \sum_{j=1}^{N} W_{jk} \psi\left(\frac{x - t_j}{s_j}\right) . \quad (6)$$

The less s, that is, the higher frequency, the time precision is higher. On the other hand, the higher s, the less frequency, the frequency precision is higher. If the flex factor s_i and the translation factor t_i are not selected appropriately, the preset function can not be approximated exactly.

Train the network using BP method, the adaptive law of the weight is selected according to the paper[18].

V. Fast Terminal Sliding mode Robust Controller Design

Through the estimation of the input torque using the inverse model of the exoskeleton dynamic equation and the motor output torque, the virtual human-machine reaction T_{hm} can be obtained. Suppose the reference signal of T_{hm} is T_{hm_ref}, which is equal to zero. Suppose the error signal of the control system is e,

$$e \approx T_{hm} - T_{hm\_ref} = T_{hm} . \quad (7)$$

The system has the following equation :

$$F(e,\dot{e}) + e = J(q)\ddot{q} + B(q,\dot{q})\dot{q} + G(q) + \tau_d . \quad (8)$$

Where τ_d stands for the modeling errors and external interference, let $u = F(e,\dot{e})$, and then design the fast terminal sliding robust controller.

Let

$$u + \boldsymbol{e} = \dot{\boldsymbol{e}} + u_1 . \quad (9)$$

Then

$$\dot{e} = J(q)\ddot{q} + B(q,\dot{q})\dot{q} + G(q) + \tau_d - u_1 . \quad (10)$$

At first, obtain the control of the nominal system u .Considering the reduced-order nature of the fast terminal sliding model, choose the sliding surface for sliding mode control:

$$s = Ce . \quad (11)$$

Where $C = diag\{c_1, c_2, ..., c_n\}$,considering writing convenience, define the vectors as follows:

$$s^{\gamma} = \left[s_1^{\gamma}, s_2^{\gamma}, \cdots, s_n^{\gamma}\right]^T, |s| = \left[|s_1|, |s_2|, \cdots, |s_n|\right]^T . \quad (12)$$

$$\hat{\phi} \circ \mathrm{sign}(\mathbf{s}) = \left[\hat{\phi}_1 \circ \mathrm{sign}(\mathbf{s}_1) \quad \hat{\phi}_2 \circ \mathrm{sign}(\mathbf{s}_2) \quad \cdots \quad \hat{\phi}_{\boldsymbol{n}} \circ \mathrm{sign}(\mathbf{s}_{\boldsymbol{n}})\right]^{\boldsymbol{T}} . \quad (13)$$

Where $\hat{\varphi}_i$, s_i ($\boldsymbol{i} = 1, 2, \cdots, \boldsymbol{n}$) are the expression of the i component of the vector $\hat{\varphi}, \boldsymbol{s}$.

The global rapid terminal reaching law:

$$\dot{s} = -K_1 s - K_2 s^{\gamma_1} . \quad (14)$$

Where $0 < \gamma_1 = q/p < 1$, p, q is positive odd, $K_1 = diag\{K_{11}, K_{12}, \cdots, K_{1n}\} > 0$, $s^{\gamma_1} = \left[s_1^{\gamma_1}, s_2^{\gamma_1}, \cdots, s_n^{\gamma_1}\right]^T$, $K_2 = diag\{K_{21}, K_{22}, \cdots, K_{2n}\} > 0$.

According to (10), (11), (14), the following can be gotten:

$$\boldsymbol{C}[\boldsymbol{J}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{B}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) - \boldsymbol{u}_1] = -\boldsymbol{K}_1\boldsymbol{s} - \boldsymbol{K}_2\boldsymbol{s}^{\gamma_1} . \quad (15)$$

Theorem 1 In the case of no modeling errors and external interference, that is, the system is the nominal system, the fast terminal sliding mode control law of the system (9) is:

$$\boldsymbol{u}_1 = \boldsymbol{J}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{B}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) + \boldsymbol{C}^{-1}(\boldsymbol{K}_1\boldsymbol{s} + \boldsymbol{K}_2\boldsymbol{s}^{\gamma_1}) . \quad (16)$$

From which the fast terminal sliding mode control law of the system (8) under nominal condition can be gotten:

$$\boldsymbol{u} = \dot{\boldsymbol{e}} - \boldsymbol{e} + \boldsymbol{J}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{B}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) + \boldsymbol{C}^{-1}(\boldsymbol{K}_1\boldsymbol{s} + \boldsymbol{K}_2\boldsymbol{s}^{\gamma_1}) . \quad (17)$$

Modeling errors and external interference is inevitablely existed in the actual system, that is, τ_d is impossible equal to zero, so fast sliding mode controller with strong robustness should be designed.

If τ_d is bounded, that means

$$\|\boldsymbol{\tau_d}\| \le \boldsymbol{l} . \quad (18)$$

Designing the fast sliding mode controller with robustness to satisfy the formula (18) .

Theorem 2 If system (8) satisfys the formula (18), design the control law shown in the formula (19)

$$u = \dot{e} - e + J(q)\ddot{q} + B(q,\dot{q})\dot{q} + G(q) + C^{-1}(K_1 s + \bar{K}_2 s^{\gamma_1}) \quad (19)$$

Within a limited time, the tracking error of the system converges to the equilibrium state. In the equation(19) $\bar{K}_2 = K_2 + \frac{\|C\|}{\|s^{\gamma_1}\|} l I_n$, I_n is a unit matrix, the meaning of other parameters are the same as in the formula (14).

Proof: According to equation (10), (14) , we have

$$\dot{s} = C\dot{e} = C(J(q)\ddot{q} + B(q,\dot{q})\dot{q} + G(q) + \tau_d - u_1) \quad (20)$$

From the formula (9), substituting the control law (19) into the above formula (20) , we obtain

$$\dot{s} = C\dot{e} = -K_1 s - \bar{K}_2 s^{\gamma_1} + C\tau_d \quad (21)$$

Lyapunov function is defined as follows

$$V = \frac{1}{2} s^T s \quad (22)$$

Obviously function (22) is positive, differentiating it with respect to time yields,

$$\dot{V} = s^T \dot{s} \quad (23)$$

Taking into account the equation (21), we obtain

$$\dot{V} = s^T\left(-K_1 s - \bar{K}_2 s^{\gamma_1} + C\tau_d\right) \quad = -s^T K_1 s - s^T\left(K_2 + \frac{\|C\|}{\|s^{\gamma_1}\|} l I_n\right) s^{\gamma_1} + + s^T C\tau_d \quad (24)$$

We also have

$$s^T \frac{\|C\|}{\|s^{\gamma_1}\|} l I_n s^{\gamma_1} = \frac{\|C\|}{\|s^{\gamma_1}\|} l \sum_{i=1}^{n} s_i^{1+\gamma_1} = \frac{\|C\|}{\|s^{\gamma_1}\|} l \sum_{i=1}^{n} s_i^{(p+q)/p} \quad (25)$$

p, q is positive odd, so $s_i^{(p+q)/p} = |s_i|^{(p+q)/p} \ge 0$, then considering the relationship between the norms

$$\frac{1}{\|s^{\gamma_1}\|} \sum_{i=1}^{n} s_i^{(p+q)/p} \ge \frac{1}{\|s^{\gamma_1}\|} \|s^{\gamma_1}\| \|s\| = \|s\| \quad (26)$$

Therefore, equation (24) satisfies

$$\dot{V} \le -s^T K_1 s - s^T K_2 s^{\gamma_1} - \|s\|\|C\| l + \|s\|\|C\|\|\tau_d\| \le -s^T K_1 s - s^T K_2 s^{\gamma_1} - \|s\|\|C\|(l - \tau_d) \quad (27)$$

According to the equation (18), equation (27) can be written as

$$\dot{V} \le -s^T K_1 s - s^T K_2 s^{\gamma_1} \quad (28)$$

The equation (28) satisfies

$$\dot{V} \le 0, \ s \ne 0 \quad (29)$$

Where $\dot{V}$ is negative definited, and V is positive definited, according to the Lyapunov stability theory , the system is stable.

VI. Simulation Realization

The human-machine interaction model mainly described the relationship between the torque that the human applies to the exoskeleton suit and the tracking error. Here, the interaction between human and machine is calculated according to the equation (1).

The system (8) is added to terminal sliding mode controller accordance with the equation (17) under the nominal case. In order to overcome the differential amplification error, the filter segment is added. In order to analyze the system's anti-interference ability, parameter perturbation is considered and the terminal sliding mode controller is added in accordance with the equation (19). Where, taking

$K_1 = [10, 10, 10]^T$,

$K_2 = [4, 4, 4]^T$ $C = [25, 25, 25]^T$, $l = 100$,

$q = 3$, $p = 5$.

From Fig. 4 to Fig. 7, the angle output curve of the exoskeleton tracking the human and the torque extered by the human and the machine are shown, which are simulated under the condition of a normal situation and the exoskeleton mass parameters were increase of 20%. It can be seen from the figure, the exoskeleton can well track the motion of the human, the human-machine interaction force is comparatively small. In the movement process, only a certain amount of the starting torque is needed to be provided by human, while the majority torque is provided by actuator. When the interference is added, the torque applied by the actuator and the operator changed little and the joint angle track well, which show the strong robustness of the system.

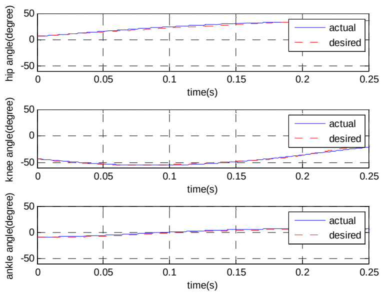

Figure 4. Joint angle tracking curve under normal condition

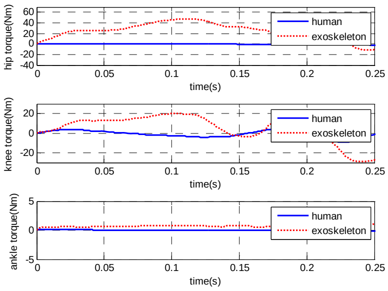

Figure 5. Torque curve under normal condition

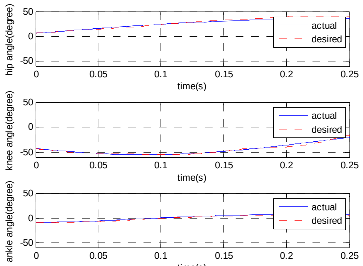

Figure6. Angle tracking under model parameter 20% decrease

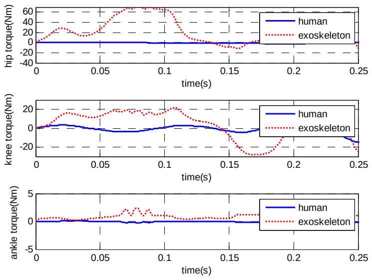

Figure7. Torque curve under model parameter 20% decrease

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