Simulation Research of Exoskeleton Suit Based on Neural Network Sensitivity Amplification Control

Zhiyong Yang[1], Lihua Gui[2], Xiuxia Yang[2], Wenjin Gu[2]

1. Department of Strategy Missile Engineering, Naval Aeronautical and Astronautical University, Yantai 264001, China

E-mail: yzy913@163.com

2. Department of Control Engineering, Naval Aeronautical and Astronautical University, Yantai 264001, China

E-mail: guilihua@taikang.com, yangxiuxia@21cn.com

Abstract: Traditional exoskeleton suit need to install many complex sensors between the pilot and the exoskeleton system to measure the human-machine interactive information, which decrease the comfort of the pilot. Sensitivity Amplification Control can control the exoskeleton suit to trace the pilot's movement as well as need no sensors between the pilot and the exoskeleton. However, Sensitivity Amplification Control seriously relies on the system's dynamic model and it is hard to build the exoskeleton suit's dynamic model exactly because the exoskeleton suit is a multi-body, multi-degree and nonlinear system. So the dynamic model of the swing leg of exoskeleton suit was identified by BP neural networks, which simplified the procedure of building the system model. Neural Network Sensitivity Amplification Control was proposed and its feasibility was validated by simulation based on Simulink and SimMechanics toolbox in Matlab.

Key Words: Exoskeleton Suit; Human-machine; Sensitivity Amplification Control; Neural Network; SimMechanics;

1 Introduction[1]

Exoskeleton suit is a mechanical system has close contact with human beings. It has two mechanic legs similar to humans, and integrates with human through connection at operator's waist, foot or lower limb. In this human-machine system, the mechanical legs carry the entire load and the operator serves as the control centre to determine the walking direction and speed. There are many sensors installed in the exoskeleton legs which can measure the motion information of the pilot. Then the control algorithm will judge the pilot's motion consciousness and control the exoskeleton leg to move. The greatest difference between exoskeleton suit and other robot is that the CPU of exoskeleton suit is human but the machine itself. Exoskeleton suit combine the human intelligence with the powerful mechanism which will make a change never realized [1].

2 Control Method

Many different exoskeleton suits have been developed from the early 1960s [2], [3]. Vukobratovic assigns a fixed programmed motion for some of the joints of his paraplegic exoskeleton, while assigning other stabilizing joint torques through dynamic equations generated using force sensors at the feet. This exoskeleton can only track some fixed motion and the patient needs to provide additional stability using crutches or a walking frame because of all of the motion is preprogrammed. Ruthenberg's Powered Gait Orthosis [4] and Colombo's Driven Gait [5] Orthosis was similar.

From 1960 to 1971, General Electric developed a full-body exoskeleton based on master slave control method which was named "Hardiman" [6]. Hardiman just realized the control of one arm and was abandoned finally because of the limited of technique. Hardiman used a master slave control method, and in this method there must be two exoskeletons: a master exoskeleton worn by the human to record joint angles or body segment positions and orientations, and a powered slave exoskeleton which mimics the motion of the human. The two exoskeletons result in a system in which space must be allocated between the machine and the human to insert the appropriate instrumentations and to enable the human to move inside the machine. All of this result in a bulky design.

Professor Saikai has developed the mostly successful exoskeleton used for walking aid of handicapped and aged people which is named HAL (Hybrid Assistive Leg) [7], [8]. HAL use the s-EMG (surface ElectroMyogram /Myoelectricity) to sense the neuromuscular signal which generated when motion. The measured myoelectricity signal was transformed to the activity of the muscles. The estimation of the torque exerted by the flexor and the extensor can be defined as a linear function of the muscles activity. Then the assist torque exerted by HAL can be expressed in a linear function of the torque exerted by flexor and extensor. But there are many disadvantages when using s-EMG: 1) surface electrode is prone to fall off, transpose when there have a drastic movement; 2) the accuracy of the electrode will be influenced when people perspiring after a long time locomotion; 3) for the same electrode there exist difference between different people; 4) the electrode must be installed on the operator every time he (her)

This work is support by the National Nature Science Foundation under Grant 60705030 and Postdoctoral Science Grant of China 20060400293.

want to wear the exoskeleton. Some similarly exoskeleton is being studied in the University of Twente, Netherlands [9] and in the University of Abertay Dundee, United Kingdom [10].

Xiaopeng Liu etc developed a Lower Extremity Exoskeleton using lower trajectory tracing and ZMP control method [11]. There must install a set angle sensors on the human's leg to measure the position of the human's leg. Then the exoskeleton was controlled to trace the leg's trajectory. At the same time, the exoskeleton's ZMP must be controlled to keep its stable. This method is not convenient and comfortable because of the sensor installed on the human.

All of the method mentioned above need to install sensors between the human and the exoskeleton which heavily decreases the human's comfort. Racine proposed a method named virtual joint torque control [12]; this method is also being called Sensitivity Amplification Control (SAC) [13], and was applied to the BLEEX (Berkeley Lower Extremity Exoskeleton). SAC needs no direct measurements from the pilot or the human-machine interface (e.g. no force sensors between the two); instead, the controller estimates, based on measurements from the exoskeleton suits itself, how to move so the pilot feels very little force. This control scheme, which has never before been applied to any robotic system, is an effective method of generating locomotion when the contact location between the pilot and the exoskeleton is unknown and unpredictable.

SAC is a control method seriously relies on the dynamic model of the system [13]. It is very difficult to built the exact mathematical model of exoskeleton suit because of it is a multi-body, multi-degree and high nonlinear system. And in simulation, the most difficult is exoskeleton suit is a human-machine system and the human-machine interface model is hard to describe. In [14], the human-machine interface was modeled as a PID controller. But it is not enough to describe the human's intelligence. In this paper, we use the SimMechanics model to mimic the human-machine interface model and propose a Neural Network Sensitivity Amplification Control (NNSAC) method. NNSAC method maintains the performance of SAC as well as simplify the procedure of model the system's mathematical model.

3 Theoretical Analysis

3.1 Describe of SAC

The Block diagram of exoskeleton suit is shown in Fig 1. Where G denote the dynamic model of exoskeleton suit, G_h denote the dynamic model of pilot, $\vec{q}_h = [q_h \quad \dot{q}_h \quad \ddot{q}_h]$ denote the desired trajectory of the pilot which is also the desired trajectory of the exoskeleton suit, $\vec{q} = [q \quad \dot{q} \quad \ddot{q}]$ denote the actual output trajectory of the exoskeleton suit, $\vec{T}_{hm}$ denote the torque exert to the exoskeleton suit by the pilot, $\vec{T}_a$ denote the torque exert by the actuator, $\vec{T}$ denote all the external torque exert to exoskeleton suit except for gravity torque and can be written as follows:

$$\vec{T} = \vec{T}_a + \vec{T}_{hm} \tag{1}$$

There was no SAC controller in Fig 1 which means $\vec{T}_a = 0$ and the pilot need to exert all the torque to move the exoskeleton suit.

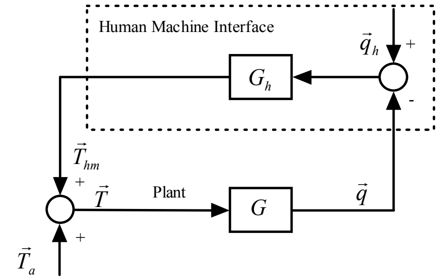

Fig 1. Block diagram of exoskeleton suit without actuation

Let the dynamic model of exoskeleton is:

$$\vec{q} = G(\vec{T}) \tag{2}$$

The inverse model is:

$$\vec{T} = G'(\vec{q}) \tag{3}$$

When the actuator doesn't work (that is $\vec{T}_a = 0$), then from equation (1) and (3), we can get:

$$\vec{T}_{hm} = G'(\vec{q}) \tag{4}$$

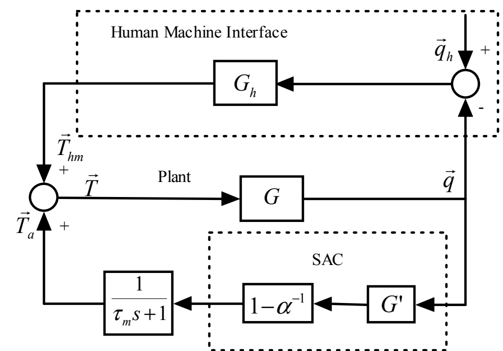

Fig 2. Block diagram of exoskeleton suit with SAC controller

If a SAC controller was added to the system, shown in Fig 2, where $1/(\tau_m s+1)$ denote a low pass filter which was used to eliminate the influence of the unmodeled high frequency dynamics, and designed the controller as:

$$\vec{T}_a = (1-\alpha^{-1})G'(\vec{q}) \tag{5}$$

Where α >1, then the torque exerted by the pilot was:

$$\vec{T}_{hm} = \alpha^{-1}G'(\vec{q}) \tag{6}$$

If we select α =10, compared with equation (4), the torque exerted by the pilot become very small which show that the SAC controller can decrease the torque exert by the pilot efficiently, as a result decrease the power consumption of the pilot.

3.2 Neural Network SAC Controller

From equation (5), we can know SAC controller seriously rely on the dynamic model of the system. In fact it is very difficult to get the exact model of exoskeleton suit because it is a multi-body, multi-degree, and high nonlinear system. Multi-layer feedforward neural network can approach arbitrary nonlinear map at arbitrary precision, which bring a novel and nontraditional method to model a complex system. We just need to know the relationship between the input and output data of the system which reflect the character of the system when we use neural network to built the system's dynamic model. This data was used to train the network and get a generalized net to replace the system model which simplifies the modeling procedure. The block diagram of exoskeleton suit with NNSAC controller is shown in Fig 3.

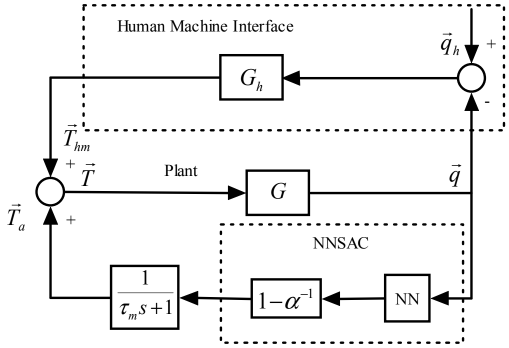

Fig 3. Block diagram of exoskeleton suit with NNSAC controller

4 Simulation

4.1 System Model

One of a human's legs has two alternatively different phases in a gait cycle that was called swing phase and support phase. Swing phase means the phase that the foot is not contact with the ground, well support phase means the phase that the foot is contact with the ground. For one leg, the support phase is complex relatively because this phase is influenced by the state of the other leg, but the swing phase is simple relatively, so the model of the swing leg is taken as research object to simulate the SAC control method. In this model, the upper body is selected as the reference frame and the swing leg is assumed to be a three segment serial manipulator (thigh, shank and foot) pinned to the upper body at the hip, which is shown in Fig 4. The length of the thigh link is L_t, and the length of the shank link is L_s. The position of the centre of the gravity of the thigh by L_{Gt} and h_{Gt}, that of the shank by L_{Gs} and h_{Gs}, and that of the foot by L_{Gf} and h_{Gf} as shown. And O_i denote the original of the local coordinate system; e_{ij} denote the unit vector in the local coordinate system.

The mathematical model of the swing leg has been given in [14]. Here the complex mathematical model was needn't but a SimMechanics model is chosen as the plant. Set the input of the SimMechanics model as joint torque we get the forward dynamics model. And if set the input of the SimMechanics model as joint motion information we get the inverse dynamics model. The forward dynamics model is taken to denote the exoskeleton suit system as shown in Fig 5.

For simplicity we assume the swing leg has a similar mass and geometry properties with human leg. So we use the anthropometric data computed from Winter D. A. as the parameters of the exoskeleton suit's leg [15].

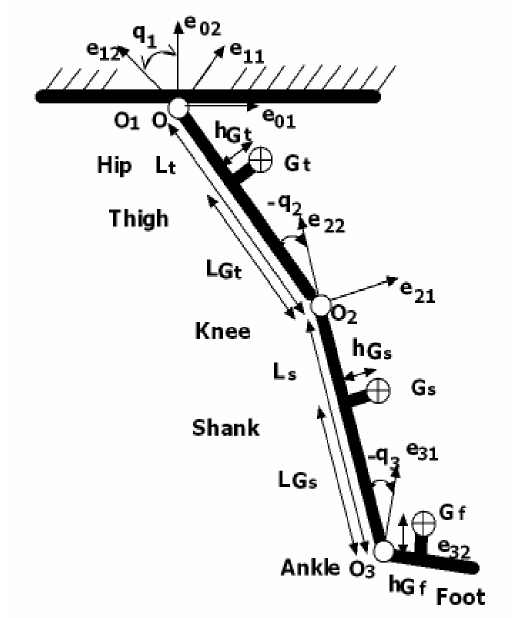

Fig 4. Swing leg model of exoskeleton suit

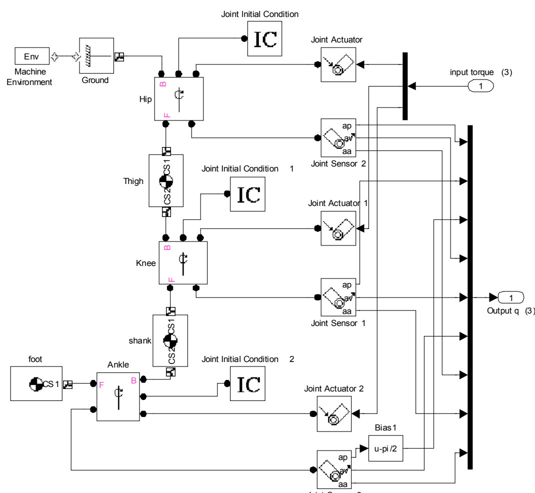

Fig 5. SimMechanics forward dynamic model of the swing leg

4.2 Neural Network Model

The key problem of NNSAC is taking the neural network as the inverse model in SAC. We must get the input and output data of the system to train the neural network so that the network has the same properties with the inverse model. SimMechanics inverse model was used to get the train data. Input some different motion trajectory (include joint angle, joint angle velocity and joint angle acceleration) to the SimMechanics inverse model, then get the output torque. In order to reflect the most of the swing leg's motion state, the input motion trajectory was composed of different frequency sinusoid signal and each joint angle range was ensuring to be in the natural range of human beings.

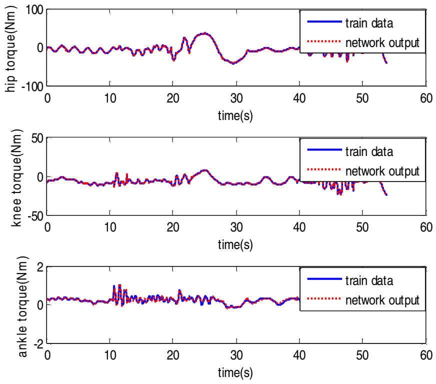

Fig 6. Train data and the neural network output data

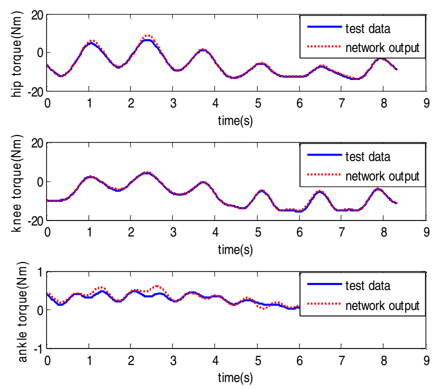

Fig 7. Test data and the neural network output data

BP network is a typical feedforward neural network which can realize arbitrary nonlinear map from the input to the output, and the learning algorithm of BP network belongs to a global approach method and have a preferably generalization ability. So a BP neural network was chosen to approach the inverse model of the exoskeleton suit. Fig 6 shows the comparison of the object torque data and the output torque data of the network after training. Fig 7 is the comparison of the test data's desired torque and output torque of the network. This two figures show the network has a good performance. Using the order "Gensim" in Matlab, the Simulink model of the network can be generated. Then the network's Simulink model can work together with SimMechanics model to simulate the exoskeleton system.

4.3 Human-machine Model

Human-machine interaction model is used to describe the relationship between the human exerted torque to the exoskeleton and the tracing error. This model just used for simulation. In [14] a PID controller is used to describe human-machine interaction model, but it is not enough to reflect the human's intelligence. Here an inverse model is used to replace the PID controller that is $G_h = G'$, which reflect the human-machine interaction factually. We also use the anthropometric data computed from Winter D. A. as the parameters of the inverse model. The input of the model is the error between the desired motion trajectory of the human and the actual motion trajectory of the exoskeleton suit. The output of the model is the torque human exert to the exoskeleton suit.

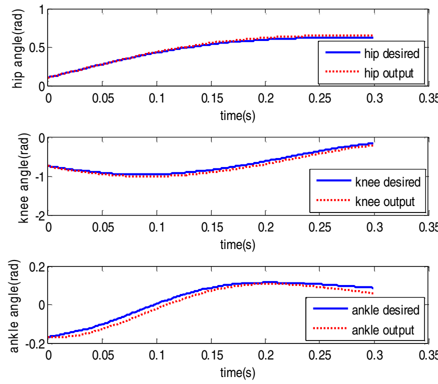

Fig 8. Trajectory of joint angle

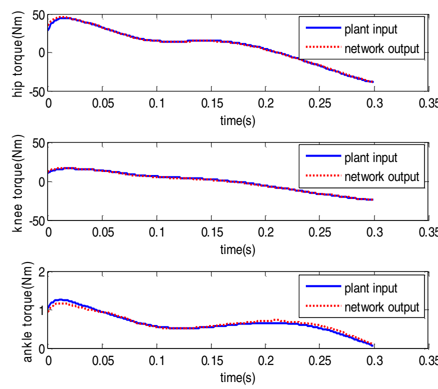

Fig 9. System input torque and neural network output torque

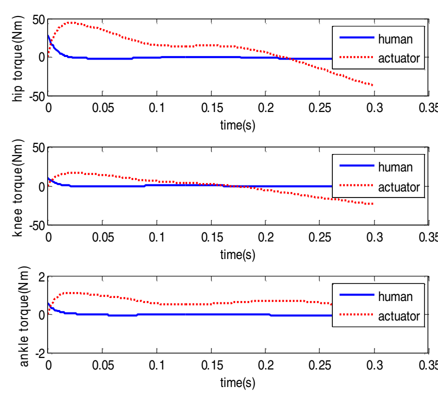

Fig 10. Torque exerted by the pilot and the actuator

4.4 Simulation Result

When simulation, we choose the swing phase data from the Clinical Gait Analysis (CGA) data as the desired motion of the pilot [16], and only the data of the swing leg is selected. The CGA data has a longer step and a fewer data, so a linear interpolation is used to get the other data. The simulation results are shown in Fig 8 to Fig 10. Fig 8 show the exoskeleton suit can trace the human's motion trajectory well. Fig 9 show the inverse model gets from the neural network can trace the input torque adequately. Fig 10 show that at the beginning of move the exoskeleton suit the pilot need to exert a big torque, but once the exoskeleton suit start to move, most torque is provide by the actuator, the pilot just need a little torque scaled down to the actuator's torque to change the motion state which show the feasibility of the NNSAC.

5 Conclusion

The main goal of SAC is maximize the sensitivity of the closed loop system to forces and torques which has a sharp contrast with the classical and modern control theory as all the effort is made to minimize the sensitivity function of a system to external forces and torques. The SAC method has the advantage that it need no sensor (e.g. force or EMG) in the interface between the pilot and the exoskeleton suit and one can push and pull against the exoskeleton in any direction and at any location without measuring any variables on the interface.

The SimMechanics toolbox in Matlab was used to build the forward and inverse model of exoskeleton suit. The forward model serve as control object and the inverse model was used to describe the human-machine interaction model. A Neural Network SAC controller was proposed to make up the limitation of SAC which need the exact dynamic model of the system. Simulation results show the feasibility of NNSAC. Further study should focus on the whole lower extremity model and the model variety in the transition process of the two legs.

REFERENCES

[1] Yang Canjun, Niu Bin, Chen Ying, "Adaptive neuro-fuzzy control based development of a wearable exoskeleton leg for human walking power augmentation", Proceedings of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Monterey, California, USA, pp. 24-28, July, 2005

[2] Vukobratovic M., Ciric V., and Hristic D., "Contribution to the study of active exoskeletons". Proceedings of the 5th International Federation of Automatic Control Congress, Paris, 1972

[3] Hristic D. and Vukobratovic M., "Development of Active Aids for Handicapped", Proceedings of the III International Conference on Biomedical Engineering, Sorrento, Italy, 1973

[4] Ruthenberg B.J., Wasylewski N.A., Beard J.E., "An Experimental Device for Investigating the Force and Power Requirements of a Powered Gait Orthosis", Journal of Rehabilitation Research and Development, Washington, Apr 1997

[5] Colombo G., Jorg M., Dietz V., "Driven Gait Orthosis to do Locomotor Training of Paraplegic Patients", Proceedings of the 22nd Annual EMBS International Conference, Chicago IL, July 23-28, 2000, pp: 3159-3163.

[6] http://www.davidszondy.com/future/robot/hardiman.htm

[7] Lee S. and Sankai Y., "Power assist control for walking aid with HAL-3 based on EMG and impedance adjustment around knee joint". In Proc. Of IEEE/RSJ International Conf on Intelligent Robots and Systems (IROS 2002), EPFL, Switzerland, pp. 1499-1504, 2002

[8] Hiroaki Kawamoto and Yoshiyuki Sankai, "Power assist system HAL-3 for gait disorder person", K. Miesenberger, J. Klaus, W. Zagler (Eds.): ICCHP 2002, LNCS 2398, pp. 196-203, 2002.

[9] J. F. Veneman, R. Ekkelenkamp, R. Kruidhof, F. C. T. van der helm, H. van der Kooij, "Design of a series elastic- and Bowden cable-based actuation system for use as torque-actuator in exoskeleton-type training", Proceedings of the 9th International Conference on Rehabilitation Robotics, June 28 – July 1, Chicago, IL, USA, 2005

[10] Camilo Acosta-Marquez and David A Bradley, "The analysis, design and implementation of a model of exoskeleton to support mobility", Proceedings of the 9th International Conference on Rehabilitation Robotics, June 28 – July 1, Chicago, IL, USA, 2005

[11] Xiaopeng Liu, K. H. Low, Hao Yong Yu, "Development of a Lower Extremity Exoskeleton for Human Performance Enhancement", Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, Sendai, Japan, September 28 - October 2, 2004, pp: 3889-3894.

[12] J. L. Racine, "Control of a lower extremity exoskeleton for human performance amplification", Ph. D. dissertation, University of California, Berkeley, 2003.

[13] J. R. Steger, "A design and control methodology for human exoskeleton", Ph. D. dissertation, University of California, Berkeley, 2006.

[14] Zhiyong Yang, Lihua Gui, Xiuxia Yang, Wenjin Gu, Yuanshan Zhang, "Simulation Research of Exoskeleton Suit Based on Sensitivity Amplification Control", Proceedings of the IEEE International Conference on Automatic and Logistics, Jinan, China, pp.1353-1357, Aug. 18-21, 2007

[15] Winter, D. A., "Biomechanics of Human Movement", John Wiley and Sons, New York, 1979.

[16] Kirtley C., Hong Kong Polytechnic University, Http://guardian.curtin.edu.au:16080/cga/data/HKfyp98/All.gcd