Review and Analysis on Main Technology of Exoskeletal Robot System for Upper Limbs Rehabilitation

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Abstract. Major function of exoskeletal robot system for upper limbs rehabilitation is to assist patient to carry out upper limbs' rehabilitation training. Main technology of exoskeletal robot system for upper limbs rehabilitation includes design of mechanical structure of exoskeletal robot, design of control system of exoskeletal robot and implemention of data and information transmission between exoskeletal robot and upper limbs of human body. Currently implemention of data and information transmission rely mainly on methods of acquiring sEMG signal and force feedback. Reviewing and analyzing the specific technical development and deficiency in field of exoskeletal robot system for upper limbs rehabilitation will be important way in improving and upgrading the technology in future.

1. Introduction

Exoskeletal robot technology for upper limbs rehabilitation is a new interdisciplinary research field of mechanical engineering and medical rehabilitation at present. Major function of exoskeletal robot system for upper limbs rehabilitation is to assist patient to carry out upper limbs' rehabilitation training. According to modern evidence-based medicine (EBM) and continuous passive motion (CPM) theory [1, 2], exoskeletal robot for upper limbs rehabilitation can assist patient to recover normal exercise capacity in a relatively short period of time. Internationally, main technology of exoskeletal robot system for upper limbs rehabilitation has been widely studied and applied.

Main technology of exoskeletal robot system for upper limbs rehabilitation includes design of mechanical structure of exoskeletal robot, design of control system of exoskeletal robot and implemention of data and information transmission between exoskeletal robot and upper limbs of human body. Currently implemention of data and information transmission rely mainly on methods of acquiring sEMG signal and force feedback. So far in the field lots of progress has been made, but there are still some problems waiting to be solved. Reviewing and analyzing development and deficiency in field of exoskeletal robot system for upper limbs rehabilitation will be important way in improving and upgrading the technology in future.

2. Review on Design of Mechanical Structure of Exoskeletal Robot System for Upper Limbs Rehabilitation

There are three main types of mechanical structures of robot system for upper limbs rehabilitation: end structure, exoskeleton structure and mixed structure. Compared with other structures of robot system for upper limbs rehabilitation, exoskeleton structure has irreplaceable superiority [3-5].

Dextrous Hand Master as in figure 1 developed by EXOS company [6] and Cybergrasp hand exoskeleton as in figure 2 developed by Immersion company [7] are both designed for multi finger joints and integrated with joint sensor, but the structures are too trouble for patients in dressing and using and are easy to make patients psychologically terrified and physically uncomfortable.

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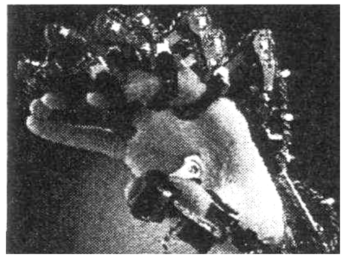

Figure 1. Dextrous Hand Master.

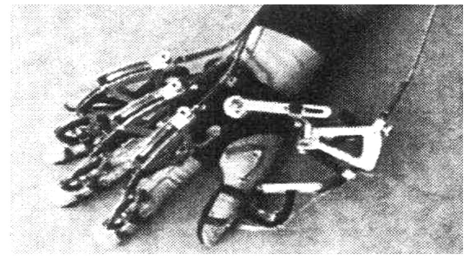

Figure 2. Cybergrasp.

CPM machine as in figure 3 developed by Ability One company and CPM machine as in figure 4 developed by Rolyan company for continuous passive motion in hand function rehabilitation are both with simple structures and comfortable for dress, but their structures with weak flexibility can only allow single joint rehabilitation motion and can't precisely control multi finger joints simultaneously in multi joints rehabilitation. Hand Mentor as in figure 5 developed by KMI company [8] with simple structure and good flexibility using pneumatic muscle can only allow finger rehabilitation combined with wrists but not allow refined finger rehabilitation training. RM II-ND Hand Master as in figure 6 developed by New Jersey State University in the USA [9] is also driven by pneumatic muscle, but its glove-type dressing structure and pneumatic muscle set in palm device restrict fingers' range of movement.

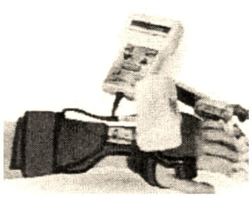

Figure 3. CPM by AbilityOne.

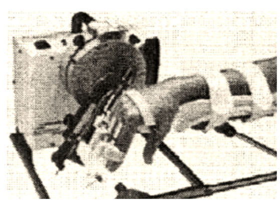

Figure 4. CPM by Rolyan.

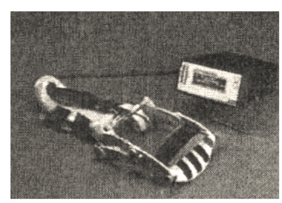

Figure 5. Hand Mentor.

Figure 6. RM II-ND.

Currently most designs of mechanical structure of exoskeletal system for upper limbs rehabilitation have problems as following: Compliance control of force and security need to be improved in rehabilitation training; there is usually no participation of first finger; structures are not simple and comfortable enough for dressing, aren't integrated with joint angle sensor, or restrict fingers' range of movement.

3. Review on Design of Control System of Exoskeletal Robot for Upper Limbs Rehabilitation

SC of exoskeletal robot for upper limbs rehabilitation belongs to so typical nonlinear control that many factors block the increase of control accuracy as following: mechanical friction, torque ripple and environmental disturbance happen among the electric motor's working; existence of static friction and coulomb friction cause great error when exoskeletal robot system control position by changing the reference signal direction frequently; exoskeletal robot system always disturbed by surrounding environment due to constraint between mechanical hand with human hand, so if control system of exoskeletal robot don't have strong robustness it will become bad; error between nominal model and the actual controlled object, structural uncertainty ignored in modeling of control system and multiple joints' nonlinear coupling effects always fail the control of robot system; position error caused by finite rigidity and clearance of transmission parts; geometric errors of components and material structures which cause the reduced accuracy. So the main design point of rehabilitation robot is how to restrain interference brought by human hand and environment to enhance the accuracy of robot tracking trajectory.

3.1. Research on Perturbation Rejection Algorithm

The main methods to restrain uncertainty of disturbance and parameter affecting system are DOB [10], ARC [11-13], MBDA [14-15], EIMC [16] and TDC [17, 18]. The methods above always need a two-ring control structure as in figure 10 that one is an inner loop compensator to realize disturbance compensation while the other is an outer loop controller to meet the system performance requirements. In this plan, inner loop compensator produce correct control inputs to compensate external disturbance as much as possible.

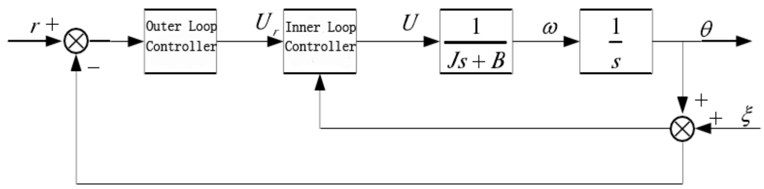

Figure 10. Two-ring Control Structure.

Among these methods, DOB is researched by many scholars due to its simple structure and good robustness. In the light of design and optimization problems of Q wave filter, Umeno T and partners defined a disturbance observer and gave a universal form of Q filter based on 2DOF controller design theory mapped in equation form as following, in which N denotes order of $Q(s)$, τ denotes time constant of filtering and r denotes relative order of $Q(s)$ [19]:

$$Q(s) = 1 + \sum_{k=1}^{N-r} a_k (\tau s)^k \Big/ 1 + \sum_{k=1}^{N} a_k (\tau s)^k \tag{1}$$

Lee and Tomizuka added robustness feedback controller based on disturbance observer to the speed loop of high precise position system in light of speed loop design of high precise position servo system to compensate disturbance outside and uncertainty of the controlled object and hence put forward a second order Q_{31} filter whose form can be mapped in equation form as following, in which τ denotes time constant of filtering [20]:

$$Q_{31}(s) = \frac{3\tau s + 1}{(\tau s)^3 + 3(\tau s)^2 + 3\tau s + 1} \tag{2}$$

White considered adding robustness feedback controller based on disturbance observer to the position loop of system to compensate disturbance outside and uncertainty of the controlled object and discussed the effects of position error signals to system [21]. Kim and Chung analyzed disturbance observer design by using doubly coprime factorizations and produced a method of number controller design based on sensitivity optimization matching to a giving $Q(s)$ [22]. In light of high-frequency interference taken by high speed CD-ROM disk spinning, Ryoo and partners designed a disturbance observer with a ordinary $Q(s)$ filter to restrain the high-frequency interference [23]. Yamada and partners designed a higher order disturbance observer by using a higher order integrator to meet the demands of fast shadow and low sensitivity to disturbance and proved higher order disturbance observers can cause a slight oscillation due to large phase lag [24]. Tesfaye used a method of numerical optimization to make the sensitivity function of system to match with the selected object's to finish the design of disturbance observer [25].

3.2. Research on Sliding mode variable structure control method

System in sliding motion has strong robustness and insensitivity to the model uncertainties and external disturbances. Variable structure control, which is reflected on the nonlinear control, needs to meet the following design goals: it exists in sliding mode; it satisfies the reaching condition. It means that the phase trajectory outside of the switching surface $S_i(x)=0$ will arrive at the sliding surface in finite time; the sliding mode motion is asymptotically stable and has good dynamic quality. The goals above can be summarized as two design problems on the design of switching function and the calculating of control law. The switching function includes linear switching function and nonlinear switching function. Linear switching function is a linear combination of the state of the system whose more common design methods include geometric method [26], pole placement method [27], terminal sliding mode method [28] and optimal quadratic method [29], etc. Because the sliding mode variable structure control designed base on linear switching function exists reaching phase, linear sliding surface applies to nonlinear systems whose requirements of speed and accuracy are not too high, such as some simple motor servo controlling system. But when it is for complex nonlinear system such as robot and so on, there is obviously insufficient on linear sliding surface, and the existence of the reaching phase reduces the robustness of the system.

There comes out many design methods of nonlinear switch function to ensure better performance of control system. Young proposed a switch function design method based on frequency shaping to avoid the effects of modeling error to system [30]. Lu and partners produced a global robust sliding mode control [31] which design a nonlinear switch function to achieve the goal with robustness in the whole dynamic process, so is integral switch function [32]. Bartoszewicz proposed a design method of time-varying switch function in light of second order nonlinear system which made the system in a sliding surface at the beginning of movement avoiding reaching movement in sliding mode control [33], but the method must improve its convergence speed. Park and Choi proposed the concept of switch function of rotation and translation motion, compared with the design of static switch function [34, 35].

In real control system, due to the existed factors of inertia and time delaying, sliding mode variable structure control system exist high frequency chattering unavoidably in sliding mode which not only affect the accuracy of control system and increase energy consumption but also the high frequency unmodeled dynamics can be excited easily to damage the performance of system even make system instable. So Slotine and partners introduced the concept of “quasi-sliding mode” and “boundary layer” in the design of sliding mode control. Quasi-sliding mode control used ordinary sliding mode control outside the boundary layer and continuous state feedback control in the boundary layer to avoid or weaken the chattering efficiently, but the use of quasi-sliding mode reduced the robustness and affected tracking accuracy of system. B. P. Kang and partners [36] designed a virtual sliding mode controller including conventional sliding mode controller and filter by adding low pass filter to the output end of controller to realize robust variable structure control of robot and ensure stability of system. M. Hamerlain and partners [37] used a dynamic sliding mode control to realize the tracking control of moving robot and avoid the chattering. G. Bartolini and partners [38, 39] realized chattering free sliding mode control of mechanical system with unmodeled dynamics and uncertainties by switching the two order derivative of function and applied to the tracking control of robot successfully.

Q. P. Ha and partners [40] adopted a fuzzy sliding mode controller made up of equivalent control, switch control and fuzzy control which used the design of fuzzy rule to reduce the impact of switch control and chattering effectively. M. Ertugrul and other scholars [41, 42] used respectively the learning ability of neural network by combining differently with sliding mode to weaken or avoid chattering and improve the robustness of system. Genetic algorithm, support vector machine and other methods can also be used to avoid the chattering of sliding mode control.

4. Discussion and Conclusion

Though great progress has been made in main technology of exoskeletal robot for upper limbs rehabilitation in last decade, there are still some problems in the practice application to be solved. Design of connection and fixation between exoskeleton and upper limb of human body currently need to be improved more reasonably, by which problems as poor blood circulation or unnatural muscle movement in fixation position would be to avoid and positioning accuracy of exoskeleton would be improved to a large extent. In the case of patient's slow movement current exoskeletal robot systems for upper limbs rehabilitation have well speed of response in experimental test results, but in the case of patient's rapid or complex movement the systems generally can't reach the same speed of response, which needs improvement from more excellent design and technology of exoskeletal robot. And in data and information transmission for obtaining patient's intention of motion, method of acquiring sEMG signal is easy to be disturbed and restricted by acquiring environment, and method of force feedback can't deal with patient's rapid or complex movement as its own hysteresis quality. It's in need of developing some more perfect technology for data and information transmission of exoskeletal robot systems for upper limbs rehabilitation in the future. Moreover, there is still very large promotion space in flexibility, security, environmental protection and degree of comfort of the exoskeletal robot.

References

[1] Molewijk A C, Stiggelbout A M, Otten W, et al. 2003 Implicit normativity in evidence-based medicine: A plea for integrated empirical ethics research *Health Care Analysis* **11(1)** 89–92
[2] Gary G E and Pinson L A 2003 Evidence-based medicine and psychiatric practice *Psychiatric Quarterly* **74(4)** 387–99
[3] Kiguchi K, Tanaka T, Watanabe, et al. 2003 Designed and control of an exoskeleton system for human upper-limb motion assist *AIM 2003* 926–31
[4] Kousidou S, Tsagarakis N G and Caldwell D G 2003 Evaluation of a "soft" exoskeleton for rehabilitation and physiotherapy of the upper limb *Autonomous Robots* **15(1)** 21–23
[5] Sugar T G, He Jiping, Koeneman E J, et al. 2007 Design and control of RUPERT: A device for robotic upper extremity repetitive therapy *IEEE Trans. on Rehabil. Engn.* **15(3)** 336–46
[6] Wrighy A K and Stanisic M M 1990 Kinematic mapping between the EXOS hand master exoskeleton and the UTAH/MIT dextrous hand *Proc. of Systems Engineering on* 101–04
[7] Zhou Zhihua, Wan Huagen, Gao Shuming, et al. 2005 A realistic force rendering algorithm for CyberGrasp *9th Int. Conf. on Computer Aided Design and Computer Graphics* 409–14
[8] Koeneman E J, Schultz R S, Wolf S L, et al. 2004 A pneumatic muscle hand therapy device *Proc. 26th Annual international Conference of the IEEE EMBS on* 2711–13
[9] Bouzit M, Popescu G, Burdea G, et al. 2002 The Rutgers Master II-ND force feedback glove *Proc. IEEE VR Haptics Symposium* 145–52
[10] Ohnishi K 1987 A new servo method in mechatronic *Transions of Japanese Society of Electrical Engineers* **107** 83–86
[11] Yao B, Mohammed A M and Masayosh I T 1997 High performance robust motion control of machine tools: An adaptive robust control approach and comparative exper. *IEEE Trans. on Mech.* **2** 63–76
[12] Yao B, Bu F, Reedy J, et al. 2000 Adaptive robust control of single-rod hydraulic actuators: Theory and experiments *IEEE/ASME Transactions on Mechatronics* **5** 79–91
[13] Xu L and Yao B 2001 Output feedback adaptive robust precision motion control of linear motors *Automatic* **37** 1029–39
[14] Choi C H and Kwak N 2001 Disturbance attenuation in robot control *2001 International Conference on Robotics and Automation* 2560–65
[15] Choi C H and Kwak N 2003 Robust control of robot manipulator by model based disturbance attenuation *IEEE/ASME Trans Mechatron* **8(4)** 511–13
[16] Zhu H A, Hong G S, Teo C L, et al. 1995 Internal model control with enhanced robustness *Int. J. Syst. Sci.* **26(2)** 277–93
[17] Youcef T and Reddy S 1992 Analysis of linear time invariant systems with time delay *Journal of Dynamic Systems, Measurement and Control* **114(4)** 544–55
[18] Chang P H and Park S H 2003 On improving time delay control under certain hard nonlinearities *Mechatronics* **13(4)** 393–412

[19] Umeno T, Kaneko T and Hori Y 1993 Robust servo system design with two degree of freedom and its application to novel motion control of robot manipulators *IEEE Trans. Ind. Elect.* **40** 473–85
[20] Lee H S and Tomizuka M 1996 Robust motion controller design for high-accuracy positioning systems *IEEE Trans on Industrial Electronics* **43(1)** 48–55
[21] White M T, Tomizuka M and Smith C 1999 Rejection of disk drive vibration and shock disturbances with a disturbance observer *6th Proc. of the American Control Conf.* 4127–31
[22] Kim B K, Chung W K, 2003 Advanced disturbance observer design for mechanical positioning systems, *IEEE Trans. Ind. Electron*, **30(6)**, 1207-16.
[23] Ryoo J R, Jin K B, et al. 2003 Track-following control using a disturbance observer with asymptotic disturbance rejection in high-speed optical disk drives *IEEE Trans. on Cons. Electr.* **49(4)** 1178–85
[24] Yamada K, Komada S, Ishida M, et al. 1997 Analysis and classical control design of servo system using high order disturbance observer *1997 IEEE Int. Conf. on Ind. Elect. Ctrl. and Instr.* 4–9
[25] Tesfaye A, Lee H S and Tomizuka M 2000 A sensitivity optimization approach to design of a disturbance observer in digital motion control systems *IEEE/ASME Transactions on Mechatronics* **5(1)** 32–8
[26] Ghezawi E I, Zinober A S I and Billings S A 1983 Analysis and design of variable structure systems using a geometric approach *Int. J. Control* **38(3)** 657–71
[27] Aggoune M E, Boudjemaa F, Bensenouci A, et al. 1994 Design of variable structure voltage regulator using pole assignment technique *IEEE Trans. on Auto. Control* **39(10)** 2106–10
[28] Man Z H and Palaniswami M 1993 A variable structure model reference adaptive control for nonlinear robotic manipulators *Int. J. Adaptive Control and Signal Processing* **7** 539–62
[29] Hsu Y Y and Chan W C 1984 Optimal variable structure controller for DC motor speed control *IEEE Proc. Pt. D.* **131(6)** 233–37
[30] Young K D and Ozguner U 1993 Frequency-shaping compensator design for sliding mode *Int. J. of Control* **57(5)** 1005–19
[31] Lu Y S and Chen J S 1995 Design of a global sliding mode controller for a motor drive with bounded control *Int. J. of Control* **62(5)** 1001–19
[32] Lee J J and Xu Y S 1994 A new method of switching surface design for multivariable variable structure systems *IEEE Trans. on Automatic Control* **39(2)** 414–19
[33] Bartoszewiez A 1996 Time-varying sliding modes for second-order system *IEEE Proc. Control Theory APP1* **143(5)** 455–62
[34] Park K B and Lee J J 1993 Variable structure controller for robotic manipulators using time-varying sliding surface *1993 IEEE Conference on Robotics and Automation* 89–93
[35] Choi S B and Park D A 1994 Moving sliding surface for fast tracking control of second order dynamical systems *ASME J. of Dynamic Systems, Measurement and Control* **116(3)** 154–58
[36] Kang B P and Ju J L 1997 Sliding mode controller with filtered signal for robot manipulators using virtual plant controller *Mechatronics* **7(3)** 277–86
[37] Hamerlain M, Youssef T and Belhocine M 2001 Switching on the derivative of control to reduce chatter *IEEE Proceeding on Control Theory and Application* **148(1)** 81–96
[38] Bartolini G, Ferrara A and Usai E 1998 Chattering avoidance by second order sliding mode control *IEEE Transactions on Automatic Control* **43(2)** 241–46
[39] Bartolini G, Ferrara A, Usai E, et al. 2000 On multi-input chattering free second order sliding mode control *IEEE Transactions on Automatic Control* **45(9)** 1711–17
[40] Ha Q P, Nguyen Q H, Rye D C, et al. 2001 Fuzzy sliding mode controller with application *IEEE Transaction on Industrial Electronics* **49(1)** 38–41
[41] Ertugrul M and Kaynak O 2000 Neural sliding mode control of robotic manipulators *Mechatronics* **10(1, 2)** 239–63
[42] Huang S J, Huang K S and Chiou K C 2003 Development and application of a novel radial basis function sliding mode controller *Mechatronics* **13(4)** 313–29