Motion and Visual Control for an Upper-Limb Exoskeleton Robot via Learning

Jian-Bin Huang[1], I-Yu Lin[1], Kuu-Young Young[1(✉)], and Chun-Hsu Ko[2]

[1] Department of Electrical Engineering, National Chiao Tung University, Hsinchu, Taiwan
kyoung@mail.nctu.edu.tw

[2] Department of Electrical Engineering, I-Shou University, Kaohsiung, Taiwan

Abstract. The arrival of an aging society brings up many challenges, including the demanding need in medical resources. In responding, the exoskeleton robot becomes one of the focuses, which provides assistance for people with locomotive problems. Motivated by it, our laboratory has developed a wearable upper-limb exoskeleton robot, named as HAMEXO. It is of 2 DOF and intended to provide motion assistance for users in their daily activities. To serve the purpose, HAMEXO is equipped with a visual system to detect objects in the environment, and also a motion controller for its governing. To deal with the coupling involved during the movements of the two joints and the need to adapt to various users, we adopted the learning approach for controller design. Experiments are performed to demonstrate its effectiveness.

Keywords: Upper-limb exoskeleton robot · Motion and visual control · Learning

1 Introduction

Along with the coming of an aging society, the number of people with limb mobility is increasing, Consequently, medical staffs, caregivers, and medical resources are highly demanded for providing assistance in walking, nursing care, and daily lives. It solicits the introduction of robots to relieve the workloads from their human counterparts. Among them, the exoskeleton robot, which can be worn on the human body directly and operated in concert with the wearer, has received much attention [1–3]. The exoskeleton robots can basically be classified into three types: upper-body, lower-body, and full-body [2–7]. Among previous research, they have been applied for rehabilitation, daily activities, and others. NTUH-ARM [6] and ETS-MARSE [7] were developed for full-arm rehabilitation, which were heavy and fixed to a base. TTL-Exo [5], a light and portable 6-DOF dual arm, was also developed for rehabilitation. Being mounted on a base or wheelchair, they can be applied for eating, drinking, brushing, etc. [1, 4]. Meanwhile, EMAS II [2] and HAL-UL [3] were designed to be light for higher portability.

When used for assistance, the exoskeleton robot can operate in either passive, active-assisted, or active-resistive mode [6, 7]. In the passive mode, the robot dictates

F. Cong et al. (Eds.): ISNN 2017, Part II, LNCS 10262, pp. 36–43, 2017.
DOI: 10.1007/978-3-319-59081-3_5

the entire motion without any force from the user. It is generally adopted for the cases that the user was almost unable to move his/her arm. In the active-assisted or active-resisted mode, the user joins force with the robot to move. The robot usually takes a supporting role when the user executes the task. For these active types of assistance, it is crucial for the robot to come up with proper assistive force. For that, biological signals from the user, such as electromyography (EMG) and electroencephalography (EEG) [1], are frequently used to detect user's motion intention. Another approach is to determine the assistive force by sensing the applied force from the user [8]. Meanwhile, these two approaches can also be combined together by using both biological and force information [1].

Motivated by the demand of motion assistance for people with weak mobility, our laboratory has developed a wearable 2-DOF upper-limb exoskeleton robot, named as HAMEXO. For the use in daily life, such as object picking or drinking, we equip the HAMEXO with a visual system for detecting the objects in the working environment. To execute the motion solicited via the visual system, we develop a motion controller for its governing. As the coupling is present during the movements of the two joints and the adaptability is demanded in applying it for different users, we propose using the learning approach for controller design. The adaptive network-based fuzzy inference system (ANFIS) is adopted for its execellence at adaptation [9]. In this stage of research, we focus on the passive mode of assistance. Meanwhile, the effectiveness of the proposed motion and visual control system is demonstrated via the experiments for object fetching.

2 Design and Development for HAMEXO

HAMEXO (Human and Machine Exoskeleton) is developed to be a 2-DOF upper-body wearable exoskeleton robot. It is designed based on the human upper-body anatomy and dynamics for better fitting in wearing [10, 11]. The two DOFs are intended for the flexion and extension of the shoulder (θ_1) and elbow (θ_2), which should provide the freedoms for simple picking and reaching tasks in daily activities. Referring to the actual range of motion of human body, the ranges of θ_1 and θ_2 are designed to be

$$0^\circ \le \theta_1 \le 90^\circ, 0^\circ \le \theta_2 \le 135^\circ \tag{1}$$

The 3D CAD modeling of HAMEXO is as shown in Fig. 1. Its frame is made of aluminum for providing the demanded strength and lightness. For each of the two links, there is a PLA (polylactide) 3D printed platform together with a strap belt for securing user's arm to the exoskeleton. The upper-arm, forearm, shoulder, and backpack are all equipped with sliding parts to accommodate to variations in human bodies. The brushless DC motors (BLDCMs) were adopted as the actuators, coupled with reduction gears and also incremental encoders for position feedback. Other designs include: hard foam as padding between the user and exoskeleton for comfort and power-kill switch for safety concern. Note that, as HAMEXO is designed to be wearable, it can also be fixed to a work station to relieve the user from its load. As shown in Fig. 2, HAMEXO can be hung on the rack of the work station and the casters allow it to move. Figure 3(a) shows the photo of the developed HAMEXO and Fig. 3(b) a user wearing it.

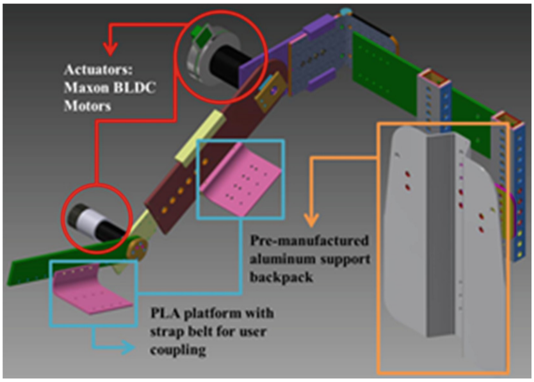


Fig. 1. 3D CAD modeling of HAMEXO.

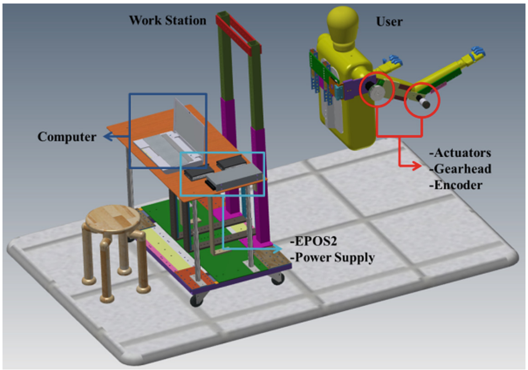


Fig. 2. HAMEXO with the work station.

(a) (b)

Fig. 3. (a) The HAMEXO and (b) a user wearing HAMEXO.

3 Proposed Motion and Visual Control System

The proposed system consists of mainly a visual system for object detection and an ANFIS PID position controller for motion governing. Figure 4(a) shows the setup of the visual system, which includes two cameras for locating the objects in the 3D workspace. Their locations are arranged according to the task, so that they well observe the objects involved. To be portable to go along with HAMEXO, we adopted the CMUcam5 pixy (shown in Fig. 4(b)) as the camera [12], which is light and also with the ability of color recognition. The calibration procedure has been performed to derive accurate parameters for the two cameras. The 2D imagines obtained by them can then be used to determine the 3D object location.

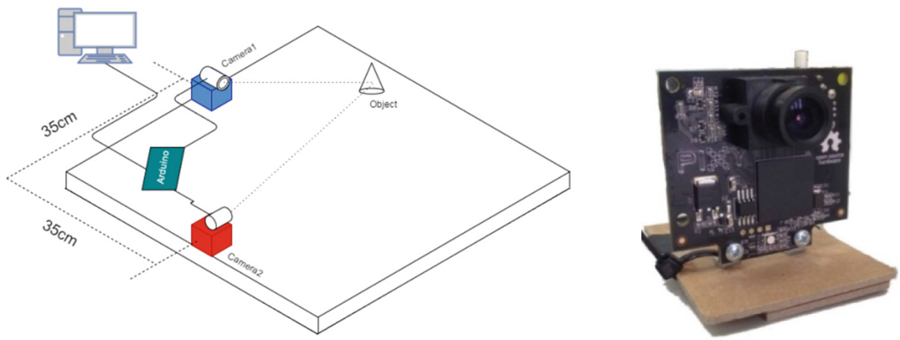


Fig. 4. The visual system for object detection: (a) the arrangement of the two cameras and (b) the CMUcam5 pixy.

After both the locations of the object and HAMEXO are identified, the ANFIS PID controller, shown in Fig. 5, is applied to move HAMEXO to reach the object. In Fig. 5, according to the relative locations between the object and HAMEXO, the motion planner first generates a path (θ_d) for execution. For smoothness consideration, we utilize the B-spline method to generate the path. The planned path (θ_d) is forwarded to

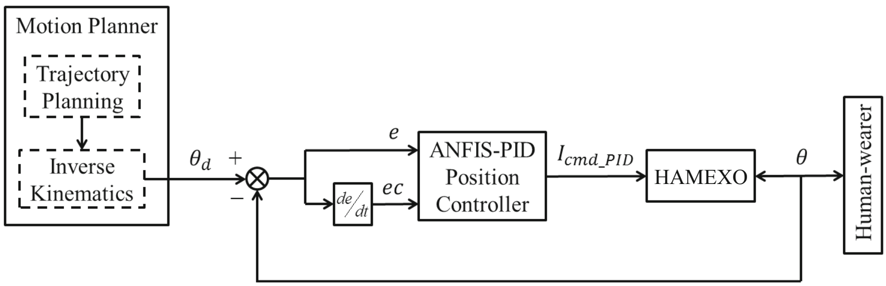


Fig. 5. The proposed motion controller based on ANFIS.

the ANFIS-PID position controller for execution. The controller then derives proper control commands in current (I_{cmd_PID}) according to the feedbacks of position error (e) and position error rate (ec), which shall drive the motors to move HAMEXO to follow the path (θ_d).

The ANFIS, famous for its excellence on adaptation, has been applied for speed control of the BLDCM [13]. In our previous work, it has been applied to determine system parameters for a multi-DOF robot control system based on EMG signals, and achieved desirable performance [14]. Figure 6 shows the system block diagram of the proposed ANFIS-PID position controller, equipped on each of the two links of HAMEXO. It is basically a PID controller with adjustable K_p, K_I, K_D gains tuned by the ANFIS. The controller starts with a set of initial gains (K_{P0}, K_{I0}, K_{D0}). Through a learning process, the ANFIS shall determine proper amount of $(\Delta K_P, \Delta K_I, \Delta K_D)$ added to (K_{p0}, K_{I0}, K_{D0}) for adjustment according to position error (e) and position error rate (ec):

$$\begin{cases} K_P = K_{P0} + \Delta K_P \\ K_I = K_{I0} + \Delta K_I \\ K_D = K_{D0} + \Delta K_D \end{cases} \tag{2}$$

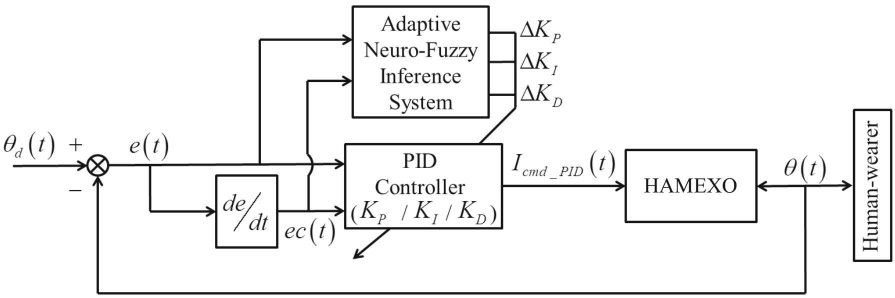


Fig. 6. Block diagram of the proposed ANFIS-PID position controller.

Current control signal $I_{cmd\_PID}(t)$ generated by the ANFIS-PID position controller will drive the motors to move HAMEXO, formulated as

$$I_{cmd\_PID}(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \dot{e}(t) \tag{3}$$

The ANFIS uses the neural network structure to realize the Takagi-Sugeno (T-S) fuzzy model [15]. The IF-THEN rules are formulated as

$$\begin{aligned} R^i : IF\ (e\,is\,A_j)\ and\ (ec\,is\,B_j)\ THEN\ (f_i = p_i e + q_i ec + r_i) \\ for\ i = 1, \cdots, m\ and\ j = 1, \cdots, n \end{aligned} \tag{4}$$

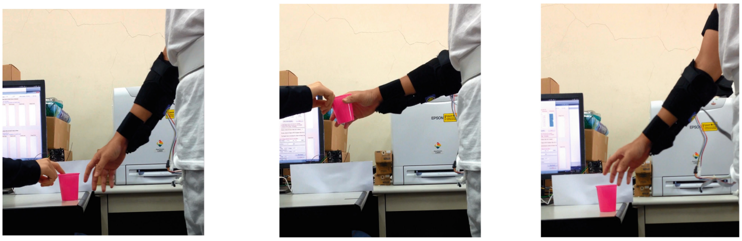
where R^i is the i's rule of the ANFIS, f_i the output variable (ΔK_p), (A_j, B_j) fuzzy sets characterized by the membership function in the antecedent, and (p_i, q_i, r_i) inference parameter sets in the consequent, respectively. The architecture of ANFIS for deriving ΔK_p, ΔK_I and ΔK_D can be constructed by referring to [16].

4 Experiment

To evaluate the performance of the proposed motion and visual system, we invited three young subjects, two males and one female (shown in Fig. 7), to conduct the experiments. They were all right-handed with the height of 160 (female), 165, and 171 cm and weight of 50, 70, and 62 kg, respectively. For safety concern, the maximum motor speeds for the shoulder and elbow were set to be 300 and 250 rpm, respectively. Evaluation on the proposed ANFIS PID position controller, including its ability in tackling the coupling effect between joints and in adapting to various users, has been reported in our previous work [16]. Here, we concentrate on how it can be linked with the visual system for object fetching. During the experiments, we applied the visual system to locate the object first and the motion controller to move HAMEXO in carrying the arm to fetch the object. We arranged the object to appear in an arbitrary manner, so that the subject did not know where it would be in advance. Figure 8 show the experimental setup for subject A, in which the cup was put on the desk first (Fig. 8(a)), lifted up to the air (Fig. 8(b)), and then put back to the desk (Fig. 8(c)). Figure 9 shows the trajectories of both the shoulder and elbow joints during the motion, in which the blue dots 1, 2, and 3 represent the three object locations, the red line the trajectory designed by the motion planner based on these locations, and the blue line the actual trajectory executed by HAMEXO. In Fig. 9, the actual joint trajectories followed the planned ones quite well, and all three target locations were reached. Similar results were also observed for the experiments conducted by subjects B and C, indicating the effectiveness of the proposed system.

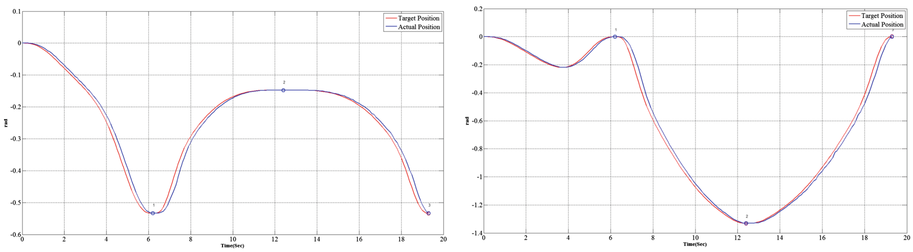
(a) (b) (c)

Fig. 7. Photos of subjects A, B, and C invited for the experiments.



(a) (b) (c)

Fig. 8. Setup for the experiment of object feching: (a) reach point 1, (b) reach point 2, and (c) back to point 1.



(a) (b)

Fig. 9. Experimental results (subject A): trajectories for (a) shoulder and (b) elbow. (Color figure online)

To further investigate the effect of learning for the proposed motion controller, we also used a pure fuzzy system, i.e., not a neural-fuzzy type of system, to tune K_p, K_I, K_D gains for the PID controller shown in Fig. 6. For this object-fetching task involving only two joints, the fuzzy system was able to derive suitable gains that led to satisfactory performance at the expense of time. In fact, the derived gains were quite close to those tuned by the proposed ANFIS. Meanwhile, to be more effective on gain tuning and also able to deal with more complicated tasks, we consider the proposed ANFIS PID position controller is more appropriate for future system development.

5 Conclusion

In this paper, we have proposed a motion and visual control system for the upper-limb exoskeleton robots, and applied it to HAMEXO, a such kind of robot developed in our laboratory. Experiments have been conducted to evaluate its effectiveness. In future works, we will enhance the visual system in its portability and also the ANFIS-based motion controller in its learning, including further study on the transferability for different wearers, so that HAMEXO can be applied for more complicated tasks and more adaptive to various users.

Acknowledgment. This work was supported in part by the Ministry of Science and Technology, Taiwan, under Grant NSC 102-2221-E-009-138-MY3.

References

1. Kiguchi, K., Hayashi, Y.: An EMG-based control for an upper-limb power-assist exoskeleton robot. IEEE Trans. Syst. Man Cybern. B Cybern. **42**(4), 1064–1071 (2012)
2. Hasegawa, Y., Oura, S., Takahashi, J.: Exoskeletal meal assistance system (EMAS II) for patients with progressive muscular disease. Adv. Robot. **27**(18), 1385–1398 (2013)
3. Otsuka, T., Kawaguchi, K., Kawamoto, H., Sankai, Y.: Development of upper-limb type HAL and reaching movement for meal-assistance. In: Proceedings of the 2011 IEEE International Conference on Robotics and Biomimetics, Phuket, Thailand, pp. 883–888 (2011)
4. Huete, A.J., Victores, J.G., Martinez, S., Gimenez, A., Balaguer, C.: Personal autonomy rehabilitation in home environments by a portable assistive robot. IEEE Trans. Syst. Man Cybern. C Appl. Rev. **42**(4), 561–570 (2012)
5. Ugurlu, B., Nishimura, M., Hyodo, K., Kawanishi, M., Narikiyo, T.: Proof of concept for robot-aided upper limb rehabilitation using disturbance observers. IEEE Trans. Hum.-Mach. Syst. **45**(1), 110–118 (2015)
6. Wang, W.W., Tsai, B.C., Hsu, L.C., Fu, L.C., Lai, J.S.: Guidance-control-based exoskeleton rehabilitation robot for upper limbs: application to circle drawing for physiotherapy and training. J. Med. Biol. Eng. **34**(3), 284–292 (2014)
7. Rahman, M.H., Saad, M., Ochoa-Luna, C., Kenné, J.P., Archambault, P.S.: Cartesian trajectory tracking of an upper limb exoskeleton robot. In: Proceedings of the 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, Canada, pp. 2668–2673 (2012)
8. Lee, H.D., Lee, B.K., Kim, W.S., Han, J.S., Shin, K.S., Han, C.S.: Human-robot cooperation control based on a dynamic model of an upper limb exoskeleton for human power amplification. Mechatronics **24**(2), 168–176 (2014)
9. Jang, J.-S.R.: ANFIS: adaptive-network-based fuzzy inference system. IEEE Trans. Syst. Man Cybern. **23**(3), 665–685 (1993)
10. Karner, J., Reichenfelser, W., Gfoehler, M.: Kinematic and kinetic analysis of human motion as design input for an upper extremity bracing system. In: Proceedings of the 9th IASTED International Conference on Biomedical Engineering, Innsbruck, Austria, pp. 376–383 (2012)
11. Masjedi, M., Duffell, L.D.: Dynamic analysis of the upper limb during activities of daily living: comparison of methodologies. Inst. Mech. Eng. H, J. Eng. Med. **227**(12), 1275–1283 (2013)
12. CMUcam5 Pixy Camera. http://www.cmucam.org/projects/cmucam5. Accessed 10 Dec 2016
13. Premkumara, K., Manikandanb, B.V.: Adaptive neuro-fuzzy inference system based speed controller for brushless DC motor. Neurocomputing **138**(22), 260–270 (2014)
14. Liu, H.J., Young, K.Y.: An adaptive upper-arm EMG-based robot control system. Int. J. Fuzzy Syst. **12**(3), 181–189 (2010)
15. Takagi, T., Sugeno, M.: Fuzzy identification of systems and its applications to modeling and control. IEEE Trans. Syst. Man Cybern. **1**(1), 116–132 (1985)
16. Huang, Y.B., Young, K.Y., Ko, C.H.: Effective control for an upper-extremity exoskeleton robot using ANFIS. In: Proceeding of 2016 IEEE International Conference on System Science and Engineering, Nantou, Taiwan (2016)