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A Study of a 4DOF Upper-Limb Power-Assist Intelligent Exoskeleton with Visual Information for Perception-Assist

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***Abstract*—This paper presents a concept of an upper-limb power assist intelligent exoskeleton with visual information as a second stage of the research on power-assist exoskeleton systems in order to help daily activities of physically weak persons. The proposed exoskeleton assists not only the motion of the user but also the perception of the user using sensors and a stereo camera. In the proposed power-assist method, the assisted user's motion can be modified based on the environmental information obtained by the sensors and the camera if problems are found in the user's motion. The effectiveness of the proposed intelligent exoskeleton was evaluated by experiments.**

I. Introduction

DECREASE in birthrate and aging are progressing in several countries. In those societies, the shortage of nursing people is a serious problem. Many exoskeleton robots [1]-[11] have been studied to assist daily activities or rehabilitation of physically weak persons such as elderly, injured, or disabled persons to cope with this problem. We have proposed power-assist exoskeletons to assist the upper-limb motion of such people since the upper-limb motion is important for daily activities [1]-[5][12]. In the power-assist exoskeleton, the motion of the user is supposed to be assisted in accordance with the user's motion intention. The skin surface electromyogram (EMG) is often used to detect the user's motion intention since it directly reflects the user's muscle activity. Therefore, information of the EMG signals and/or force sensors is often used to predict the user's motion intention in the conventional power-assist exoskeleton. In the case of physically weak persons, however, perception ability is also weakened sometimes. It is important to assist the sensing ability of those persons by sensors of the robotic exoskeleton [13].

This paper proposes a concept of a 4DOF upper-limb power-assist intelligent exoskeleton with visual information as a second stage of the research on power-assist exoskeleton robot systems in order to help daily activities of physically weak persons. The concept of power-assist with perception-assist, which assists not only the motion of the user but also the perception of the user by using sensors, was proposed in [13]. In that study, perception-assist with a sonar sensor was used to modify the motion of the user based on the proposed information if the exoskeleton detects some problems in the user's motion. This paper proposes a concept of an intelligent exoskeleton using image feedback together with the sonar sensor for the 4DOF upper-limb exoskeleton robot to improve the perception level and intelligence of the robot to assist the user's motion when interacting with the environment.

In the proposed intelligent exoskeleton with visual information, a sonar sensor and a stereo vision digital camera are used as the sensors for perception-assist. Part of the algorithm of the sonar sensor identifies whether user is moving the arm towards an object or not. If the user is moving the arm toward an object, visual information obtained by using the stereo vision digital camera is used to identify the object. Algorithm of the camera part does the pre-processing of raw input images. Then it does the stereo processing to create depth maps to calculate the position of the object. If exoskeleton doesn't find any problem in the user's intended motion, ordinal power assist is performed. If exoskeleton identifies any problem in the user's motion, then it modifies the user's motion to solve the problem. For example, if the estimated trajectory based on the information of the sensors is the same as the trajectory of the end effecter of the exoskeleton, exoskeleton determines that there is no problem in user's motion, hence no trajectory modification is performed. When the user moves the arm toward the object, if the exoskeleton identifies that there are some problems in the current trajectory like the arm is going to collide with an object or required trajectory of grabbing the object is wrong, then the trajectory modification is carried out by the exoskeleton to correct the trajectory to avoid the collision of the arm with the object or to grab the object. If the corrected trajectory is wrong, then user doesn't follow it. In that case, the exoskeleton identifies that the modification of the trajectory is wrong and changes its strategy. Algorithm of the camera searches for another object near by. If such an object is identified, then calculate the position of the new object by the image processing algorithm and trajectory modification is carried out by exoskeleton to guide the arm toward the new object.

The proposed power-assist method is applied to a 4DOF upper-limb power-assist exoskeleton and effectiveness of the proposed intelligent exoskeleton has been evaluated by

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experiment.

II. 4DOF Upper-Limb Power-Assist Exoskeleton

In order to assist 4DOF upper-limb motion, a power-assist exoskeleton (Fig. 1) which consists of a shoulder motion support part, an elbow motion support part, and a forearm motion support part was developed [12].

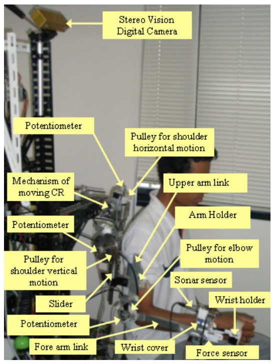


Fig. 1. 4DOF upper-limb power-assist exoskeleton.

The shoulder motion support part, elbow motion assist part, and forearm motion support part are the main parts of the exoskeleton. The exoskeleton upper-limb is supposed to install in a wheel chair [13]. The stereo camera system is also supposed to install on the wheel chair as shown in figure 1.

The stereo vision digital camera and sonar sensor is used for perception-assist. The camera is placed in a position high enough over the head of the user, hence visual images in front of the user's arm can be obtained. Therefore, it is possible to detect the positions of the objects in front of the user which are possible to grab or touch by the user. The sonar sensor is placed in the wrist arm holder, hence it moves with the arm of the user and can detect the object toward which the user is moving his/her arm. This location of the sonar sensor helps to track the trajectory of the arm toward the object.

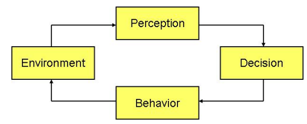
The movable ranges for the upper-limb exoskeleton were decided by considering the minimally required motion in everyday life and the safety of the user (see Table I) [12], [14].

III. Power-Assist with Perception-Assist

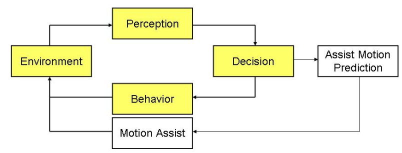
In the conventional power-assist exoskeleton, user's motion intention is estimated in real-time based on the information from force sensors and/or EMG signals and then the estimated motion is assisted by the power-assist robot systems [13]. However, perception ability is also weakened sometimes in the case of physically weak persons. Therefore, there is a possibility of collision with an obstacle, tumbling over a small obstacle, or fail in object grasping even though the motion is assisted according to the user's intention. In this study, perception of the environment is also assisted by the exoskeleton. In the proposed method, the interaction between the user and the environment is monitored by the exoskeleton.

TABLE I
Range of Motions of Upper Limb

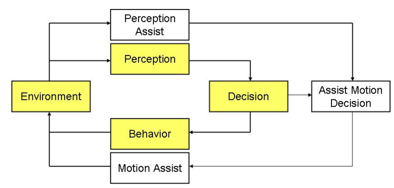
Type of Motion		Daily life [deg]	Exoskeleton [deg]
Shoulder	Flexion	180	90
	Extension	60	0
	Abduction	180	90
	Adduction	75	0
Elbow	Flexion	145	120
	Extension	-5	0
Fore arm	Pronation	50	50
	Supination	80	80



(a) Human behaviour cycle.



(b) Conventional power-assist cycle.



(c) Proposed power-assist cycle.
Fig. 2. Power-assist cycles.

IV. Control Method

A. EMG

To control the exoskeleton in accordance with the user's motion intention, the root mean square (RMS) values of raw EMG signals that directly reflect the user's motion intention are used as main input signals to the controller [13].

When certain motion is performed, the EMG signals of the related muscles show the unique pattern. Since the magnitude of the RMS of the EMG signal indicates the activity level of the muscles, upper-limb motion of the user could be predicted by monitoring EMG signals of certain muscles of the user.

In order to predict the 4DOF motion the EMG signals of 12 locations (Ch 1–Ch 12) of the related muscles are used [12], [14]. The location of each electrode is depicted in Fig. 3.

B. EMG-BASED CONTROL [13]

The basic architecture of the controller is depicted in Fig. 4. The controller basically consists of power-assist part with three stages and perception-assist part. This power-assist part is basically the same as the conventional EMG-based controller [13]. In the first stage of the power-assist part, the EMG based control or the wrist sensor based control is applied in accordance with the muscle activity levels of the user. In the second stage of the power-assist part, proper neuro-fuzzy controllers are selected according to the shoulder and the elbow angle region. In the third stage of the power-assist part, the torque required for each joint motion assist is calculated with the selected neuro-fuzzy controllers.

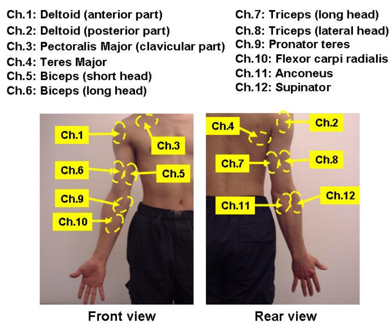


Fig. 3. Location of each electrode.

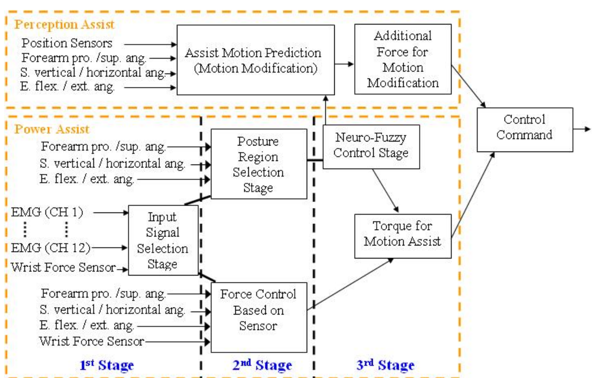


Fig. 4. Controller architecture.

In the perception-assist part, motion modification is considered if some problems are found in the user's motion when the user is interacting with the environment. Sensor information and the estimated user's motion intention (the output of the neuro-fuzzy controllers) are used to decide the motion to be modified in this part. In this study, the ultrasonic sensor [FW-H10R, Keyence] is applied to detect the objects and stereo vision digital camera [Bumblebee 2, Point Grey Research] was used to acquire shape and position of the objects in the working plane.

The position of the user's hand can be calculated from the joint angles of the exoskeleton. The force vector in the tip of the assisting motion at the user hand can be calculated based on the estimated torque (the output of the neuro-fuzzy controllers) from the EMG signals in the third stage of the power-assist part. Since the estimated force vector contains noise and estimated error, it is averaged with the estimated force vector data in the past. The relationship between the force vector at the user hand and the joint torque vector of the user upper-limb is written as:

$$F = J^{-T}\tau \qquad (2)$$

where F is the force vector at the user hand (averaged with the past data), τ is the joint torque vector of the user upper-limb, and J is the Jacobian matrix. The estimated force vector of the user directly indicates the user's motion intention.

V. Perception Assist With Sonar Sensor And Stereo Vision Digital Camera

When a user is moving his/her arm toward an object to grab or touch it, trajectory of the hand (tip of arm) is the almost straight line toward the object [15]. Therefore, change in distance of the tip of arm and distance reduction between the tip of arm and object are supposed to be the same. Change in distance of tip of arm is calculated by the kinematics of the exoskeleton. Distance reduction toward the object is calculated by using the ultrasonic sensor. When the arm is moving toward the object, these two values become close to each other but vary in a particular range. This range is determined based on the experimental results. It is important to select this range as narrow as possible to identify the trajectory of the arm more accurately.

When the user moves the arm towards an object, exoskeleton identifies it and calculates the position of that object by using the stereo camera. If the motion trajectory toward the object is the same as estimated trajectory, then no modification of the motion is carried out. If the trajectory is different from the estimated trajectory, then the exoskeleton tries to modify the trajectory toward the identified object by stereo camera by applying the additional force at the tip of arm. Dot product between additional force vector and fuzzy-neuro generated force vector is calculated to check whether the modification (i.e., the decision of the robot) is correct or not. If user follows the modified trajectory, directions of additional force vector and fuzzy-neuro generated force vector are the same, hence the dot product is positive. Therefore, if the dot product is positive, exoskeleton determines that the trajectory modification is correct and guides the arm toward the identified object by the camera. If the user doesn't follow the modified trajectory by the exoskeleton, directions of additional force vector and fuzzy-neuro generated force vector are in opposite directions, hence the dot product becomes negative. If dot product becomes negative while modifying the trajectory, then exoskeleton determines that the current modification is wrong and try to identify a near by object by using the stereo camera. If there is such an object, position of that object is calculated by using stereo camera and modify the trajectory toward newly identified object. If the user follows this new modified trajectory, dot product becomes positive again. If dot product becomes positive due to the second modification, exoskeleton determines that the new strategy is correct and guides the arm towards the newly identified object by the camera. If the dot product doesn't become positive within a defined time period due to the second modification, then exoskeleton stop further modifying the trajectory and let the user to carried out ordinal power assist.

If the current trajectory modification is wrong and if there is no identified object near by, then exoskeleton determines the already found object as an obstacle and obstacle avoidance algorithm is carried out to prevent the user by grabbing or touching it.

When calculating the position of an object measured by the stereo camera, camera coordinate system was converted in to the global coordinate system of the robot by using the equation (3), where θ is the tilt angle of the camera. ${}^{G}P$, $R_X(\theta)$, ${}^{R}P$ and ${}^{G}P_{RORG}$ are the position of the object with respect to global coordinate system, rotation matrix around X axis, position of the object with respect to the coordinate system of the camera and position vector of the origin of camera coordinate system with respect to global coordinate system, respectively.

$$ {}^{G}P = R_X(\theta)\ {}^{R}P + {}^{G}P_{RORG} \tag{3} $$

$$ R_X(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} $$

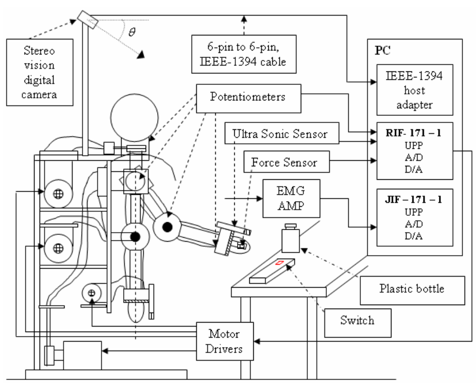
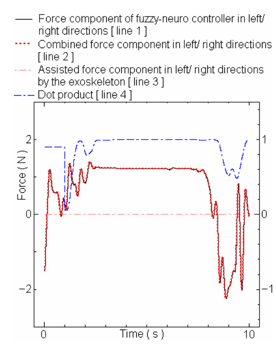


Fig. 5. Experimental setup.

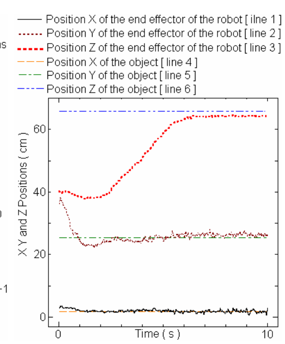
VI. Experiment

The experimental set up is shown in Fig. 5. A plastic bottle and a switch were used as objects for the experiment. Two interface boards (RIF–171–1 and JIF–171–1) are used to process A/D operations of potentiometer signals, force sensor signals, EMG signals, and ultrasonic sensor signals and to process D/A operations required to send the calculated torque commands back to motor drivers to control the motors. Stereo vision digital camera is connected to 400 Mbps IEEE-1394 OHCI PCI host adapter fire wire interface card, for high speed communication of the digital video data, by using a 6-pin to 6-pin IEEE-1394 cable. Measured EMG signals are amplified by the EMG amplifier prior to be sent to the interface board. Amplified EMG signals (i.e., output of the EMG amplifier) are fed to the JIF–171–1 interface board. Motor torque commands are calculated in the PC and then sent to four motor drivers to operate four motors. Output of the ultrasonic sensor is sent to RIF–171–1 interface board. All the input signals except EMG signals are filtered with software implemented second order butter worth filter. EMG signals are filtered by the EMG amplifier itself. Except stereo vision data, acquisitions of all the other input signals are done with a sample rate of 1400Hz frequency to realize the real time controller. Image acquisition rate of the controller is set to five per second avoiding the delays that can affect to the real time controller implementation.

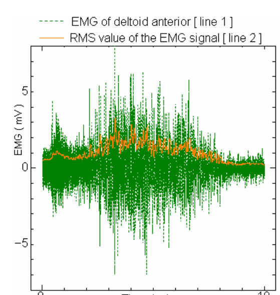
Three kinds of experiment were performed with a same young male subject to evaluate the effectiveness of the proposed power-assist method. In the first experiment, the subject tried to move the hand toward the object (i.e. the plastic bottle) to grab it with the correct hand trajectory. In the second experiment, the subject also tried to move the hand toward the same object to grab it, but with the wrong hand trajectory on purpose. In the third experiment, the subject tried to move the hand forward to put the switch avoiding the collision with the plastic bottle. In this experiment, the wrong hand trajectory (i.e., the trajectory that the hand collides with the plastic bottle) is generated on purpose.



(a) Motion modification.



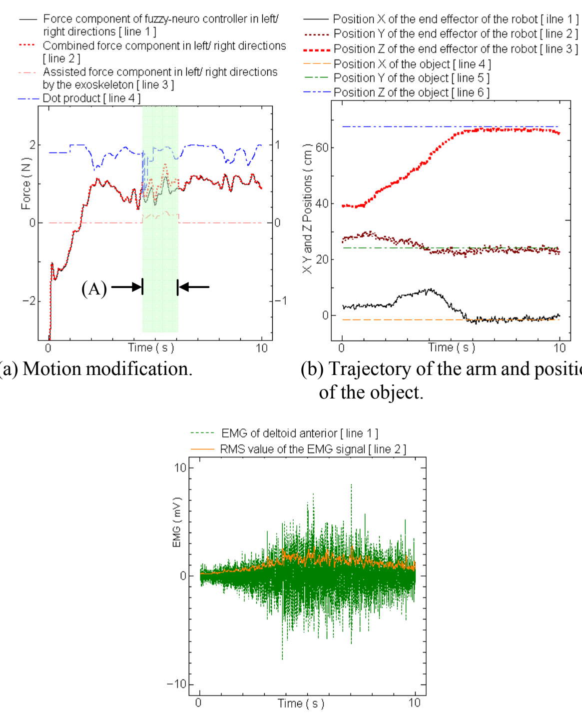
(b) Trajectory of the arm and position of the object.



(c) EMG signal.

Fig. 6. Experimental results of the first experiment.

Figure 6 shows the results of the first experiment. The estimated force vector at the user hand (calculated from the output of the neuro-fuzzy controllers), the combined force vector (modified force vector), the assisted force vector (additional force for the motion modification) and the dot product are shown in Fig. 6 (a). The hand trajectory in terms of x, y and z positions with respect to the global coordinate system of the robot calculated by the kinematics model of the exoskeleton (line 1, 2 and 3, respectively), the x, y and z positions of the object with respect to the global coordinate system, measured by the stereo camera (line 4, 5 and 6, respectively), are shown in Fig. 6 (b). The raw EMG signal of the deltoid – anterior part and the RMS value are shown in Fig. 6 (c). These experimental results show that the exoskeleton effectively carries out the power-assist (conventional power-assist) based on the user's motion intention, when any problems do not exist in the user's motion.



(a) Motion modification.

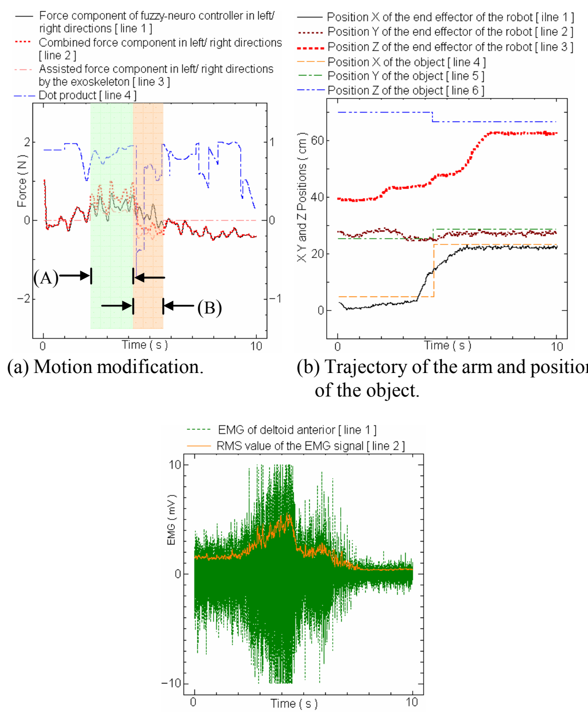
(b) Trajectory of the arm and position of the object.

(c) EMG signal.

Fig. 7. Experimental results of the second experiment.

Figure 7 shows the results of the second experiment. The same kinds of experimental results as those in Fig. 6 (a), (b) and (c) are shown in Fig. 7 (a), (b) and (c), respectively. During the term (A) in Fig. 7 (a), the motion modification was performed to change the trajectory of the user's hand to the correct trajectory toward the object since the exoskeleton found out that the hand trajectory of the user is different from the estimated one. Since the decision of the exoskeleton was correct, user follows the modified trajectory, hence dot product (line 4) remains positive. When the trajectory becomes the same as the estimated trajectory, the ordinal power-assist (power-assist without any motion modification) was carried out until the user grabs the object after term (A).

Figure 8 shows the results of the third experiment. The same kinds of experimental results as those in Fig. 6 (a), (b) and (c) are also shown in Fig. (a), (b) and (c), respectively. During the term (A) in Fig. 8, the motion modification was performed to change the trajectory of the user's hand to the trajectory toward the plastic bottle since the exoskeleton found out that the hand trajectory of the user is different from the estimated one. Sign of the dot product has changed due to first modification, implying that the modification required to the user is different than that of the modified trajectory by the exoskeleton. Therefore, exoskeleton changes its strategy and search for a near by object by using the stereo camera.



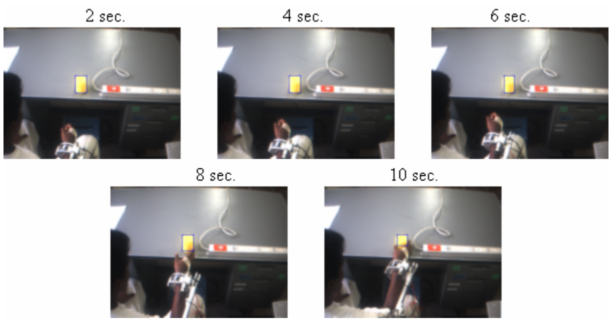
(a) Motion modification.

(b) Trajectory of the arm and position of the object.

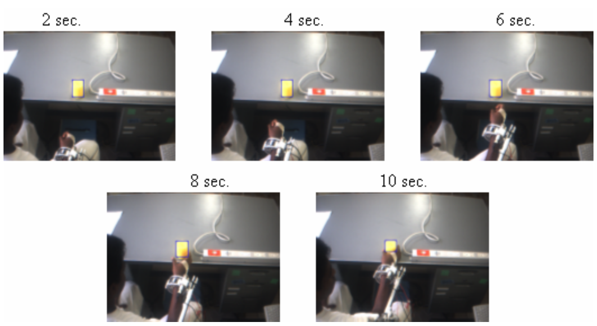
(c) EMG signal.

Fig. 8. Experimental results of the second experiment.

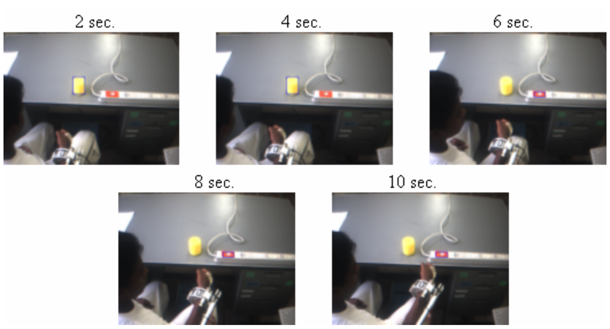
During the term (B) in Fig. 8, the exoskeleton found out that its strategy had been wrong and changed its strategy to modify the hand trajectory of the user to avoid the collision with the object and toward the newly identified near by object i.e. the switch. Since the second decision of the exoskeleton was correct, dot product has become positive again within a shorter period than the specified maximum threshold time period. When the trajectory is become the same as that of the estimated one, the ordinal power-assist (power-assist without any motion modification) was carried out to move toward the switch. In each experiment, grabbed images by the stereo vision digital camera were saved to the hard disk of the computer after every 2 seconds. Figure 9 (a), (b) and (c) show the position of the arm grabbed by the stereo vision digital camera after every 2 seconds in each experiment. In each image, blue color square shows the identified object by the camera algorithm. It can be seen from the images that in figure 10 (a) and (b), identified object is the bottle. In figure 10 (c), first bottle is identified as the required object to the user. When the robot realize that the first modification was wrong then it has found the near by object that is switch as the required object to the user.



(a) Position of the arm after every 2 seconds in experiment 1.



(b) Position of the arm after every 2 seconds in experiment 2.



(c) Position of the arm after every 2 seconds in experiment 3.

Fig. 9. Positions of the arm grabbed by the stereo camera after every 2 s.

These experimental results show the effectiveness of the proposed power-assist method with perception-assist.

In these experiments, motion modification was carried out in horizontal planar directions as a first step towards this new concept. In the future, the concept will be expanded to 3 dimensional motions to cater for daily life requirements.

VII. Conclusion

A concept of intelligent exoskeleton that assists not only the motion of the user but also the perception of the user using a sonar sensor and a stereo camera is proposed. In the proposed method, the user motion is modified by the exoskeleton if it is necessary, although the conventional power-assist robot never modifies the user motion. The effectiveness of the proposed method was verified experimentally.

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