Paper:

Perception-Assist with an Active Stereo Camera for an Upper-Limb Power-Assist Exoskeleton

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[Received May 18, 2009; accepted August 26, 2009]

This paper presents perception assistance with an active camera for an upper-limb power-assist exoskeleton that assists user perception as well as user motion when the user interacts with the environment using sensors of the exoskeleton. The active stereo camera monitors user interaction with the environment, so the exoskeleton identifies objects that can be touched or grabbed by the user. Stereo camera positioning is controlled to continuously track the exoskeleton end-effector, ensuring that the user's hand always lies within the camera viewfield. If any obstacle might block the camera viewfield, the camera is controlled to avoid the obstacle. The effectiveness of the proposed concept is evaluated in experiments.

Keywords: exoskeleton, power-assist, perception-assist, active camera

1. Introduction

Several types of exoskeleton robots [1–15] have been proposed to assist in activities in daily life (ADL) or rehabilitation of physically weak persons. Because upper-limb movement is important in ADL, power-assist exoskeletons have been proposed to assist upper-limb movement [1–12, 15], presumably based on user intent. Skin surface electromyography (EMG) is often used to detect user intent because it directly reflects user muscle activity [1–7]. Information on EMG signals and/or force sensors is often used to predict user movement intent in conventional power-assist exoskeletons.

In the case of physically weak persons, however, perception ability may also be weakened sometimes, for example, by age, it is important to assist sensing ability robotic exoskeleton sensors. Therefore, the robotic exoskeleton which assists not only the power but also the perception of the user using the sensors of the exoskeleton was proposed [15].

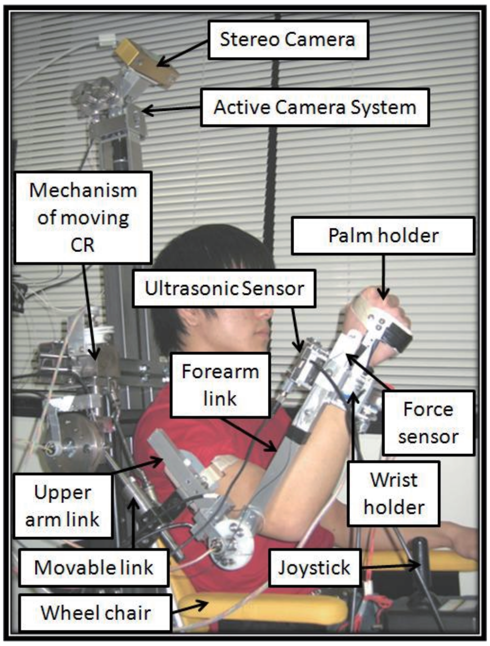
This paper proposes perception assistance with an active camera for an upper-limb power-assist exoskeleton, aiding user perception efficiently and intelligently, in interacting with the environment. User/environment interaction is best monitored by changing stereo camera positioning using an active camera. Active camera positioning ensures that the exoskeleton end-effector lies within the image viewfield of the stereo camera. Based on environmental information gained from exoskeleton sensors, user movement is modified if any problem arises in the user's hand trajectory in user interact with the environment. For example, if a user grabs an object with a wrong trajectory, the exoskeleton automatically tries to correct the trajectory to grab the object, assisting user perception. Horizontal and vertical camera positioning is controlled to trace the position of the exoskeleton end-effector. Camera positioning is controlled to avoid obstacles possibly blocking the camera viewfield, e.g.,. by rotating the camera clockwise or counterclockwise. The exoskeleton thus continuously monitors the process of user interaction with the environment. We evaluated the effectiveness of this in experiments.

2. Upper-Limb Exoskeleton

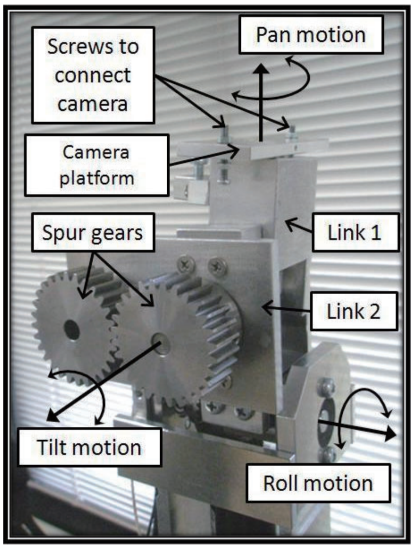
The 4DOF upper-limb power-assist exoskeleton robot we developed, shown in **Fig. 1**, assists shoulder vertical flexion/extension, shoulder horizontal flexion/extension, elbow flexion/extension, and forearm supination/pronation [14]. It mainly consists of a shoulder motion support part, an elbow motion support part, a forearm motion support part, and a mobile wheel chair (i.e., a platform of the exoskeleton). The shoulder motion support part consists of an upper arm link, drive and driven pulleys (one for shoulder horizontal flexion/extension and one for shoulder vertical flexion/extension), two DC motors, two potentiometers, an arm holder, and a mechanism of moving centre of rotation of the shoulder joint. The 1DOF elbow motion assist part consists of a forearm link, pulleys, a DC motor, and a potentiometer. The forearm motion support part consists of a wrist frame, an inner and an outer wrist holder, a wrist cover, a wrist force sensor, and potentiometers. The wrist force sensor measures force caused by the difference in movement between the user's hand and exoskeleton wrist holder. The movement range is decided based on the user's ADL and safety as detailed in **Table 1**.

Another three DC servomotors with drivers control the active camera roll, tilt, and panning, as shown in **Fig. 2**.

Sensor candidates for perception-assist were an ultrasonic sensor [FW-H10R, Keyence] and a digital stereo



(a) 4DOF upper-limb power-assist exoskeleton robot



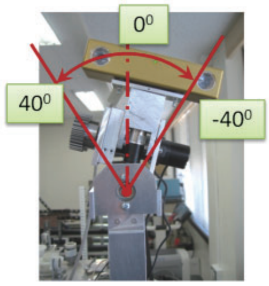
(b) Active camera platform

Fig. 1. Upper-limb exoskeleton.

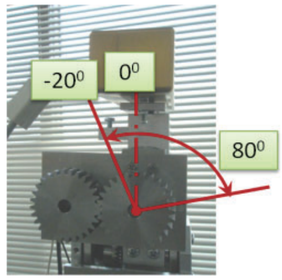
Table 1. Upper-limb movement range.

Movement		Human Rang [deg]	Exoskeleton Range [deg]
Shoulder	Vertical Flexion	180	90
	Vertical Extension	60	0
	Horizontal Flexion	90	90
	Horizontal Extension	60	0
Elbow	Flexion	145	120
	Extension	-5	0
Forearm	Pronation	50	50
	Supination	80	80

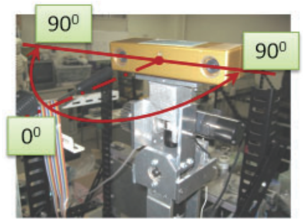
camera [Bumblebee 2, Point Grey Research]. The ultrasonic sensor is on the forearm wrist cover of the exoskeleton, as shown in **Fig. 1(a)**. The digital stereo camera on a



(a) Roll



(b) Tilt



(c) Panning

Fig. 2. Active camera movement range.

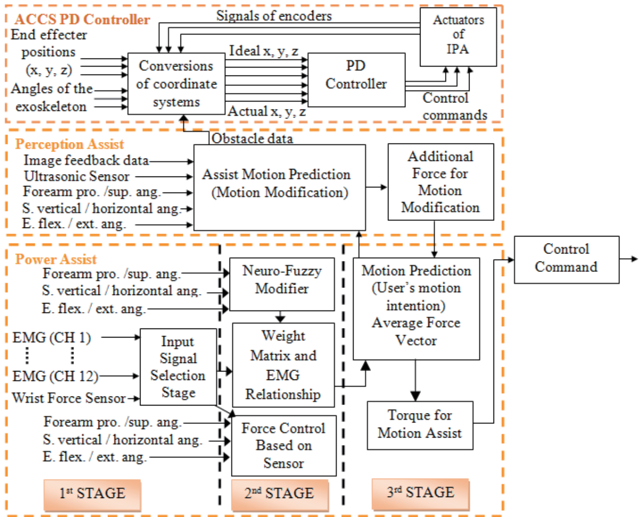


Fig. 3. Basic controller architecture.

3DOF active camera platform over the head of the user, as shown in **Fig. 1(a)**, acquires the environmental information in front of the user's arm, detecting objects in front of the user that the user may grab or touch. Sensor accuracy affects perception-assist results. Proposed movable active camera ranges are shown in **Fig. 2**. The palm holder enables the user to grab or touch objects in the fingers.

3. Exoskeleton Control

The basic architecture of the controller is depicted in **Fig. 3**. The controller basically consists of power-assist part, perception-assist part and an active camera system (ACS) part. The skin surface electromyogram (EMG) is used to predict the user's intended movement.

3.1. EMG

To control the exoskeleton based on user intent, the root mean square (RMS) of raw EMG signals directly reflecting user intention are used as main input signals to the controller [5]. Because raw EMG signals are difficult to use as e controller input information, the RMS is calculated to extract signal features. The user's 4DOF upper-limb movement, i.e., force vector of the user's hand, is predicted by monitoring EMG signals from 12 muscle locations [5].

3.2. Power-Assist Control

The power-assist part of the controller, basically the same as a conventional EMG-based controller, consists of three stages. Stage 1, the input signal selection stage, is when EMG-based control or wrist force sensor-based control is applied based on the user's muscle activity. Stage 2, calculates required joint torque. If EMG-based control is selected in Stage 1, required joint torque is calculated from EMG signals as follows:

$$\begin{bmatrix} \tau_{sv} \\ \tau_{sh} \\ \tau_e \\ \tau_f \end{bmatrix} = \begin{bmatrix} w_{sv1} & w_{sv2} & \cdots & w_{sv11} & w_{sv12} \\ w_{sh1} & w_{sh2} & \cdots & w_{sh11} & w_{sh12} \\ w_{e1} & w_{e2} & \cdots & w_{e11} & w_{e12} \\ w_{f1} & w_{f2} & \cdots & w_{f11} & w_{f12} \end{bmatrix} \begin{bmatrix} CH1 \\ CH2 \\ \cdot \\ \cdot \\ CH11 \\ CH12 \end{bmatrix} \quad (1)$$

where τ_{sv}, τ_{sh}, τ_e, and τ_f are torques for shoulder vertical flexion/extension, shoulder horizontal flexion/extension, elbow flexsion/extension, and forearm pronation/supination motions, respectively. CHn is the RMS of the n^{th} EMG channel and w_{svn} is the weight for the n^{th} EMG channel for estimating torque for shoulder vertical flexion/extension, w_{shn} is the weight for the n^{th} EMG channel for estimating the torque for shoulder horizontal flexion/extension, w_{en} is the weight for the n^{th} EMG channel for estimating the torque for elbow, and w_{fn} is the weight for the n^{th} EMG channel for estimating the torque for forearm pronation/supination. A neuro-fuzzy modifier adjusts matrix weights in Eq. (1) based on upper-limb positioning. The controller is adjusted to suit individuals based on neuro-fuzzy modifier training [5].

In stage 3, the wrist force vector, i.e., that on the exoskeleton end-effector, is estimated based on user intent and averaged to ensure smooth movement. If the perception assist part prepares an additional force vector to modify movement, this additional force is added to the wrist force vector [15], then, the desired joint torque command for power-assist is calculated and sent to motor drivers to control the exoskeleton.

3.3. Perception-Assist

Modifing assistance movement is considered by the exoskeleton, if problems arise in the user's hand trajectory in interacting with the environment. Additional force vector is introduced at the exoskeleton end-effector to correct the hand trajectory [15]. Otherwise, only conventional power-assist is performed.

3.4. Active Camera System (ACS)

Three DC servomotors with inbuilt incremental encoders are used to control stereo camera roll, tilt, and panning angles. Initialstereo camera positioning and the virtual camera focus point are shown in **Fig. 4**. For the camera to track the user's hand, the camera should be positioned so that its virtual focus point exoskeleton end-effector positioning as shown in **Fig. 5**. Both end-effector and virtual focus point positioning are calculated for base camera coordinates $\{^{bcam}P\}$. PD control makes the difference between the two zero, enabling the camera to track exoskeleton end-effector positioning.

Vision feedback data is used to determine whether obstacles exist in the environment, then the stereo camera, is rotated clockwise or counterclockwise to avoid the obstacle. In obstacle avoidance, the minimum distance between the obstacle and the closest neighboring edge (x_r), as shown in **Fig. 6**, is calculated for the number of image pixels. The distance from the edge of the object – the number of pixels between the object edge and the virtual wall – to the virtual wall is fixed (x_i) to be the same as the natural length of the virtual spring and damper.

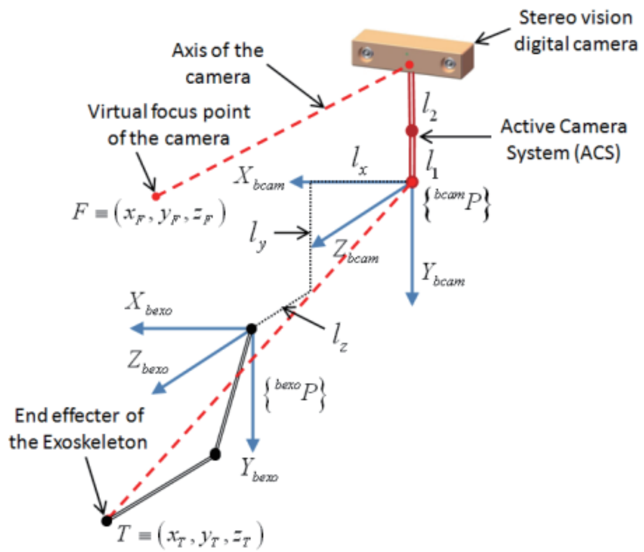


Fig. 4. Initial camera positioning and virtual camera focus.

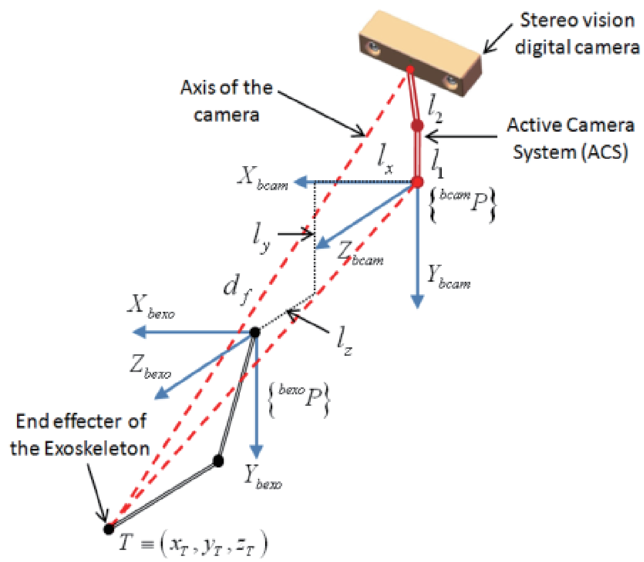


Fig. 5. Camera positioning for tracking the end-effector.

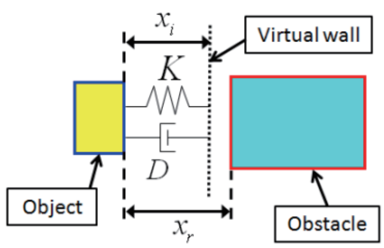


Fig. 6. Virtual wall for obstacle avoidance.

The difference between $x_i$and x_r is considered as follows to determine whether the object has penetrated the virtual wall:

$$x = |x_i| - |x_r|. \quad (2)$$

$x > 0$ indicates that the obstacle has reached the object and penetrated the virtual wall, so the torque command is executed to avoid the obstacle by applying a virtual spring and damper, given as:

$$\tau = M\ddot{x} + D\dot{x} + Kx \quad (3)$$

where M is the moment of inertia of rotating ACS links and the camera, D the viscous coefficient, and K the spring coefficient, and τ is the torque command for the actuator rolling in obstacle avoidance to continue monitoring user interaction with the object. The sign of τ (i.e., whether rotational camera rolling is clockwise or counterclockwise) is determined based on the sign of x_r. If the obstacle moves to the right of the object, x_r is positive and if to the left, x_r becomes negative as shown in **Fig. 7**.

4. Perception-Assist with Ultrasonic Sensor and Active Digital Stereo Camera

The exoskeleton has two types of sensors to monitor user/environment interaction – an ultrasonic sensor and a digital stereo camera. When the user moves an arm to grab or touch, hand trajectory is almost straight toward the object [16]. Based on this and considering ultrasonic sensor output and user hand positioning, it can be determined whether the user is moving a hand toward an object [15]. When the user moves the hand in working space, the active camera is positioned to track the exoskeleton end-effector, ensuring that the user's hand lies within the captured image.

ACS obstacle avoidance ensures that the stereo camera continuously monitorsuser/environment interaction effectively.

5. Experiments

In the experimental set-up in **Fig. 8**, interface boards RIF−171−1 and JIF−171−1 (Just Ware) process input and output signals to control the exoskeleton and active camera. To process A/D input signals, potentiometer signals, force sensor signals and ultrasonic sensor signals are

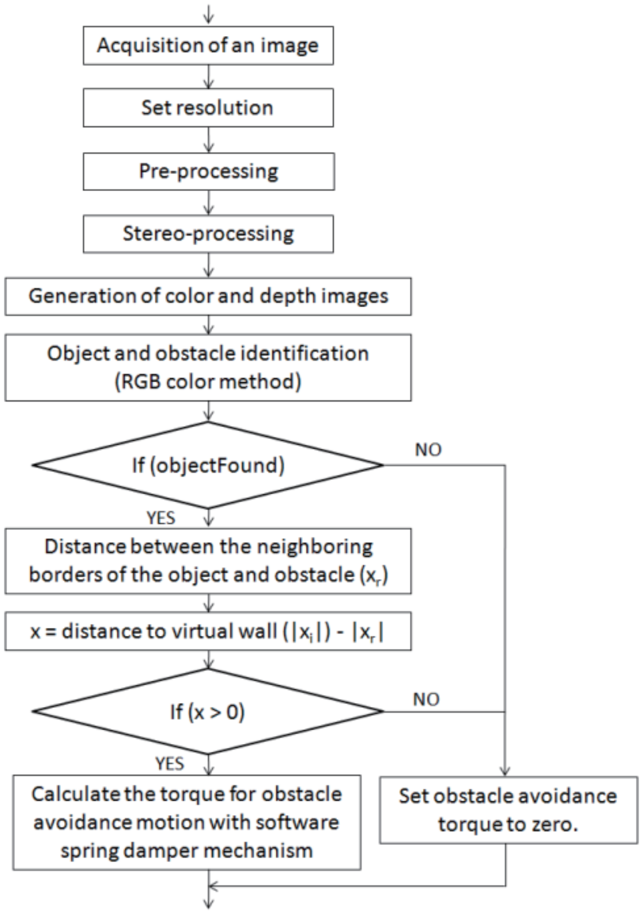


Fig. 7. Obstacle avoidance algorithm.

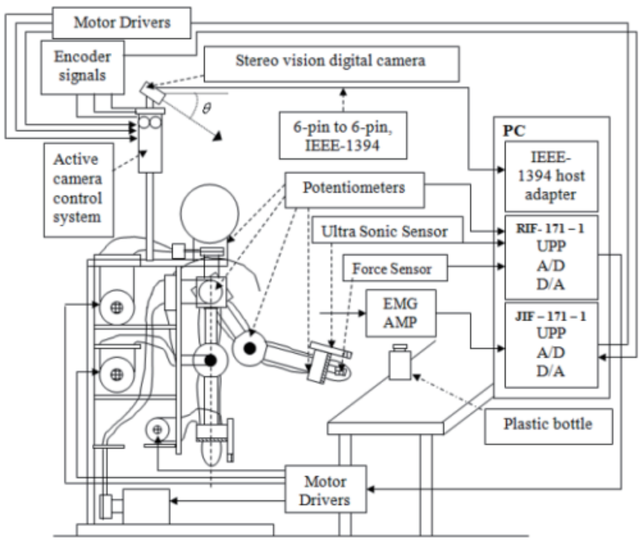
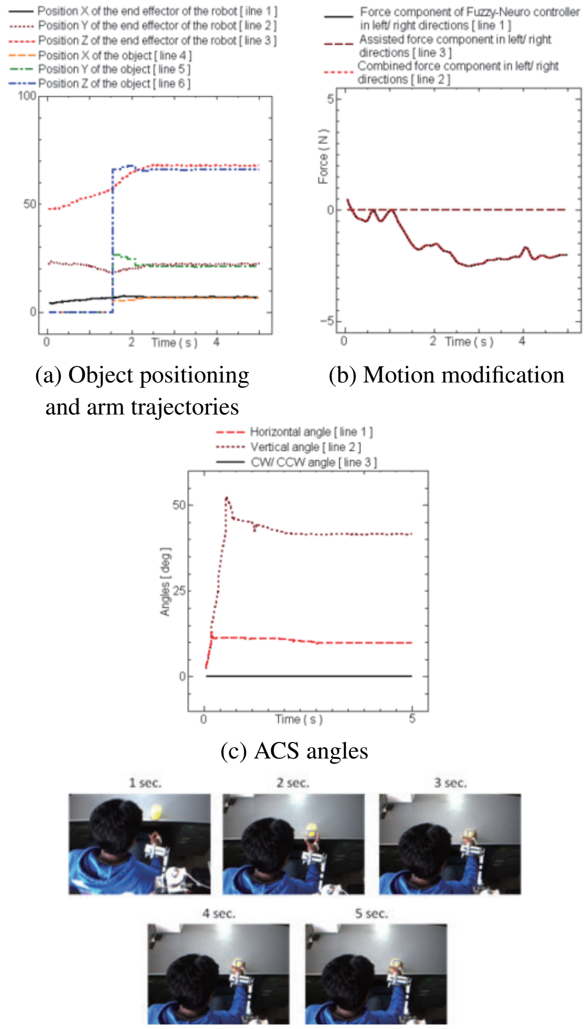


Fig. 8. Experimental setup.

fed to the RIF−171−1 card A/D port where, as EMG signals are fed to the A/D port of the JIF−171−1 card, measured EMG signals are amplified by the EMG amplifier before being sent to the interface board. Motor torque commands calculated in the PC are then sent to seven motor drivers – four operating the exoskeleton and three operating the active camera. Calculated torque commands for exoskeleton actuators are sent via the RIF−171−1 card D/A port and active camera torque commands are



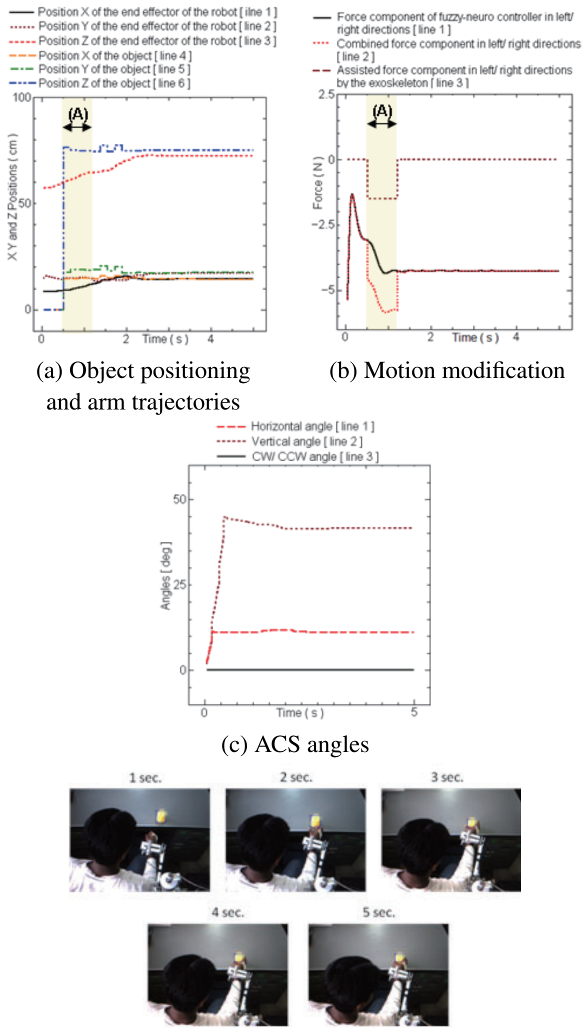
(a) Object positioning and arm trajectories

(b) Motion modification

(c) ACS angles

(d) Sequence of images saved to the PC each second

Fig. 9. Results of experiment 1.



(a) Object positioning and arm trajectories

(b) Motion modification

(c) ACS angles

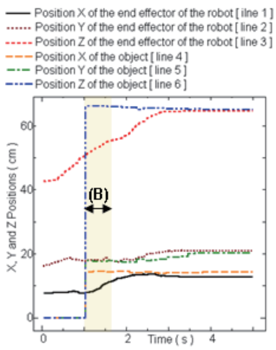
(d) Sequence of images saved to the PC each second

Fig. 10. Results of experiment 2.

sent via the JIF−171−1 D/A ports. Three DC incremental encoder outputs in the active camera are fed to the ENC port of the same interface card. The digital stereo camera is connected to a 400 Mbps IEEE-1394 OHCI PCI host adapter fire-wire interface card for high-speed communication of digital video data, using a 6-pin to 6-pin IEEE-1394 cable. All input signals except EMG signals and stereo vision data of the camera are filtered with software using a second-order butter-worth filter. EMG signals are filtered by the EMG amplifier. Controller image acquisition is set at five per second to avoid delays adversely affecting real-time controller implementation.

To evaluate perception-assist effectiveness, we conducted three experiments using a healthy young male subject. In experiment 1, the subject tried to move his hand toward the object – a plastic bottle – to grab it with the correct hand trajectory. In experiment 2, the subject moved his hand toward the object, but with a purposefully incorrect hand trajectory. In experiment 3, the subject tried the object with the incorrect hand trajectory while an obstacle was introduced to block stereo camera vision. Sensor errors are ignored in experiments.

Results for experiment 1 are shown in **Fig. 9**. Hand trajectory for positioning x, y, and z in global robot coordinates calculated by exoskeleton kinematics model lines 1, 2, and 3, and positioning x, y, and z of the object for global robot coordinates measured by stereo camera lines 4, 5, and 6, are shown in **Fig. 9(a)**. The estimated force vector of the user hand calculated from controller output, the combined (modified) force vector, and the assisted force vector added for motion modification are shown in **Fig. 9(b)**. Because the user's hand trajectory is the same as the estimated trajectory in experiment 1, the exoskeleton does not modify any motion. Angles in the horizontal (paning), vertical (tilt) and clockwise/counterclockwise (roll motion) direction of active camera control are shown in **Fig. 9(c)**. Stereo camera positioning is controlled to track exoskeleton end-effector using vertical and horizontal angles shown in lines 1 and 2 in **Fig. 9(c)**. The clockwise/counterclockwise, i.e., line 3, is zero because no obstacle blocks the camera, so hence no obstacle avoidance is done. Images showing user/environment interaction were saved to a PC each second as shown in **Fig. 9(d)**. Experimental results show that the exoskeleton effectively conducts conventional power-assist based on user intent, when any problem is not found in the user's motion.



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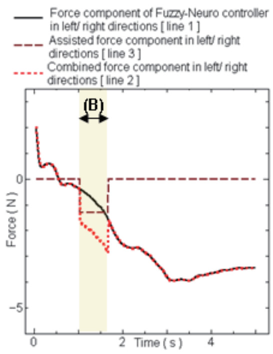
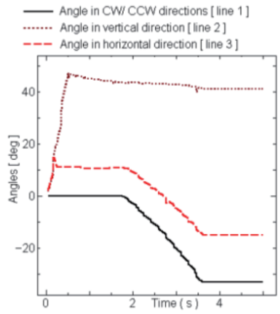
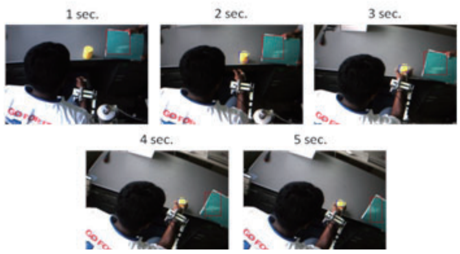


(b) Motion modification



(c) ACS angles



(d) Sequence of images saved to the PC each second

Fig. 11. Results of experiment 3.

Figure 10 shows results of experiment 2. **Fig. 10** shows similar results. When the user moved his hand toward the object, motion modification was performed in term (A) in **Figs. 10(a)** and **(b)** to correct the hand trajectory because the exoskeleton determined that the user's hand trajectory differed from that estimated. Since no obstacle blocked the camera, the camera angle clockwise/counterclockwise remains zero as shown in **Fig. 10(c)**. Image sequences saved to hard disk of user hand positioning are shown in **Fig. 10(d)**.

Figure 11 shows results of experiment 3, which resemble results in **Fig. 9**. When the user moved his hand toward the object, the exoskeleton determined that the user's hand trajectory differed from that estimated, so movement was modified to correct the trajectory in term (B) in **Figs. 11(a)** and **(b)**. The exoskeleton also identified an obstacle in the camera view, so the camera was rotated clockwise to avoid the obstacle and monitor user/environment interaction. The camera is positioned horizontally, vertically, and clockwise/counterclockwise in **Fig. 11(c)**. The user's hand and the obstacle are positioned as shown in the image sequence saved to the PC each second in **Fig. 11(d)**.

6. Conclusions

Perception-assist using an active camera for an upper-limb power-assist exoskeleton that assists user movement and perception we propose modifies user movement if problems arise in user interaction with the environment. The active camera continuously tracks the user's arm trajectory to effectively avoid obstacles possibly blocking camera monitoring, as confirmed in experiments.

Acknowledgements

We gratefully acknowledge support for this research provided by the Japan Society Promotion of Science (JSPS) Grant-in-Aid for Scientific Research (C, 19560258).

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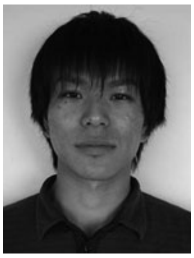

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