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Development of a Wheelchair-based Rehabilitation Robotic System (KARES II) with Various Human-Robot Interaction Interfaces for the Disabled

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Abstract
This paper describes our ongoing project about a new wheelchair-based rehabilitation robotic system for the disabled, called KARES II (KAIST Rehabilitation Engineering Service System II). We shall concentrate on the issues of design and visual servoing of the robotic arm with three human-robot interaction subsystems: an eye-mouse, an EMG interface, and a haptic suit interface. First, the specific required tasks of the robotic arm system are defined according to extensive surveys and interviews with the potential users, i.e., the people with spinal cord injury. In order to design the robotic arm for the predefined tasks effectively, a target-oriented design procedure is adopted. Next, a visual servoing subsystem for the robotic arm is designed and is integrated to perform the predefined tasks in an uncertain/time-varying environment. Finally, various human-robot interaction devices are proposed as interface for diverse users with physical disability. One or more of these interfaces may be selected on the basis of each user's need. These diverse input devices can be used in a complementary way according to the user's preference and to the degree of disability. Experimental results show that all subsystems can perform the defined tasks through the robotic arm in an integrated way.

Keywords
Wheelchair-based Rehabilitation Robotic System, Human-Robot Interaction Interface, Disabled

INTRODUCTION
This paper introduces our new wheelchair-based robotic arm system, KARES (KAIST Rehabilitation Engineering Service System) II, and its human-robot interaction devices which assist independent life of the elderly and/or the disabled persons that have disadvantages in sensory and motor functions of their limbs. The wheelchair robot system consists of a powered wheelchair and a mobile-platform based robotic arm (Fig. 1). The system possesses the mobile capability through the motorized wheelchair as well as a manipulatory function with the robotic arm. For a user and a robot in the same environment, a safe and comfortable interaction between them is important. It has been reported that many difficulties exist in human-robot interactions in existing rehabilitation robots [1]. For example, manual control of the robotic arm takes a high cognitive load on the user part while physically disabled persons may have difficulties in operating joysticks dexterously or pushing buttons for delicate movements. Thus, human-robot interaction is one of the essential technologies to be developed in using the robot system for people with disabilities.

Two factors are of great interest in the intelligent human-robot interaction technology; one is intention reading of the user, and the other is an autonomous capability of the robot. Intention reading allows the user to command the robot system in a human-friendly way, which can be achieved possibly by using bio-signal, wearable haptic suit, voice/sound perception, or the "eye" mouse device that utilizes eye movements. Intention information can be used as a system state feedback for human-robot interaction. The autonomous capability in controlling the robot system is needed to realize the user's high-level commands when the user has a limited physical ability. A typical example is visual servoing-based or compliance-based control of a robotic arm.

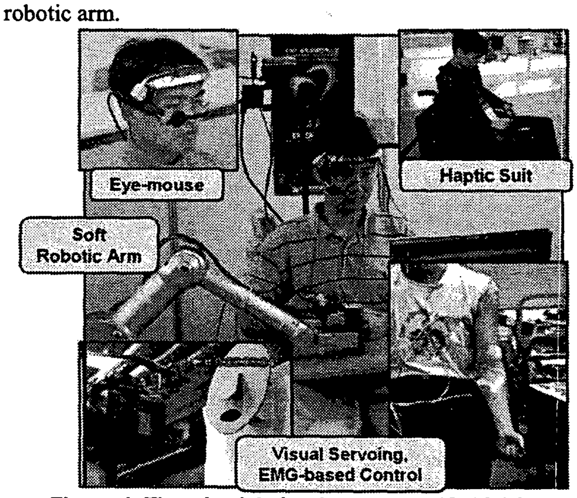


Figure 1. The wheelchair robot system, KARES II

In this paper, we consider a wheelchair robot system, KARES II, which we are developing as a service robotic system for the disabled and/or the elderly, and discuss its human-robot interaction techniques. In Section II, we describe the whole structure of KARES II system. In Section III, we present the design method of the robotic arm and its visual servoing function. Other human-robot interaction interfaces are discussed in detail in Section IV. Finally, concluding remarks follow in Section V.

KARES II SYSTEM: OVERVIEW

The H/W structure of KARES II system consists of a mobile platform and a wheelchair platform as represented in Fig. 2. KARES II system is a hybrid-type rehabilitation robotic system, taking some advantages of a wheelchair-based system [2] and those of a mobile robot-based system [3].

For the user in the wheelchair platform, various interfaces are designed for command/control or interaction with environment. These interaction/interface subsystems should be easy to use, and should be human-friendly in the overall design, because being in the wheelchair can be considered as a part of living for people with spinal cord injury. As a test bed, we have developed a set of various human-robot interfaces to be properly adopted according to the levels of disability.

The mobile platform enables KARES II system to have an effect of enlarging the workspace. Different from the case of conventional wheelchair-based system, the mobile platform can provide not only safety for users avoiding possible collision but also wider range of workspace. In view of the predefined 12 tasks (Table 1), the mobile platform renders a very effective solution for those tasks which deals with remotely located objects (for example, 'Turning Switches On/Off', 'Opening/Closing Doors' and etc.). Moreover, due to separation between the robotic base and wheelchair, structural problems such as vibrational errors in the end-effector of the robotic arm caused by flexible rubber wheel of the wheelchair are effectively resolved.

As shown in Fig. 2, the mobile platform contains the robotic arm as main body to perform the given tasks and the visual servoing subsystem for providing KARES II with autonomy.

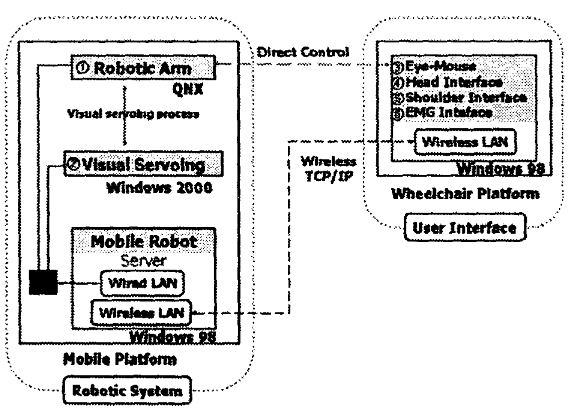


Figure 2. H/W structure of KARES II system

Table 1. The predefined 12 tasks

No	Name
1	Serving a Meal
2	Serving a Beverage
3	Wiping & Scratching Face
4	Shaving
5	Picking Up Objects
6	Turning Switches On/Off
7	Opening/Closing Doors
8	Making Tea
9	Pulling a Drawer
10	Playing Games
11	Changing CD/Tapes
12	Removing Papers from Printer/Fax

Table 2. Specifications of Mobile Platform

Size(mm)	536×500×920 (W×H×L)
Max. Payload	80kg
Max. Speed	0.5m/s
Power Supply	1kWh
Motor Power	150W
Gear Reduction Ratio	43:1

Mobile Base

Mobile platform of KARES II system gives the mobility and extends the workspace of KARES II system. Considering the predefined 12 tasks, we find that the role of the mobile platform is very effective to perform some tasks which should be done in the spots far from the user: example tasks are picking an object, turning switches on/off and opening/closing doors. The specifications of the mobile platform are given in Table 2.

Wheelchair Platform

In consideration of the cost factor to construct KARES II, we use Partner P/W6000 wheelchair, manufactured by Dynamics, which has two motorized rear wheels and two casters in front. The maximum speed is 12km/s, and the weight is 70kg.

ROBOTIC ARM WITH VISUAL SERVOING ON THE MOBILE BASE

Design of a Robotic Arm

In our design, we adopt a target-oriented design (TOD) to reduce energy and effort required for iterative redesigning process. In TOD, the design targets should be first defined clearly and carefully prior to all the other design procedures since all subsequent procedures are aimed to accomplish the targets. The TOD procedure, an effective design procedure for a robot arm to achieve the design targets both in kinematic and dynamic sense, is described in Fig. 3.

According to the proposed TOD procedure, a 6 DOF robotic arm with all revolute joints (Fig. 4) is developed to perform the predefined 12 tasks. It has the PUMA type Denavit-Hartenberg parameters [4] and the lengths of links are optimized for the predefined tasks. The robotic arm is mounted on a mobile base so as to perform those tasks that are executed far from the user as well.

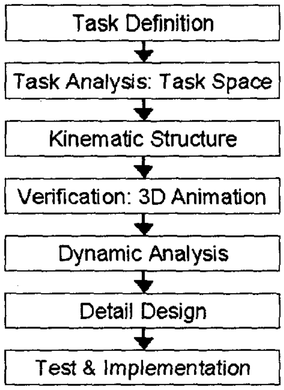


Figure 3. Target-Oriented Design procedure

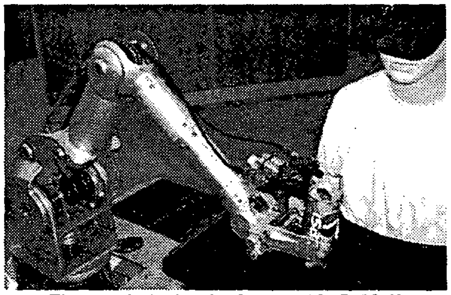


Figure 4. Robotic Arm of KARES II

In KARES II system, the robotic arm is controlled by commands given from the user. The command of the user is read from some interfaces and is translated into subcommands related to the task and/or desired position. These commands are sent to the controller of the robotic arm. By following the commands, the robotic arm performs the given task according to the user's command.

Our robotic arm has two special functions. First, the robotic arm is designed to have the compliance function because the robotic arm may frequently contact with the user in the course of task execution. The compliance function can increase safety level when there occurs an unexpected collision with the user. Moreover, it can provide more comfortable services to the user [5].

Second, it is noted that the robot arm is equipped with visual servoing function. This function is required not only for detecting and locating an object autonomously but also for basic intention reading by analyzing the facial expression of the user.

Visual Servoing of a Robotic Arm

Visual servoing refers to controlling the 3-D pose (3-D position and orientation) of a robotic arm/hand based on the image information from vision camera which is a kind of non-contact sensors [6].

According to our experiences on a wheelchair-based rehabilitation robotic system, called KARES I, we had found that visual servoing is not an easy task due to requirements of real-time control and robustness to varying illumination, and in particular, the performance is deteriorated due to vibration of the robotic base supported by flexible rubber tires of the wheelchair [7]. In KARES II system, we have separated the robotic arm from the wheelchair platform and have used a vision technique called "space variant vision" for real-time control and robustness to varying illumination.

To evaluate visual servoing functions, we have selected two primitive subtasks such as "Grasping a cup on the table" and "Approaching the user's mouth with grabbed cup". For effective execution of the above two subtasks, we used a small-sized stereo camera head in an eye-in-hand configuration [9]. The developed small-sized/light-weighted stereo camera head system in the eye-in-hand configuration further shows negligible backlash due to novel cable-driven mechanism and reliable depth extraction based on vergence movement. Table 3 shows specification of the developed stereo camera head.

Table 3. Specification of developed stereo camera head

Weight	290g (including two cameras and two motors)
Size	110mm (W) × 113mm (D) × 57mm (H)
Vergence	-30 ~ 45 degrees (velocity: 200 degrees/sec)
Note	Cable-driven mechanism

For fast image processing, the log-polar mapping is adopted which is a kind of space variant vision technique [8]. However, as the camera gets very near to an object, visual servoing with conventional log-polar mapping becomes difficult due to its limited capability to acquire near motion information of the object. To solve this difficulty, we have devised a modified log-polar mapping characterized by weighting the periphery of the image [9].

For testing, two subtasks for visual servoing were performed by using the technique of modified log-polar mapping. Regarding the first task of "grasping a cup on the table", we successfully confirmed that the robot can grasp a cup with success ratio about 92%. The next task we considered is to let the robot hand approach the user's mouth with the grabbed cup. Here, we report that we have performed an experiment of "intention reading" by utilizing the visual images obtained through visual servoing. We assumed that one can show one's intention to drink or not to drink by opening or closing one's mouth. Thus, we implemented an intention reading skill based on the information about the user's mouth [10].

In our approach, the Gabor-filter based Gaussian weighted feature (GG feature) is proposed to extract the degree of mouth openness. GG feature is defined as:

$$f_G = \frac{\sum_{j=1}^{H-1} w_G(j) dy_{proj}(j)}{\sum_{j=1}^{H-1} w_G(j)}, \quad (1)$$

where, H denotes the height of the Gabor-filtered image. represents the Gaussian weights $w_G(j)$, and $dy_{proj}(j)$ denotes the absolute values of the derivative of the projected values $y_{proj}(j)$ in the Gabor-filtered image, respectively.

Fig. 5 shows sequential images of the user's face with different degree of mouth openness and the result of intention reading. According to the extracted features about the user's mouth, we can easily estimate the positive/negative level of the user's intention to drink or not to drink [10].

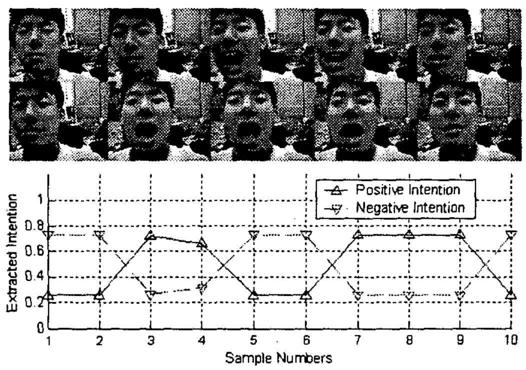


Figure 5. Intention reading from sequential images: ten sequential face images and corresponding extracted intentions

VARIOUS HUMAN-ROBOT INTERACTION INTERFACES ON THE WHEELCHAIR PLATFORM

In operating KARES II, many interaction interfaces can be used by people with various levels of spinal cord injury(Fig. 6). For example, people with C4 lesion are able to move only head with paralysis of muscles below sternocleidomastoid and trapezius muscles while people with C5 lesion are able to move only head and shoulder because of paralysis of muscles below deltoid and biceps brachii muscles. It is then quite difficult to develop appropriate human-robot interfaces for people with such spinal cord injury.

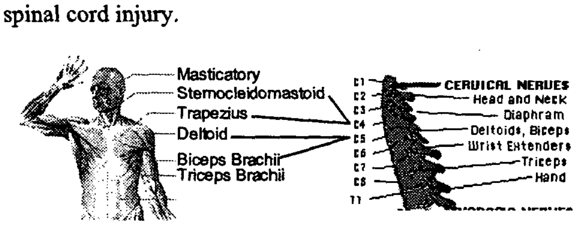


Figure 6. Relationship between level of disability and human-robot interfaces [16]

For the user of KARES II, there are four types of human-robot interfaces as will be described shortly, and it is proposed that the user choose a proper combination of interfaces according to one's level of disability. Such combination has an advantage of guaranteeing better reliability of the system. Generally speaking, the eye-mouse and head interface are suitable for people with C4 lesion, whereas shoulder interface and EMG interface are suitable for people with C5 lesion.

Eye-Mouse

An eye-mouse system was designed for the people with severe motor disability, e.g. C4 lesion. The users can indicate the position of an object that they want to grab and transfer commands to the robot by using the Eye-mouse.

Since the eye movement needs to be obtained before extracting the eye gaze direction, we have implemented CCD camera-based wearable type system. However, in this case, the eye movement is obtained with respect to the head, so the head movement should also be acquired to calculate the eye gaze direction. We have used magnetic position sensor to measure the head movement.

We have tried to track the pupil in order to detect the eye movement in the image captured by the CCD camera. However, it is usually difficult to distinguish between the pupil and the iris for people with black eyes. To solve this problem, the 'Dark eye effect' is used. The Dark eye effect allows an easier segmentation of the pupil region as shown in Fig. 7 [11].

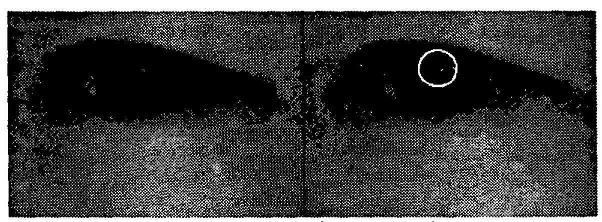


Figure 7. Pupil region extraction: Dark eye effect and pupil region

In Fig. 8, the proposed system is shown. The IR LED is placed in front of the user and it emits light to the user. The camera is attached on the side of the user's head with a mirror for convenience. The magnetic sensor, which is used to detect the head movement, consists of a transmitter and a receiver.

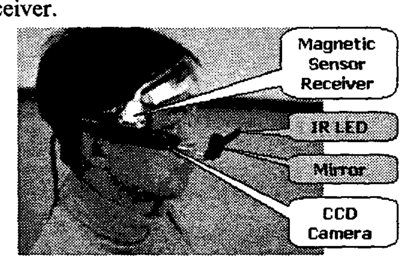


Figure 8. Proposed Eye-mouse

EMG Interface

EMG (electromyogram) signal is a form of electric manifestation of neuromuscular activation associated with contracting muscle [14]. In some cases, EMG interface is more useful than existing input devices of rehabilitation robots such as voice, a laser pointer, a keypad, and a 3D input device in the following senses. First, it can be more natural and direct to use one's shoulder or neck for a disabled than other devices when the disabled is to control a rehabilitation robotic arm. Second, such a learning process of complex system commands, such as syntax in voice commands, is not required. Finally, EMG signals may provide the rehabilitation robot with useful additional information, such as the moving speed or fatigue level of the arm.

KARES II adopts EMG interface for the user with disability who can move one's shoulder or head for controlling a robotic arm or powered wheelchair. We developed a small sized LNA (low noise amp)-type EMG AMP with specification as shown in Table 4.

To extract the user's intentions from movement of shoulders, we defined basic 8 motions (Fig. 9). To make the user-independent system, we propose an algorithm capable of classifying the EMG signals obtained from different subjects into the predefined classes using a Fuzzy C-means algorithm and a rough set-based technique selecting a necessary and sufficient set of features [15].
By applying feature extraction algorithm and Fuzzy Min-Max Neural Networks(FMMNN)-based classification method in [15], the basic 8 motions are recognized with success rates of approximately 90% for four untrained subjects.

Table 4. Specification of the EMG AMP system

Number of input channel	4
Size (mm)	100×100×10 (W×H×D)
Input voltage range	-5 V ~ 5 V
Gain	1400 V/V
Pass Band	20 Hz ~ 470 Hz
Stop rate	-32.5dB at 60Hz
Note	Biquad 2 level notch filter

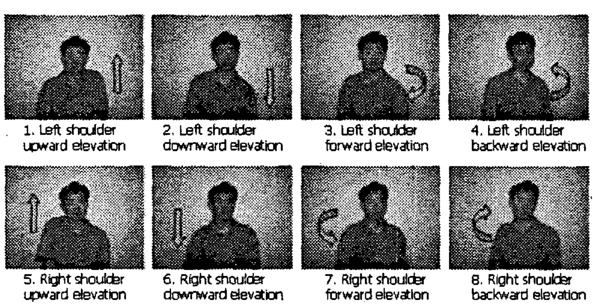


Figure 9. The basic 8 motions

Haptic Suit

FSR (force sensitive resistor) is a suitable element for developing a human-robot interface because of its features: low price, ease to measure, arbitrary shape, and thinness. FSR is a three-layered variable resistor indicating resistance in inverse proportion to magnitude of force [12].

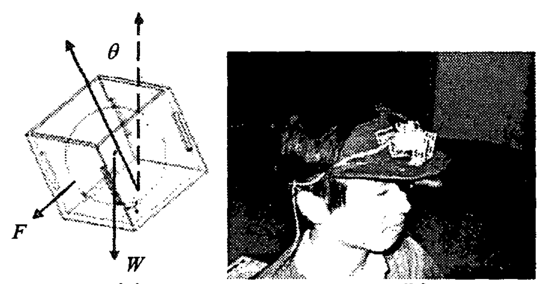
Haptic suit is basically defined as a human body motion-based interface. Among many kinds of possible human body parts, especially for the disabled who are candidate users for KARES II, we choose two body parts that is, the head and the shoulder.

Head Interface

Head interface is a two DOF interface for people with C4 lesion. It is used for body-operated control of a wheelchair and a robotic arm.

Human head motion is analyzed in order to determine the motion detection range of the head interface. The maximum tilt angles of human head are obtained by subtraction of the data. Average maximum tilt angles are 41° for the front, 73° for the rear, and 60° for right and left side. A head interface valid in the analyzed range (73°) has been developed as shown in Fig. 10.

Four FSRs are attached to the four inner surface of the wall as Fig. 10(a). Tilt motion of the cube changes the resistances of four FSRs by the weight of the steel ball. The relation between the tilt angle and the exerting force on FSR is as $F = W\sin\theta$. Fig. 10(b) shows a prototype of the head interface that is attached to an ordinary cap.



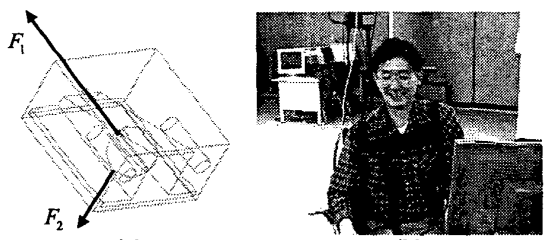
(a) (b)

Figure 10. Head Interface:
(a) angle sensor, (b) the user with head interface

Shoulder Interface

Shoulder interface is a wearable sensor suit converting the human body motion into a useful command [13]. Humans shoulder motion is also analyzed in the same method as in head interface. Average maximum ranges of shoulder motion are 7.5cm for the front, 7cm for the rear, 10.1cm for the upper direction, and 2.5cm for the downward direction. However, backward and downward motions are restricted within narrow limits because of the back and armrest of the wheelchair. We find the lift motion of shoulder is most useful for human-robot interaction.

A tension sensor measuring the lift motion of shoulder has been developed as shown in Fig. 11(a). Fig. 11(b) shows a prototype of the shoulder interface that consists of the two tension sensors and an elastic shoulder strap for measuring right and left shoulder motions.



(a) (b)

Figure 11. Head Interface:
(a) angle sensor, (b) the user with head interface

CONCLUDING REMARK

KARES II system is designed for people with the spinal cord injury. It is divided into two parts: the robotic arm subsystem and the user interfaces. The robotic arm is designed to perform twelve tasks and it has two special functions: active compliance function for safety and visual servoing function for self-autonomy. For the user's intention reading, various interfacing devices are developed to cope with different levels of disability. The eye-mouse, head/shoulder interfaces, and EMG signal interfaces are used to make commands to the robotic arm. And these interfaces are utilized under the common control architecture through GUI and sequencers.

Currently, we focus on the improvement of reliability and performance of each subsystem for pre-commercialization. Besides, as a customer-oriented approach, we make a plan to perform the clinical evaluation with potential users who have physical disabilities in motor functions with their limbs.

ACKNOWLEDGMENTS

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