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Noninvasive sEMG-based Control for Humanoid Robot Teleoperated Navigation

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This paper presents an application of noninvasive sEMG-based interface to humanoid robot navigation control between remote places via wireless internet communication. sEMG signals to recognize three wrist movements are measured from the skin of a user's arm. The wrist movements generate commands to the humanoid robot. The wrist movement directions are assigned to be intuitively comparable with the robot movement directions, therefore a user can control the robot in a natural way. By combining the state automation machine to the sEMG-based interface, possible robot movements are extended. To provide the environmental information of remote places, the images from the camera on the robot's head are transmitted into the interface PC screen. We conducted experiments in which subjects control a humanoid robot to navigate from a starting position to a destination in a maze. The experimental results demonstrate the feasibility of the proposed interface method by comparing it with the keyboard control.

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1. Introduction

Neural signal-based human-computer interfaces (HCIs) have been of huge interest and some cases have demonstrated the capability of the approaches successfully. Extracting users' intentions through noninvasive sensory equipment provides information related to body movements faster than kinematic and dynamic sensory devices such as force sensors and motion trackers. Electromyography (EMG) is one of the most interesting neural signals to detect user's intentions because it can be measured online achieving an acceptable signal-to noise ratio under current technologies. Surface EMG (sEMG) is measured on the skin noninvasively by electrical voltages which represent neuromuscular activities generated in muscles during their contraction. The activities are known to be discriminated according to intended behaviors.[1,2] Some investigations have challenged to develop noninvasive sEMG-based interface techniques based on the fundamental properties of EMG. Some used EMG signals from eyebrows and jaw movements,[3] from arms,[4,5] and from legs.[6] To cope with users' desired commands (i.e., the direction of movements) in natural manner, sEMG signals from arms may be most appropriate because the interface protocol is intuitive enough to be familiarly operated. Furthermore, even the disabled and the elderly can use the sEMG-based interface to assess a controlled device without much training. Among the disabled, people with bilateral hand amputations and Spinal Cord Injuries (SCIs) at C6-C7 functional levels could use their residual and controllable limbs. Due to its potential advantages, sEMG-based interfaces have been attempted to various applications: teleoperation, exoskeleton, computer interface, manipulation, fatigue estimation.[2,7-11] However, there has been no attempt which applies a sEMG-based interface to control an independent agent such as a humanoid robot in a concrete practical scenario to the best of our knowledge.

This work presents humanoid robot navigation control by extracting users' intentions through light and wearable sEMG sensors and wireless remote communication between a user and a robot. Furthermore, we propose to integrate a finite state automation scheme to extend the number of discriminated intentions. To be practically usable, all processing procedures can be run in real-time without perceptible delay time.

This paper is organized as follows. The components of the proposed method are explained in next section. Section 3 reports the experiment procedure and its results, and Section 4 concludes this paper.

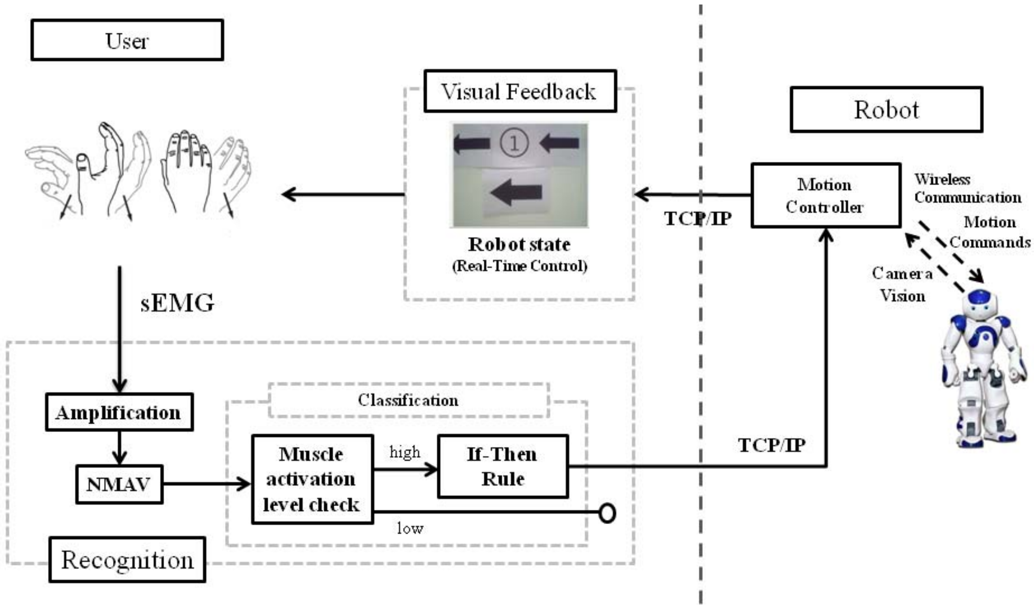

Fig. 1 Overall system architecture

2. Methods

2.1 Overall system architecture

Fig. 1 illustrates the proposed system architecture. Each user sat in front of a PC screen with surface electrodes attached in a place. A PC near the user ran the sEMG signal processing and pattern recognition algorithm while receiving muscle signals from the sensors. The user used wrist movements to generate commands to a humanoid robot looking at the vision images transferred from a camera vision of the humanoid robot. In real time, the user recognized the robot's state based on the vision information, and generated appropriate wrist movement to produce a command to the robot. The wrist movement was detected through sEMG electrodes, and the muscle signal was classified to select an adequate motion command to the robot.

The humanoid navigation system was located in the other place separately. The wireless TCP/IP transferred all information between the robot system and user. The humanoid robot was equipped with a camera (X-cam RCW-1000, iNovia Inc.) on the top of its head to provide visual feedback to the user. To overcome narrow view range, the robot could turn its head left or right by commands from the user.

The sequential subsections explain system components in detail separately.

2.2 Motion and muscle selection

The motions and target muscles to be used to control the robot must be selected by taking into account the easiness of mapping the signals to robot operating commands as well as the clear observability of the signals on the skin surface. To map the signals to the commands, three different wrist movements (wrist flexion, wrist extension, and ulnar deviation) were chosen as shown in Fig. 2 (top), and these movements were mapped to the commands ("Left", "Right", and "Forward"). The commands "Left" and "Right" turned the robot's head to the left and right respectively. The command "Forward" ordered the forward walk or body turn of the robot.

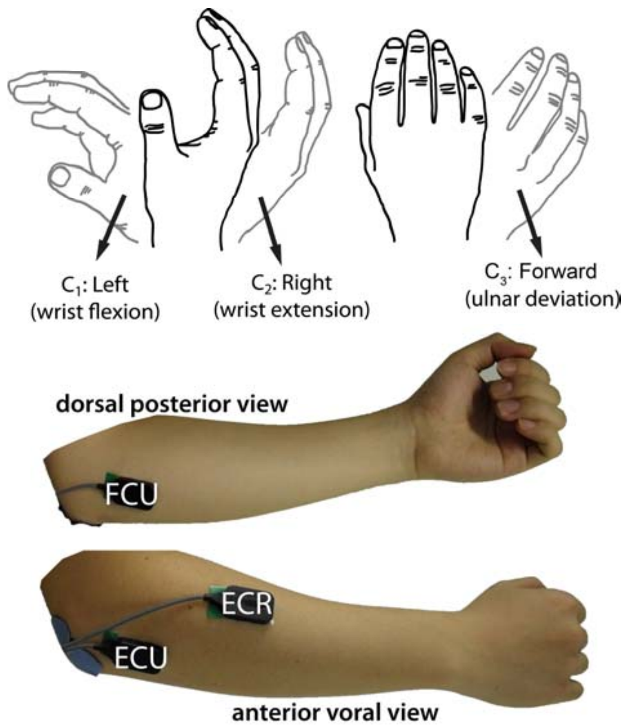

Fig. 2 (top) Wrist movements, and (bottom) sEMG electrodes' locations

The user can intuitively control the humanoid robot through these movements because the direction of the wrist movement corresponds to the direction of the movement of the robot. To observe the movements, three muscles that produce the chosen wrist movements were selected. Their activities were easily observable on the skin surface: the flexor carpi ulnaris (FCU), the extensor carpi radialis (ECR), and the extensor carpi ulnaris (ECU) as shown in Fig. 2 (bottom).

2.3 sEMG signal processing and pattern recognition

We placed three bipolar, noninvasive surface electrodes (DE-2.1, Delsys, U.S.A.) with built-in amplifiers over the target muscles using medical adhesive tape. The electrodes were connected to a data acquisition board (PCI 6224, National Instruments™, U.S.A.), and signals were sampled at 1000 Hz. The sampled data were rectified and smoothed using the mean absolute value (MAV) with a 200-msec window that moved every 100 ms.[12] A personal computer (Pentium 4, 2.4 GHz processor) and Microsoft Visual Studio 2005 were used for the experiment.

The maximal voluntary contraction (MVC) of each muscle was measured prior to the experiment, and the MAVs of the sEMG signals were then normalized to one using MAVs of MVC (normalized MAV, or NMAV). An IF-Then Rule algorithm was used to classify the control intentions of the user. First, the muscle with the greatest activation was selected by comparing magnitudes of NMAVs among the three muscles. Second, when NMAV from the selected muscle was greater than 10% of its MVC, each designated command was generated with respect to the selected muscle. The high NMAVs (>10% of MVC) from FCU, ECR, and ECU triggered the commands, "Left", "Right", and "Forward" respectively.

2.4 Humanoid navigation system and control

A Nao humanoid robot (Aldebaran Robotics Inc., France)[13] with 25 degrees of freedom is the robot platform used in this work. A monocular vision on its head captured a front view. Thus, the user could see what the robot saw on the PC screen while controlling the robot using the sEMG control system. The robot can execute walking forward, turning, and head rotation. To secure its stability, the robot was programmed to not walk or turn itself during observing its environment by rotating its head. The robot walked at a speed of 3.3 cm/s and made turns at speed of 0.13 rad/s.

We applied the state automation diagram to control the robot motions with three commands from sEMG. Fig. 3 illustrates the state automation diagram used in this work. Five motions were programmed to control the robot. The robot could rotate its head to the left or right up to 90 degrees maximally. While the robot stayed still, either a "Left" or "Right" command made the robot turn its head by three degrees. On the other hand, while the robot moved, either a "Left" or "Right" command stopped the robot. If the robot looked straight ahead and the command from the sEMG signal was "Forward", it walked straight until "Left" or "Right" command occurred. Otherwise, it made the robot turn its body to be aligned with the head.

2.5 Communication

As already mentioned, the user and humanoid robot were in different places and the communication between the two was carried out through the wireless TCP/IP. The motion commands were transferred every 100ms to the robot from the user through the wireless communication. The visual images are measured at 5 fps, and transferred every 200ms to a PC near the robot through the wired USB connection. Then, the PC sent the images to the user through the wireless communication.

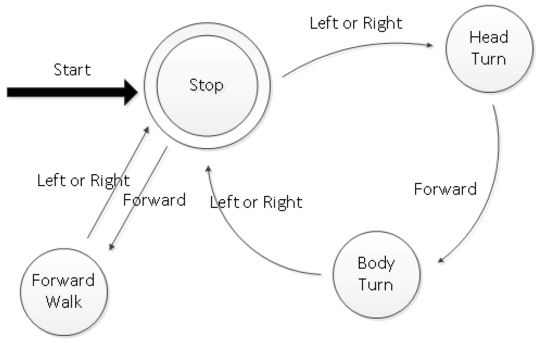

Fig. 3 State automation diagram

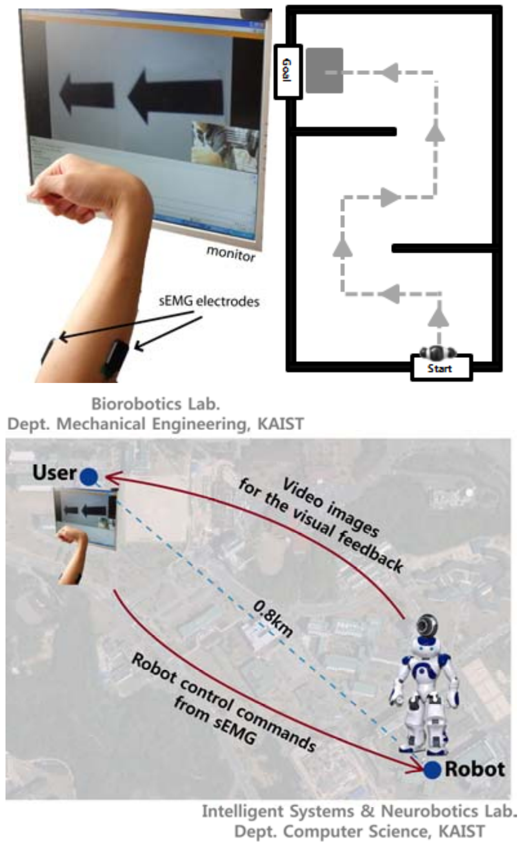

Fig. 4 (top) Experimental setup and robot navigation maze setting, and (bottom) remote communication

3. Experiments

3.1 Subjects

Three healthy male subjects were volunteered with an average age of 27.3 years for the experiment. The KAIST Institutional Review Board approved the experimental protocol and the publication of this study. All participants reported no history of upper extremity or other musculoskeletal complaints, and participants were fully informed of the details of the experimental procedure.

3.2 Experimental protocol

Subjects were comfortably seated on a chair in front of a monitor. The MVC of each muscle was measured prior to the

Table 1 Summary of the performance comparison between the sEMG-based and keyboard controls (averaged over trials)

		Forward Steps (times)	Turning Steps (times)	Head Movement (degrees)	Time (sec)	Travelled distance (cm)	Collisions (times)	Transitions (times)
Subject 1	Keyboard	108.3 (± 1.5)	51.5 (± 9.8)	466.5 (± 89.7)	339.8 (± 13.3)	387.5 (± 5.1)	0.8 (± 0.5)	19.8 (± 4.9)
	sEMG	112.8 (± 1.7)	51.8 (± 4.0)	477.0 (± 29.7)	334.8 (± 9.5)	404.5 (± 7.1)	0.5 (± 0.6)	19.8 (± 3.8)
Subject 2	Keyboard	118.3 (± 5.3)	56.8 (± 5.1)	471.8 (± 14.6)	363.3 (± 31.0)	423.7 (± 19.5)	0.0 (± 0.0)	24.0 (± 5.4)
	sEMG	124.0 (± 3.4)	60.0 (± 8.2)	513.3 (± 72.8)	391.3 (± 41.3)	431.2 (± 25.1)	0.0 (± 0.0)	21.5 (± 4.7)
Subject 3	Keyboard	119.3 (± 6.3)	54.5 (± 2.5)	463.5 (± 21.8)	362.3 (± 21.8)	429.0 (± 21.1)	0.3 (± 0.5)	19.5 (± 1.9)
	sEMG	124.5 (± 7.6)	57.5 (± 7.2)	487.3 (± 9.1)	393.8 (± 14.8)	447.7 (± 30.0)	0.5 (± 0.6)	26.3 (± 4.2)
Mean (± std)	Keyboard	115.3 (± 6.8)	54.3 (± 6.4)	467.3 (± 47.7)	355.1 (± 23.8)	413.4 (± 24.5)	0.3 (± 0.5)	21.1 (± 4.5)
	sEMG	120.4 (± 7.2)	56.4 (± 7.1)	492.5 (± 44.3)	373.3 (± 36.8)	427.8 (± 27.9)	0.3 (± 0.5)	22.5 (± 4.8)

experiment. The examiners offered verbal encouragement while all subjects were attempting to reach the MVC. The subjects were instructed to produce a series of three MVCs as rapidly as possible and to maintain each one for 3 sec. The peak MAV of the MVCs from the five trials was recorded. In addition, the subjects were instructed to rest both forearms for 20 sec. to determine the MAV during non-contraction of the muscles. Using the three wrist movements, the subjects were asked to navigate the Nao humanoid robot from a starting position to an end position via waypoint regions in an indoor maze (see Fig. 4). The maze size was 1.5 m (width) x 3 m (length). The route was guided by arrow signs on the environment. Looking at the signs through the visual feedback on the PC display, the subjects could decide appropriate robot motions by moving his or her wrist. The experimental setup is shown in Fig. 4. The experiment consisted of eight trials in total for each subject (four trials: sEMG and four trials: keyboard). The subjects and robot were placed at two different locations which are about 0.8 km away on the KAIST campus.

3.3 Experimental results

Fig. 5 illustrates the robot's travelled pathways in the maze during a subject conducted the humanoid navigation experiments with the sEMG-based and keyboard controls each five times respectively. In addition, some snapshots during experiments are included in Fig. 5. The results demonstrate the robot navigated along fairly reasonable pathways without seriously losing direction through the sEMG-based interface control. Table 1 summarizes the humanoid navigation performances through both sEMG-based and keyboard controls using the following metrics over each task trial; 1) *Forward Steps*: the number of walking steps during forward movement; 2) *Turning Steps*: the number of walking steps to turn the robot body; 3) *Head Movement*: the total turning angle of the robot head to explore the surrounding environment (in degrees); 4) *Time*: total time taken to accomplish the task (in sec); 5) *Travelled Distance*: distance traveled to accomplish the task (in centimeters);

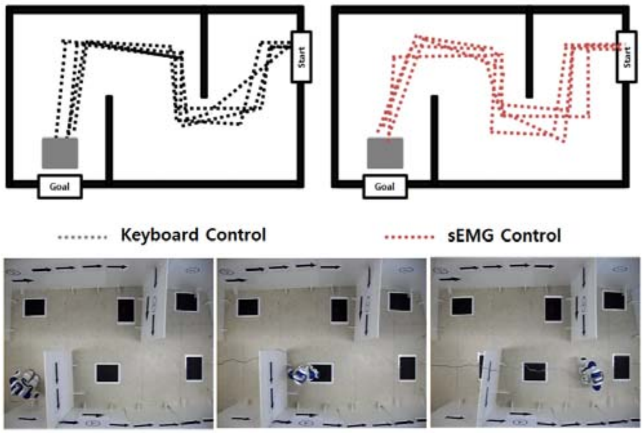

Fig. 5 Experimental results

6) *Collisions*: the number of collisions with the wall. 7) *Transitions*: the number of transitions between walking and exploration modes.

It is clearly shown that all subjects performed similarly between the two control protocols. In terms of time consumption and travelled distance, the averaged ratios between the two controls were 0.951 and 0.966 respectively. All other factors such as forward or turning steps, and head movements, and state transitions demonstrate the similar results. The averaged ratios of the factors between the two controls were at least above 0.93. Based on this analysis, the performance of the sEMG-based control is comparable with that of the manual control. This seems a promising result for the disabled and the elderly; they may be able to control a robot or a machine as well as healthy people if we assume that they can control their residual limbs such as wrist.

Fig. 6 shows raw sEMG profiles measured from the three locations on a subject's arm during an experiment trial of the subject and NMAV profiles computed from the sEMG signals in real time. Based on the NMVA detection, commands to the robot were selected as shown in the bottom of Fig. 6. It is easily seen that, walking forward, left turn, walking forward, right turn, walking

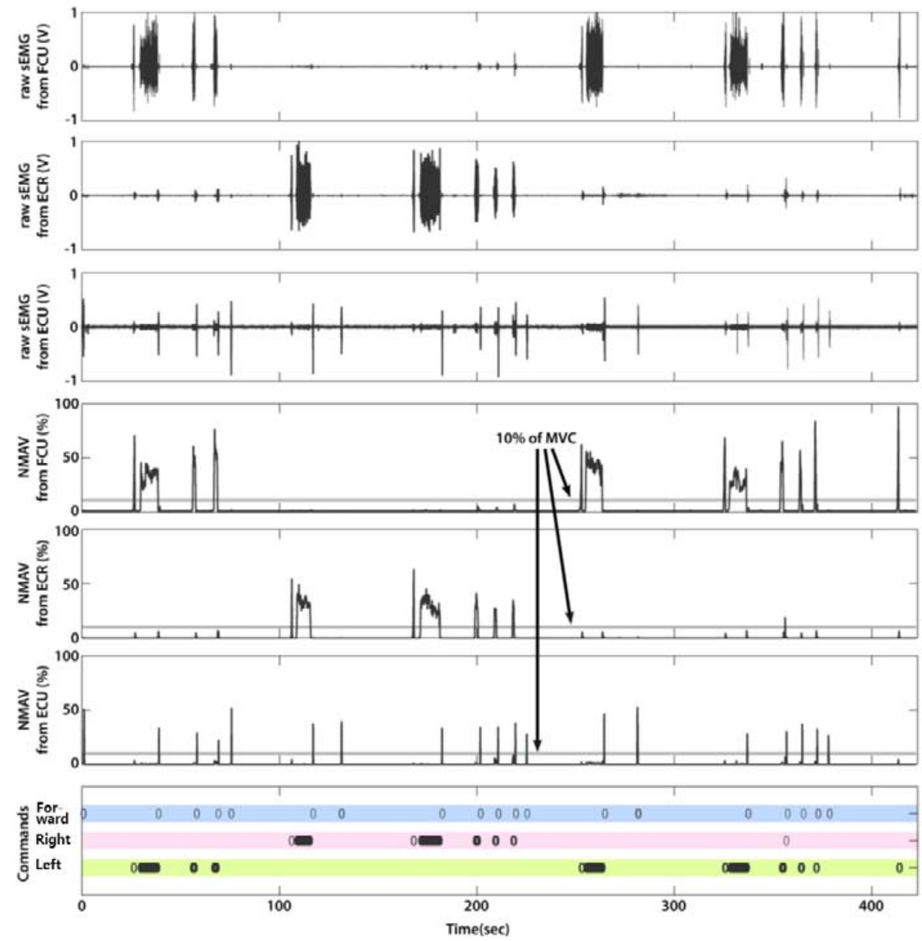

Fig. 6 sEMG and NMVA profiles at the three locations on a subject's arm and selected commands during an experiment

forward, right turn, walking forward, left turn, walking forward, left turn, and walking forward were conducted successively. The movement sequence is consistent with the route from the initial position to the destination as shown in Fig. 5. To turn the robot to an appropriate direction, turning commands are repeated sufficiently because each command makes a turn by three degrees only. Some turning commands are sparsely distributed to adjust the robot's orientations temporally. Once a "Forward" is commanded, the robot keeps walking forward until any command evokes. Thus, the forward commands are sparse over time.

4. Conclusions

The experimental results demonstrated that the proposed interface protocol enables people to interact with a humanoid robot reliably and naturally. This study chose a humanoid robot as a test-bed. During navigation, the robot could look around and execute various locomotive motions based on mere limb movements of a user. Notably, the proposed system includes real-time visual feedback. Therefore, the user could sense visually the environment near the robot while controlling the robot movements according to his or her intention. Even though an erroneous movement was instantly commanded, the subject could modify the movement quickly. Our approach proposed to extend the number of classified intentions by incorporating with the state automation diagram without further classification of muscle signals.

For simple tasks such as the cursor movement control on the screen,[9] it has been reported that EMG-based interface is somehow between the mouse and the commercial interfaces in performance efficiency. However, for more complicated tasks such as humanoid navigation control, no study has evaluated the performance of sEMG-based interface. According to the best of our knowledge, this work is the first attempt to apply a sEMG-based interface technology to humanoid robot control. This work examined the feasibility of the proposed sEMG-based interface control through the performance comparison with the manual keyboard control. In the future work, we plan to develop an objective performance evaluation method for various interfaces during implementing complicated tasks.

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