A Novel Interface for Intuitive Control of Assistive Robots Based on Inertial Measurement Units

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1 Introduction

Tetraplegia is defined as the partial or total loss of motor and/or sensory function of the arms, legs, trunk, and pelvic organs. Besides traumatic injuries also disorders like cerebral palsy, amyotrophic lateral sclerosis, or multiple sclerosis can lead to this severe disability [12].

The motor function of tetraplegics is severely restricted but many of them can still move their heads, eyes, tongues, and all facial muscles to produce inputs for smart interfaces. Existing interfaces therefore use inputs generated by speech [16], neural activity [4, 5] or motion of the eyes [10, 18], chin [1], tongue [3] or head [13]. While speech recognition and neural interfaces only provide discrete control commands other interfaces provide proportional control signals as well.[1] Within this work we focus on Inertial Measurement Units (IMUs) with integrated signal processing to generate signals and commands from head motion.

However, the choice of the most suitable input device depends on the preferences and physical abilities of the user as well as on the underlying control scheme. In general, control commands are appropriate for automated high level tasks and control

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[1] A signal in contrast to a command can be varied in duration. Proportional signals can additionally be varied in strength.

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signals when direct user intervention is required, respectively. Until now, the execution of automated high level tasks lacks the required robustness, in particular when the environment is unknown. Therefore, direct control either to perform the entire control task or to assist automation in case of failure is requested.

In recent years IMU-based interfaces have been used to control wheelchairs [2, 11] and other vehicles [15] or a mouse cursor [2, 14], which are all two degrees of freedom (DOFs) applications. Few attention has been paid to more complex applications with numerous DOFs like an assistive robot as described in [6]. The interface which is proposed here uses head motion signals in order to translate them into robust, quick and intuitive control signals for a multi-DOF robot arm which is equipped with a gripper. The challenge is to map the three DOFs of the head onto the numerous DOFs of a robotic arm while preserving intuitive generation of control signals while guaranteeing robustness and user safety.

2 System Layout and Control Structure

2.1 Proposed Mapping Between Head and Robot Motions

Physicians agree to approximate the cervical spine by a ball joint which leads to three DOFs of the head. We adopt this view and therefore distinguish between three independent DOFs, namely pitch (extension and flexion = nodding), yaw (rotation = head shaking), and roll (lateral flexion = head bending). These DOFs are used to generate proportional input signals for robot control. It is proposed that the user controls the position of the gripper in the world coordinate system and its orientation in the gripper coordinate system. The calculation of the joint angles of the robot arm is carried out by inverse kinematics. In addition to the six DOFs of the robot arm there is an additional DOF to open or close the gripper. That means the user has to control seven DOFs in total.

As the number of head DOFs is smaller than the robot DOFs, it is necessary to use the control signals obtained from head movements in multiple ways. However, a specific control command has to be defined for switching between the different groups to be controlled. The available robot DOFs have been decomposed into groups with three or less DOFs for the proposed human–machine interface (HMI) concept. Head movements have been mapped onto the DOFs of each group of robot motion in a user-centered intuitive way. Figure 1 shows the proposed mapping:

- **Orientation (3 rotational DOFs)**: Changes the orientation of the gripper the same way the user changes the orientation of his head.
- **Plane (2 linear DOFs)**: Moves the gripper within the plane which is perpendicular to the user’s line of sight by using yaw and pitch movements.
- **Depth (1 linear DOF)**: Moves the gripper along the user’s line of sight by moving the head up or down.

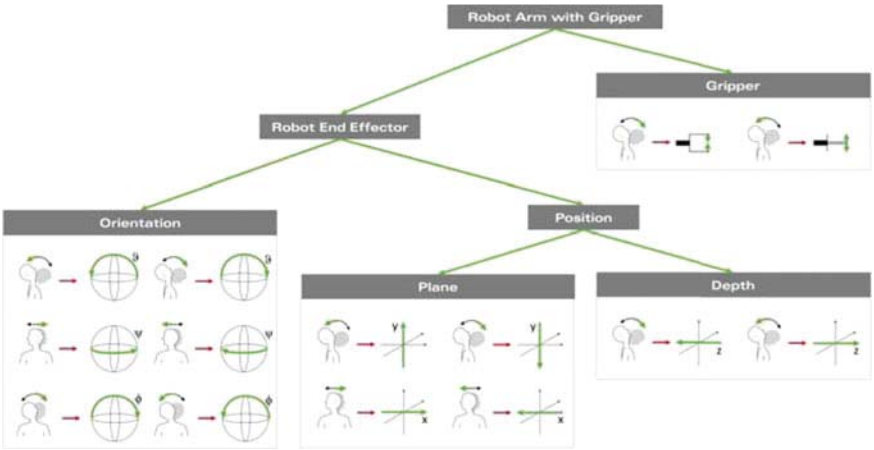

Fig. 1 Decomposing of robot DOFs into groups with maximum three DOFs and proposed mapping of head movements onto robot DOFs. Gripper position is indicated with x, y and z. The roll, pitch, and yaw angle of the gripper are denoted as ϕ, ϑ, and ψ, respectively

- **Gripper (1–3 DOFs)**: Up to three DOFs of a gripper may be controlled. For a 1-DOF gripper the pitch motion of the head is used to open or close the gripper.

Any DOF of the robot arm can be controlled by switching between these groups. The presented mapping assumes that the user does not suffer from neck movement limitations which affect his ability of producing all the three control signals, i.e., roll, pitch and yaw. A solution if this precondition does not hold is presented in Sect. 3.2.

Additional procedures like turning the control unit on and off, calibrate the mapping and switch between cursor mode and robot control mode are required for full system integration.

2.2 Switching Strategy and Command

As explained before it is necessary to switch between the different meanings of head movements.

Switching commands must be detected quickly as well as reliably. They can be generated by head movement patterns. Future research will focus on the generation of suitable motion patterns and their integration into the control system.

It has been shown [8] that also facial muscle contractions are capable of providing commands as required for switching. In addition, such commands are independent of head orientation. That means, there is no relevant interference between IMU data and facial electromyography (fEMG) signals. Integration into the control system is therefore easier.

If only a single switching command is used, the user can access the different groups of DOFs in a predefined order (sequential switching). In comparison, multiple switching commands allow direct access of each group (parallel switching). Experience with sequential switching which was used in another application [17] shows that this method is time consuming. Parallel switching on the other hand requires higher mental effort to remember the different head movements for switching. In order to bypass these drawbacks, we propose the concept of GUI-aided two-stage parallel switching which combines cursor control at a screen using head motions to chose a specific group and switching commands to activate the group. Details are described in the next section. In general, controlling a graphical user interface (GUI) does not require high mental effort, is relatively quick and capable of providing optical as well as auditory feedback. Furthermore, only one switching command is necessary. The different switching strategies are visualized in Fig. 2.

2.3 GUI-Aided Two-Stage Parallel Switching

According to the mapping described in Sect. 2.1 a control structure and a corresponding GUI (Fig. 3) have been developed within this work. The different motion groups are arranged vertically because vertical head movements (pitch) are easier and quicker to perform than horizontal ones (yaw) [9]. The associated control system works as follows:

When the system is turned off (sleeping mode) it still acquires and processes sensor data but does not respond to any head movement unless a switching command is sent. When the user produces such a switching command, the system is turned on. Afterwards, the user can navigate through the GUI by controlling a cursor at a screen (first stage). His head then works as a computer mouse emulator. In this mode the pitch movements of the user's head, i.e., neck extension and flexion, are mapped onto the y-axis of the screen. The yaw movements (neck rotation) are projected onto the x-axis, respectively. A linear relationship is assumed between head displacement and cursor position.

Clicking is carried out using a switching command. The user can switch to robot control by clicking on a corresponding button of the GUI (second stage). To keep the robot from moving unintendedly when switching between cursor and robot coordinate system, the system waits for the user's head to reach a previously defined region around the origin of the coordinate system that was defined during the calibration of robot control. We refer to this position as "reference position" in the following. When the user enters this zone, the system enters robot control mode and provides auditory feedback to inform the user about the chosen control mode and that every control signal is translated into robot motion from then on. During robot control, the user's head position is mapped onto the speed of a specific DOF of the robot. That may be a linear or angular velocity depending on the DOF to be controlled. If the user holds his head in a constant position other than the reference position, the device moves with constant velocity. Increasing or decreasing the head displacement

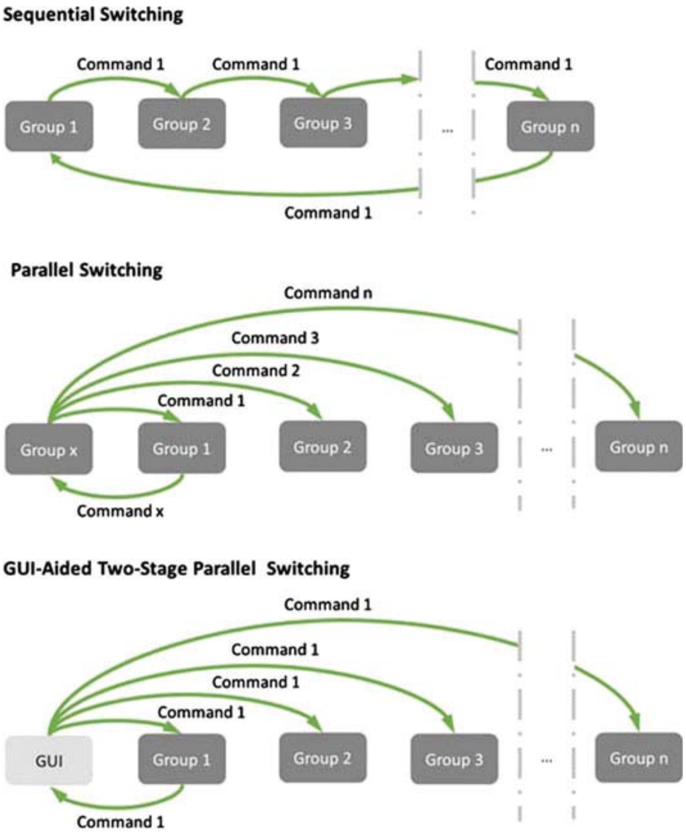

Fig. 2 When using sequential switching, groups are accessed in a predefined order with one switching command. For parallel switching, each group can be accessed directly from any other group using the corresponding switching command. For simplification only the transitions from an arbitrary group x to the other groups are displayed. As shown for group 1 returning to group x is also possible with the corresponding switching command. With the help of a GUI each group can be accessed directly from the GUI with only one switching command. If the user wants to switch to another group, he first has to return to the GUI as shown for group 1. That means the GUI introduces an intermediate state

accelerates or decelerates the device movement. A sigmoidal function is proposed to map head displacement onto robot velocity.

If the user wants to return to cursor mode, he first has to stop the robot by turning his head toward the reference position and generate a switching command. Sleeping mode can be entered by moving the cursor to the corresponding button and clicking.

Two calibrations are necessary to set up the system: The first one defines which head position corresponds to which cursor position on the screen (cursor control calibration). The second one measures the ranges of motion of each user in order to normalize maximum robot velocity to these values (robot control calibration).

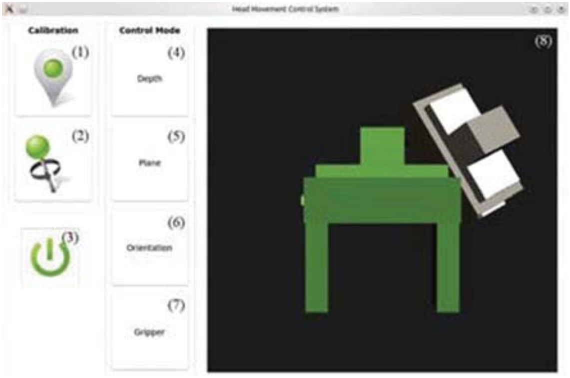

Fig. 3 GUI to control a robot arm with head motion. After startup the user has to calibrate the system for cursor (*1*) and robot control (*2*). The user can control a DOF-group of the robot (*4*)–(*7*) by clicking the corresponding button. Sleeping mode can be entered by clicking on (*3*). A widget (*8*) provides visual feedback

3 Methods

3.1 Procedure

In this section, the proposed control structure is tested. Subjects were instructed to align two virtual grippers relative to each other within a certain tolerance by moving and rotating the first object using the previously described control structure. The general system control structure was explained and presented in a short demonstration. Afterwards, all subjects completed an evaluation sheet on the usability of this novel HMI concept. Subjects were able to rate the following statements from 1 (“I do not agree at all”) to 5 (“I totally agree”):

1. Cursor control was very quick
2. Accurate cursor positioning was very easy
3. Cursor control was very intuitive
4. Gripper control was very quick
5. Accurate gripper positioning was very easy
6. Gripper control was very intuitive
7. Neck fatigue was very low
8. The overall control structure was very intuitive
9. I can image to use this interface myself

The GUI was displayed on a 23-inch screen with Full-HD resolution. As clicking using fEMG or head movements has not yet been fully implemented into the system, mouse clicks were used for switching. Head movements were measured with the FSM-9 by Hillcrest Labs [7]. The FSM-9 outputs which are used for the proposed HMI are the Euler angles for yaw, pitch, and roll orientation.

The sampling rate was set to 100 Hz. The FSM-9 was mounted onto the top of a hair band of velvet-like material. This material has a high coefficient of friction which minimized relative motion between the user’s head and the FSM-9. For mechanical

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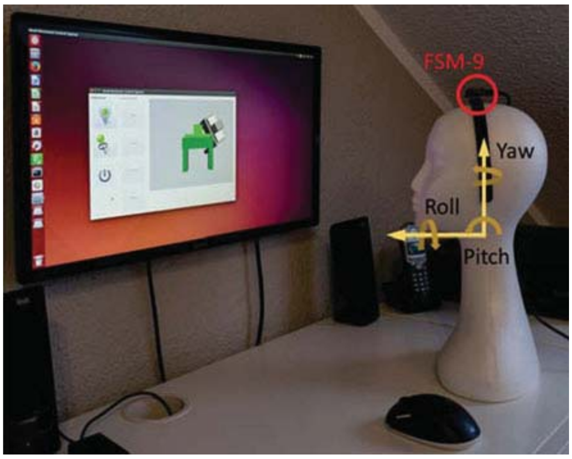

Fig. 4 The FSM-9 sensor module by Hillcrest Labs mounted on a hairband was used to measure head orientation. Head movements were used to perform a control task

strain relief the USB cable was clipped to the hair band. The experimental setup is shown in Fig. 4. Prior to usage the magnetic field sensors of the FSM-9 were calibrated by moving the sensor module along a path in form of the number 8.

3.2 Subjects

Two female and three male able-bodied subjects took part in the experiment. Their mean age was 30.4 ± 4.6 years. Because of the subjective character of the experiment the authors did not participate. All subjects were regular computer users.

Additionally, one tetraplegic person suffering from multiple sclerosis tested the usability of the system. Due to the disease, this subject was not able to perform neck lateral bending and therefore could not control the roll DOF. For this reason, the proposed mapping had to be adapted. As a result, the orientation group was split into two groups: One group to change the pitch and yaw angles of the gripper using pitch and yaw motion of the head, and the second one to change the grippers roll angle using yaw motion.

4 Results and Discussion

All the subjects were able to use the interface and solve the control task without any further instruction than mentioned previously. Speed, accuracy and intuitiveness of cursor control have been scored with 4.4 ± 0.5, 4.2 ± 0.4 and 4.4 ± 0.5, (Fig. 5) respectively. Gripper control was on average one score below cursor control (Speed: 3.2 ± 0.8, accuracy: 2.8 ± 0.4, intuitiveness: 3.2 ± 0.4). Because of the small number of participants no test for significance has been carried out. The main reason

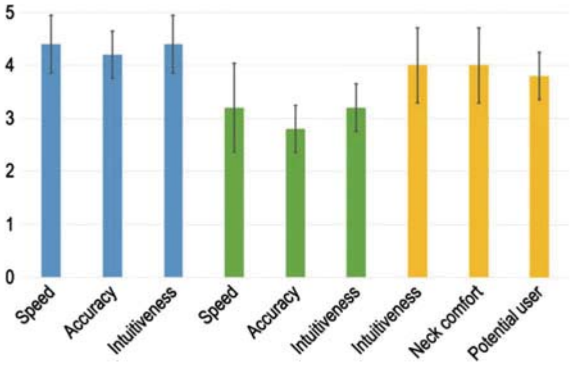

Fig. 5 Mean value and standard deviation of subject ratings for cursor control (*blue*), gripper control (*green*), and the overall system (*yellow*)

for the lower scores was that subjects experienced control of the gripper orientation group as mentally demanding. It was difficult for them to relate their head DOFs to the DOFs of the object once it was rotated. Another challenge was to stop the object when desired because the time which subjects needed to move their heads back into the reference position had to be taken into account. However, control of plane and depth group as well as the sigmoidal mapping of head orientation onto object velocity was experienced as intuitive.

Overall, intuitiveness of the entire system was rated with 4.0 ± 0.7. Furthermore, within the period of the experiment subjects hardly perceived neck fatigue (4.0 ± 0.7) and they could imagine to use the interface themselves (3.8 ± 0.4).

In contrast to the able-bodied subjects the tetraplegic required higher mental effort to solve the task even though her ability to move her head along the used DOFs was not significantly affected by the disease. A possible reason is that she learnt to substitute her entire body language with eye, face, and head motion. So she had to suppress all the head movements which were not intended to be used for control.

5 Conclusion

There are already several assistive devices for tetraplegics available but to our best knowledge there is none providing the capability to directly control a robotic arm in a simultaneous as well as proportional manner. Besides, this motion-sensor-based system is low-cost and unobtrusive for the user. The fact, that all users were able to solve the control task during first-time usage quickly shows that this novel human–machine interface is a promising alternative to existing interfaces. However, there are still some adjustments that have to be made. For example, more mappings for users with limited head movement capability have to be integrated in order to make the system available for a large user group.

Feedback will be another important part of subsequent research. A visualization of the current head position in the current coordinate system could be useful. It may help to inform the user about involuntary head motion which he is not aware of. Furthermore, a gripper camera might facilitate relating head motion to object rotation.

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