Towards a User-Friendly AHRS-Based Human-Machine Interface for a Semi-Autonomous Robot

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Towards a User-Friendly AHRS-Based Human-Machine Interface for a Semi-Autonomous Robot

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***Abstract*— Assistive Robots have to support the user in a wide range of tasks. An economical solution provides automation for a range of basic tasks and the inclusion of the disabled user to support the assistive robot if necessary for a correct completion of the tasks. The user interface plays a central role in assistive robotics. This paper proposes a new user interface based on an Attitude Heading Reference System (AHRS). The usability of this novel HMI was tested with healthy and disabled subjects by solving a control task within a virtual environment. The results imply that the new HMI is suitable for intuitive semi-autonomous robot control. However, various measures of adaption have to be taken into account to meet the needs and preferences of each individual user.**

I. INTRODUCTION

The assistive robot FRIEND [1] is designed to assist completely paralyzed people in professional and daily life by performing high level tasks autonomously. However, the execution of automated high level tasks still lacks the required robustness that is necessary for a commercially available assistive system, in particular when the environment is unknown. The experience with FRIEND [2] shows that only semi-autonomous control is economically reasonable for the near future.

Different HMI concepts such as speech control [3] and neural interfaces [4] have already been tested in order to assist automation. However, we come to the conclusion that head tracking systems based on motion sensors have advantages over other approaches because they are unobtrusive and capable of providing both discrete control commands and proportional control signals. Therefore, we focus on head tracking systems.

II. SYSTEM LAYOUT AND CONTROL STRUCTURE

In this section the boundary conditions to control a robot arm with head movements using an Attitude Heading Reference System (AHRS) are analyzed. Based on these investigations, a novel control structure is proposed.

A. Input and Output Degrees of Freedom and Proposed Mapping

The cervical spine is modeled as a ball joint which leads to three rotational DOFs of the head, namely roll φ (lateral flexion), pitch ϑ (extension and flexion) and yaw ψ (rotation). These DOFs are used as control signals $s_h = (\varphi, \vartheta, \psi)_h$.

It is proposed that the user navigates the end effector in the world coordinate system $(x, y, z)_e$ and rotates the end effector in the device coordinate system $(\varphi, \vartheta, \psi)_e$. In addition to these 6 DOFs of the robot there is another DOF to open or close the gripper. The state of the robot end effector can then be described as $s_e = (x, y, z, \varphi, \vartheta, \psi, g)_e$.

As the number of control signals is less than the DOFs to be controlled it is necessary to use the control signals obtained from head movements in multiple ways. A specific control command has to be defined to switch between the possible control signal modes. Therefore, the available robot DOFs have been decomposed into groups with three or less DOFs for the proposed HMI concept. Head movements have been mapped onto the DOFs of each group as follows (Fig. 1):

- *Orientation (3 rotational DOFs):* Changes the orientation of the arm's end effector $(\varphi, \vartheta, \psi)_e$ the same way the user changes the orientation of his head $(\varphi, \vartheta, \psi)_h$.
- *Plane (2 linear DOFs):* Moves the arm's end effector within the $(x, y)_e$-plane which is perpendicular to the user's line of sight by using yaw and pitch movements $(\psi, \vartheta)_h$.
- *Depth (1 linear DOF):* Moves the arm's end effector along the user's line of sight z_e by moving the head up or down (ϑ_h).
- *Gripper (1 DOF):* The pitch motion of the head ϑ_h is used to open or close the gripper (g_e).

Any DOF of the robot arm can be controlled by switching between these groups.

B. Switching Strategies

As explained before it is necessary to switch between the different meanings of head movements. Using a single switching command different DOF-groups can be accessed sequentially in a predefined order. Direct access of each group is possible with multiple switching commands. The first switching strategy is slow and the second one requires higher mental effort to remember the different switching commands. For the proposed HMI, we suggest the novel concept of a GUI-aided two-stage parallel switching as described in the next section. Controlling a graphical user

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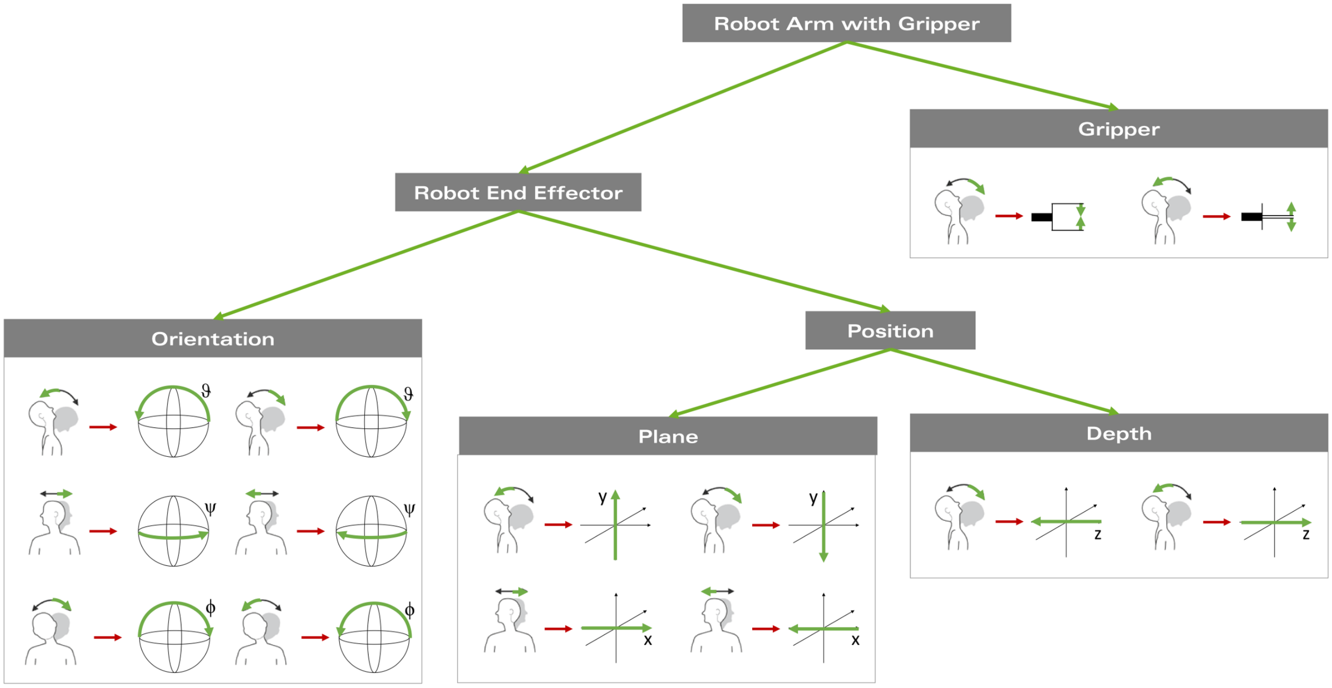

Fig. 1. Decomposing of robot DOFs into groups with maximum 3 DOFs and proposed mapping of head movements onto robot DOFs.

interface (GUI) does not require high mental effort and is relatively quick. A GUI also provides the possibility to integrate optical as well as auditory feedback. Furthermore, only one switching command is necessary. Switching commands 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. However, in this early stage of development we use conventional mouse clicks for switching.

C. GUI-aided Two-Stage Parallel Switching

According to the mapping described in section II-A a control structure and a corresponding GUI (Fig. 2) have been developed within this work. Related objects of the GUI are arranged in a vertical manner because vertical head movements (pitch) are easier and quicker to perform than horizontal ones (yaw) [5]. The associated control system works as follows:

When the system is turned off (sleeping mode) it still acquires sensor data but does not respond to any head movement. When the user produces a switching command the system is turned on. Afterwards, the user can navigate through the GUI by controlling a cursor on a screen (first stage). The head then represents a computer mouse emulator. A linear relationship is assumed between head displacement $(\psi, \vartheta)_h$ and cursor position $(x, y)_c$:

$$\begin{pmatrix} x \\ y \end{pmatrix}_c = \begin{pmatrix} m_x \\ m_y \end{pmatrix} \cdot \begin{pmatrix} \psi \\ \vartheta \end{pmatrix}_h + \begin{pmatrix} b_x \\ b_y \end{pmatrix} \tag{1}$$

The parameters (m_x, m_y) and (b_x, b_y) are obtained during the calibration routine described in section II-D.1.

Clicking on a button is performed by navigating the cursor to the button and using a switching command. The user can switch to robot control by clicking on the relevant 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 which was defined during the calibration of robot control. When the user enters this zone, the system enters robot control mode. During robot control the user's head position is mapped onto the speed of a specific DOF of the robot. A constant head position unequal to the zero position is related to constant device velocity. Increasing or decreasing the head displacement accelerates or decelerates the device movement. A Gompertz function is proposed to map head displacement $\alpha \in [\varphi_h, \vartheta_h, \psi_h]$ onto robot velocity $\dot{w} \in [\dot{x}_e, \dot{y}_e, \dot{z}_e, \dot{\varphi}_e, \dot{\vartheta}_e, \dot{\psi}_e]$:

$$\dot{w}(\alpha) = \begin{cases} a \cdot e^{b \cdot e^{c \cdot \alpha_n}} & \text{if } \alpha \geq 0 \\ -a \cdot e^{b \cdot e^{-c \cdot \alpha_n}} & \text{else} \end{cases} \quad \text{with } \alpha_n = \frac{\alpha}{\alpha_{th}} \tag{2}$$

The parameter a indicates the upper asymptote. In this work this corresponds to maximum robot velocity. The negative coefficient b sets the displacement along the α-axis and c indicates the growth rate. The threshold α_{th} represents the range of motion of a certain DOF of the head which is measured during a calibration routine as described in section II-D.2.

For every time step the robot position is computed using (2):

$$w_{new} = w_{old} + \Delta w \quad \text{with } \dot{w} = \frac{\Delta w}{\Delta t} \tag{3}$$

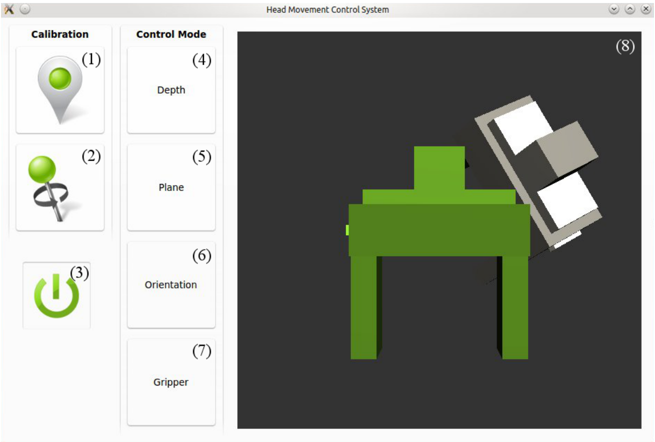

Fig. 2. GUI to control a robot arm with head motion. After startup the user has to calibrate the system for cursor (1) and robot control (2). The user can control a DOF-group of the robot (4)-(7) by clicking the corresponding button. Sleeping mode can be entered by clicking on (3). Widget (8) provides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

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

D. *Calibration*

Two calibrations are necessary to set up the system. The first one relates head position with cursor position on the screen (cursor control calibration). The second one measures the ranges of motion of the user in order to normalize head positions to these values (robot control calibration).

1) Cursor Control Calibration: For the cursor calibration routine users have to fix their gaze in a straight position and then turn their heads towards two different points $p_0 = (x_0, y_0)$ and $p_1 = (x_1, y_1)$ which are sequentially displayed on the screen. The corresponding head positions $(\psi_0, \vartheta_0)_h$ and $(\psi_1, \vartheta_1)_h$ are saved by clicking commands. Point p_0 is displayed in the center of the screen and point p_1 in the upper left corner.

2) Robot Control Calibration: At the beginning of the calibration, users have to face the desired origin of the coordinate system $(\varphi_0, \vartheta_0, \psi_0)_h$. This head position can differ from the zero position defined during cursor control calibration. Once the coordinate system is defined, the users perform one repetition of each neck extension, neck flexion, neck rotation to the left, neck rotation to the right, neck lateral bending to the left and then to the right. They are instructed to move their heads as far as they can without perceiving any discomfort and to save the corresponding position by clicking. In this way two values are obtained for each DOF. One in positive direction (α_+) and one in negative one (α_-). To guarantee a symmetrical mapping only the smaller value is used to define the extent of motion. The thresholds α_{th} are then calculated as follows:

$$\alpha_{th} = \begin{cases} \alpha_+ & \text{if } \alpha_+ \leq |\alpha_-| \\ |\alpha_-| & \text{else} \end{cases} \tag{4}$$

III. METHODS

In this section a test of the proposed control structure is presented. The subjects had to perform a control task in a virtual environment. Their motion times within the different groups of DOFs were recorded. Afterwards, all subjects were asked for feedback on the usability of this novel HMI concept.

Head movements were measured with an FSM-9 sensor module by Hillcrest Labs [6]. The FSM-9 is an AHRS that provides various outputs such as real-time 3D orientation in terms of both Euler angles and quaternions. In the proposed HMI Euler angles were used.

The sampling rate was set to 100 Hz. That means, every time step $\Delta t = 10\,\text{ms}$ a triplet $(\varphi, \vartheta, \psi)$ with $\varphi \in [-\pi, \pi]$, $\vartheta \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ and $\psi \in [-\pi, \pi]$ was obtained. 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 strain relief the USB cable was clipped to the hair band. 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.

A. *Subjects and Procedure*

Twelve able-bodied subjects with no known neck motion limitations and one tetraplegic patient suffering from multiple sclerosis participated in this experiment. The authors also took part in the test. Five subjects were female and eight ones male. Their ages ranged from 22 to 66. All healthy subjects were regular computer users. Aside from the first author, the healthy subjects did not have prior experience with head-operated input devices.

During the experiments the parameters of the Gompertz function were set to $a = 10$, $b = -30$ and $c = -10$.

Two 3D objects were presented to the subjects in a (580 px x 570 px)-sized OpenGL window. The gripper DOF was not used in this experiment. The state of the first object was initialized with $s_{1,e} = (0, 0, -5, 0°, 0°, 0°, -)$ and the state of the second one was $s_{2,e} = (0.5, 0.3, -6, 30°, 135°, 45°, -)$. The first object represented the actual state of the robot's end effector and the second one its desired state. Therefore, subjects were instructed to align both 3D objects with each other within a certain tolerance by moving and rotating the first object using the previously described control structure. The tolerance for the translational DOFs was set to $\Delta w_t = 0.05$ and for the rotational ones to $\Delta w_r = 5°$. The real-time state difference was displayed in a command window for user-feedback.

The subject's motion times within each group of DOFs were recorded. After test completion, subjects were asked for feedback on the usability of the system.

IV. RESULTS AND DISCUSSION

Fig. 3 shows the movement times per DOF-group for all the subjects who have been able to complete the task. The average motion time was 35 s ± 17 s for the depth group, 47 s ± 25 s for the plane group and 98 s ± 56 s for the

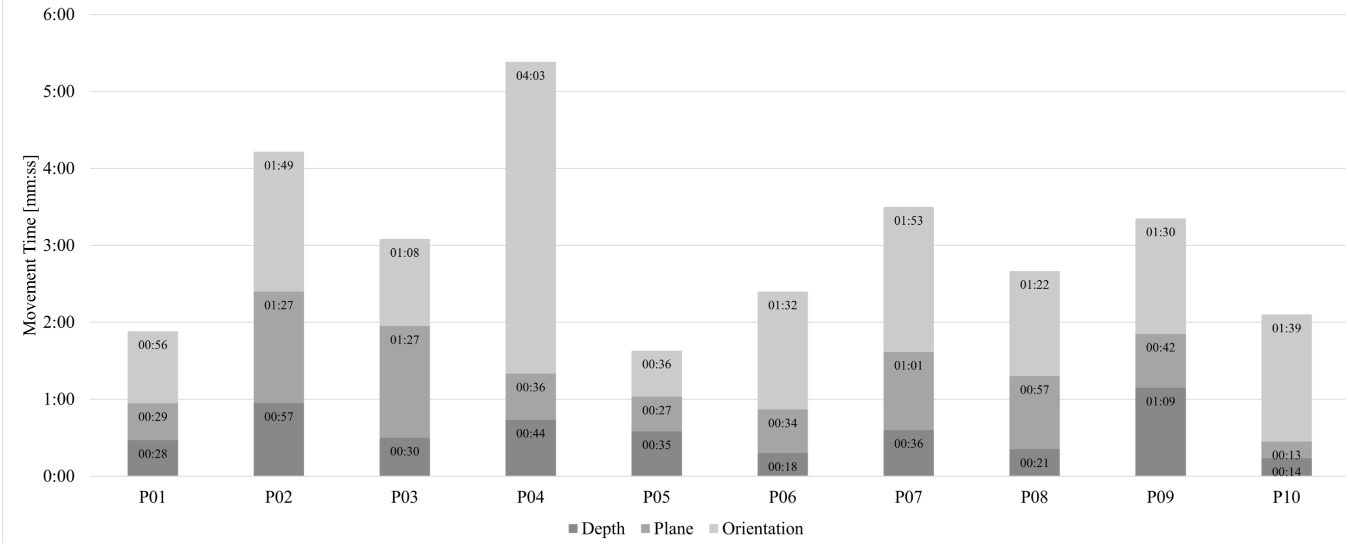

Fig. 3. Motion time per DOF-group and subject.

orientation group, resulting in an average task completion time of 181 s ± 69 s. Three of 13 subjects, including the tetraplegic patient, were not able to finish the task. The tetraplegic patient has not the ability to control the roll DOF any more and therefore had to abort the task. As she was able to move the object using pitch and yaw DOFs, the orientation DOF group could simply be split into two groups to meet her requirements. The other two subjects failed to rotate the 3D object into the desired position. They reported that they found it too hard to imagine which head rotation resulted in which object rotation. Even though the other subjects were capable to fulfill the task they also experienced the simultaneous way of control as difficult. For that reason, they solved the task by turning their heads around one axis at a time only. This sequential way of control as well as the difficulties of understanding the mapping explain why the percentage of motion time per DOF-group is highest for the orientation group (45,19%) although the possibility to control multiple DOFs simultaneously should result in a higher operation speed as can be observed for the plane group (22,13%) in comparison to the depth group (32,68%).

V. CONCLUSION AND FUTURE WORK

It has been shown that the proposed interface is suitable to perform semi-autonomous control tasks intuitively. The user-feedback demonstrated that users prefer simple and unobtrusive systems. Using proportional control around three axes simultaneously is more difficult than operating a sequence of one DOF operations. Therefore, we propose to provide different levels of difficulty, i.e. beginner's mode, advanced mode and expert mode. For example, a new user would prefer discrete and sequential rotation of a 3D object (beginner's mode) because he first has to get used to the mapping of head movements onto object movements. After the user got used to it, he can change to advanced mode which is proportional, sequential control and then to expert mode and control the 3D object proportionally as well as simultaneously. Our experience with FRIEND and disabled users supports the idea of the proposed training concept. The structure is also beneficial for people who suffer from progressive diseases because they can switch to a simpler control mode when their physical or mental ability is not sufficient any more for a more sophisticated one.

To help the user understand the mapping of head rotations onto end effector rotations, we will use a gripper camera and display the image in the GUI. In this way, the user views the world from the gripper's perspective and has an intuitive feedback about rotation motions.

We will also provide additional mappings for users who can only control one or two head DOFs. As a consequence, the system can be adapted easily to a large user group.

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