Feasibility Analysis of Sensor Modalities to Control a Robot with Eye and Head Movements for Assistive Tasks

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ABSTRACT

Assistive robotics has offered a way for people with severe motor disabilities (i. e. tetraplegics) to perform every day tasks without help. New sensor modalities to control a robot system are investigated within this work to enable tetraplegics to gain more autonomy in everyday life. In this work several modalities to capture information related to the user are tested and compared. The five sensor modalities, electrooculography, video-based eye tracking, MARG sensors, video-based head tracking and electromyography of the posterior auricular muscle, can be used to control a robot hands-free. It is proposed to use movements of the head as continuous control and eye movements as discrete event control. The tests show that the MARG sensors are most reliable to track head movements and eye tracking glasses to capture movements of the eyes.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Interaction devices.*

KEYWORDS

HRI, Human Robot Interaction, Sensor Modalities, Assistive Robotics, Eye Tracker, Head Tracker, MARG Sensor

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1 INTRODUCTION

People with severe motor disabilities are often unable to perform basic tasks of everyday life. Tetraplegics (paralysis of all four limbs) need assistance to eat, drink or dress. Autonomous eating and drinking is highly desired by most tetraplegics [3]. The purpose of assistive robots is to enable them to perform some of these tasks independently to regain more autonomy. In order to enable tetraplegics to control a robot with the remaining head or eye mobility, sensor modalities have to be investigated.

Existing technologies often use head switches or chin joysticks to control the robot system, like the FRIEND system [9]. Novel approaches using head movements, gaze or BCI[1] signals have been developed to control a robotic arm. These approaches each represent monomodal systems. To control a robot system with head movements using a MARG[2] sensor system, Rudigkeit et al. [20] mapped the three Degrees of Freedom (DoF) of the head (Roll, Pitch, Yaw) onto the seven DoF (three rotational, three translational DoF and gripper closure) of a robotic arm using four groups. Inside the groups, a continuous velocity control to move the robot in different planes, rotate it or open and close the gripper was applied. By using BCI signals, groups can be selected using several switches whereas a continuous velocity or position control is not possible because of the low transfer rate of a non-invasive BCI. In this approach the robot is moved in discrete steps using SSVEP signals. A usability study with 12 tetraplegics and 24 healthy people has shown that the continuous control of a robot arm with MARG sensors is intuitive and easy to use. Gestures with MARG sensors to switch between groups proved to be not suitable for daily use due to neck muscles fatigue [11].

In this work different sensor modalities are proposed to control a robot. It is proposed to use head movements as continuous control and eye gestures to perform events to switch between groups or trigger different actions. An overview of existing interfaces is given in the section on Related Work. Various sensor modalities are described, whereof some are described in detail and analysed further in practical tests. Finally the tests are discussed and a conclusion as well as the directions for further research are identified.

2 RELATED WORK

Below five sensor modalities are introduced which have been tested within this work. The JINS MEME ES is a pair of glasses that allow eye tracking using electrooculography [13]. It can be used to write by using a spelling application [2] or to determine the reading speed of a participant [17].

To track eye movements, video-based approaches capture the pupil position using cameras. Several interfaces have been developed to control complex systems like robots or wheelchairs. To steer a wheelchair, the desired direction can be estimated using gaze and the motion can be triggered by blinking [19]. To control a robot, a graphical user interface can be used to display buttons that can be pressed [15, 18]. Alsharif [1] developed an interface in which

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[1] Brain Computer Interface
[2] Magnetic Angular Rate and Gravity

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the user selects a group by using gaze gestures. An approach to write and draw on a whiteboard with a robotic arm was developed in [6]. They used a stationary eye tracker to track the gaze point on the whiteboard to control the end-point of the robot movement. To write or draw, an algorithm calculated the trajectory of the pen at the end-effector.

MARG sensors can measure translation and rotation in three axes each. Approaches that use MARG sensors to control a complex system hands-free, can gather head, shoulder or other residual movements of a person. MARG sensors can be used to operate systems like a wheelchair [4, 23] or a robotic arm [8, 20, 27]. In [27] the end position of a gripper is controlled while in [8] the head and shoulder movements are used to control a robotic arm using the head orientation continuously and the shoulder movements as switching commands. Rudigkeit et al. [20] control a robotic arm by head orientation using switches to select groups and continuous control to determine the robot velocity.

Video-based head pose estimation has a wide variety of applications. These include the control of a camera in a video game or teleoperation of a robotic arm [25], where the robotic arm follows the orientation of the user's head.

The muscular activity of the posterior auricular muscle is used in [21] to control an electric wheelchair. Intentional contraction of both posterior auricular muscles (ear wiggling) is used to determine the direction and velocity of the wheelchair. For that the side and contraction strength is considered.

In the following, the requirements of the sensor modalities for robust robot system control will be introduced. To increase user acceptance the modalities have to be easy and comfortable to use. For this objective the control also has to be lightweight and small. Sample rate and resolution of the modalities need to be as high as possible to ensure a robust and reliable measurement. Accordingly the error of measurement has to be as low as possible. To ease the use, the effort to calibrate the modality needs to be small. To minimize the effort of assistive people to adapt the ergonomics, the control will be adjusted to user needs. The modalities have to be non-invasive.

Below some further sensor modalities are listed and it is explained why they are not any longer in the focus of this work. Eye tracking with the scleral search coil will not be analysed although it has the highest spatial and temporal resolution because of its lack of wearing comfort and low user acceptance. The infrared-based approach to track head orientation will not be examined because of its high sensitivity to sun light. Brain Computer Interfaces have a low user acceptance, among other things due to the unpleasantness of the electrode gel on the head. The information transfer rate is also low with less than 100 Bit/min when using non-invasive electrodes [10]. Voice interfaces have a high user acceptance but low security of user data because the voice data are transmitted over the internet to third-party servers in professional speech recognition.

3 PROPOSED SENSOR MODALITIES

In this paragraph, the five hands-free sensor modalities with technologies for the control of a robot system or computer are described. It is specified how the sensor modalities are working. State of the art and commercially available modalities are introduced.

Figure 1: JINS MEME ES

3.1 Electrooculography

For an electrooculogram (EOG) the naturally occurring electric dipole of the human eye is used. Because of the high nerve density in the retina, this part carries a negative charge towards the front of the eye bulb. With electrodes attached to the skin around the eye, the resulting voltage can be measured, amplified and digitalized [16]. It totals up to about 15−200 μV [5]. In a conventional EOG, the four electrodes above, beneath, left and right from the eye combined with a reference and a ground electrode are used. The horizontal (V_H) and vertical (V_V) differential voltages are measured.

The JINS MEME ES is a commercially available pair of glasses that can measure the electrooculogram using electrodes in the nose bridge and both pads (see Fig. 1) [13]. Analog to the conventional EOG the differences result to [14]:

$$\begin{aligned} V_H &= V_L - V_R \\ V_V &= -\frac{V_L + V_R}{2}, \end{aligned} \tag{1}$$

where V_H and V_V are the horizontal and vertical differences and V_L and V_R are the voltages measured by the left and right electrode.

The EOG is captured with a resolution of 12 Bit and a sample rate of up to 200 Hz [12]. To compare the EOG glasses, a conventional three-point EOG is tested using a G.TEC USBamp in combination with adhesive electrodes. The USBamp captures the signals with up to 24 Bit and 38.4 kHz. In this test, the sample rate was set to 125 Hz, because it is sufficient for measuring eye movements in the proposed application.

3.2 Video-Based Eye Tracking

Video-based eye tracking is an optical method. Eye trackers often use the so called "pupil tracking". While tracking, the face is illuminated using IR light and captured with an IR camera. The border of the irides are recognized and tracked using image processing.

In this work, the Tobii Eye Tracker 4C (see Fig. 2) is used, which measures the gaze of both eyes with a frequency of 90 Hz and calculates it on board on a microprocessor [24]. Besides stationary eye trackers, eye tracking glasses like the SMI Eye Tracking Glasses 2W (see Fig. 3) are available. These glasses are most often used in research for user experience and behaviourism. It captures the gaze of both eyes with 60 Hz natively. The scene camera has a resolution of 1280×960 p at 24 fps or 960×720 p at 30 fps respectively [22].

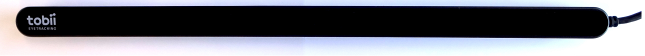


Figure 2: Tobii Eye Tracker 4C

Figure 3: SMI Eye Tracking Glasses 2W

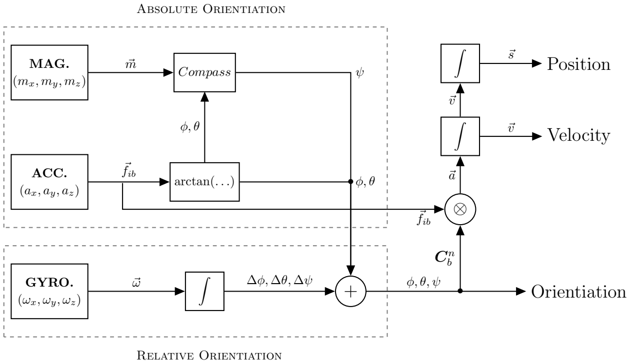


Figure 4: Simplified sensor fusion algorithm to calculate orientation from angular rate, gravity and magnetic field (adapted from [26]).

3.3 MARG Sensors

Magnetic **A**ngular **R**ate and **G**ravity sensors (MARG sensors) combine a 3-axis accelerometer, a 3-axis gyrocsope and a 3-axis magnetometer.

An accelerometer measures gravity and linear acceleration by measuring the capacity between an inert mass and an electrode. As the sensor is accelerated, the mass is deflected, changing the capacitance which can be measured. The gyrometer consists of an oscillating mass that is deflected when the sensor is rotated. The mass is deflected by the Coriolis force. Thereby the capacitance between the mass and an electrode changes which can be measured. A magnetometer can measure the magnetic field using the Fluxgate, magnetoresistance or Hall-Effect. To compute the pose of the sensor, the data of the three sensor types have to be combined. By integrating the angular rate, the orientation could be calculated. Because of the sensor bias, the angle drifts after a short period of time. For this the gravity (roll and pitch) and magnetic field of the earth (yaw) are used as a reference (see Fig. 4) to correct the drift [26].

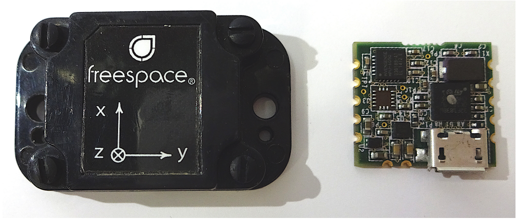


Figure 5: MARG sensor FSM-9 from Hillcrest

There are several sensors available on the market, i. e. the FSM-9 from Hillcrest Labs (see Fig. 5) or the BNO055 from Bosch Sensortec. Both incorporate a MARG sensor and a microprocessor. The FSM-9 for example has a sample rate up to 250 Hz. In this test the sample rate is set to 100 Hz. Acceleration is measured with a resolution of 6 mg, angular velocity with 0.04 °/s and the magnetic field with 1 μT. The sensor can output the orientation or the raw sensor data.

3.4 Video-Based Head Tracking

Video-based head trackers work with image processing and machine learning. An algorithm recognizes contrast differences and edges (i. e. nose, lips, eyes) and fits a three dimensional model of a generic face to the image. The model is trained prior to the application using machine learning. It is then fitted by stretching, rotating and relocating. Because the model is three dimensional the rotation and position of the head can be estimated [7]. Available products involve the Tobii Eye Tracker 4C (see Fig. 2) and a software called "FaceTrack" from Visage Technologies. Both are not dedicated to head tracking but provide this functionality. For the test the Tobii Eye Tracker 4C was used. Unlike the eye tracking, the tracking of the head orientation and position is not processed on board but on the CPU of the host computer.

3.5 Electromyography

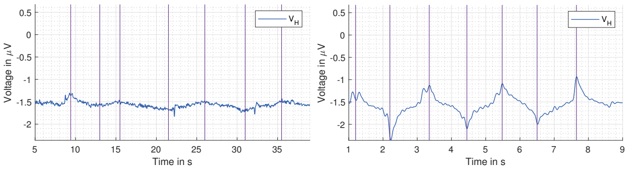
Measuring the electrical activity of the muscles is called electromyography (EMG). An action potential causes a depolarisation of the muscle fibers. This triggers muscle contraction. The depolarisation of the muscle can be measured with electrodes on the skin. With surface electrodes, the measured muscle activity is a sum signal of all surrounding muscles. Subcutaneous wire electrodes can be used to measure the activity of individual fibers. These electrodes are inserted into the muscle. In this test the USBamp from G.TEC is used. It captures the signals with up to 24 Bit and 38.4 kHz. Here the sample rate was set to 125 Hz as given in [21]. Schmalfuß et al. [21] measure the activity of the posterior auricular muscle to control a wheelchair.

4 TEST AND RESULT

The tests were conducted with one ($n = 1$) healthy, 24 years old, male test person. The results are preliminary and a bigger study has to be conducted to verify the results.

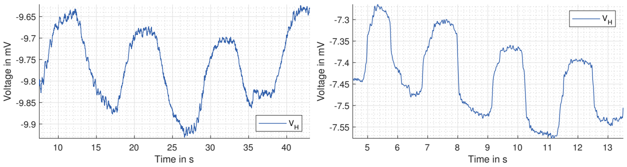
4.1 Test and Results Electrooculography

Tests with two different hardware setups were performed. The EOG glasses were tested primarily. The results were compared to a standard three-point EOG. Sitting in front of a computer monitor, the test person was looking at an "X" that was moving from left to right and back four times in two different velocities. The target moved on a 24" monitor from one side to the other within 1 s or 5 s respectively. Hence a slow and a fast mode was tested.



(a) **EOG glasses slow movements**

(b) **EOG glasses fast movements**



(c) **Conventional EOG slow movements**

(d) **Conventional EOG fast movements**

Figure 6: Horizontal movements of the practical tests of EOG glasses and conventional three-point EOG. The data were filtered using a digital lowpass filter.

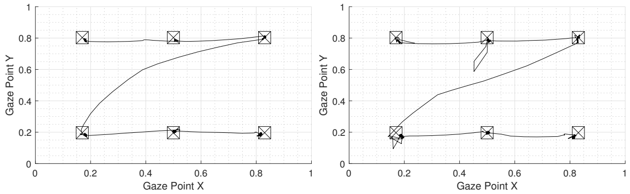
The test results are shown in Fig. 6. Figure 6a and b show the test with the EOG glasses whereas Fig. 6c and d show the conventional electrooculogram. The tests show no proportional relationship between the gaze angle and the EOG signal using the EOG glasses. The movements are visible with the fast moving target because of the muscular activity. While measuring the conventional three-point EOG, the eye movements were visible with the fast and the slow moving target.

According to the information given by the manufacturer, the glasses can immediately display gaze. When the participant moved the eyes quickly, this was possible, unlike when the eyes were moved slowly. That is caused by the muscle activity which causes a higher voltage than the eye dipole. Horizontal movements in particular were better observable than vertical movements as a result of the higher travel distance. In contrast to the EOG glasses, the eye movements were clearly visible in the conventional three-point EOG (see Fig. 6c and d) independent of the movement speed. Poor signal transmission due to steel electrodes and the lower quality amplifier of the JINS MEME ES, explain the more useful voltages with the conventional three-point EOG.

4.2 Test and Results Video-based Eye Tracker

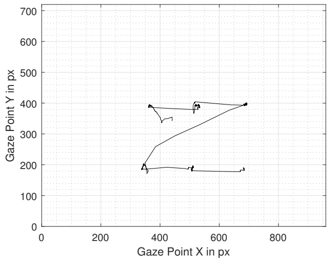
In this test a stationary eye tracker and eye tracking glasses were compared to test the overall performance. The test with the stationary eye tracker was conducted to identify whether spectacles are a noticeable disturbance. In one of the two tests with the stationary eye tracker the user was wearing frameless spectacles with corrective lenses. To extract the raw data, the Stream Engine API (Application Programming Interface) from Tobii respectively the software "BeGaze" from SMI in combination with the "Smart Recorder" was used. The task for the test person was to look on an "X" appearing on six different spots of a display for five seconds each. The results are shown in Fig. 7.

The results show that the stationary eye tracker provide a stable measurement regardless of the user wearing spectacles or not. As can be seen, the test does not have a higher noise levels or any failure while wearing spectacles (see Fig. 7b). The noticeable error was presumably caused by saccades (fast eye movement) of the test person due to distraction. The test revealed that spectacles do not have an influence on the trackers eye tracking functionality.



(a) without spectacles

(b) with spectacles



(c)

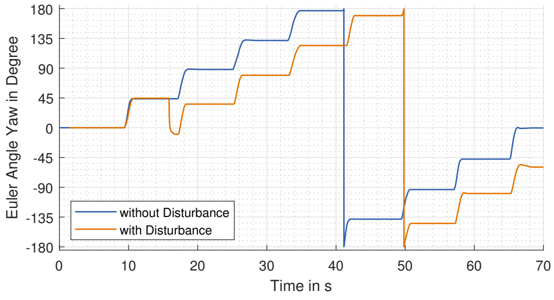
Figure 7: Results of test with stationary eye tracker (a and b) and the eye tracking glasses (c)

The test with the eye tracking glasses were similar but a bit more unsteady because the glasses do not offer any compensation of the head movements, while the stationary eye tracker does. When the user fixates on a certain point in the environment and moves the head, the calculated gaze point changes, because the coordinate system of the eye tracking glasses moves. The stationary eye tracker in contrast, provides a more stable measurement because the coordinate system is fixed to the environment. The missing compatibility with spectacles is disadvantageous for the user acceptance. The test person observed, that performing gestures for an event control is feasible and comfortable.

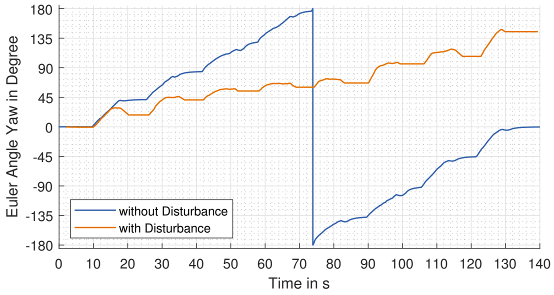
4.3 Test and Results MARG sensor

For the test, the sensor was attached to a camera tripod which then was rotated in 45 ° steps, according to the scale on the tripod. Four tests were performed. First, the sensor was rotated quickly, followed by a break of 10 s. Second, the sensor was moved slowly with a duration of 10 s followed by a break of another 10 s. Lastly, both test were repeated while manually rotating a magnetized ferromagnetic rod to provoke drift of the sensor signal.

The results of the tests are shown in Fig. 8. With fast rotation and without disturbance the sensor does not drift (see Fig. 8a). In the case of magnetic disturbance, the rotation and breaks are still visible, but with a deviation caused by a wrong correction of the angle using the disturbed reference. When rotating slowly, the sensor drifts. The breaks and the rotating phases are not clearly distinguishable. Despite the drift, the angle still reaches the final value. The sensor drifts heavily when being rotated slowly, while a magnetic disturbance is present (see Fig. 8b).

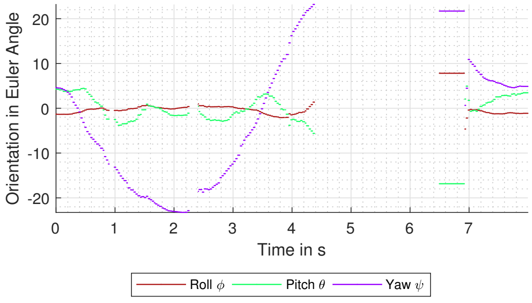


(a) Fast Rotation

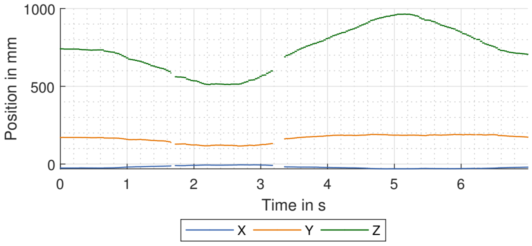


(b) Slow Rotation

Figure 8: Tests using the MARG sensor



(a)



(b)

Figure 9: Head tracking functionality of the Tobii Eye Tracker 4C, Yaw angle (a) and moving away from the tracker (b)

Figure 10: Setup for measuring the activity of the posterior auricular muscle. The electrodes are positioned at the posterior auricular muscle (red), the ispilateral pinna (reference, green) and ear clips for grounding (black).

The observable drift derives from the bias of the gyroscope. With faster movements, the bias is compensated using the magnetic field as a reference whereas when the reference is disturbed, the behaviour is the same but with a deviation. When the sensor is rotated slowly, the drift intensifies especially when the reference is disturbed.

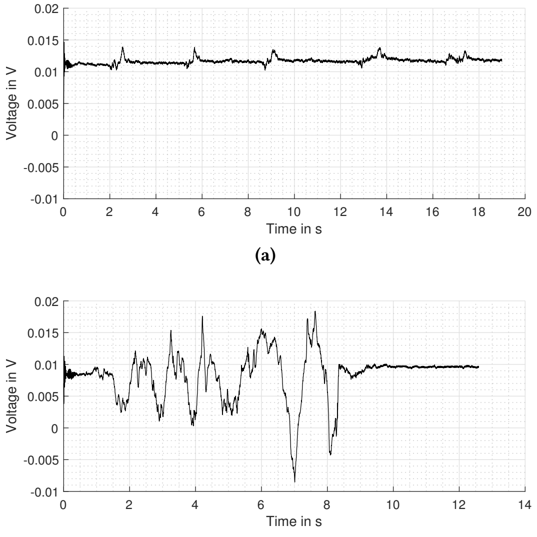
4.4 Test and Results Video-based Head Tracking

The test with the head tracking functionality of the stationary eye tracker is conducted to qualitatively measure the rotation of the head in yaw direction and the movement away from the tracker and to examine when the sensor is not able to track the head. To test the maximal rotation angle with which the sensor can compute the head pose, the test person rotated the head to the left and the right while sitting in front of the monitor. In a second test the test person moved away from the tracker to examine the maximal distance to obtain the head pose correctly. The results of the tests are shown in Fig. 9. In Fig. 9a the three Euler angles of the head orientation are shown. Figure 9b shows the head position of the test person in the second test.

While rotating the head, the algorithm loses the virtual markers (at approx. 4.4 s) and tracking fails until the head is rotated back (at approx. 7 s). The same happens while moving away from the tracker at 1.7 s and 3.2 s. The head tracking functionality of the stationary eye tracker cannot obtain the full functionality when the user is wearing glasses. It does not detect the head pose when the user turns the head too far, which is caused by an incorrect or failed tracking of the landmarks in the face.

4.5 Test and Results EMG of the Posterior Auricular Muscle

For the test, adhesive surface electrodes and an amplifier were used. The setup for the electrodes is shown in Fig. 10. The test subject was instructed to wiggle his ears. The result is shown in Fig. 11. The contractions of the posterior auricular muscle are observable in the EMG in Fig. 11a. The test person wiggled his ears at $t = 2$ s, 5.5 s and 9 s. He held the contraction at $t = 13$ s and contracted two times consecutively at $t = 16.5$ s. Figure 11b shows movements of the head. The test subject moved his head slightly left and right (yaw) which affected the signal to the extent that the activity of the posterior auricular muscle is no longer observable.



(a)

(b)

Figure 11: Result while wiggling with the ears (a) and moving the neck (b)

In the test the high influence of biological artifacts were obvious. There were no other influences other than that. EMG is robust against sunlight or external magnetic fields.

5 DISCUSSION

Based on the results of the five sensor modalities, the most suitable sensor modality for robot control by tetraplegics is proposed here. It is suggested to use the MARG sensor modality as continuous control and video-based eye tracker gestures to perform events to switch groups or trigger different actions. Table 1 summarizes the advantages and disadvantages of the sensor modalities.

MARG sensors have a small form factor, price and weight. The test shows that small movements are measurable due to the high resolution. Furthermore the sensor itself is self-contained. The video-based eye trackers and especially the eye tracking glasses offer a robust functionality. Fast movements like saccades can be measured as the tests show. The glasses are robust against external magnetic fields and sunlight. The test indicates, that performing gestures for an event control is feasible and comfortable.

Using the EOG glasses the gaze direction is not observable due to low signal transmission and inadequate resolution of the amplifier. The measurement with the conventional three-point EOG is more suitable because of a better output. To achieve the better signal, more expensive hardware and additional adhesive electrodes are required. The signal-to-noise-ratio is low as a result of biological artifacts like muscular activity or blinking. The stationary eye tracker is not self-contained and requires further hardware mounted to a monitor or a desk. The video-based head tracking functionality of the stationary eye tracking system is not usable when the user is wearing glasses. Also when the user rotates the head too far, the algorithm loses the landmarks in the face and tracking fails. When using the EMG of the posterior auricular muscle, extra hardware is needed in addition to the adhesive electrodes. While measuring the EMG, the disturbances originating from the neck muscles have a much higher amplitude than the signal. The high effort filtering and processing the data also is disadvantageous. However the MARG sensors drifts as shown in the tests when the sensor rotates slowly and a magnetic disturbance occurs using the commercial algorithm. Furthermore, the eye tracking glasses cannot be used with spectacles.

6 CONCLUSION AND FUTURE WORK

In this work different modalities to control a robot with eye or head movements were proposed. Video-based eye tracking and electrooculography were addressed. To capture the head pose, video-based systems as well as MARG sensors were examined. An additional modality was introduced with the electromyography of the posterior auricular muscle. As shown in the tests, the MARG sensor modality is the most suitable approach for continuous robot control. Furthermore MARG sensors are reliable, have a small form factor and a low weight and price. Video-based eye tracker glasses are more appropriate for switching or more general discrete event control. Also eye tracking glasses are self-contained and reliable.

However, the drift in yaw orientation due to gyroscope offset and disturbing magnetic fields is unacceptable for a robust control of robot systems. Future work will concentrate on algorithms for sensor fusion of MARG and especially eye tracking modalities. The sensor modalities proposed here offer the opportunity to implement a multimodal MARG-Eye-Tracker unit for continuous and discrete control of robot systems. The aim is to enable more autonomy for tetraplegic people by providing a save and robust robot control. Furthermore a user-centred study with more users will be designed and conducted related to acceptance and comfort.

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Table 1: Summary of the advantages and disadvantages of the five sensor modalities

Sensor Modality	Advantages	Disadvantages
Electrooculography	• Ease of use with EOG glasses	• Gaze direction not measurable using EOG glasses • Additional expensive hardware and electrodes are needed to measure eye movements • High noise due to biological artifacts
Video-based Eye Tracker	• Robust functionality • Fast movements are measurable	• Glasses not usable while wearing spectacles • Stationary eye tracker not self-contained
MARG sensor	• Small form factor • Low price • Low weight • Self-contained • High resolution	• Angle drifts with disturbed magnetic reference using commercial algorithm
Video-based Head Tracking	• Ease of use • Low cost solutions available	• Not usable while wearing spectacles • Tracking fails when head is moved to wide
EMG of the Posterior Auricular Muscle	• Additional input signal	• Additional expensive hardware and electrodes are needed • High noise due to biological artifacts

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