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Robotic Wheelchair Control Interface based on Headrest Pressure Measurement

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***Abstract*—We introduce a novel approach for proportional head control for robotic wheelchairs. An array of force sensors embedded into the headrest is used to monitor the pressure distribution changes due to the intentional head motions of the patient. The force signals are analysed and converted into fully proportional signals that control the wheelchair direction and speed. We developed a prototype interface that generates signals similar to the signals of a standard joystick control box and connected the new interface to a standard Invacare wheelchair. Tests showed that all users adapted to the control algorithm very quickly and were able to follow very precisely complex target trajectories on various speeds. The interface does not require any attachments to the user's head and does not cause any limitation of the user's field of view.**

I. INTRODUCTION

Powered wheelchairs are commonly used by patients with moderate to high levels of movement paralysis. Such wheelchairs are navigated by the user who sets commands for the movement direction and movement speed of the wheelchair by intentional motions or biosignals that are recognized by special Human – Wheelchair Interface (HWI). The role of the HWI is to convert the user's signals into relevant electrical control signals. Usually, wheelchairs are designed to allow the connection of various types of user interfaces. This way, the same wheelchair can be adapted to the abilities and preferences to a wider user group. Various interfaces are developed so far for different patient conditions. Joysticks are a good solution for users who have preserved own hand motions. However, joystick interface is not applicable to users who suffer from hand paralysis or patients who cannot perform fine hand motions. Good solutions for such patients are the control interfaces based on head motions. Some head interfaces use a few large-diameter switches that are embedded in the headrest and activated by the head [1, 2]. Unfortunately, such interfaces give only coarse information about the desired movement direction and the wheelchair can move on a preliminary set speed that cannot be controlled by the user.

Proportional head interfaces based on ultrasonic transducers, magnetic, or capacitive sensors are another tendency in the wheelchair head control [2, 3, and 4]. Such head trackers can produce up to three independent proportional signals that correspond to forward-backward head tilting, left-right head rotation, and lateral head tilting. Such interfaces give good results when used indoors but often such interfaces are quite sensitive to humidity and moisture due to rain, etc. Adaptive Switch Labs (ASL) introduced an interface that is based on proximity switches that detect the distance between the sensor and the user's cheek [2].

Widely used in the rehabilitation engineering practice are the head interfaces with a linkage system that moves a standard joystick when the user performs intentional head motions. However, such system requires direct contact between the linkage system and the user's head.

Tracker 2000 and Tracker Pro of Madentec [5] use a reflective dot attached to the user's head and detected by a camera-based sensor. Such systems are widely used in the environmental control and could also be used for wheelchair control. Moreover, the Tracker 2000 has a dedicated joystick mode of operation. Stefanov et al proposed another interface based on infrared LEDs mounted to eyeglasses frames whereby a signal is received by a sensor mounted on the headrest [6, 7]. The disadvantage of such systems is that they require attachment of the sensors to the user's head which causes significant restrictions to some patient groups.

Magitek introduced their wireless Magi-Mouse that is attached to the user's head and responds to the changes in head orientation [8]. The interface was introduced as a mouse head control. The technology requires the attachment of a small-sized sensor to the user's head.

Head interfaces based on analysis of the user's face image are another direction in the wheelchair head interface. The WATSON wheelchair control system developed at the Robotics Laboratory of the Nara Institute of Science and Technology uses one or two cameras directed at the user [9, 10]. After processing the image signals and calculation of the directions of the face and eyes, the signals are used to control a wheelchair. The user can stop the wheelchair by repetitive fast head motions.

In this paper, we propose an interface for proportional wheelchair control. The headrest mounted system for proportional pressure sensing allows the operation of the wheelchair by intentional and intuitive head movements. The system generates, depending on the head position, electrical

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signals similar to the joystick signals. In the following section II we explain the required compliance of the basic technical solution. Hardware and software components are described in section III. In section IV, the current prototype is discussed. Drive tests and results are described in section V. An appraisal of the results is presented in section VI.

II. Technical Solution

The target of this study was to design a patient independent head control interface system that does not require any physical object attached to the occupant's head. The interface system was supposed to control powered wheelchairs with intuitive head movements and without any obstruction to the field of view due to mechanical attachments to the headrest. We also set a goal to develop a solution that can be connected easily to most existing wheelchair controllers of the main wheelchair manufacturers.

The interfaces that are based on head motions have significant advantages. Most of the people who suffer from spinal cord injuries preserve their ability of head movement. Head control can be an efficient solution for them. Intentional head-movement can provide enough information to control different input devices like a PC mouse curser, rehabilitation robot, a TV remote control, or a powered robotic wheelchair.

The goal of this project is to connect head movements with powered wheelchair operation and the development of a control system that fulfils the following conditions:

- The system needs to be universal. Many people should benefit from the technology. It has to be simple to integrate patients into the system, which also means that less help from the caregiver will be required.
- The design solution should not involve any hardware attached to the operator's head. Otherwise, the natural head movement could be restricted and the head attachment could cause certain inconvenience to the user.
- The interface system should not include any components or attachments that restrict the user's field of view and head movements during the wheelchair operation.
- The sensor system needs to be designed in a manner that allows the user to operate the wheelchair with intuitive head movements. This will reduce the patient's mental efforts for controlling the wheelchair and will make the process of control less tiring. Also, the time for adaptation of the user to the wheelchair interface will be reduced if a simple control algorithm is used. Consequently, the number of potential users able to use that interface will increase.

A. *The idea*

In this work we introduce a solution for wheelchair control that is based on analysis of the pressure distribution on the headrest. In order to explore the change of the pressure distribution on the headrest when the user changes the direction of his head, we used a Conformat pressure mapping system of Tekscan [11]. For the tests we covered the original wheelchair headrest with the pressure sensitive mat and recorded the changes of the pressure distribution when the subject changes his/her head direction. Three subjects aged 21 to 25 were used for the experiments. We explored the pressure distribution for three ranges of pressure applied by the user to the headrest. We named these as 'low' (L), 'medium' (M), and 'high' (H) head force. During the experiments, the computer screen which presented the headrest pressure distribution map was placed in front of the subject. The contact area between the head and the headrest appeared on the screen as a spot. The inner area of the spot changes depending on the pressure applied to the headrest. Subjects were asked to lean their heads on the headrest, to monitor the picture on the screen, and to keep the inner area of the contact spot always red-coloured by changing the head pressure to the headrest. The experiment scenario is shown in Fig. 1.

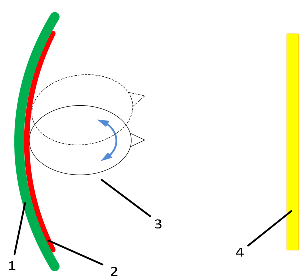

Figure 1. Scenario of headrest pressure assessment (1. Headrest; 2. Pressure mat, 3. Head, 4. Screen of the pressure mapping system)

Initially, the pressure monitoring system was set up so that the red colour corresponded to pressure 7.7kPa. The subject was asked to rotate his /her head consecutive to 15, 30 and 45 degrees to the left and then to the right. The position of the centre of the spot and the shape of the spot were recorded for each head rotation. Next, the sensitivity of the mapping system was decreased and the areas pressurized with 14.1kPa appeared in red. The contact spot position and shape during the head rotations were recorded. The pressure mapping system was reset again to represent in red the areas loaded with 23.8kPa and the contact spot parameters were recorded.

We explored the movement of the contact spot within a narrow horizontal area around the centre of the pressure image. In addition to that, we divided the horizontal strip into 16 cells as shown in Fig. 2.

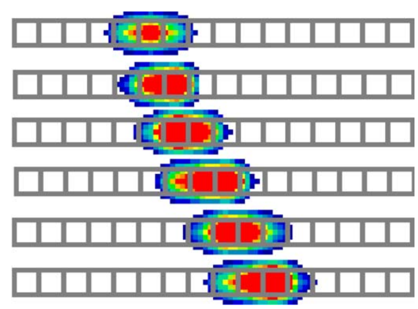

Figure 2. Frames of pressure distribution on the headrest

We noticed that the contact area usually covers a few neighbouring segments. We considered the cells which represent significant pressure and ignored the segments where pressure was below a certain threshold. Cell ***k*** is considered to be the centre of the spot if the following relation is achieved:

$$\sum_{i=1}^{k} P_i \geq \frac{\sum_{i=1}^{n} P_i}{2} \quad (1)$$

Where i= 1,..k,..n is the number of the sequential neighbouring pressurised cells.

B. *Control strategy*

The wheelchair control is based on three components as shown in Fig. 3.

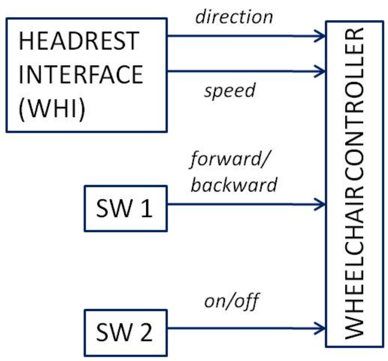

Figure 3. Control strategy

The headrest wheelchair interface (HWI) provides commands for the direction of travelling and the wheelchair speed. The intentional rotation of the user's head changes the position of the application of the force to the headrest and thus, the wheelchair direction. As the user presses harder with his/her head on the headrest, as the wheelchair goes faster. The wheelchair stops when the pressure applied to the headrest decreases under a set minimum value.

SW1 is a push button that allows the setting of forward movement or reverse. The user can choose forward or backward motion by sequential pressing of SW1.

SW2 is a push button that deactivates the signals from the head interface and immobilises the wheelchair program when the user wants to use the headrest for head support but not for wheelchair control. Operating the same button in active mode initiates the start of the program.

In the developed prototype, SW1 and SW2 are located on the armrest. The same switches can be located on both ends of the headrest to be activated by head. Alternative techniques of activation of the switches, such as chin control, sip-and puff switch, etc. can be used.

The headrest interface allows proportional control of the wheelchair speed. However, the headrest signals can be set easily to produce proportional signals for wheelchair direction and movement on constant speed.

III. System Design

A. *Block diagram of the HWI*

The complete system is displayed in Fig. 4.

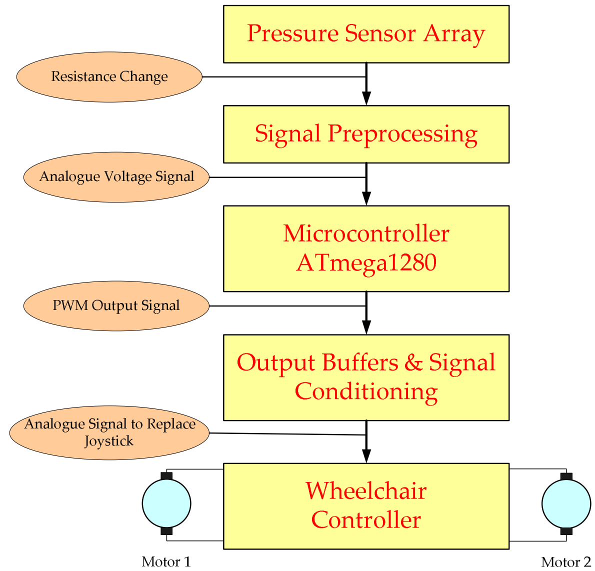

Figure 4. A block diagram of the wheelchair control

For sensing the pressure distribution, we used an array of 16 thin force sensors arranged in one single row and embedded into the middle of the wheelchair headrest. These sensors produce analogue signal proportional to the pressure applied to them. An analogue sensor signal is sent to the input pins of a microcontroller that processes the signals of the force sensors and generates PWM output signals that depend on the orientation of the user's head. The microcontroller processes sensor signals coming from the pressure sensors. An Atmega1280 microcontroller was used in this project. The microcontroller outputs PWM signals need to be converted into an analogue DC signal with a voltage level between 1.6V to 3.0V in order to become compatible with the signals produced by the original joystick box. The original joystick control box is disconnected and the signals from the new interface are applied to the wheelchair control box. The components of the interface are explained below.

B. *Sensors*

The design of the head controlled interface is based on thin-film Force Sensing Resistors (FSR). Such sensors use a resistive-based technology and read forces perpendicular to their sensing plane. The sensing head consists of two flexible silver layers printed on flexible substrates. A layer of pressure sensitive ink is located between the conductive layers. In an electrical circuit, this sensor acts as a variable resistor, where the change in resistance is inversely proportional to the force applied. The higher the applied force, the more "resistance-bridges" are built between the fingers. A picture of such a sensor is shown in Fig. 5.

The force-resistance curve is non-linear [12]. For the low force range, the resistance rapidly decreases from more than 1MOhm to about 100kOhm. Also, if the applied force rises outside the sensing range (>100N) the sensor starts to saturate and as a result, the resistance remains constant despite the force change. For the project we ensured that the force sensors are used in the middle section of the force-resistance characteristics, which is linear for that range.

The pressure sensor FSR400 (Interlink Electronics, Inc.) was selected because of its shape, size and characteristics [13]. The active surface of the FSR400 is round and 5mm in diameter. In the required pressure range, the sensor characteristic is nearly linear which makes the sensor ideal for the new application design.

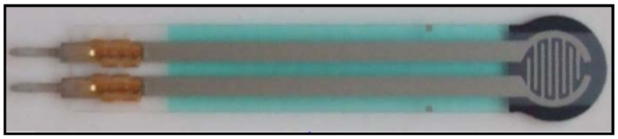

Figure 5. Thin-film force sensor

C. Sensor Bridge system

The force coming from the user's head needs to be concentrated on the active sensor area. On the other hand, the active sensing area of the force sensors is very small. To solve the problem, we developed special flexible plastic bridges that contain adjustable pins to concentrate the force to the pressure sensor. The design is shown in Fig. 6. Adjustable pins with rounded off ends were mounted against the active sensor area of each sensor. These metal pins apply the force from the user's head in exactly the same position of the force sensor. Sixteen bridges are made of strips of plastic material and can bend individually. Each bridge covers the whole width of the aluminium headrest plate. The bridges are covered with a soft foam material.

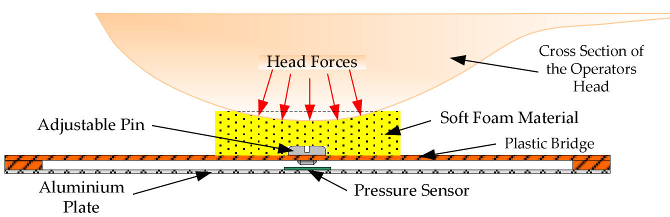

Figure 6. A sensor bridge system

D. Headrest sensor assembly

The sensor system is built up on an aluminium base plate, which can be embedded into the original wheelchair headrest as shown in Fig. 7.

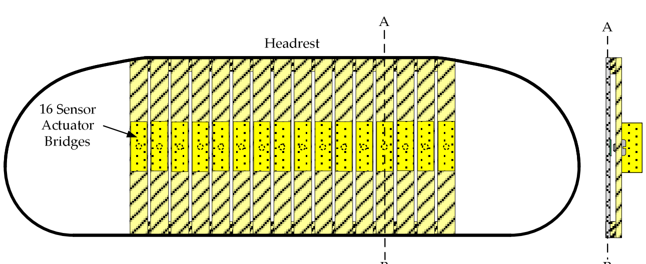

Figure 7. Headrest sensor assembly

Sixteen sensor bridge modules similar to the bridge of Fig. 6 are arranged in one horizontal row on the headrest middle. The pressure distribution picture, sensed by the FSR array, changes depending on the head position on the headrest.

E. Signal Processing

FSRs act as variable resistors. We used a half-bridge system to derive voltage signals that correspond to the measured forces.

The actual sensor signal processing was done in the microcontroller unit. We used a microcontroller board "Arduino Mega" [14] that is equipped with an Atmega1280 controller and USB interface. The board has sixteen analogue inputs and four PWM outputs, processor speed is 16MHz, and the flash memory is 128KB.

The program algorithm converts the input signals into PWM output signals. When the system starts, the program performs an initial setup to configure the sensor signals. The initial start-up procedure also checks if any of the force sensors are pressurised at the start-up point. If any of these sensors is activated the system generates a warning signal and waits until the user moves his head from the headrest. If none of the force sensors is pressurised the main loop starts. The program performs a new reading of the values of all sixteen sensors and the state of the button for reverse wheelchair motion (SW1, Fig. 3). The sensor values are saved. In the next periods, these memorized values will be used as references for comparison with the ongoing signals. When the user's head came into contact with the headrest, the signals of one or more force sensors are changed. The centre of the pressure spot is calculated by using a program based on (1). The number of the initially activated sensor is memorised and used further as a reference point. The position of the moment pressure spot is then measured with respect to the reference sensor. In the different control sessions, the reference point may change due to slight differences in the user's body position in the wheelchair. The head direction (forward, left and right) is judged with regards to this reference point. The correct calculation of the reference point is important for the smooth operation of the wheelchair system. After the initial contact areas have been selected, all sensor values in each area are sampled. The program starts to analyse the signals from the force sensors and converts them into smooth proportional signal that correspond to the orientation of the user's head. Also, the program calculates the signals for the wheelchair speed from the amount of pressure to the headrest in the separate parts of the headrest. The output values are transferred to the output pins as PWM signals. The output values are inverted if the button for forward-backward motion is activated.

Output Buffers and Signal Conditioning: The original joystick produces analogue signals and the signal of the microcontroller board needs to be converted from PWM to DC, level conditioned, and buffered. Low-pass filter circuits were used to change the PWM signals into analogue DC voltages. Two voltage signals are generated for setting the wheelchair speed. Two other signals are produced to simulate the joystick signal for left and right turn.

IV. PROTOTYPE AND ADDITIONAL SYSTEM APPLICATIONS

In order to test the viability of the proposed idea and the efficiency of the control algorithm we developed a functional prototype interface that generates signals similar to the signals of a standard joystick control box and connected the new interface to a standard wheelchair model Invacare Storm II that used a "Dynamic" controller [15]. A picture of the prototype wheelchair is shown in Fig. 8. The prototype interface unit was attached to the original headrest of the wheelchair. For the experiments we used the original joystick box to change the wheelchair speed ranges. We used a separate switch to change the movement directions (forward/reverse), noted on the picture as position 3. The prototype also included a simple LCD to inform about the current status of the system.

Figure 8. The prototype 1-headrest sensor plate; 2-reverse button; 3-LCD for reference information

V. TESTING

The aim of the tests was to collect some preliminary information about the viability of the idea and about the performance of the system in various driving conditions. The head control system was tested by four able-bodied persons of different age groups. The system tests were carried out in a room of about 45m^2 with carpeted floor. The floor is mainly smooth and only partly uneven due to floor attachments. We used a wheelchair (Invacare Storm II) that has 5 speed ranges. Depending on the chosen speed range, the maximum speed is limited to a certain value. The maximum speed in range 1 is limited to 0.5 km/h. In range 5, the wheelchair speed can be changed from 0 to 6 km/h. We used different speed ranges during the tests.

Initially, each participant was briefed on the correct operation of the wheelchair. Then, the wheelchair was set to the lowest speed (speed range 1) and each participant was allowed to practice for 10 minutes to adapt to the control algorithm. We noticed that after about two minutes, including the introduction time, all persons who participated in the test were able to manoeuvre the wheelchair accurately. No individual adjustment was needed.

Next, the wheelchair was set in speed range 1 and participants were asked to follow a circle-shaped reference path marked with coloured tape on the floor while driving forward. The wheelchair speed was increased in each test and set sequentially from speed range 2 to 5. During this test, the participants were asked to change the wheelchair's direction around the reference path. The change of the direction did not cause noticeable change of the steering performance.

With the third series of tests we explored the manoeuvrability of the wheelchair in tasks for obstacles overcome. For the tests we used two obstacles with dimensions 30x30x30 cm and 300 cm distances between them, and asked each participant to move around the obstacles. All users were asked to follow 3 reference trajectories: "S" shape, "8" shape and "O" shape around the obstacles as shown in Fig. 9. In this trial we wanted to explore whether participants were able to follow the reference trajectory relatively accurately. We installed pairs of obstacles around the reference path. The distance between the obstacles was 105 cm. Since the wheelchair width was 65 cm, we limited the allowed deviations of the wheelchair trajectory with respect to the reference path to ± 20 cm. The reference trajectories were marked on the floor with colour adhesive tape. Initially, the tests were performed on low speeds and the wheelchair was set into speed range 1. Then, participants were asked to repeat the same tests while the wheelchair was set in speed ranges 2 and 3. The test results show that all participants were able to perform the tests and the deviation of the performed trajectory did not exceed ± 20 cm.

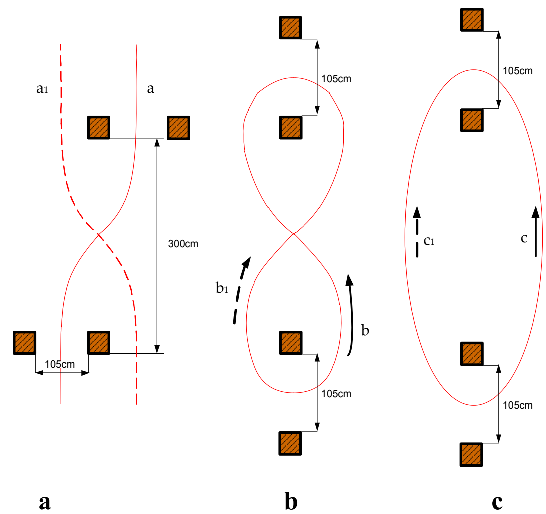

Figure 9. Reference test path

Fourthly, we did tests to explore the wheelchair manoeuvrability when it passes through narrow corridors or doorways. For the experiment, we used two obstacles dimensioned as 30x30x30cm and set the distance between them to 85 cm which was just 20 cm more than the wheelchair width (Fig. 10). The wheelchair was set initially in speed range 1 and then the same test was performed on speed range 2. The tests showed that all participants were able to pass through the obstacles without colliding with them.

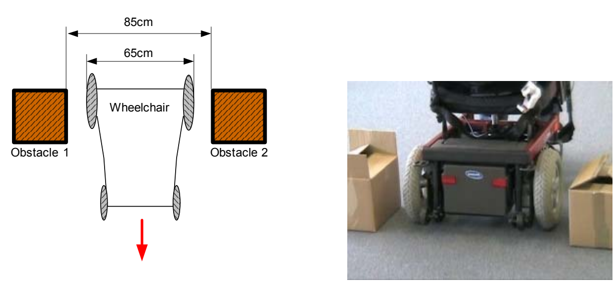

Figure 10. Passage through narrow "corridor"

For the fifth test, we asked participants to pass through the room door (90 cm) while operating the wheelchair in speed range 1. The tests show that all participants were able to perform the task without colliding with the doorframe.

We explored the manoeuvrability of the wheelchair while it moves backward. The forward/backward movement was set by a special button on the new interface (see Fig. 8, position 2). The wheelchair was set to speed range 1. Initially, the participants were asked to practice obstacle overcome while moving backward. We attached a small mirror to the wheelchair to inform the driver about the obstacle location. We used the same reference trajectories as shown in Fig. 10. Next, we explored the manoeuvrability of the new interface in "parking" tasks. For that purpose, we simulated a "parking space" as shown in Fig. 11. The participants were asked to enter the parking space by using backward motion. Results show that two participants were able to perform the task from the first attempt while the other 2 persons performed successfully the same task from the second attempt.

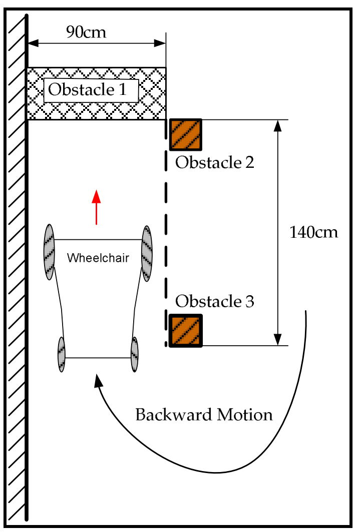

Figure 11. Parking test

Every participant was able to operate the powered wheelchair quickly and accurately after the short introduction time. There have been no complaints about pain or uncomfortable drive positions. All participants found this new interface solution interesting and easy to control.

VI. CONCLUSION

We developed a new wheelchair head interface and performed initial tests of the head control prototype with different operators. The tests showed that users adapt very quickly to the new algorithm and can drive the wheelchair accurately after a few minutes of practice. The only adjustment for a new operator is the height of the headrest. The experiments showed that the navigation through narrow doorways with the new interface can be performed easily. The new interface does not cause any limitations on the head movements and does not obstruct the wheelchair operator's field of view. Due to the use of pressure sensors, the developed system produces fully proportional commands. The pressure system also has advantages over other head control solutions. Its normal operation stays unaffected from humidity or rain unlike the ultrasonic systems. Ferromagnetic materials and interference with strong external magnetic fields may affect the normal operation of inductive head control systems but the new system stays unaffected by external magnetic fields. Further improvement of the system might concern the development of control algorithm that allows the user to change speed ranges and to switch between forward/backward modes by head motions. Such system will become easily applicable to patients who cannot use their hands to switch among the wheelchair modes. The proposed design does not require extra attachments to the user's head.

The initial tests of the system will be followed by precise tests of the wheelchair operability by using quantitative measurement of the wheelchair speed and deviation from the reference trajectories. The tests will involve a much wider group of drivers. Further outdoor tests and testing the control interface with disabled wheelchair operators will allow precise evaluation. A long lasting drive test would be important to identify eventual effects of tiredness and problems caused by the use of the interface device.

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