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RESEARCH ARTICLE

Fuzzy Logic Control of a Head-movement Based Semi-autonomous Human–machine Interface

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Abstract
Quadriplegia is a neuromuscular disease that may cause varying degrees of functional loss in trunk and limbs. In such cases, head movements can be used as an alternative communication channel. In this study, a human–machine interface which is controlled by human head movements is designed and implemented. The proposed system enables users to steer the desired movement direction and to control the speed of an output device by using head movements. Head movements of the users are detected using a 6 DOF IMUs measuring three-axis accelerometer and three-axis gyroscope. The head movement axes and the Euler angles have been associated with movement direction and speed, respectively. To ensure driving safety, the speed of the system is determined by considering the speed requested by the user and the obstacle distance on the route. In this context, fuzzy logic algorithm is employed for closed-loop speed control according to distance sensors and reference speed data. A car model was used as the output device on the machine interface. However, the wireless communication between human and machine interfaces provides to adapt this system to any remote device or systems. The implemented system was tested by five subjects. Performance of the system was evaluated in terms of task completion times and feedback from the subjects about their experience with the system. Results indicate that the proposed system is easy to use; and the control capability and usage speed increase with user experience. The control speed is improved with the increase in user experience.

Keywords Human–machine interface (HMI) · Head-movement · Obstacle avoidance · Inertial measurement unit (IMU) · Fuzzy logic

1 Introduction

Spinal Cord Injury (SCI) is a damage to the spinal cord, which causes temporary or permanent changes in its function, resulting from trauma, diseases, or degeneration. Worldwide, every year, approximately 250,000–500,000 people suffer from SCI. Loss of muscle function and sensation depends on the severity and level of injury. Tetraplegia is a type of SCI that results in varying degrees of functional loss in the upper and lower limbs, neck and trunk. SCI may cause people to be dependent on their caregivers and cause them to be isolated from their social environments. In these cases, assistive technologies are solutions that make life easier for users thanks to facilitate mobility, communication, self-care or activities [1].

Human–Machine Interfaces (HMIs) are communication pathways between humans and machine, system, or device. During the last decades, there has been a growing interest in HMIs, which generally focus on rehabilitation or replacement of extremities, or to control assistive devices [2]. According to the degree of the impairment of the people and their residual movement capabilities, HMIs enable people to control assistive devices by the means of physiological or electrophysiological signals [3–5]. As well as the physiological signals such as speech, eye movements [6], hand movements [7], facial expressions [8], and gestures [9–11], electrophysiological signals such as electrooculography [12], electromyography [13, 14], and electroencephalography [15] are employed as alternative communication channels to control HMIs. Sensors, which are designed thanks to

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developments in nanotechnology and wearable technologies, enable the development of novel HMI interfaces, such as epidermal surface EMG interface [10], triboelectric-based control interfaces [11] and epidermal surface EMG [14]. None of these systems are superior to another. The key point is to use the communication channel so that the people still have the control capability.

Because depending on the level of the disease, it may be one of the residual capabilities that tetraplegia patients are able to use, head movements are also preferred signals in the design of HMIs [16, 17]. Head movement control is generally employed for multi-axis movement and speed control, as in wheelchairs. In these studies, Inertial Measurement Unit (IMU) sensors, which are capable of gathering three-axis movements, are the most commonly used sensors to detect head movements. However, some of these studies lack speed control and just enable direction control [18–21]. However, speed is a significant control parameter, especially for the control of machine interfaces related to motion. Sezer et. al. [22] proposed using x and y axis angles of head movements to control the direction and speed of a semi-autonomous electric wheelchair, respectively. Qamar et. al. [23], designed a driving aid system based on head tilts by using an accelerometer. The driving aid system determined the speed and steering signals by using pitch and roll movements, respectively. Gomes [24] also designed a head motion-based wheelchair interface by using pitch (rotation around y axis) to define a base speed, and roll (rotation around x axis) for the angular velocity. All these studies require the use of the two individual axes of head movements to determine the direction and speed of the output systems, at the same time. Although using two axes movements to determine speed and direction individually is theoretically acceptable, it is a difficult approach to use two-axis movements for speed and direction management, in practice. Furthermore, most the systems have a limitation to a wired connection between human and machine interfaces that restricts the control of the remote systems or applications.

On the other hand, obstacle avoidance is an essential function of numerous robotic systems [20]. The crucial task of an obstacle avoidance algorithm is to compute a safe steering path by considering unforeseen and dynamic obstacles [25]. In addition to its traditional methods, artificial intelligence and optimization techniques, such as fuzzy logic, neural networks, neuro fuzzy, genetic algorithm, ant colony optimization, particle swarm optimization, have been **used** in the development of obstacle avoidance algorithms recently [26]. Fuzzy Logic (FL) algorithm is a method that provides a great advantage in that it is very close to the human way of thinking. Since the FL approach does not need rigorous mathematical models, time-varying and non-linear systems whose mathematical model is not well defined are the most successful application areas. FL has been employed in the controlling and steering of complex industrial processes and automation systems as well as in robotic applications [27]. In the FL approach, preprocessing the signals and reducing the values spread over a wide area to a few membership functions enables applications to reach the results faster. Additionally, the closed-loop operation of the system provides advantages in terms of obtaining faster system response, reducing errors and increasing stability [28]. FL has been used in many studies to provide speed and direction control [7, 18, 22]. Fuzzy logic-based control algorithm, that is used in this study, is employed for obstacle avoidance and thus collision avoidance by determining the speed of the vehicle according to the obstacle distance and the speed information requested by the user.

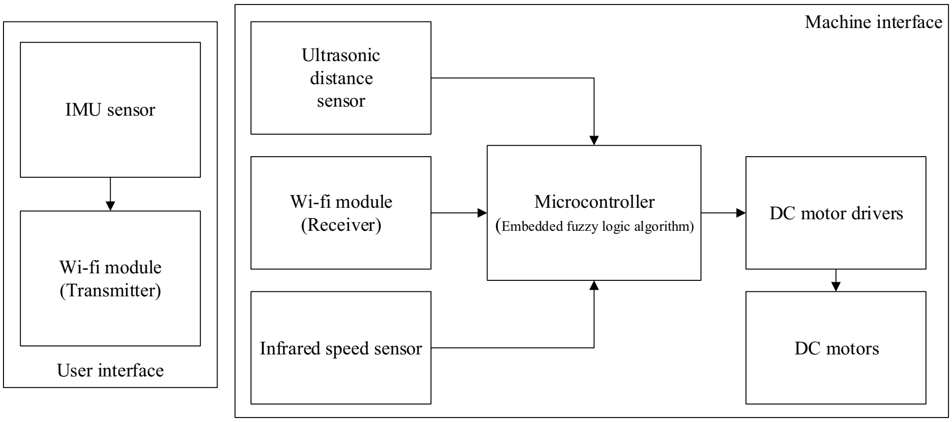
In this study, fuzzy-logic control of a head-movement-based HMI is proposed. The proposed approach allows the users to steer the desired movement direction and speed of the output device by using a unique axis movement. To determine the desired direction and acceleration, IMU sensor was employed. The movement axes and the Euler angles were associated with movement direction and speed, respectively. To provide a safe driving opportunity for the users, fuzzy-logic control algorithm, which determines driving speed based on obstacle distances on the driving route and desired speed information obtained from the IMU is used. The FL algorithm provides obstacle avoidance and collision avoidance by limiting the user's speed according to the distance of the obstacles toward the device. The wireless communication between human and machine units also enables to control remote devices or systems. As the machine interface of the proposed system, a prototype electric wheelchair, which consists of two DC motors in the front and a free-moving carrier wheel at the back, was used. The implemented system was tested on five subjects in a labyrinth in a closed environment. Results were evaluated in terms of task completion times and feedback from the subjects about their experience with the system.

The remainder of the paper is organized as follows: In section two, materials, methods and the algorithm which are employed in this study are introduced. In section three, the results of the study are evaluated in terms of performance tests and questionnaire results. Finally, in the last section, a general summary and planned future directions are presented.

2 Material and Method

In this study, we designed and implemented a head-movement-based HMI for wireless control of an electric wheelchair prototype. This section gives the design and implementation details of the head-movement-based HMI. The block diagram of the proposed HMI system is shown in Fig. 1.

Fig. 1 Block diagram of the proposed system



The system consists of two main modules: user module (on human) and the control-output module (on machine). The user module, which is established on a helmet frame, is placed on the user's head. Users determine the direction and speed that they want to steer the machine interface/output device by moving their heads. The user module includes IMU sensor and a wi-fi transmitter module. By using the embedded accelerometer and gyroscope, the IMU sensor determines the pitch and roll axis angles based on the user's head movements. The communication between the user module and the output module is wireless that enables the users to control remote output devices. The transmitter wi-fi module transfers the axis angles to the machine interface. The receiver wi-fi module also transfers the axis angles, which include the reference speed and directions, to the microcontroller. Ultrasonic distance sensors measure the distance to the obstacles encountered on the driving route and transmit the distance to the microcontroller. The infrared speed sensors determine the instantaneous speed of the motors. In this way, the FL algorithm embedded in the microcontroller determines the speed of the output device by considering the error value between the reference speed, which is demanded by the user, and the instantaneous speed and the obstacle distance measured by the distance sensors. In this way, in case an obstacle is encountered, the speed of the device would be limited and a possible collision will be prevented.

2.1 Hardware Design

The circuit diagrams of the user module and the control-output modules are shown in Fig. 2. The user interface module contains an IMU sensor (MPU-6050) to collect head movements and a wi-fi transmitter module (ESP 8266) for wireless transmission of data to the machine interface module. The MPU-6050 is an integrated 6-DOF motion tracking device that combines a 3-axis gyroscope and a 3-axis accelerometer. It uses I2C serial protocol for communication with the wi-fi module. The inertial sensor generates values based on the user's head movements and scales/translates them to speed and direction data, which are used to control the machine interface/output device. The communication between the user module and the output module is wireless which enables the users to control remote output devices. To this end, ESP-8266, which is a programmable wi-fi module that communicates in the 2.4 GHz communication band, is employed. The user module, which is placed on a helmet frame, is shown in Fig. 3a.

An electric wheelchair prototype with two dc motors at the front and a drunk wheel at the back was employed as the output device at the machine interface. The prototype of the designed mobile device is shown in Fig. 3b. A machine interface was placed on the prototype device. The machine interface consists of a wi-fi receiver module (ESP 8266), a microcontroller (Arduino Mega 2560), infrared speed sensors (LM-393), ultrasonic distance sensors (HC-SR04), a two-channel DC motor driver (L298N) and DC motors. The wi-fi receiver module is connected to the microcontroller through UART. The receiver transmits the 3 axis angles to the microcontroller. Three distance sensors were placed on the right, left and front of the device to determine the obstacles between 0 and 150 cm in the steering direction. The infrared speed sensors determine the instantaneous speed of the DC motors. The microcontroller is responsible for steering the machine interface by determining both the speed and direction. The FL control algorithm embedded in microcontroller determines the speed of the machine interface by considering the reference speed data collected from inertial sensors, the instantaneous speed of the DC motors, and the distance to the obstacles. The determined speed value by the FL system on the microcontroller, is transmitted to the DC motors through the pwm driver.

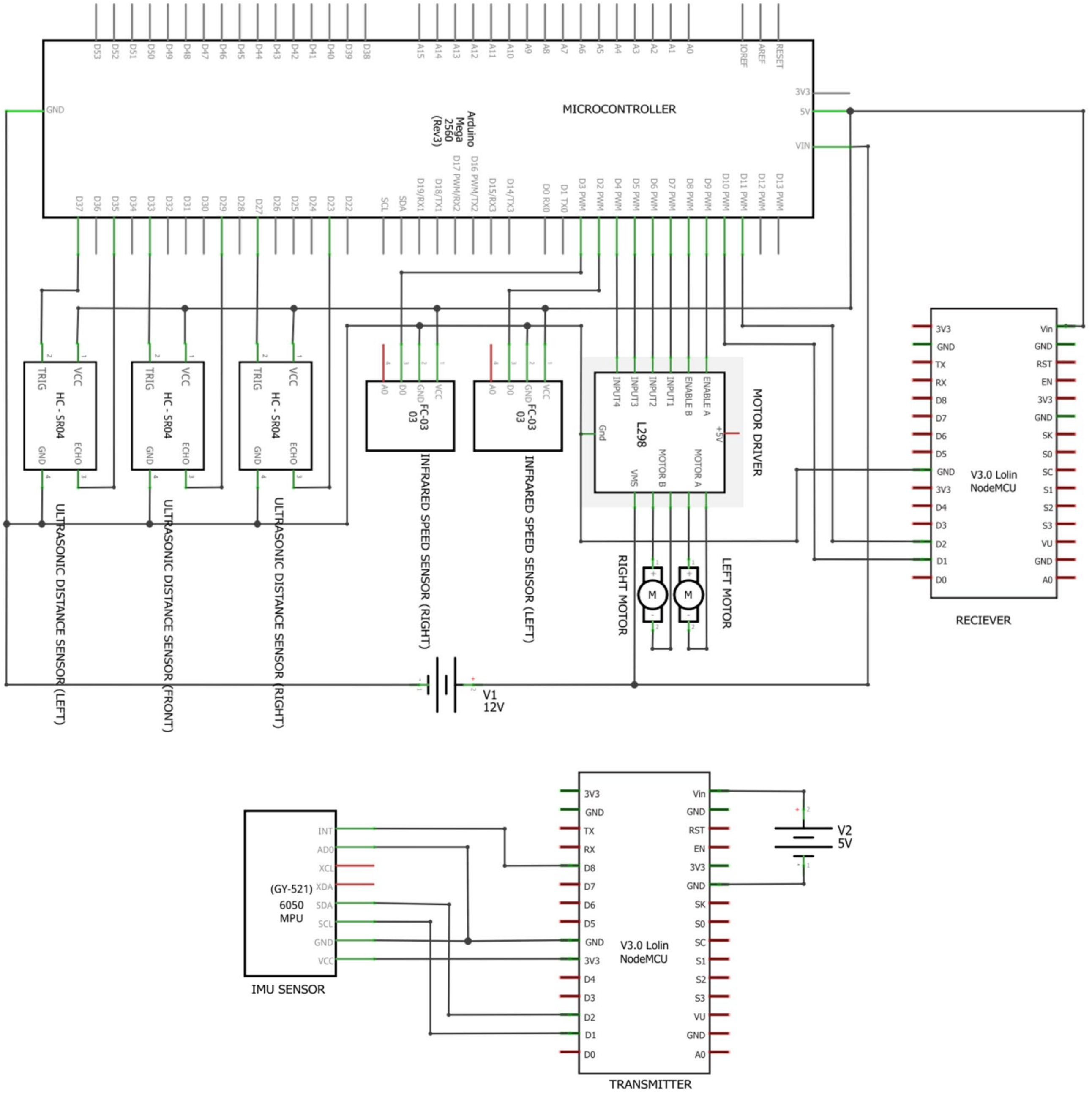
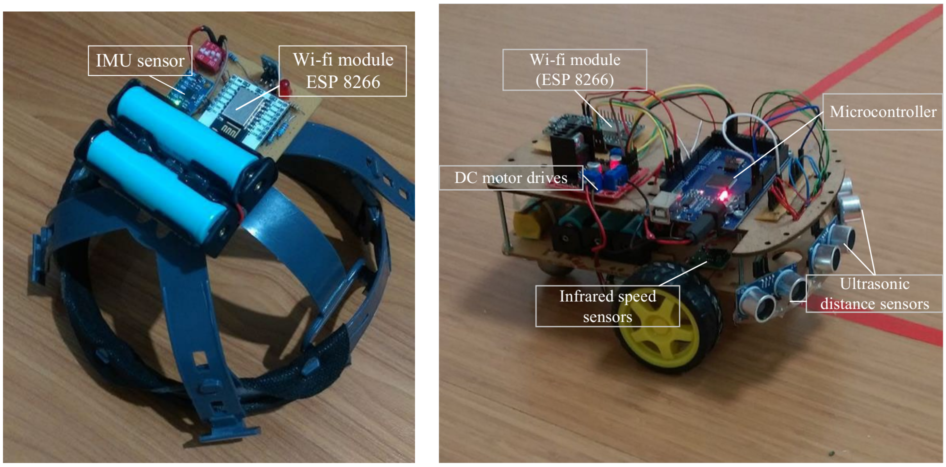


Fig. 2 Circuit diagram of the system

2.2 Head Movement Based Control Algorithm

The accelerometer is a sensor used to measure the linear gravitational acceleration of an object on three axes. The gyroscope, on the other hand, is a sensor that uses the momentum change of an object to measure the orientation angle of the object from the angular velocity values in three axes. The IMU sensor, which houses the accelerometer and gyroscope sensors, processes the data of these two sensors and ensures the correct positioning of an object on three axes. In this study, head movements were used to control the direction and speed of a device. The inertial sensor on the user interface measures the head inclination angles. The steering direction of the machine interface is obtained through the rotation of the head movement while the steering speed is determined using the tilt angle of the head on the related axis. The inertial sensor is capable of decoding movements at the three axes: pitch, roll and yaw. The pitch, that is rotation around y axis, corresponds to the rotational movement of the head toward

Fig. 3 The designed system (**a**) The user module placed on a helmet frame (**b**) The control-output module placed on the prototype of the designed mobile device



(a) (b)

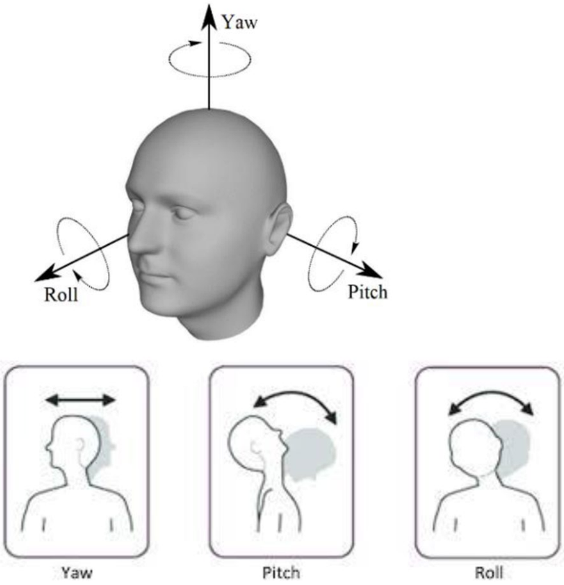


Fig. 4 Yaw, Pitch and Roll movement axes [29, 30]

and against the chest. The roll, that is rotation around x axis, corresponds to the rotational movement of the head toward the shoulders. The yaw, that is rotating around the z-axis, corresponds to the rotational movement of the head around the chest, such as in looking left and right. Pitch, roll and yaw movement axes are shown in Fig. 4. In this study, pitch and roll were associated with forward–backward and right-left movements, respectively. In the other words, while the user's head movement toward the chest along the pitch axis moves the device forward, the movement of the user's head toward the right and left shoulder on the roll axis directs the device to the right and left, respectively. Besides, the proposed system also allows a two-axis motion. In the other words, crosshead movement toward the chest on the pitch axis and toward the right or left shoulder on the roll axis enables the device to move forward-right or forward-left.

2.2.1 Direction Detection

Each sample acquired from the IMU sensor contains triple axis angles,$\beta(\psi, \varphi, \theta)$ simultaneously. The Euler angles of an IMU sensor that refer to pitch, roll and yaw are defined by Eq. 1.

$$\begin{aligned} &\text{Pitch} \rightarrow \psi : \text{Rotation around X} \in \left[-90...90^{\circ}\right] \\ &\text{Roll} \rightarrow \varphi : \text{Rotation around Y} \in \left[-180^{\circ}180^{\circ}\right] \\ &\text{Yaw} \rightarrow \theta : \text{Rotation around Z} \in \left[-180^{\circ}180^{\circ}\right] \end{aligned} \tag{1}$$

The studies in the literature use the two individual axes of head movements at the same time, to determine the direction and speed of the output systems. Although using two axes movements to determine speed and direction individually is theoretically acceptable, it is a difficult approach to use two-axis movements for speed and direction management, in practice. Therefore, we aimed to determine the speed and direction using the head movement on a single axis. The head movement axes and the Euler angles were associated with movement direction and speed of the output device, respectively. For example, a head movement in the pitch axis means moving the output device forward, while the value of the pitch angle is used to determine the movement speed requested by the user. Similarly, a head movement in the roll axis moves the output device right/left, while the value of the roll angle is used to determine the movement speed requested by the user. As stated in Eq. 3, positive values of the roll axis indicate right-sided movements and negative values indicate left-sided movements.

To prevent errors due to involuntary head movements and to provide comfortable usage to the users, a Confidence Zone (CZ) was defined. The CZs for pitch and roll are defined in Eq. 2. The CZs have been determined as 15°, experimentally. According to Eq. 2, only the pitch and roll angles $\beta\left(\psi_{\mathrm{CZ}}, \varphi_{\mathrm{CZ}}\right)$. within the CZs were considered to create control commands. The direction assignments are defined in Eq. 3.

$$\begin{aligned} \psi_{\mathrm{CZ}} &\in \left[\psi_{\min} \dots -15^{\circ}\right] \cup \left[15^{\circ} \dots \psi_{\max}\right] \\ \varphi_{\mathrm{CZ}} &\in \left[\varphi_{\min} \dots -15^{\circ}\right] \cup \left[15^{\circ} \dots \varphi_{\max}\right] \end{aligned} \tag{2}$$

$$\begin{aligned} \psi_{\mathrm{CZ}} &\in \left[15^{\circ} \dots \psi_{\max}\right]\text{Forward} \\ \varphi_{\mathrm{CZ}} &\in \left[15^{\circ} \dots \varphi_{\max}\right]\text{Right} \\ \varphi_{\mathrm{CZ}} &\in \left[\varphi_{\min} \dots -15^{\circ}\right]\text{Left} \\ \\ \psi_{\mathrm{CZ}} &\in \left[15^{\circ} \dots \psi_{\max}\right] \&\& \varphi_{\mathrm{CZ}} \in \left[15^{\circ} \dots \varphi_{\max}\right]\text{Forward} - \text{right} \\ \psi_{\mathrm{CZ}} &\in \left[15^{\circ} \dots \psi_{max}\right] \&\& \varphi_{\mathrm{CZ}} \in \left[\varphi_{\min} \dots -15^{\circ}\right]\ \text{Forward} - \text{left} \end{aligned} \tag{3}$$

To ensure the driving safety of the user, the maximum control angles have been determined so that the users' field of view is not blocked and that they can follow the driving area. In this study, the maximum limit values of $\varphi_{\max}$, $\varphi_{\min}$ and $\psi_{\max}$ angles were experimentally selected as ± 45 degrees. However, the maximum limit values can be determined individually, by considering the patient's movement capabilities.

2.2.2 Speed Detection

To determine the reference speed demanded by the users, the angle value on the motion axis is used. For angle-velocity conversion, the angle values in the CZ range are normalized and are scaled between 0 and 100. The angle-velocity conversion equation is given in Eq. 4, where φ_{CZ} and φ_{CZR} are the demanded and the normalized speed data. $\varphi_{\max} and \varphi_{\min}$ angles can be selected by considering the mobility capabilities of the user.

$$\varphi_{CZR} = \frac{\left|\varphi_{CZ}\right| - 15^{\circ}}{\left|\varphi_{\max}\right| - 15^{\circ}} \times 100 \tag{4}$$

2.2.3 Microcontroller

In this study, Arduino Mega 2560, which is based on the ATmega2560, is employed as the microcontroller. The number of analog inputs (16 analog inputs each of which provides 10 bits of resolution), communication facilities, such as UART, I2C, and SPI communication protocols, and memory capacities have been the reason to be preferred in this study. 256 KB of Flash Memory, 8 KB of SRAM, and 4kB of EEPROM capacity has been an important requirement to be able to program the embedded FL algorithm. The flowchart of the control algorithm of the program running on the microprocessor is shown in Fig. 5. According to the flowchart, the IMU sensor on the user interface detects the pitch and roll axis angles; the embedded program on the wi-fi transmitter module translates them to the direction and speed data and transmits the data to the wi-fi transmitter module on the machine interface.

At the first stage of the algorithm, the steering direction determination stage runs. The direction is determined as right, left, forward, forward-left and forward-right, according to the head movement on the pitch and roll axes, as explained in Sect. 2.2. The starting position is the state that there is no head movement on any axes, and in this case, the machine interface is stationary. At the second stage of the algorithm, the FL algorithm runs to determine the speed of the device. The proposed semi-autonomous speed control is controlled by the FL algorithm embedded in the microcontroller. The algorithm uses two inputs for the control strategy: the error value between the reference speed requested by the user and the instantaneous speed of the machine interface, and the distance to the obstacles that it encountered in the direction of its route. The wi-fi receiver module acquires the direction and speed data, which are demanded by the users; and transmits them to the microcontroller through the UART serial communication protocol. The microcontroller assigns the speed data as the reference values for the FL algorithm. On the other hand, the instantaneous speed, which represents the actual linear velocity value of the machine interface, is determined at the same frequency as the reference value. The microcontroller also receives distance to the obstacles that it encounters in the direction of its route through ultrasonic distance sensors. The microcontroller determines the error value between the reference and the instantaneous values and transmits the error value to the FL algorithm. Two individual FL algorithms, which are activated respectively, are employed for right and left motor control. The speed values determined by the FL algorithm, are transmitted to the right and left DC motors through PWM motor drivers. To run FL commands, < fis header.h > library has been added to the program.

2.3 Fuzzy Logic Control Design

The FL control algorithm determines the velocity of the output device according to the data from the distance sensors that measure the distance of the obstacles in the direction of the device and the error value calculated from the difference between the reference speed value received from the user and the instantaneous speed values measured by the infrared speed sensors, as shown in Fig. 6. Two FL control algorithms have been created to control the two motors individually. The control algorithm consists of two inputs and an output.

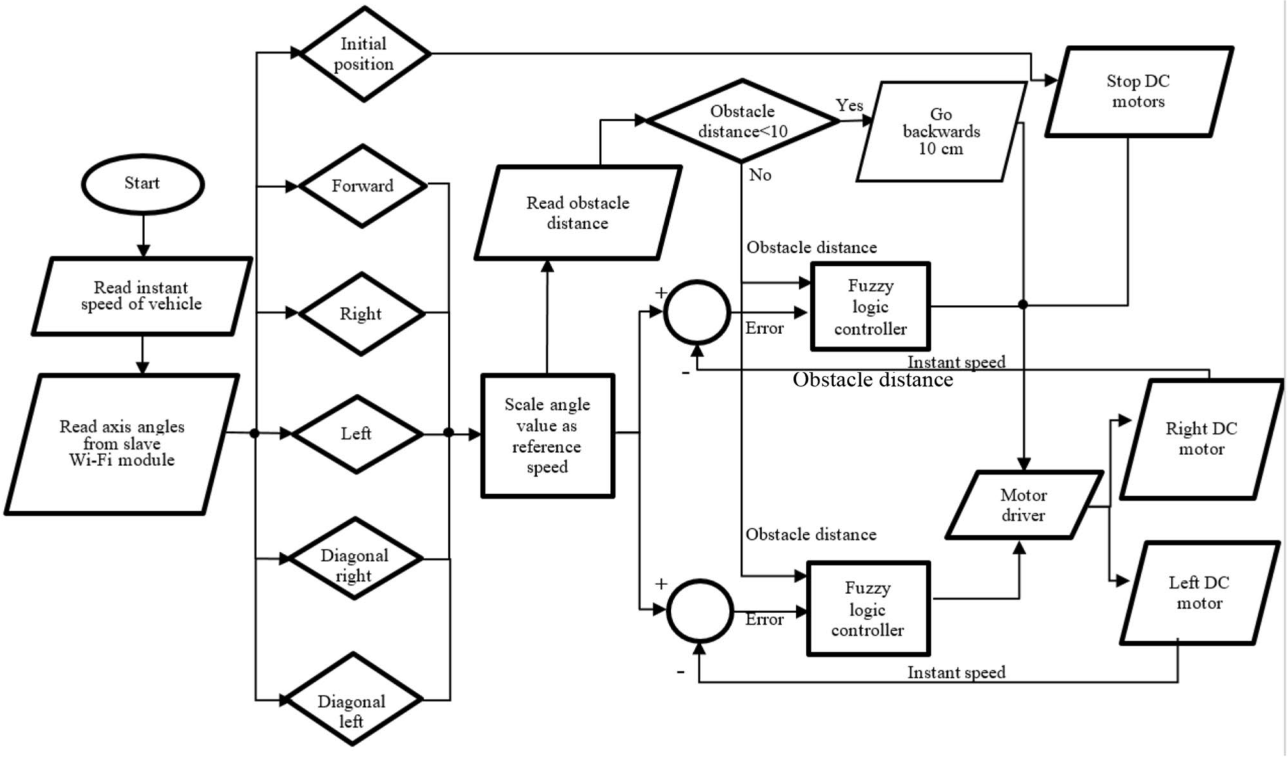


Fig. 5 Flowchat of the control algorithm

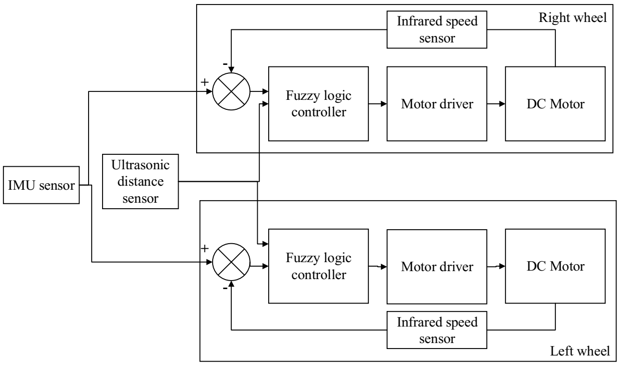


Fig. 6 Fuzzy logic controller block diagram

The first stage of an FL algorithm is primarily fuzzing the input data. In the fuzzing process, fuzzy clusters are created between the minimum and maximum values of the input data. One of the inputs of the proposed system, the error in speed, consists of five clusters among [− 75 75]. Triangle-type membership functions are employed as the cluster type. The membership functions of the error in speed variable are shown in Fig. 7a. The second input variable, obstacle distance, consists of three triangular-type clusters between the [0 150] values shown in Fig. 7b (ND: Near Distance, MD: Middle Distance, FD: Far Distance). Speed, which is the output variable, consists of 5 triangle type clusters among [55 75] as shown in Fig. 7c (NB: Negative Big, NS: Negative Small, Z: Zero, PS: Positive Small, PB: Positive Big). The algorithm infers according to the input variables within the framework of the rule base.

The FL control algorithm is a safe speed planner algorithm. The algorithm allows the users to control the speed of the machine interface depending on the user's demand for speed and the distance of the obstacles. The algorithm determines the command to slow down or speed up the machine interface according to the error value. In the case of positive error values, the algorithm provides the machine interface to be accelerated. In contrast, in the case of negative error values, the algorithm ensures to slow down the machine interface. As the error in speed decreases in negative or positive values and the distance of the obstacle increases, the speed of the machine interface increases. Besides, as the error in speed increases in negative or positive values and the distance of the obstacle decreases, the speed of the machine interface decreases. In the other words, the speed of the machine interface is directly proportional to the distance of the obstacle in the moving direction while it is inversely proportional to the magnitude of the error in velocity. The rule table summarizing this situation is given in Table 1. The output of the fuzzy inference mechanism is also a fuzzy set. Therefore,

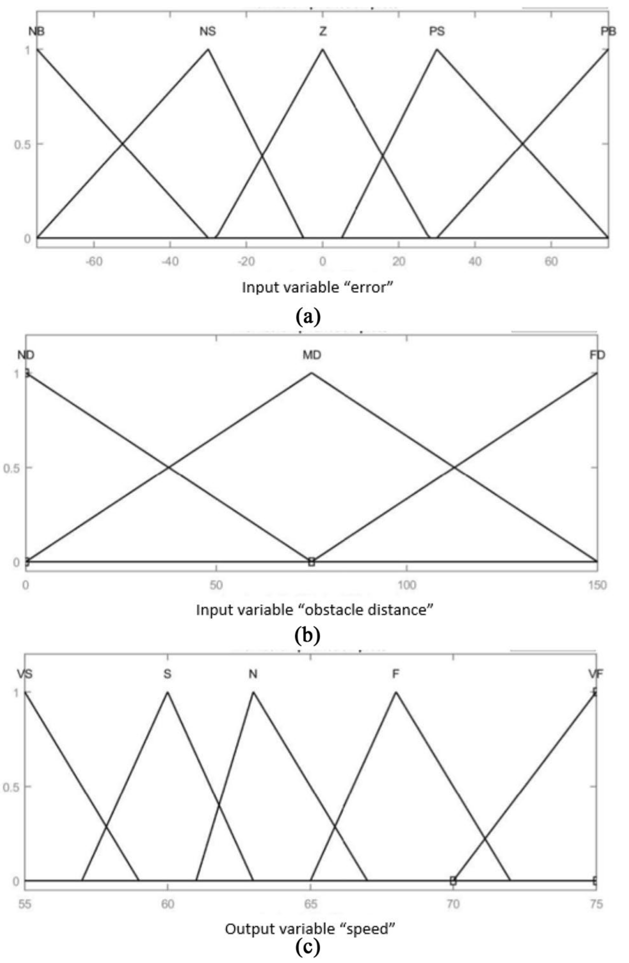


Fig. 7 Membership functions (**a**) Input membership-1: Error in speed (**b**) Input membership-2: Obstacle distance (**c**) Output membership: Speed

Table 1 Fuzzy logic controller rule base

Error in speed/ Obstacles distance	NB	NS	Z	PS	PB
ND	VS	S	S	S	VS
MD	S	N	F	N	S
FD	N	F	VF	F	N

NB Negative Big, *NS* Negative Small, *Z* Zero, *PS* Positive Small, *PB* Positive Big, *ND* Near Distance, *MD* Middle Distance, *FD* Far Distance, *VS* Very Slow, *S* Slow, *N* Normal, *F* Fast, *VF* Very Fast

the defuzzification stage is used for the conversion of fuzzy results into numerical results. For defuzzification, in the other words, for the conversion of the fuzzy results into numerical results, min–max inference method and Center of Gravity (CoG) approach were used. CoG is calculated using Eq. 5.

$$z = \frac{\int \mu_c(z).zdz}{\int \mu_c(z).dz} \tag{5}$$

The characteristic of the output variable i.e., the speed of the output device, produced by the FL algorithm within the framework of the rule base and the membership functions, is seen on the fuzzy surface given in Fig. 8. As can be seen from the fuzzy surface, when the error approaches zero, the output speed increases; while the error increases in the negative or positive direction, the output speed decreases. On the other hand, in terms of obstacle distance, the increase in the obstacle distance enables the speed of the machine interface to increase, while the decrease in it decreases the speed of the machine interface.

3 Results and Discussion

In this study, fuzzy-logic algorithm is proposed for semi-autonomous control of a head-movement-based HMI system. The proposed fuzzy-logic-based semi-autonomous control prioritizes user safety by determining the speed of the machine interface, considering the obstacle distances and the demanded speed by the users. To test the performance of the designed system, we created a labyrinth in a closed environment. The route of the labyrinth includes right and left turn maneuvers, as well as obstacles in the driving route.

The proposed system was tested by five voluntarily subjects. All the subjects are able to body and naïve to use such a system. Therefore, all the subjects were informed about the operation of the system and were allowed to experience driving before the experiments independent of a pre-defined specific route. During the experiments, subjects were asked to follow and complete a given route three times. The total length of the route to be completed is 18 m. The duration to complete the given task was measured and saved. To observe

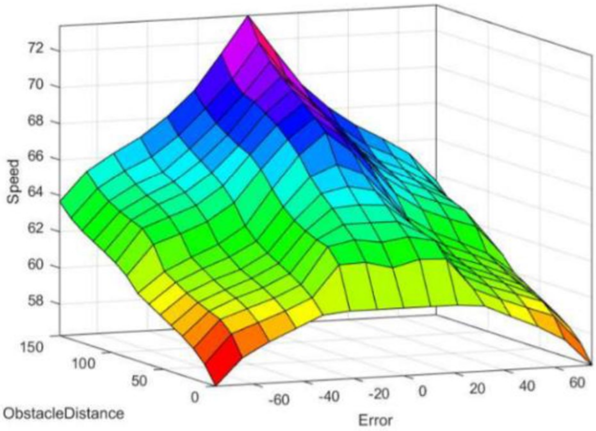
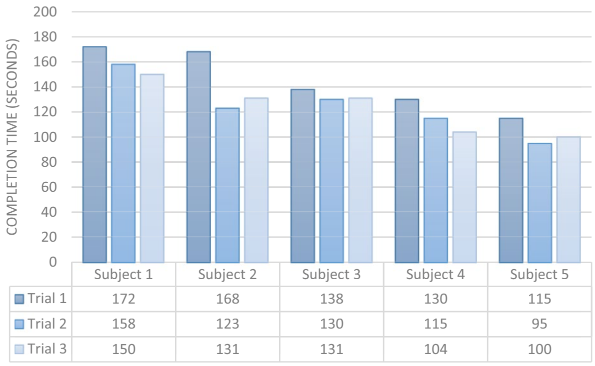


Fig. 8 Fuzzy surface of the fuzzy logic controller



	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Trial 1	172	168	138	130	115
Trial 2	158	123	130	115	95
Trial 3	150	131	131	104	100

Fig. 9 Time needed to complete the given tasks at each repetition for each subject

Table 2 Questions of the questionnaire

Question number	Question
Q1	It is easy to use the system with head movements
Q2	It is easy to control the direction of the mobile device
Q3	It is easy to control the speed of the mobile device
Q4	The direction and speed of the mobile device are consistent with my head movements
Q5	Response time of the system
Q6	It is an ergonomic system

the development of using skills of the subjects, all the subjects attended three experiment sessions. The performance changes of the subjects in 3 sessions are shown in Fig. 9. According to Fig. 9, it can be said that as the experience of the users increased, they completed the given route in a shorter time and started to control the direction and speed better. In other words, it can be said that users may need a familiarization process to use such a system.

At the end of the experiments, to get feedback on their experience, a survey was applied to the subjects. The subjects were asked to rate the questions in Table 2 on a rating scale of 1 to 5, where a rating of one as absolutely disagree and five as absolutely agree. The questionnaire results are given in Table 3. According to the results, the users find the head movement-based system easy to use. However, they think that direction control can be done more easily than speed control. They also think that the response time and ergonomics of the system can also be improved.

The experimental results of the study and feedback from the users show that it is easy to control the direction of the device while it is more difficult to control speed than direction. However, considering the route completion duration, it is clearly seen that speed control capability improves with increasing repetitions of use. Furthermore, task completion times shortened in each session indicate that the ability to use the head movements to control a human–machine interface may improve over time. Nevertheless, a noteworthy mentioning limitation of this work is that although this is designed as a general solution for physically (upper-lower limb) impaired people, depending on the source and severity of their disabilities, it could not be suitable for some people who have no capabilities to control head position.

In the proposed system, during the experiments, the user controlled the mobile output unit on a flat surface by sitting at a fixed point. However, in case users sit on a moving wheelchair, some issues should be considered. One of the issues is that the angle measured by the IMU will be affected by linear acceleration, that is, the acceleration of the user in motion. In order to calculate axis angles, the IMU sensor uses linear acceleration of the accelerometer and angular velocity of the gyroscope. Therefore, for a user sitting on the running wheelchair, motion and the acceleration of the wheelchair would affect the sensing of the accelerometer to the pure head movements. To overcome these issues, a system can be created by setting up two coordinate systems or by setting up a closed-loop system that will use the angle information as feedback. The other issue is cases that the user is steering or starting from the position on a ramp. If the users were in wheelchair on the ramp, calibration would be required for the system to work properly. The calibration can be done by establishing a coordinate system of both the user's head position and the wheelchair's position. In this case, to create two coordinate systems, two IMU sensors are required, one is in the user's head and the other one is in the wheelchair. Calibration can be done using the axis angles of the head and wheelchair positions obtained from the two created coordinate systems. In this case, the reference velocity

Table 3 Questionnaire results

Subject	Q1	Q2	Q3	Q4	Q5	Q6
1	3	3	2	2	4	3
2	4	5	3	3	4	3
3	3	4	3	4	4	4
4	4	5	4	4	4	4
5	4	5	5	3	4	4
Average	3.6	4.4	3.4	3.2	4	3.6

that the user wants to steer the output device can be calibrated using the angle difference between the co-axes of the two coordinate systems.

4 Conclusions

In this study, head movement-based semi-autonomous HMI was designed to enable people with disabilities to control a device wirelessly using head movements. The most important advantage of the system is that both speed and direction demands of the user can be detected with a single head movement. According to the survey results, users think that the system is easy to use. It is thought that this user-friendly feature will improve the usability of the system by the target patient groups. The semi-autonomous control capability is provided by the fuzzy-logic algorithm which considers the obstacle distances and the demanded speed by the users. The semi-autonomous control provides driving safety capabilities. Driving safety limits the speed demanded by the users in case of decreasing obstacle distance and allows the mobile device to avoid the obstacle in its steering direction. The most important advantage of fuzzy logic controlled speed control is that it can provide safer driving with cluster intervals that will be determined individually according to the residual muscle control abilities of the user, by the doctor and specialist. The proposed human–machine interface can be adapted to the output devices such as electric wheelchair, robot, robot arm, and the control capability of patients can be improved.

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Data availability Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study. The algorithm and program codes of the current study are available from the corresponding author on reasonable request.

Conflict of interests The authors have no conflicts of interest or competing interests to declare.

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