Gyro-Accelerometer based Control of an Intelligent Wheelchair

Rafia Hassani, Mohamed Boumehraz✉, Maroua Hamzi, Zineb Habba

Laboratoire de Modélisation des Systèmes Energétiques (LMSE), Université de Biskra, B.P. 145 R.P. 07000, Biskra, Algeria

Received 19 December 2017
Published online: 9 June2018

Keywords
Electric wheelchair
Head gesture
MEMS sensors
Kalman filter
Ultrasonic sensor

Abstract: This paper presents a free-hand interface to control an electric wheelchair using the head gesture for people with severe disabilities i.e. multiple sclerosis, quadriplegic patients and old age people. The patient head acceleration and rotation rate are used to control the intelligent wheelchair. The patient head gesture is detected using accelerometer and gyroscope sensors embedded on a single board MPU6050. The MEMS sensors outputs are combined using Kalman filter as sensor fusion to build a high accurate orientation sensor. The system uses an Arduino mega as microcontroller to perform data processing, sensor fusion and joystick emulation to control the intelligent wheelchair and HC-SR04 ultrasonic sensors to provide safe navigation.The wheelchair can be controlled using two modes. In the first mode, the wheelchair is controlled by the usual joystick. In the second mode, the patient uses his head motion to control the wheelchair. The principal advantage of the proposed approach is that the switching between the two control modes is soft, straightforward and transparent to the user.

1. Introduction

Sever disabled and elderly people cannot control an electric wheelchair using the conventional joystick, and a wide range of support devices and care equipment have been developed to improve their quality of life. The scientific progress in artificial intelligence, robotics and electronics has given new issues and opportunities to develop promising solutions. In particular, intelligent wheelchairs have received considerable attention as mobility aids. Intelligent wheelchairs are electric powered wheelchairs with embedded computer and sensors so that they may have environment perception ability and certain intelligence (Simpson 2005, Reis 2015, Leaman 2017).

Up to now, instead of the traditional joystick, various alternative control methods and techniques have been developed to make elderly patients' life easier. Voice recognition and guidance (Peixoto 2013, Pirs 2002, Skraba 2015), vision based head gesture control (Hassani 2015, Ju 2009, Chen 2003, Jia 2007), eye tracking techniques [9-10], bio-signal(EEG, EOG or EMG) based control (Barea 2002, Lv 2018), tongue movement based control (Huo 2009, Nam 2012) ,brain based control using brain computer interface (BCI) (Eugene 2018, Abiyev 2016, Pinheiro 2018, Rebsamen 2007), and MEMS(Micro-Electro-Mechanical Systems) based control (Pajkannovic 2013) are examples of alternative solutions. Voice based wheelchair control is very efficient and accurate. However, the voice recognition rate may decrease when the surrounding environment is noisy and sometimes, people do not like to speak loud when it is quiet. Vision based head gesture control is particularity useful for severely-handicapped people who have spinal cord injuring quadriplegia and cannot use their hands to control the wheelchair, but the problem with this technique is the sensibility to lightness and the need to face the camera continuously which can be tedious.. For eyes controlled wheelchair, the eye tacking may force and affect the user vision causing tiredness and dizziness. EEG, EOG or EMG signal based control needs skills and a mental burden is added on the patient by using electrodes to measure these signals, and the sensors are quite expensive. In the tongue movement based control, the movement data are obtained from a magnetic tracer on the tongue. This is a little invasive for long-term usage since the user should receive a tongue piercing embedded with the magnetic tracer. In brain-controlled wheelchair, the patient could easily command the wheelchair by his though using a brain computer interface (BCI). Unfortunately, the accuracy of this approach is still low, and some problems may arise while trying to use a BCI. Brain activity varies greatly from individual to individual, and a person's brain activity changes substantially over time (Simpson, 2005). Recently, many researchers proposed the use of the MEMS sensor as a controller for intelligent rehabilitation applications. Accelerometer sensors are able to measure the applied acceleration on its axis. MEMS based accelerometer is very sensitive to environmental noise. Therefore, this sensor does not provide reliable orientation measurements. Gyroscope is another sensor used to measure angular rate change on its axis. This sensor is capable of measuring three axis orientation angle changes. However, MEMS based gyroscope does not provide reliable orientation measurement because of bias drift problem. Thus, fusion of accelerometer and gyroscope allow the minimization of noise and bias drift errors.

In this paper, a microcontroller system that enables the control of a standard electric wheelchair by head motion is developed.The

✉ Corresponding author. E-mail address: medboumehraz@netcourrier.com

system consists of an MPU6050 IMU board (placed on patient's head) as orientation sensor, ultrasonic sensors for obstacle detection and an Arduino Mega as main board. The system uses the head movement and orientation to control the intelligent wheelchair. The user's head angles around the X and Y axis are interpreted as a wheelchair movement commands in the forward, backward, left and right directions. The head movement around Z-axis is not used to give the user the ability of moving his head around without affecting the control of the system. Euler head angles pitch and roll are used to estimate the head orientation. The Euler angles are picked up using two combined MEMS sensors; accelerometer and gyroscope. The two sensors outputs are combined together using Kalman filter as sensor fusion to build a high accurate orientation sensor. The rest of the paper is organized as follows.

Section II describes the system architecture. Main system components are presented in Section III. In section IV, the head gesture system operating is described in more details. Experimental results are given in Section V to show the feasibility of the proposed system. Finally, Section VI concludes the paper with some discussion and future work.

2. System architecture

The system block diagram is shown in figure 1. The intelligent wheelchair components are a standard electric wheelchair, a head orientation module for head gesture estimation, a set of ultrasonic sensors for obstacle detection, a low pass filter for joystick voltages generation and an Arduino Mega based main board for data processing. The wheelchair can be controlled using two modes. (i) In the first mode, the wheelchair is controlled by the usual joystick, (ii) In the second mode, the patient uses his head motion to control the wheelchair. The principal advantage of the system is that the switching between the two control modes is soft, straightforward and transparent to the user. The switching is done by software, if the joystick is active, the signals generated by the joystick are delivered via the micro-controller to the motion control system and the head motion control is inhibited. If the joystick is inactive,

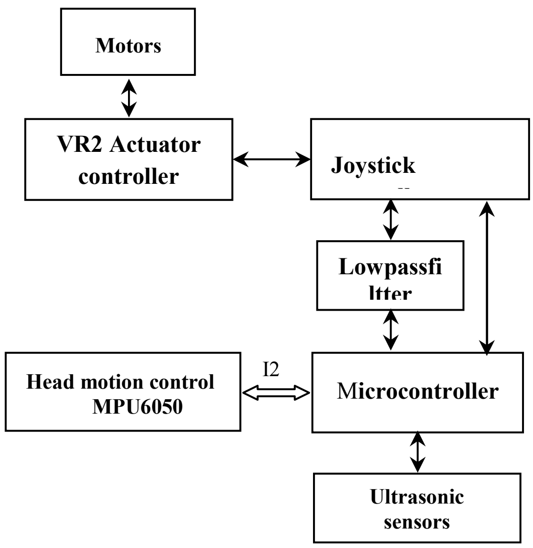


Fig. 1. Bloc diagram of the wheelchair control system.

the commands delivered by the head motion mode are used to control the wheelchair, while keeping the priority to manual mode. The microcontroller and the filtering stage act like a virtual joystick controlled by head gesture.

The proposed system allows the user to give only five different commands: "forward", "backward", "left", "right" and "stop".

3. System components

As mentioned in figure 1, the system is designed based on the following components:

3.1 MPU6050 LMU board

The MPU-6050, shown in figure 2, is the world's first motion tracking device designed for the low power, low cost, and high-performance requirements of smart phones, tablets and wearable sensors.

The MPU-6050 device comprises a combination of a 3-axis gyroscope and a 3-axis accelerometer on the same silicon die, together with an onboard Digital Motion Processor (DMP) for motion fusion and a peripheral controller.

The MPU 6050 main features are (InvenSense 2013):

- Programmable accelerometer full-scale range: ±2g, ±4g, ±8g, and ±16g,
- Programmable gyroscope full-scale range: ±250 °/s, ±4g, ±8g, and ±16g. ±250, ±500, ±1000, and ±2000 °/sec,
- Programmable output data rate: max: 1 kHz,
- I2C and SPI communication interface,
- Internal Digital Motion Processing unit.

In this work, the MPU6050 is used to measure the wheelchair patient's head gesture and send data to the microcontroller for processing. Estimated head gesture, using geometry rules and sensor fusion, is used to control the wheelchair movement.

3.2 The joystick

The joystick, JC 2000 contactless joystick from Curtis-Wright, is a two-axis potentiometer with two outputs per axis as shown in figure 3 (Curtis-Wright, 2007).

The voltages generated by the axis movement are used to control the wheelchair movement via VR2 controller. If the joystick moves along X axis then the wheelchair turns right or left, if the

Fig. 2. MPU6050 IMU board.

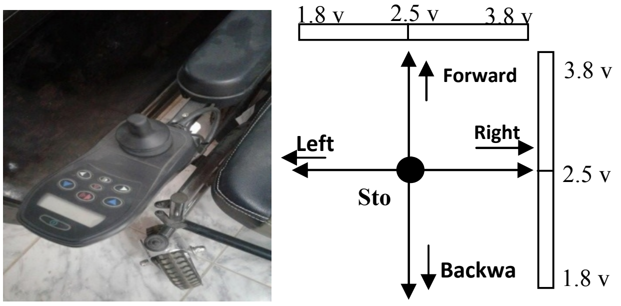


Fig. 3. The Joystick and the generated voltage from joystick axis.

joystick moves along Y axis then the wheelchair goes forward or backward (i.e. the generated voltage is 3.8 v for “forward” and “right” direction , 1.8 v for “backward and left direction and 2.5v for center position “stop” action).

3.3Arduino Mega 2560

The Arduino Mega 2560 (fig. 4) is a microcontroller board based on the AT mega 2560 (Store.arduino.cc, 2018). It has 54 digital input/ output pins (14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button.

In addition to obstacle detection, the microcontroller acts like a virtual joystick. It delivers to the wheelchair the same signals coming from X and Y-axis of joystick if the joystick is active, and emulates joystick signals according to head motion control, if the joystick is inactive and the control by head gesture is used.

3.4 Ultrasonic sensor

In order to maintain a safer distance from obstacles, a set of ultrasonic sensors modules are placed around the wheelchair. The ultrasonic sensor used here is HC-SR04 shown in figure 5.

This sensor is compact, Arduino compatible and provides precise and stable non-contact distance measurement from about 2 cm to 400 cm with very high accuracy. The module includes ultrasonic transmitter, receiver and control circuit.

Fig. 4. Arduino Mega 2560 board.

Fig. 5. HC-SR04 sensor.

Three modules are placed in each side of the wheelchair; front, right, left and back, in such a way that the area between 2-3 m in each side is covered. The Arduino receives distance information from the sensors. If there is an obstacle in the movement direction then the control system will stop the wheelchair before it hits obstacles and disable any commands in this direction.

4. Head gesture control system

The sensor board MPU6050 placed horizontally on the front of a cap, worn by the user, detects head acceleration and rotation rate as raw values. The main board estimated the corresponding head angle using geometrical calculation and sensor fusion with Kalman filter. The estimated head angles are compared with angle thresholds to select the direction of the wheelchair (fig. 6).

4.1 Head gesture estimation

The roll and pitch angles of the user's head are used to control the wheelchair. The comparison of their values with prefixed thresholds is used to generate joystick-like voltages. Therefore, it is important that the estimated head gesture angles must be as accurate as possible

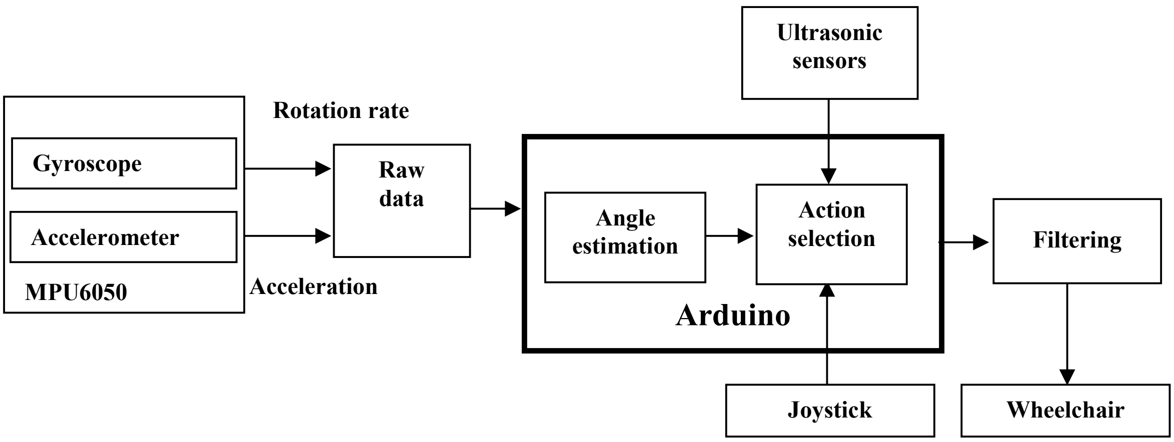


Fig. 6. Wheelchair control flow chart.

The sensor provides some raw value but its output is relatively noisy. MEMS gyroscope uses the Coriolis acceleration effect on a vibrating mass to detect angular rotation. The gyroscope measures the angular velocity, which is linear to rate of rotation. It responds quickly and accurately, but it has a tendency to drift over time because it only senses changes and has no fixed frame of reference. Therefore, a platform system, using a gyroscope only, could not work in case of high precision requirements. The output of the gyroscope is the angular rate of rotation about the three axes (figure 7). Integrating the angular rotation rates over a time period yields angular rotation increments. Therefore, after summing all the increments, we can obtain the orientation estimation relative to the starting orientation. But if there was a small error during theIntegration, the small error is accumulated over time and provokes drift in the resulting orientation estimation.

On the other hand, while the gyroscope causes drift when orientation is estimated, the accelerometer is not affected. Combining the outputs of the two sensors can provide better estimation of orientation. The accelerometer measures linear acceleration based on the acceleration of gravity, it is more accurate in static calculation when the system is closer to its fixed reference point. The problem of accelerometer is that it tends to distort acceleration due to external forces as gravitational forces in motion, which accumulates as noise in the system and erroneous spikes in resulting output. With the addition of the long-term accuracy of a gyroscope combined with the short-term accuracy of the accelerometer, these sensors can be combined to obtain more accurate orientation reading by utilizing the benefits of each sensor.

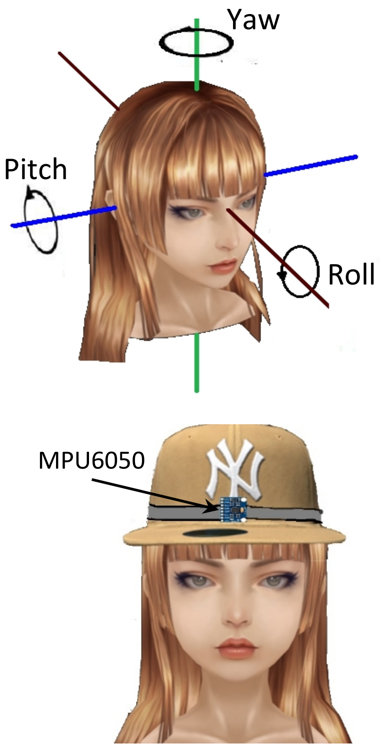


Fig. 7. Head angles and MPU6050 position

Combining the outputs of the two sensors can provide better estimation of orientation. The accelerometer measures linear acceleration based on the acceleration of gravity, it is more accurate in static calculation when the system is closer to its fixed reference point. The problem of accelerometer is that it tends to distort acceleration due to external forces as gravitational forces in motion, which accumulates as noise in the system and erroneous spikes in resulting output. With the addition of the long-term accuracy of a gyroscope combined with the short-term accuracy of the accelerometer, these sensors can be combined to obtain more accurate orientation reading by utilizing the benefits of each sensor.

Sensor fusion is a set of adaptive algorithms for prediction and filtering (Stanley 2018). It takes advantage of different and complementary information coming from various sensors, combining it together in a smart way to optimize the performance of the system.

Currently, the Kalman filter is one of the most popular fusion methods, which is implemented in various sensing domains due to its simplicity and acceptable accuracy.

Roll angle φ_a is obtained using the accelerations $a_x$and a_z along x and z axes, while pitch angle θ_a is found using the accelerations a_y and a_z along y and z axes.

$$\varphi_a = atan2\ a_x, a_z \tag{1}$$

$$\theta_a = \mathrm{atan2}\ a_y, a_z \tag{2}$$

Data for gyroscope are found similarly, except that the gyroscope output represents angular rates $\dot{\varphi}$ and $\dot{\theta}$ in deg/s with a sensitivity factor of 14.375.

$$\varphi_k = \varphi_{k-1} + \varphi_k.\Delta t \tag{3}$$

$$\theta_k = \theta_{k-1} + \theta_k.\Delta t \tag{4}$$

Where $\dot{\varphi}$ is the roll rate, $\dot{\theta}$ is the pitch rate of the gyroscope, and Δt is the time step.In the following, θ denotes the estimate angle, θ_a the angle calculated from the accelerometer measurements, and ω the rotation rate measured by the gyroscope.

4.2 Sensor fusion

Filter is designed by selecting pitch angle as a state vector and using accelerometer to estimate gyroscope constant deviation$b$. The estimated angle can be written as:

$$\theta_k = \theta_{k-1} + \omega_k - b_{k-1}\ \Delta t \tag{5}$$

The state space model of the system is derived as:

$$\begin{aligned} x_k &= Ax_{k-1} + Bu_k \\ y_k &= \theta_{ak} \end{aligned} \tag{6}$$

where x_k denotes state vector at time k, $\theta_{ak}$is the accelerometer measurement value at time k, A the state space matrix, B the control matrix and u_k the measured rotation rate

$$x_k = \begin{matrix} \theta_k \\ b_k \end{matrix},\ A = \begin{matrix} 1 & -\Delta t \\ 0 & 1 \end{matrix},\ B = \begin{matrix} \Delta t \\ 0 \end{matrix},\ u_k = \omega_k \tag{7}$$

discrete-time Kalman filter equations are as follows (Simon, 2001):

State prediction step:

$$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_k \quad (8)$$

State estimation is:

$$\hat{x}_k = \hat{x}_k^- + K_k(\hat{y}_k - C\hat{x}_k^-) \quad (9)$$

Where the superscript - denotes prior estimate value and K_k is the Kalman gain.

The error covariance matrix for prediction estimation is

$$P_k^- = AP_{k-1}A^T + Q \quad (10)$$

Where, P is the prediction uncertainly matrix, Q, is the system process noise covariance matrix, and Kalman gain is:

$$K_k = \frac{P_k^- C^T}{CP_k^- C^T + R} \quad (11)$$

Where R is the measurement noise covariance matrix.

The roll angle is estimated using the same process by choosing the roll angle as the state vector and calculating the prediction using Kalman filter.

4.3 Action selection

The direction of wheelchair depends on how the user moves his head as shown in figure 8. Five commands are allowed by the control system: moving forward, moving backward, turning right, turning left and stop. If the user's head roll or pitch angle exceeds 20° than the wheelchair will move in the corresponding direction (Forward, backward, right, and left). If the user still or back to the center position, that make the wheelchair stopped. Threshold values can be adapted according to the user's capacity.

5. Experimental results

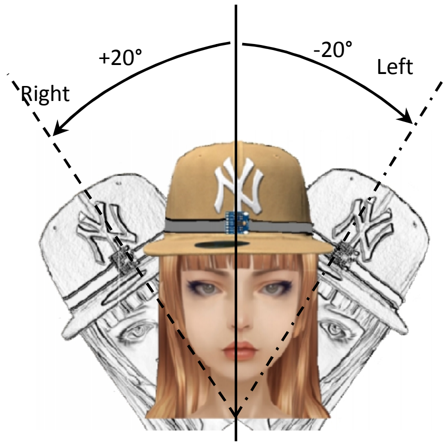
The hardware set up for the intelligent wheelchair with proper fabrication of all the control modules is shown in figure 9. The MPU 6050 is placed in the front of a cap to be worn by the patient.

5.1 Action recognition

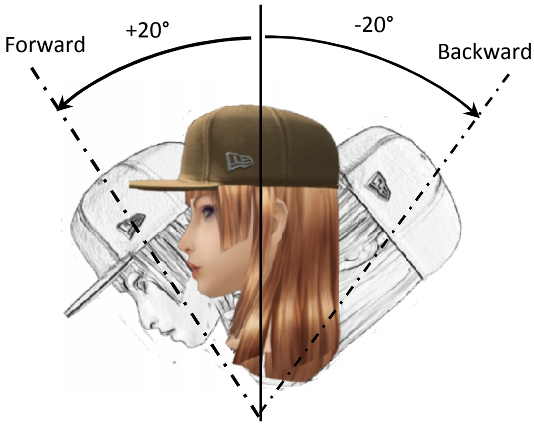
To evaluate the performance of the head gesture system, the five commands are tested by a healthy student. The experiment results show that the intelligent wheelchair moves forward, backward, turn right, turn left and stop according the head gesture control, as shown in figure 10, and the system is able to generate the appropriate voltages.

In Fig.10 (a), when the user tilts her head down with an angle 20° or more, the gesture is recognized as the forward movement, and the wheelchair moves in the forward direction.

In Fig.10 (b), when the user inclines her head right with an angle 20° or more, the gesture is recognized as the right turn and the intelligent wheelchair moves in the right direction.



(a)



(b)

Fig. 8. The position of the MEMS sensor relative to head motion in different directions (a) Left-Right, (b) Forward-Backward.

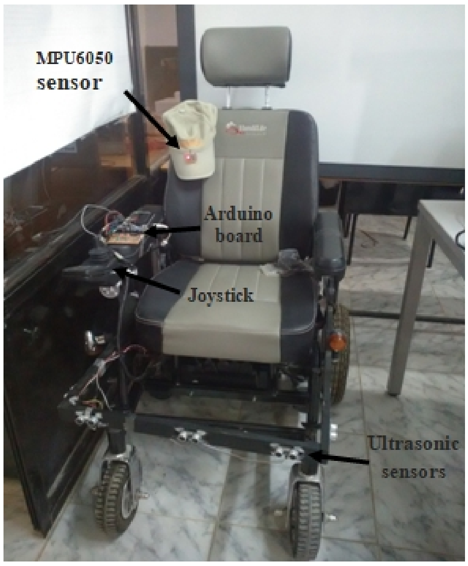


Fig. 9 . Hardware set up for the Intelligent Wheelchair

In In Fig.10 (c), when the user slopes her head left with an angle 20° or more, the gesture is recognized as the right turn and the intelligent wheelchair moves in the left direction.

Fig. 10. Experimental results.

In fig.10 (d), when the user tilts her head up with an angle 20° or more, the gesture is recognized as the backward movement and the intelligent wheelchair moves in the backward direction.

In fig.10 (e) when the user keeps or backs her head at the wheelchair center, the gesture is recognized as stop, the Arduino generate three different voltages corresponding to stop (2.5 V for right/left pin , 2.5 V for forward/backward pin and 2.5 v for center position pin) ,then the intelligent wheelchair stops .

In fig.10 (f), when the user's head is somewhere between the two gestures, i.e., the MEMs output values are somewhere between the direction thresholds, then the intelligent wheelchair stops.

In all cases, the system generates the appropriate voltages without error, and the wheelchair executes the appropriate command perfectly.

5.2 Running experiment in the laboratory environment

Both control modes of the proposed system, head gesture mode and the joystick mode have been tested by controlling the intelligent wheelchair in the laboratory environment.

The distance between the desks was about 2 m. The width of the wheelchair was about 60cm.The total distance was about 14 m. Three experiments were achieved by each control mode. In each experiment, the student has to follow the route shown in fig. 11.

The trajectories of wheelchair using the two control modes are shown in the figure 12, figure 12 (a) for the conventional joystick mode and figure 12 (b) for the head gesture based control mode. Experimental results show that the proposed system is reliable for controlling the wheelchair.

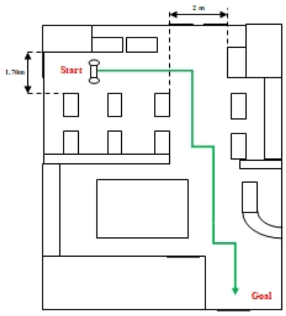


Fig. 11. The route to follow in the laboratory environment.

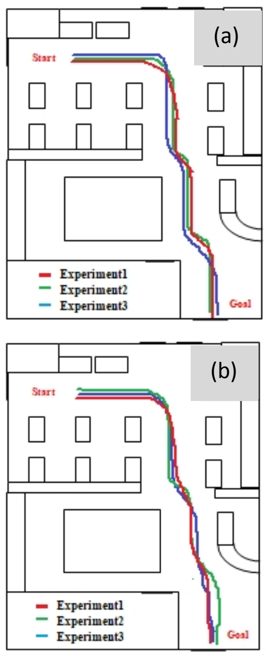


Fig. 12. Trajectories of wheelchair using two control modes, (a)-Joystick mode, (b)-Head gesture mode

6. Conclusion

In this paper, a head gesture recognition system based on Arduino and MPU6050 is designed to control an intelligent wheelchair. The sensor board MPU6050. fixed to the front of a carp worn by the user, detects head orientation and sends data to an Arduino board to calculate the appropriate head inclination angles using geometry rules and sensor fusion using Kalman filter, then the wheelchair is moved by comparing calculated angles with predefined thresholds. Furthermore, instead of inhibiting the control by conventional joystick, in this work, it is kept, as a second operating mode, in addition to the control with head gesture and the switching between the modes is smooth, straightforward and transparent to the user.
The experimental test applied to this wheelchair in real environment, showed the success of proposed control system based on head gestures.

This work presents a solution for the elderly or severe disabled people with a paralyzed arm or a severe handicap. For more flexibility, the wired system will be replaced by a wireless system using Bluetooth, and the commands and the thresholds can be adapted to the patient capacities. In the future, the system can be improved by increasing the system sensitivity and flexibility and the addition of other intelligent modes and the implementation of intelligent behaviors

References

Abiyev, R., N. Akkaya, E. Aytac, I. Gunsel, A. Cagman (2016) Brain-Computer Interface for Control of Wheelchair Using Fuzzy Neural Networks, Biomed Research International ID9359868: 1-9.

Barea, R., L. Boquete, M. Mazo, E. López (2002) System for assisted mobility using eye movements based on electrooculography, IEEE transactions on neural systems and rehabilitation engineering 10(4): 209-218.

Chen, Y., S. C. Chen, W. L. Chen, J. F. Lin (2003) A Head Orientated Wheelchair for People with Disabilities, Disability and Rehabilitation 25(6): 249-253.

Curtis-Wright (2007), JC2000 Multi Axis Contactless Joystick, [online] available at www.cw-industrialgroup.com/getattachment/ a6bb9db0-f4be-47c9-8e9d-e8931694969f/jc2000_brochure, (accessed 1 June 2018).

Hassani, R., M. Boumehraz, Z. Habba (2015) An Intelligent Wheelchair Control System based on Head Gesture Recognition, International Electrical and Computer Engineering Conference’2015, Setif, Algeria.

Huo, X., M. Ghovanloo (2009) Using Unconstrained Tongue Motion as an Alternative Control Mechanism for Wheeled Mobility, IEEE Transactions on Biomedical Engineering 56(6): 1719-1726.

InvenSens (2013) MPU 6000 and MPU 6050 Product Specification. |online] Available at: https://www.invensense.com/wp-content/uploads/ 2015/02/MPU-6000-Datasheet1.pdf (Accessed 01 Jun. 2018).

Jia, P., H. Hu, T. Lu, K. Yuan (2007) Head Gesture Recognition for Hands-Free Control of an Intelligent Wheelchair, Journal of Industrial Robot 34(1): 60-68.

Ju, J., Y. Shin, E. Y. Kim (2009) Intelligent Wheelchair Using Head Tilt and Mouth Shape, Electronics Letters, 45(17): 873-875.

J. Leaman, H. M. La (2017) A Comprehensive Review of Smart Wheelchairs: Past, Present and Future, IEEE Transactions on Human-Man Systems 47(4): 486-499.

Li G., Y. He, Y. Wei, S. Zhu, Y. Cao (2013) The MEMS Gyro Stabilized Platform Design based on Kalman Filter”, Proceedings of the 2013 International Conference on Optoelectronics and Microelectronics (ICOM2013), China.

Lv, Z., C. Zhang, B. Zhou, X. Gao, X. Wu(2018) Design and implementation of an eye gesture perception system based on electrooculography, Expert Systems with Applications 91: 310-321.

Nam, Y., Q. Zhao, A. Cichocki, and S. Choi (2012) Tongue-Rudder: A Glossokinetic-Potential-Based Tongue–Machine Interface, IEEE Transactions on Biomedical Engineering 59(1): 290-299.

Pajkanović, A., B. Dokić(2013) Wheelchair Control by Head Motion, Serbian Journal of Electrical Engineering 10(1): 135-151.

Peixoto, N., H. G. Nik, H. Charkhkar (2013) Voice Controlled wheelchairs: Fine control by humming, Computer Methods and Programs in Biomedicine 112(1): 156-165.

Pinheiro, O., L. Alves, J. de Souza (2018) EEG Signals Classification: Motor Imagery for Driving an Intelligent Wheelchair, IEEE Latin America Transactions 16(1): 254-259.

Pires, G., U. Nunes (2002) A Wheelchair Steered through Voice Commands and Assisted by a Reactive Fuzzy-Logic Controller, Journal of Intelligent and Robotic Systems 34(3): 301-314.

Rebsamen, B., C. L. Teo, Q. Zeng, M. H. Ang Jr., E. Burdet, C. Guan, H. Zhang, and C. Laugier (2007) Controlling a Wheelchair Indoors using Thought, IEEE Intelligent Systems 22(2): 18-24.

Reis, L., B. M. Faria, S. Vasconcelos and N. Laun (2015) Multimodal Interface for an Intelligent Wheelchair, Ed. J. L. Ferrier et al. Berlin, Springer, pp.1-34.

Simon, D. (2001) Kalman Filtering, Embedded System Programming 14(6): 72-79.

Simpson, R. (2005) Smart Wheelchairs: A Literature Review, Journal of Rehabilitation Research & Development 42(4): 423-436.

Skraba, A., R. Stojanovic, A. Zupan, A. Kolozvari, D. Kofjac (2015) Speech-controlled cloud-based wheelchair platform for disabled persons, Microprocessors and Microsystems 39(8): 819-828.

Stanley, M., J. Lee (2018) Sensor Analysis for the Internet of Things, Morgan & Claypool Publishers.

Store.arduino.cc (2018) Arduino Mega 2560 Rev3. [online] Available at: store.arduino.cc/usa/arduino-mrga-2560-rev3 (Accessed 1 June 2018).