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A Novel Approach in Head Orientation Controller for Robotic-Wheelchair Using MEMS Sensors

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Abstract: ***There are many people who have lost the ability to control upper and lower limbs due to quadriplegia, paralyses or ageing side effects. This type of users requires special control systems to use an electrical wheelchair instead of using traditional control by joystick. In this paper a novel auto calibrated head orientation controller for wheelchairs and rehabilitation robotics application is proposed. The system use two Orientation Detection (OD) units, each unit includes three MEMS sensors: accelerometer, gyroscope and magnetometer which are combined together. The first OD unit reads the wheelchair orientation, which is used as a reference orientation to calibrate the system performance, when the system is faced non straight road. The reference orientation is used to cancel the changes in orientation in case of non-straight roads and also to compensate the speed in case of ascent or descent a ramp. The second OD unit is fixed on the user's head and is used to control the speed and direction of the system. The head orientation is measured using Euler angles (Roll, Pitch and Yaw). The system movement and speed control depend on the position of the user's head related to X, Y and Z axis. The system uses powerful ARM cortex M3 microcontroller to perform the control of the intelligent application.***

Keywords: Intelligent Wheelchair, Orientation Detection, Quadriplegia, Embedded system, Euler Angles

1.Introduction

Many researchers work in the field of rehabilitation engineering to help quadriplegia, hand amputees, elderly and paralyzed patients. This type of patient cannot use traditional electrical wheelchairs with joystick control. One of the important goals of intelligent rehabilitation systems is to allow the user to do his daily movement and activities without the need of others help. Voice control is an important solution to control the wheelchair which is performed by using the Voice Recognition (VR) technology. The VR technology converts the sound wave to an electrical signal. The electrical signal is further digitized and used as a control signal, which can be understood by computers and microcontrollers. The VR technology shows acceptable accuracy in low noise environments and in indoor navigation. The voice recognition technology cannot give excellent performance in high noise and in outdoor application [1-4].

Other solutions are using different bio signals from the user's body in the regions of neck, shoulder and head, which are still under control of the quadriplegia and other target users. The bio signals, including the electromyogram (EMG), electroencephalogram (EEG) [7-8] and electrooculogram (EOG) [9] can be used as a controller for a wheelchair or robotic application.

Alternatively, the head movement can be used as a controller for the wheelchair using different procedures. Infrared and ultrasound sensors were used to detect the head movement and used as controller [10-12]. Other researchers used cameras to detect the head gesture as a wheelchair controller [13]. Recently, many researchers proposed the use of the accelerometer and orientation sensor as a controller for the intelligent rehabilitation application. S. Manogna et al. and Deepesh K Rathore et al. [14-15] proposed an accelerometer based control system for a wheelchair. The system applied simple tilt threshold conditions to make virtual motors (PC simulator) or prototype wheelchairs move in 4 directions with fixed speed without using speed control. Tao Lu et al. [16] proposed an accelerometer based hand gesture controller for wheelchairs. The system uses the hand motion in four directions as a control command in a simulation. The system uses many algorithms for recognition and motion smoothing without speed control. The current system does not have the ability to calibrate the hand orientation in non-straight roads and outdoor navigation and it is not sufficient for quadriplegia, amputated arms and paralyzed users.

There are many drawbacks and limitation in the previous methods. Most of them used one or more computer to implement the controlling algorithm and classification of the input data, which adds high costs and more complexity to the system. Most of the body signals like EEG, EMG and EOG are highly affected by the electrical interference from the user's body and from the power source. The small value of these signals makes the processing and use of these body signals more complex to be used as a main controller for rehabilitation applications. In this paper, an auto calibrated head orientation controller and, speed compensation algorithms for wheelchair and rehabilitation robotics are proposed. The system uses the head movement and orientation as a controller for intelligent application. The user's head tilts around the X and Y axis is interpreted to a wheelchair movement in the forward, backward, left and right directions. The head movements around Z-axis are not used in the controller to give the user the chance of moving his head around without affecting the control of the system. The system has the ability to adjust the speed depending on the road slope. The system uses Euler angles (Pitch, roll and Yaw) to detect the head orientation. The Euler angles picked up by using three MEMS sensors, which are accelerometer, gyroscope and magnetometer. The three sensors are combined together to build a high accurate orientation sensor. The system uses two orientation sensors.

The first is fixed in the wheelchair chassis to be used as a reference orientation supplier. The second is fixed in the user's head to detect the head movement and give the orientation data to the microcontroller. Compared to previous work, the presented work is performed of uses two control algorithms. Thus, the auto calibrated orientation algorithm prevents wrong control commands to the system in case of changing the position of the user's head in outdoor non-straight roads. It has the flexibility to perform the head movement control when the system is used in outdoor environments with non-straight roads. The threshold control angle is changeable with the road slope. The algorithm gives the flexibility to the user to change the speed of the wheelchair in all directions from the minimum to the maximum speed depending on the head tilt angle. The speed compensation algorithm is used to keep the wheelchair speed constant by controlling the motor torque in case of decent or ascent and also when the road has different side altitudes. The algorithm controls the torque of each motor individually depending on the slope angle value of the road to compensate the speed loss due to gravitational forces. The system works standalone without a PC to process the orientation information. It can be used successfully for indoor and outdoor applications.

2.System Construction

The proposed system is a part of a multi-input control system that uses different available body signals to control any intelligent rehabilitation application (wheelchairs, robots, etc.). The system design takes into consideration that it can be used easily and comfortably by quadriplegia and elderly patients. It includes also a voice controller, which gives the user the option to abort the head tilts controller when necessary [1]. Fig. 1 shows the block diagram of the system. It includes the core microcontroller and the main units and sensors. The system blocks and structures will be explained in detail in the next section.

A. Microcontroller Unit

Since the proposed system is a part of a multi input control system a careful selection of the microcontroller unit is required. It represents the "brain" of the system. It must have special characteristic and specification to cover the required input/output ports and peripherals for the system design. This will make the interface between the microcontroller and the input and output units more flexible.

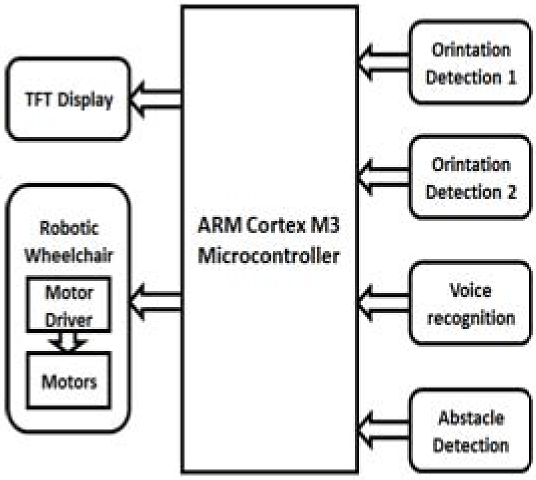

Figure 1: Block Diagram

The EFM32GG990F1024 ARM cortex M3 (Energy micro, Norway) has been selected to be the main controller of the system. This powerful microcontroller is one of the most energy friendly products. It has all the required peripheral communication ports for the system design, including General Purpose Input Output (GPIO) pins, universal asynchronous serial receiver and transmitter (UART) and I2C ports with configurable peripheral I/O locations. The wide range of ports diversity makes the system updating more easily. The 32 bit processor shows high performance with up to 48 MHz speed. It has two separated I2C bus which allow the system to read from two orientation units at the same time separately. It has 86 configurable General Purpose input, output pins, three Universal Synchronous/Asynchronous Receiver/Transmitter (USART), two Universal Asynchronous Receiver/ Transmitter (UART), two Low Energy UART and many important embedded features [17].

The rotation of Pitch angle around the x-axis is defined as:

$$R_x(p) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos p & -\sin p \\ 0 & \sin p & \cos p \end{bmatrix} \quad (1)$$

The rotation of Roll angle around the y- axis is defined as:

$$R_y(r) = \begin{bmatrix} \cos r & 0 & \sin r \\ 0 & 1 & 0 \\ -\sin r & 0 & \cos r \end{bmatrix} \quad (2)$$

The rotation of Yaw angle around the z-axis is defined as:

$$R_z(y) = \begin{bmatrix} \cos y & -\sin y & 0 \\ \sin y & \cos y & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The angles p, r, y represent pitch, roll and yaw which are Euler angles [19].

B. Orientation Detection Unit

The orientation detection unit consist of two BNO055 orientation detection modules (Bosch, Germany). The BNO055 module includes three MEMS sensors, which are accelerometer, gyroscope and magnetometer. The three sensors are combined together in one chip with powerful Arm cortex M0 processor to access the data from the three sensors. The BNO055 is a 9 Degree of Freedom (DOF) module. It can use each MEMS sensor separately, or use more than one sensor in fusion mode, which can give the orientation of the module in the different form like: Euler angles (Pitch, Roll, and Yaw) and Quaternion vector. In the present work the Euler angles were used to detect the orientation [18]. Fig. 2 shows the used BNO055 orientation module.

Figure 2: Adafruit BNO055 Orientation Module

Euler angles represent the orientation of a body rotation around principal axis. Fig. 3 shows the Euler Angles axes.

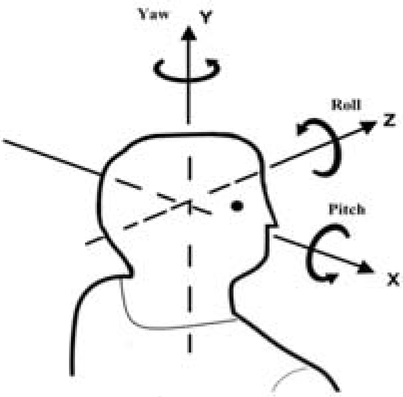

Figure 3: Euler angles axes

C. LCD Display

A 320*240 pixel LCD display is used to view the control commands and the current activated control mode. It shows

Figure 4: TFT LCD Display

the Euler angles of the head orientation and the control commands producing by system. It also shows the response of the intelligent control system at all situations, in orientation control in all directions, in obstacle detection alarm and in case of wrong orientation of the user's head. Fig. 4 shows the sample command and function of LCD display.

D. Dr. Jaguar lite Robot (Motors Driver Unit)

The system was tested with the two wheels, Jaguar lite robot (Dr. Robot Inc., Canada), which is similar to the construction of a wheelchair. The system interfaces with the Jaguar lite robot by using the UART communication port from both sides. The ARM microcontroller is sending the control commands to the BMS5005 robot controller. Sabertooth 2x25 motor driver unit realizes the final motor control action. One of the orientation modules is fixed on the robot chassis to give reference orientation if there is any slope or not straight portion of the road. The robot has two DC motors, is operated at 24 V and 7.5 A rating current (see. Fig. 5).

Figure 5: Jaguar lite robot

3. Work Description

The head orientation controller consists of two BNO055 orientation modules; each of them has different tasks in the System. The first module is fixed to the chassis of the jaguar lite robot to measure the orientation of the robot related to the slope of the road. The orientation of the robot is represented by pitch and roll angles related to the x and y-axis. The measured orientation represents the reference orientation in the auto calibrated algorithm.

The second BNO055 orientation module is fixed on the user's head as a part of a small wearable device. It measures the user`s head orientation related to the reference orientation module, which is fixed on the robot.

The input data to the system are acquired from the two orientation modules. The orientation data are sent to the ARM cortex M3 microcontroller for processing. The two modules communicate with the microcontroller through the I2C bus. The EFM32GG990F1024 microcontroller has two I2C buses. It can use both of them to communicate with the two orientation modules. In the current system, only one I2C bus is used to communicate with the two orientation modules. Two different I2C addresses have been used for the two modules. The first module takes the I2C address (0x28) and the second module takes the I2C address (0x29).

The microcontroller processes the information from the two orientation modules using the auto-calibrated orientation algorithm. The algorithm will give the right decision depending on the user`s head orientation related to the reference orientation. The output control signal is sent to the jaguar lite robot to implement the required movement in direction and speed. The communication with the jaguar lite robot is done using the UARTs communication port from the both sides (robot and microcontroller). The UARTs setting is as the following: 115200 kbps, N, 8, 1. another output signal is sent to the LCD display. The microcontroller communicates with the LCD display using the GPIO pins. The LCD display, view all the executed, control commands and alert message if there are errors in head position or in a case of obstacle detection. The system design to implement control command depending on the user head orientation at pitch and roll Euler angles. Table 1 explains the system response for each tested command.

Table 1: Command control action

Command	Definition
Forward	Both motors rotate forward
Left	Right motor rotates forward and left motor rotates backward
Right	Left motor rotates forward and right motor rotates backward
Backward	Both motors rotate backward
Stop	Both motors stop
Forward-Left	The right motor rotates faster than left motor
Forward-Right	The left motor rotates faster than right motor

In the presented work, Euler angles have been used to perform the control action. Two angles cover the system requirements, which are pitch and roll. The pitch angle represents the body rotation around the X axis and is used to perform forward and backward movement of the wheelchair. The roll angle represents the body rotation around the Y axis and is used to perform left and right movement. The two angles are measured and compared with both orientation modules (on the robot chassis and on the user's head). There are two scenarios for using the auto calibrated controller:

A. Auto calibrated head orientation controller scenario

When the robot passes through a straight road, the auto calibrated algorithm will not be activated since the value of the two Euler angles of the two orientation sensors will be near the straight position limit (-10 to +10 degrees). In the case of a slope in the road (ascent or descent), the value of the Euler angles of the orientation module at the robot chassis will change relative to the value of road slope. The second orientation module also takes the same road slope and the difference between the Euler angles of two OD modules will keep in the range of (-10 to +10 degrees) to avoid the drift of the non-straight road. When the user wants to control the forward movement of wheelchairs, he must tilt his head in the forward direction. He needs to make the difference between wheelchair pitch angle and user head pitch angle more than the threshold level. The threshold (T) for the forward command is $10° < T \leq 45°$ degrees. If the head tilt angle is larger than the threshold the system starts moving at minimum speed. The speed increases proportionally to the head tilt angle. The maximum speed can be reached when a head tilts angle ≈ 45 degrees. This scenario can be applied in all the direction (forward, backward, left, right, continues left and continues right). If the road has slope up or down, this will cause errors in the orientation control. The user head orientation will be changed related to the change in the road slope. When the road slope reaches the threshold level, it can give wrong control commands. The auto calibrated algorithm cancels the road slope by making the orientation of the wheelchair as reference orientation. In this case, the system will not reach the threshold level when the road is not straight. It will reach the threshold level only when the user's head moves in a specific movement to choose the direction and the speed of the system. The user needs to keep his head perpendicular with his body as a normal situation to apply the stop command. Fig. 6 shows the system in different road slope position.

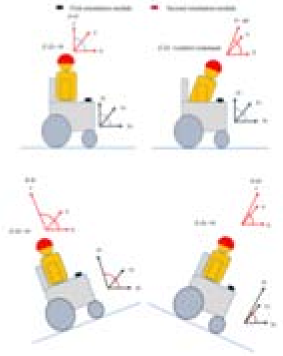

Figure 6: System in different road slope

Fig. 7 shows the flowchart of the auto-calibrated orientation control algorithm, which is written in Keil µVision5 C/C++ environment. The algorithm starts with the acquisition of the orientation data from the two orientation modules. The orientation of each module is recorded at six internal 8-bit registers in the orientation module. The values of both registers (high and low) represent the value of one Euler angle as 16-bit representation (8 bit high + 8 bit low). This 16-bit value can be changed to degrees or radians by controlling the internal register (UNIT_SEL) to represent the value of the Euler angle in specific measuring unit. In the next step, the algorithms compare the value of each Euler angle from the first orientation module with the equivalent from the second orientation module. The algorithm checks the errors in the head position and sends an alarm on the LCD display to inform the user to correct the head position. If there is no error it checks the value of the comparison of Euler angles. If it reaches the threshold of any control command, then it will send the required command (Forward, left, etc.) to the motor driver unit of the jaguar lite robot.

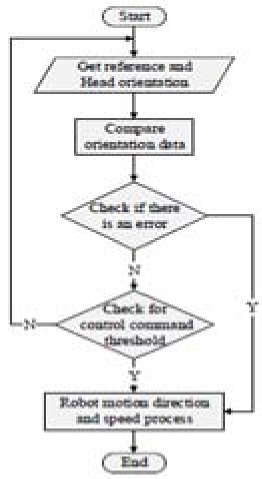

Figure 7: Auto calibrated orientation algorithm

B. Speed compensation scenarios

In a case of ramp ascent or descent, another kind of control can be applied to the wheelchair using the two orientation sensor as speed compensation controller in case of ramp ascent or descent. In this scenario, the system uses the reference orientation to control the torque (increment or decrement) depending on the angle of slope. Any increase in the angle of road slope of ascent makes the algorithm increase the motor torque to keep the speed of the wheelchair constant and to compensate the lost speed in rising road. The value of the increment in the torque is calculated depending on the value of the slope angle of the road, which is proportional to the angle of inclination of the road. The same procedure is applied in the case of driving downhill, the algorithm reduces the torque of the wheelchair to cancel the increasing in the speed because of the forces of gravity. This will give more stability to the wheelchair and rehabilitation robot. When the road sides having the same altitude, the motor torque will increase or decrease by the same factor for both motors. In another case, when the road sides have different altitudes, each motor has different torque factors depending on the slope angle value of the road sides (Roll angle). For example, if the left side altitude is larger than the right side, the torque factor for the right motor will increase to keep the wheelchair in stable movement. This algorithm depends only on the orientation sensor to compensate or calibrate the speed without reading the real speed of the motor. PID controller can be used with this algorithm to give closed loop speed control in case of descent or ascent a ramp. This is the part of future work. Fig. 8 shows the flow chart of the second scenario algorithm.

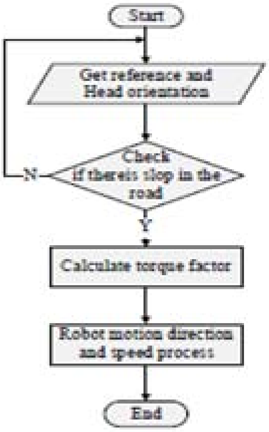

Figure 8: Speed compensation algorithm

4.Results

The auto calibrated algorithm has been tested for 7 control commands. The algorithm controls the motor speed from minimum (0 m/s) to the maximum speed of the motor proportional to the value of the tilt angle of the user's head. This procedure can be applied to any rehabilitation application. The algorithm has been tested successfully at different 6 slope angles, which are 15, 30, 45, -15, -30 and -45 degrees. Each command in table-1 tested 10 times for each slope angle (SA) by 5 users. The test has been performed at the Center for Life Science Automaton (celisca), University of Rostock, Germany. Artificial wooden ramp with manual angle adjusting has been used to implement the tests. The tests show accurate control performance at all tested slope angles with accuracy ≈ 97.4 %. The threshold value of the Euler angles (pitch and roll) can be adjusted individually for each user. The system can be perfectly used for outdoor rehabilitation application, which needed to deal with non-straight roads or to go up and down from the sidewalk. The system will automatically stop in case of unconsciousness depending on the head orientation and also, the user can abort the head tilts controller by using voice controller. Fig. 9 shows the test results. The speed compensation algorithm with different slope angles of the road has been tested successfully. The algorithm needs to be enhanced by adding a PID controller with closed loop control to enhance the accuracy and movement stability. This can be implemented by using optical encoders.

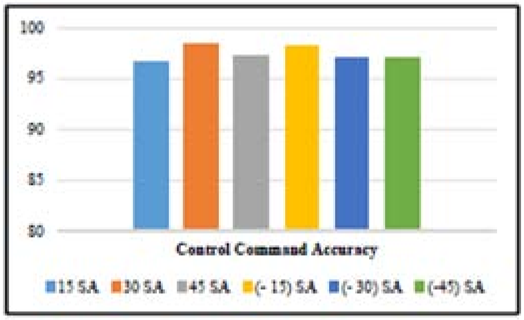

Figure 9: Auto calibration algorithm test for different slope angles

5.Conclusions

In this paper, an auto-calibrated head orientation controller and speed compensation algorithms for rehabilitation application are proposed. The system aims to help quadriplegic, paralyzed and elderly patient to control robotic wheelchairs by using their head movements instead of traditional joystick controller. The system is a part of a multi input control system, which also includes a voice controller to give the user multi-control options to drive the system. The system has a novel method to avoid the errors in control commands due to any change in the user's head orientation and position in case of passing on non-straight roads, which is an important feature allowing the use in outdoor environments. The result shows high control performance with accuracy of ≈ 97.4 %. The speed compensation algorithm adds another important speed calibration feature to the system.

It keeps the wheelchair speed constant and gives more stability against the gravitational force in ascents or descents during outdoor navigation. The system has been tested with Jaguar lite robot and it can be used directly with Hawk and H20 robots. The system can be used to control the movement of any robot- wheelchair after motor driver parameter modifying. In the future works, closed loop PID control with feedback from an optical encoder needs to be used to enhance the speed control of the speed compensate algorithm. As the system is used for handicap and elderly users, obstacle avoidance system should be added to the system to provide higher safety conditions.

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