BIOMEDICAL ENGINEERING | RESEARCH ARTICLE

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Abstract: This paper presents the design and development of a prototype of a reconfigurable wheelchair for rehabilitation and self-assistance to fit the size of a seven years old child (average 35 kg weight). Though the developed prototype is developed at this stage to fit a child, it can be resized, after considering variations in weight and size, to fit an older adult. The developed prototype has a mechanism that enables the user to transform from sit-to-stand (STS) posture and vice versa. With the help of the developed wheelchair, the user will also be able to adjust the posture of his upper body using an adjustable back support using two linear actuators. This configuration will allow the user to use the wheelchair as a mobility device as well as for rehabilitation purposes without the need of external support. The availability of STS and back adjustment mechanisms will allow the user to do regular exercising which will enhance blood circulation as sitting for long periods inflates lower limbs disability. The proposed configuration will help in enhancing the functional capabilities of end-users allowing for increased independence and ultimately quality of life.

Subjects: Assistive Technology; Rehabilitation Medicine

Keywords: wheelchairs; sit-to-stand; assistive technologies

ABOUT THE AUTHOR

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PUBLIC INTEREST STATEMENT

The quality of life of elderly and disabled people can be improved by special education, training, rehabilitation and the availability of public facilities. One of the important issues to improve their quality of life is to develop assistive devices to meet daily-life needs and to be more involved in their community. Worldwide population is ageing and by 2051 one in four will be aged 65 or older. This has direct implications on health expenditure because there is a significant rise in the incidence of disability with age and an increased need for health treatment and care and social services. The demand for assistive devices and to support elderly and to increase their engagement in the society and workforce is expected to also increase. The developed wheelchair aims at developing an engineering solution for both mobility and rehabilitation for disabled and elderly people. The wheelchair provides facilities for sit-to-stand and back seat adjustment for the user.

1. Introduction

Assistive technology for mobility includes wheelchairs, exoskeletons, walking devices, lifting aids and other devices (Dubowsky et al., 2000; Kaneshige, Nihei, & Fujie, 2006). In most cases; the patient eventually requires assistance to use the device. This may include someone to push a wheelchair, to help in lifting from the bed, to support using the toilet or to provide guidance through cluttered areas. With fewer caregivers and increased number of older adults, there is a significant need for improved assistive devices to provide more independence (Bostelman & Albus, 2007). Research in assistive robotics has a multidisciplinary nature that involves bio-mechanics, mechanical design, electronics, materials science, computer science and robotics (Guo-zheng, Ai-guo, & Hui-jun, 2009; Li-ning, 2006). Assistive robots can help patients to perform independently effective exercises which may lead to fast and better recovery of their functions (Zhang, Bai, & Yi, 2011). In particular, wheelchairs with sit-to-stand (STS) support enable individuals to have a better environmental access and health benefits including: improved functionality of daily life activities, enhanced independence and productivity, maintaining vital organ capacity and bone mineral density, improved blood circulation, reduced occurrence of pressure sores, and enhanced psychological well-being (Arva et al., 2009).

Many older adults who can walk are trapped in chairs due to the lack of standing ability. Many others who struggle to stand require means of rehabilitation and care. With the availability of such facilities, physical rehabilitation and damage prevention may be assured (Wang & Jin, 2005). It is expected that the need for assistive technologies for the physical support and rehabilitation will increase around the world (Hirata, Higuchi, Hatsukari, & Kosuge, 2008).

1.1. Wheelchairs standards

According to Food and Drug Administration (FDA, 2004), wheelchairs are classified as medical devices and they are subject to regulatory control. Voluntary standards have been adopted to provide objective information about the performance and safety characteristic of wheelchairs for consumers, manufacturers, and clinical practitioners, American National Standard Institute (ANSI) for wheelchairs (1998). The International Standards Organization (ISO) for wheelchair standards consists of standardized tests simulating three to five years of typical wheelchair use. Those voluntary test standards can be used to determine the fatigue life, static tipping angles, braking distances, energy consumption, obstacle-climbing ability, and environmental and electromagnetic compatibility of the wheelchair. Furthermore; they can be used to compare different wheelchairs to help consumers determine which device best matches their needs (Axelson, Mince, & Cheney, 1994).

Using standards to improve mobility devices can increase wheelchair reliability and reduce risks to end-users. Unfortunately, the voluntary ISO standards do not require discoursing all test results in product literature provided by the manufacturer (Cooper, 1998). For example, the standard for testing wheelchair fatigue life requires the wheelchair to only complete a minimum number of test cycles (Fitzgerald, Cooper, Boninger, & Rentschler, 2001). However, a more valuable evaluation would report the results of testing a wheelchair until the end of its useful life. ISO wheelchair transportation standards regarding the use of wheelchairs for seating during transportation on buses or vans have been developed by Hobson (2001), American National Standards Institute (ANSI)/Rehabilitation Engineering & Assistive Technology Association of North America (RESNA) (2000) and ISO/DIS (2000).

2. Related work

2.1. Advancements in wheelchairs

Manual wheelchairs have significantly improved from the one size fits all depot-style design, shown in Figure 1, to the heavy depot-style, shown in Figure 2. Nowadays, custom-fit ultralight manual wheelchairs are available for active wheelchair users as shown in Figure 3.

Figure 1. Attendant-propelled wheelchair.

Figure 2. Heavy, folding frame, depot-style.

There is a tremendous progress in advancements of powered, wheeled mobility to enhance functional independence for individuals with more severe disabilities. Examples of such powered wheelchairs are illustrated in Figures 4 and 5 which provide better flexibility of the user through increasing the number of degrees of freedom (DoF) in terms of inclination and rotation of the chair.

Numbers of powered wheelchairs are developed for persons with disabilities and older adults who cannot walk or have extremely poor dexterity (Cooper, 1995; Ding & Cooper, 2005; Hoyer, 1995; Katevas, 1997; Yanco, 1998). These devices are well-suited for people who have little or no mobility. However, they are not appropriate for older adults with significant cognitive problems. Consequently, they are generally reluctant to permit the older adults to use powered wheelchairs (Zhu et al., 2010).

Figure 3. Ultralight, adjustable manual wheelchair with rigid frame.

Figure 4. Powered wheelchair with reclining seat technology.

2.2. Sit-to-stand (STS) transformation

Transferring from a sitting to standing represents a fundamental aspect of daily activities which greatly affect persons with disabilities and independence of older adults (Arcelus et al., 2009; Janssen, Bussmann, & Stam, 2002). STS transfer is considered a basic test of functional mobility whether measured alone, within a laboratory environment (Yamada & Demura, 2009) or as part of a larger activity monitoring system for the older adults (Najafi et al., 2003). One of the most used tasks in the ability/disability evaluation is the STS task (Giansanti, Maccioni, Macellari, Costantini, & Carota, 2006). The ability to rise from a chair by means of STS support is a basic activity for life quality. Furthermore, STS is largely considered as one of the more mechanically demanding functional task of daily activities (Kerr, White, Barr, Mollan, & Frcs, 1997; Kralj, Jaeger, & Munih, 1990). There are numbers of problems associated with maintaining a sitting position for long time including haematogenous disorder of leg, excretion failure, and arthropathy. Furthermore anxiety is likely to happen to persons sitting for longer periods due the prolonged time the person is looking up while speaking with others (Mori, Taniguchi, Inoue, Fukuoka, & Shiroma, 2011).

Figure 5. Powered wheelchair with tilt function.

There are several studies on STS movement which studied joint motion, joint torque, and posture. Kawagoe, Tajima, and Chosa (2000) and Kawamoto, Kanbe, and Sankai (2002) analyzed the effect of foot placement with different chair height on the STS transfer. (Mederic, Pasqui, Plumet, & Bidaud, 2002) described the design of a walking aid with the capability to assist older adults in STS transfer. Robot-assisted STS transfer was also addressed in Kuzelicki, Kamnik, Burger, and Bajd (2001) for a system used for a person with lower limb prostheses. Developing chairs that allow transformation from STS has been given noticeable attention by researchers. Bae and Moon (2010) proposed a chair to help in transformation between STS for low seat. Hendreson (1992) developed a wheelchair that includes hip-up function. Auel (1991) developed a wheelchair equipped with a control mechanism to measure the angle of backrest, leg-rest and the angle of tilting of the chair. Komura, Kaneda, Yamashia, Adachi, and Mizuseki (2004) developed a wheelchair that includes lifting and hip-up functions.

There are number of commercial wheelchairs equipped with a STS facility and are currently available in the market. Examples include XO-202 shown in Figure 6(a), SuperStand (SS-1) in Figure 6(b), a conceptual wheelchair design shown in Figure 6(c) and the LEVO C3 as appears in Figure 6(d).

2.3. Overview and contribution

Although the transformation from STS has been given a lot of interest either in research-based work or through building facilities to support this motion, as per the authors knowledge there are few contributions focused on building and studying one device with both mobility and rehabilitation capabilities. Adjusting the back seat allows the user to exercise his back while sitting as well as to make adjustment of his posture while standing. We believe that this particular feature of back seat adjustment has attracted few contributions. The mechanism for adjusting the back support is considered novel and simply designed using two linear actuators. Back seat adjustment (tilt and recline) helps in health preservation and daily living activities including trunk positioning, gait balance and stability, remaining in contact with shape of the backrest and functional enhancement (Dicianno et al., 2009). In this paper; the authors aim at designing and building a reconfigurable wheelchair, with a STS and a back seat adjustment mechanisms, for the purpose of rehabilitation and self-assistance for a 35 kg child. This configuration is believed to enable the user to be more independent and to change his/her posture when he/she needs. Though the wheelchair has been developed to suit the

Figure 6. Multi-purpose and reconfigurable wheelchairs.

(a) Karman Healthcare XO-202 **(b)** Super Stand (SS-1) wheelchair

(c) Concept wheelchair, the P'GASUS **(d)** LEVO C3

size of a child, the conceptual design can be resized to suit an older adult user after considering size and weight variations. A seven years old child (an average 35 kg weight) has been used to derive the weight measures for prototype developing and testing.

The contribution of this paper is the design and realization of a research-based facility for various research focus including: studying the interaction between the user and the device, investigation of the kinematics and dynamics of the wheelchair and the human body, studying energy consumption in the wheelchair and the equivalent energy needed by the human muscles. The proposed compact technology solution with both mobility and rehabilitation capabilities will help in saving the time and effort of the user, guardians and parents to visit clinics, hospitals and physiotherapy centres as well as allowing the user to practise necessary exercises at home.

2.4. Paper organization

The work presented in this paper is arranged as follows: Section 2 presents an overview of contributions in wheelchairs and mechanisms with STS transfer. In Section 3, three design alternatives of the wheelchair are presented while mentioning limitations of each specific concept. Based on the investigations of the three design options; a final design is refined considering all drawbacks identified earlier. The detailed design process of the refined concept is described with detailed explanation of the system integration. A full detailed explanation is provided in this section covering most of the major parts of the wheelchair. The control architecture of the device with the different modes of operation is explained in Section 4. The design safety recommendations are presented in Section 5 and the work is concluded in Section 4 highlighting the main points covered in the research and the limitation of system at this preliminary stage.

3. Wheelchair design details

The design procedure of the wheelchair followed a standard design process which can be applied for a full size wheelchair. The developed prototype is developed as a test rig for research purposes. There are various features and designs for reconfigurable wheelchairs which are commercially available as shown in Figure 10. Three design alternatives have been proposed due to certain social and economic impacts. All designs are proposed in a way to let the wheelchair rider transform from sitting to a standing position and vice versa without need of any external help.

3.1. First conceptual design

The first design option as illustrated in Figure 7 is based on the fact that one of the current trends in industry is to minimize the area occupied by a product while manoeuvering. This design mainly simulates an inverted pendulum scenario moving on two wheels. This configuration of the proposed wheelchair allows it to occupy a limited area while standing comparing to currently existing wheelchairs. However, it has the disadvantage of being highly unstable in the standing mode due to the continuous change of the location of the centre of mass of the person which leads in turn to a significant energy consumption at the start of motion as well as the risk of being fallen down.

3.2. Second conceptual design

The second design option appears in Figure 8 is a modified version of the previous design where two small caster wheels are added at the rear side of the wheelchair to gain more stability. Two more pair of motors needs to be added to the wheelchair legs to separate them from the wheels in order to provide a reaction force to the patient movements instead of letting the wheel's motors trying to stabilize the wheelchair. This modification will overcome the problem of instability associated with the inverted pendulum configuration in addition to it will provide the wheelchair with more safety while changing between sitting and standing modes. Both previous design alternatives; Figures 7 and 8, are equipped with a geared system to change between the chair base and the lower legs of the wheelchair. Although this option offers the same function of the STS transformation; it is still suffering from the instability condition while performing the transformation. This design was rejected because of the high energy consumption due to using six motors. In addition; the motors have to be always in the active mode in order to keep the system stable. Furthermore; this configuration is considered to be a double inverted pendulum.

3.3. Third conceptual design

In order to overcome the problems associated to the first two alternative designs; an enhanced proposed design is shown in Figure 9 where each rear leg is composed of two links. The lower part of wheelchair comprises four wheels and four legs. This design offers better stability if compared to

Figure 7. First design alternative.

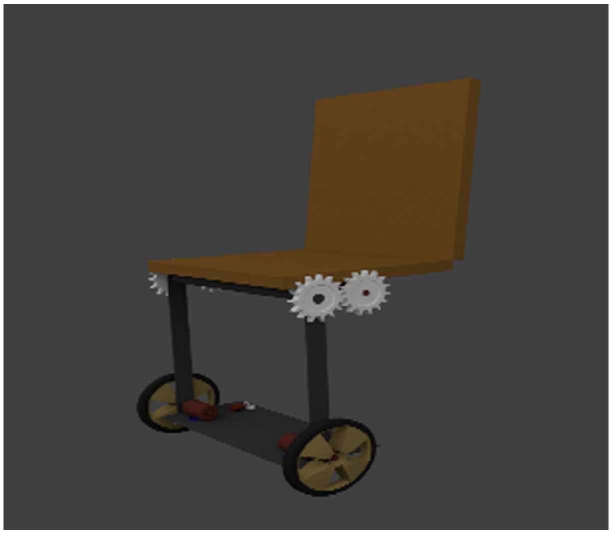
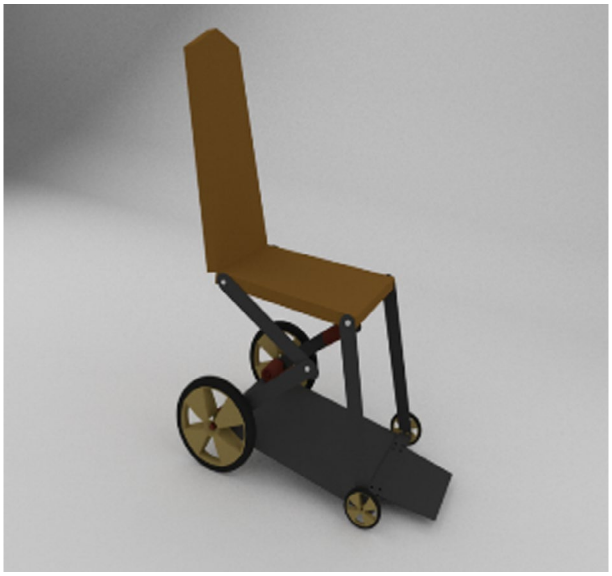


Figure 8. Second design alternative.

Figure 9. Third design alternative.



previously mentioned ones. In addition it will consume a relatively less power comparing to the other two alternative designs because the motors will be used only while transforming between sitting and standing modes.

Furthermore; the weight of the person will be distributed among the four legs which mean that only a one quarter of the body's weight will apply the force on the lifting motors. In order to justify the selection of the proposed final design; a summary, shown in Table 1, is presented to show the main differences between the three designs in terms of the working occupied space, power consumption and stability. The data available in this table has been verified based on simulations of the three design options under the same conditions of loading. Each individual design is tested in a simulation environment. Driving power is calculated for all actuators while considering same working time of the wheelchair, same loading and same working path.

3.4. Final design details

A wheelchair equipped with a STS mechanism is designed and realized that enables a child to be more independent and to change his/her posture when he/she needs to do so (Fadlallah & Goher, 2013;

Table 1. Comparison between the three alternative designs

Comparison	Power consumption	Working space	Stability
1st design	High	Small	Unstable
2nd design	Very high	Small	Low stability
3rd design	Low	Average	Stable

Figure 10. SolidWorks® design of the wheelchair.

(a) Sitting mode (b) Standing mode

Goher, 2013; Goher, Shafiq, & Al-Yahmadi, 2013). The wheelchair is designed using SolidWorks® CAD package as shown in Figure 10.

A design process is followed through all stages of the project following certain design constraints. Figure 11 represent the developed reconfigurable wheelchair. The mechanism enables the wheelchair user to transform from STS posture and vice versa as shown in Figure 12. The wheelchair will allow the user to use it as a mobility device as well as for rehabilitation purposes without any external support. In order to support the user while standing; the wheelchair is equipped with a leg stand which provides support while standing.

Figure 11. The developed wheelchair.

(a) Sitting mode (b) Standing mode

Figure 12. Wheelchair 1st generation—transition mode.

(a) Sitting mode **(b)** Partial standing I

(c) Partial standing II **(d)** Full standing

The final selected design, realized as shown in Figures 11 and 16, is taking care of threats and/or problems associated with the previously presented design alternatives. Two linear actuators are used on both sides of the wheelchair to adjust the back support. The wheelchair is undertaking various stages while transforming between sitting and standing as shown in Figure 12.

Detailed explanation of the implementation and the working principle of the linear actuators are illustrated in Figures 13–15. The developed prototype has the capability to support a weight of a 25 kg child and is equipped with a built in mechanism that transform the wheelchair user between sit and stand modes as per his/her desire.

Figure 13. First design option for back joint.

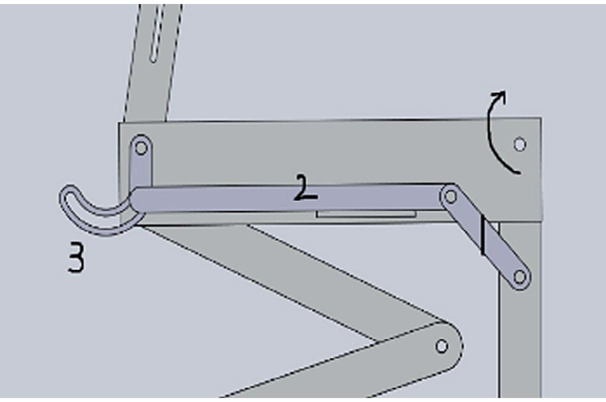


Figure 14. Linear actuator used to adjust the back seat.

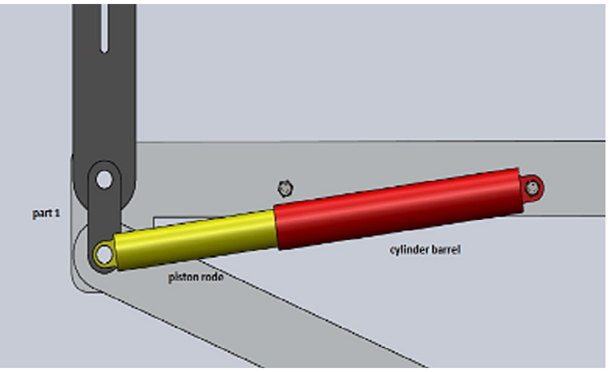
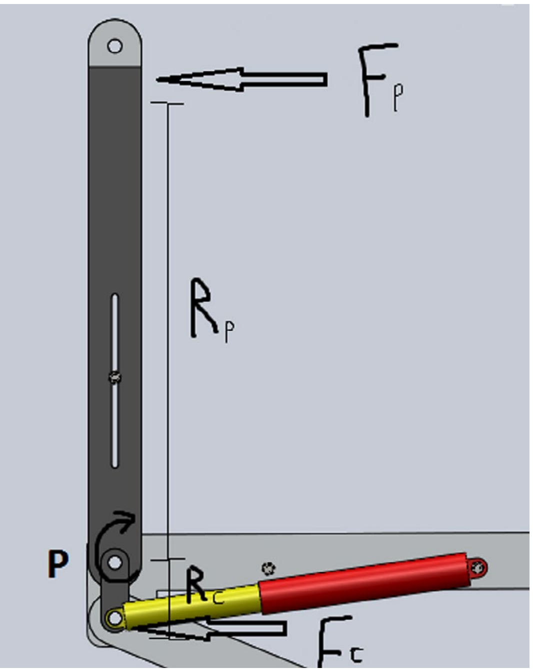


Figure 15. Moment equation for back seat.



3.4.1. Selection of the linear actuator

As appeared in Figures 13–15; part one is fixed to the back seat and connected to the linear actuator using a revolute joint and the actuator is connected to the seat using a similar joint. This design enables the patient to fully control the back angle as per his/her desire and comfort. However for the time being; this design will be only used to automatically adjust the back seat angle in sit/stand modes. For typical situation; the actuator will be fully extended in the sit mode and the linear distance that the piston rode will move, while changing to the stand position, is equal to the length of part 1 which is 4 cm. The force applied by the linear actuator can be calculated by equating the moments around the pivot point shown in Figure 15. This force is necessary to counteract the patient's pushing reaction force due to his/her back. The range of change the orientation angles of the chair and the lower legs are designed in order to allow the person with disability user to full stand; detailed values of those angles are shown in Table 2.

Since the linear actuator has to exert a minimum force F_a which is equal to the patient's force F_p; the moment due to the actuator's force has to be equal and opposite to the patient's moment.

3.4.2. Calculation of the user's force (F_p)

In order to calculate the patient's force F_p; a force sensitive resistor is used and placed on a solid surface at a distance equal to R_p from the ground. For the condition of light weight participants, a sample of six children, aged between 6 and 10 years old, is used to calculate the patient's force. Children are advised to lean on the solid surface, one at a time, where his/her body-exerted force is measured by the sensor. The sensor's output is found to be in the range between 0 for maximum force and 1,023 N for zero force.

In order to interpret the output readings of the sensor, all measurements have been calibrated and compared with loads with known weights. Table 3 summarizes the details of the children and their associated exerted forces. Considering the following; $F_p = 46.09$ N, $R_a = 4$ cm, $R_p = 37$ cm, the average force which was used to calculate F_a was calculated from the table to be $F_a = 426.33$ N which represents the minimum axial force required to be exerted by each linear actuator for the back seat.

Though the forces calculated in this section, this may not apply for general public and in particular older adults. World Health Organisation (WHO) (2014) defines overweight in terms of the body mass index (BMI) of weight-to-weight. In older adults, WHO defines overweight where the BMI is greater than or equal to 25.

Table 2. Angle comparison between sitting and standing modes

Comparison	Sitting mode	Standing mode
Angle 1	90	180
Angle 2	22.45	39.57

Table 3. Force measurement for the user's body

Age (year)	Gender (M/F)	Force applied
9	M	55.01
10	F	54.54
7	M	46.09
7	F	43.69
9	F	39.69
6	F	35.86

Table 4. Lifting motor specifications

Voltage	12 or 24 V DC
Motor power	320 W
No load current	2.5 A (12 V), 1.2 A (24 V)
Rated current	24 A (12 V), 12.5 A (24 V)
Stall current	32 A (12 V), 17 A (24 V)
Torque	72 Nm
No load speed (rpm)	30 rpm
Rated speed	27 rpm
Gearbox ratio	50:1
Net weight (kg)/motor	4.5 kg

3.4.3. Wheelchair main parts

3.4.3.1. Ball bearings. Steel ball bearings are used to connect most of the links of the mechanism. The bearing size was decided to be with a diameter of 11 mm and a bore size of 5 mm. It supports a dynamic load up to 970 N.

3.4.3.2. Joystick. The joystick will be used to control the movement of the wheelchair. There will be one of them to control the driving motors and the other will be used to control the lifting.

3.4.3.3. Lifting motors. These motors will be used during the transition mode between sitting and standing. The technical specifications are illustrated in Table 4 where 72 Nm is the torque needed to make the transformation.

3.4.3.4. Driving motors. The two driving motors; responsible for forward/backward motion and maneuvering, have the following specifications: These are the specifications of the chosen motors:

- Working voltage: 12 V.
- Peak torque: 20 Nm.
- Motor speed: 160–180 rpm.
- Rated current: 16 A.

3.4.3.5. Motor drivers. Choosing the motor drivers was based on the lifting motors since they draw higher current than the driving motors. The specifications of the chosen driver are summarized as follows.

- It works on nominal voltage 6–30 V.
- It is equipped with 60 A continuous, 120 A peak per channel for few seconds.
- It can supply two DC brushed motors with up to 60 A each.

A motor driver or a motor controller is used as an output to the microcontroller to supply the motor with the required power to operate since the microcontroller gives an output voltage of 5 V that is not enough to start the selected motors. This driver can control two motors with dual directions. For this project, two drivers are used to control the four motors and the two actuators. The drivers communicate with the microcontroller serially with a baud rate of 38,400.

3.4.3.6. Battery. A Lithium Iron Phosphate 12 V, 20 Ah battery is chosen because of the safety issue and its light weight. As per the 1st generation of the wheelchair; the working time of the wheelchair is limited to half an hour and hence the chosen battery will be enough. Due to importing restrictions; the only option was to provide a battery from the local market.

4. Control of the wheelchair

As per Perrin, Chavarriaga, Colas, Siegwart, and Millán (2010); a semi-autonomous navigation strategy designed for low throughput interfaces with the aim of minimizing the user involvement with a robotic wheelchair is proposed. The navigation strategy tested both in simulation and with a real robot, and a feasibility study for the use of a brain–computer interface confirms the potential of such an interface. Leishman, Horn, and Bourhis (2010) proposed implementation of assistance to the driving of a smart wheelchair through a deictic approach. Lopes, Pires, and Nunes (2013) proposed assisted navigation system for a robotic wheelchair that is based on a semi-autonomous controller and requires two agents; a Human/User Agent (HA/UA) and a Machine Agent (MA), which need to collaborate to control the robot. Del Castillo, Skaar, Cardenas, and Fehr (2006) developed a computer controlled navigation system for a powered wheelchair. The objective of his research is to give a certain level of autonomy to persons who have lost the use of their legs and lack the necessary coordination to manipulate the joystick or other user-input device of a motorized wheelchair. In the following section; the control system for the STS transfer will be discussed. Furthermore; the components, circuits and connections will be explained in detail.

4.1. Flow chart of the system

The flow chart shows the scenario of how the system of the reconfigurable wheelchair works. As shown in Figure 16, at first when the system is turned on, it will check what mode has been chosen by the user. The user has the ability to choose between two modes: lifting mode and driving mode.

4.1.1. Lifting mode

If the user chose the lifting mode, first the system will check if the seatbelt has been fastened or not. If the seatbelt is fastened the system will take the readings from the joystick and will lift the reconfigurable wheelchair up and down according to the commands giving from the joystick. And if the seatbelt is not fastened the reconfigurable wheelchair will not move until the seatbelt is fastened.

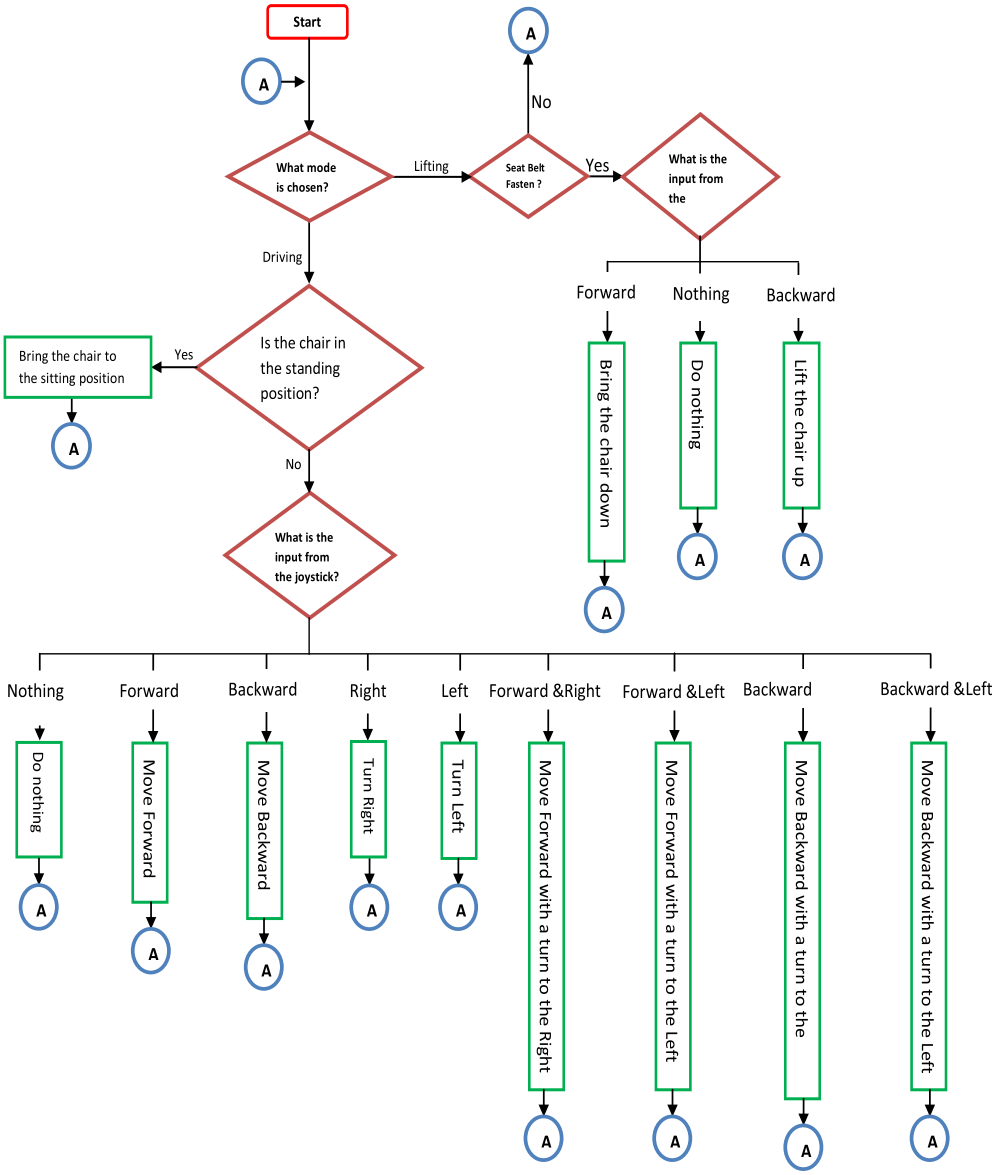
4.1.2. Driving mode

If the user chose the driving mode, before the system goes to the driving functionality (moving the wheelchair forward and backward) it will first check if the position of the chair is in the stand or sit position (this will be checked by the magnetic sensors that will be explained in details in the safety issues). If the wheelchair is in the standing mode, the control system will bring the wheelchair to the sitting position first and then it will proceed with the driving functionality, if it was in the sitting position it will proceed to the driving functionality. The movement of the reconfigurable wheelchair will be controlled by the joystick from the remote of the system. Driving commands will be explained in details in the components section. This all is controlled using the arduino, the code is provided.

4.2. Joystick working principle

The joystick is selected to control the movement of the four motors; the two lifting and two driving motors. The joystick is considered to be an input to the system where it consists of two potentiometers, one controls the vertical direction and the other controls the horizontal direction by moving the stick. When the stick is moved vertically or horizontally the values of the potentiometers change respectively and give an analogue signal (0–1,024) to the arduino. This signal is used to control the direction of the motors. Figure 17 shows the axis of movement and the corresponding commands that are given to the motors for driving the wheelchair, where the arrows show the direction of the joystick. In case of lifting the wheelchair, the directions forward and backward of the joystick will be as the command for sit and stand. A tolerance is taken into consideration in reading the values of the joystick, for some stability issues.

Figure 16. Control flow chart of the wheelchair.



4.3. Push buttons

Four push buttons are used to limit the motor from rotating when the wheelchair is fully standing or fully sitting and while occupant is trying to exceed that limit. Two push buttons are attached to the base of the wheelchair and will give a high signal when the chair is in the sitting mode as the links will be pressing on them. The other two push buttons are attached to each of the two front legs of the wheelchair and will give a high signal when the chair is in the fully standing mode as the links will be pressing on them.

Figure 17. Joystick input and corresponding commands.

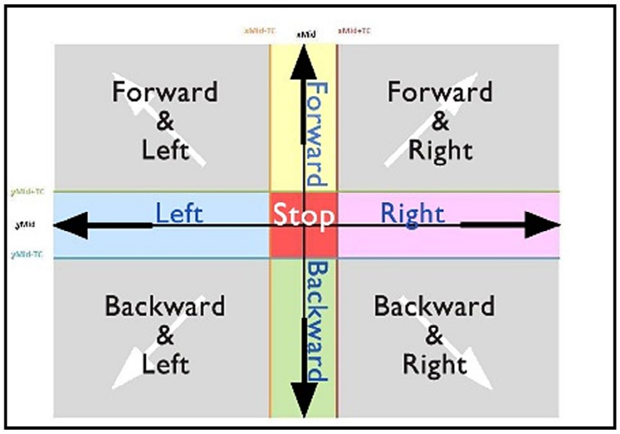
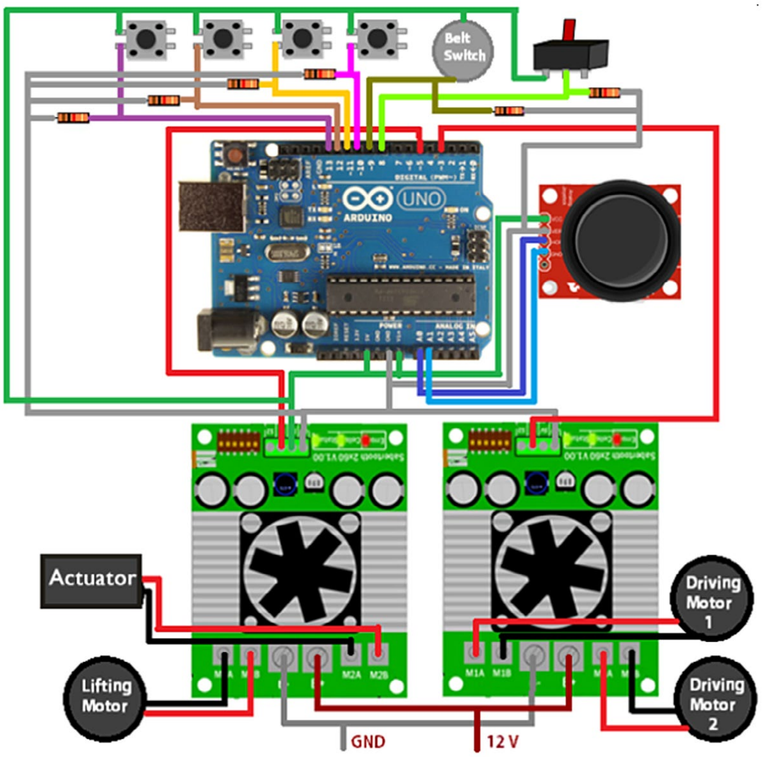


Figure 18. System full circuit.



4.4. Full circuit connections

The circuit shown in Figure 18 describes the connection of all components with the arduino. In addition, two light emitting diodes (LED) with different colors are connected to pins 6 and 7 on the arduino to indicate whether the seatbelt is fastened or not so that the chair can move from STS mode.

5. Safety design facilities

Most wheelchairs are not designed to sustain crash-level forces encountered during motor vehicle accidents. Typically, the characteristics that make wheelchairs user-friendly are sometimes those factors that make wheelchairs inappropriate for effective safe seating during transportation on buses or vans. For example, ultralight wheelchairs may not have brakes or armrests. Lack of brakes and armrests makes it difficult to stabilize the wheelchair occupant during transportation (Bertocci & Hobson, 2009). According to the national highway traffic safety administration; an estimated number of 1,500 persons who use wheelchairs are injured or killed nationally from wheelchair transportation accidents (Shaw, 2000). The wheelchair developed in this research has considered number of design safety considerations which ensure the safety of the user. The following sections represent detailed explanation of two main safety features that are considered in the developed device.

5.1. Limit switches for the wheelchair positions

Magnetic sensors are used to act as the limit switches for the wheelchair positions. Figure 19 shows the two parts of the magnetic sensor. Figure 20 shows the connection and the output of the magnetic sensor when it is activated or not. It is clear that when the sensor is far from the actuator the internal switch is still opened and when the actuator is close to the sensor, the sensor is energized hence the internal switch closes and works as a closed circuit which gives a 5 V output.

For the sitting position two magnetic sensors are sticked on the wheelchair link as shown in Figure 21, the sitting position will activate the magnetic sensor which will act to stop the motors from lifting down the wheelchair further more.

Figure 22 above shows the placement of the magnetic sensors to sense the fully standing position. This will help in stopping the motors from lifting up the wheelchair further more.

5.2. Seatbelt safety system

A circuit was designed inside the buckle of the seatbelt to insure that the seatbelt is fastened before activating the wheelchair transforming from sitting to standing to lift the person with. This system

Figure 19. The magnetic sensor.

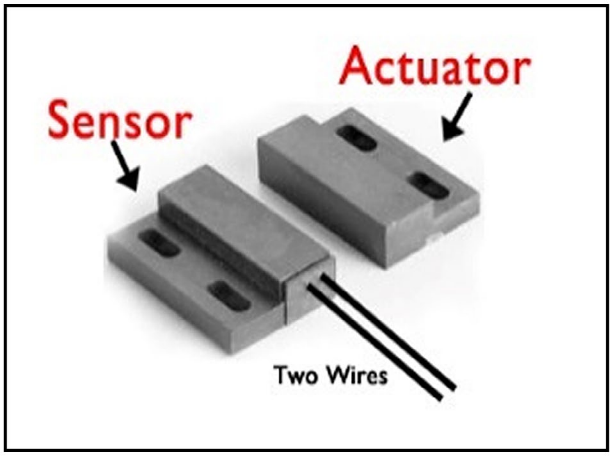


Figure 20. Connection and corresponding output of the magnetic sensor.

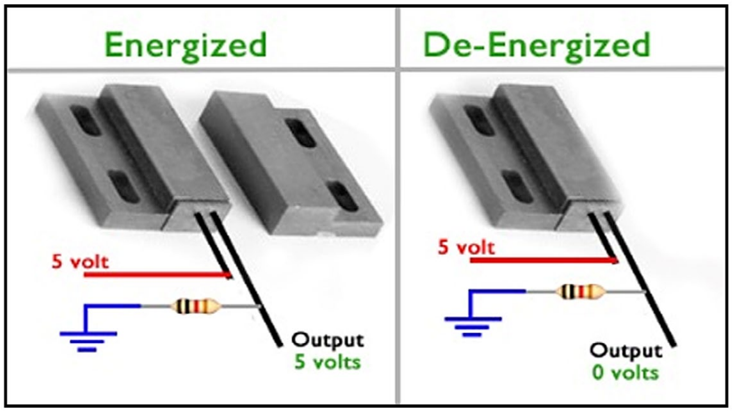


Figure 21. Magnetic sensor for sensing the sitting position.

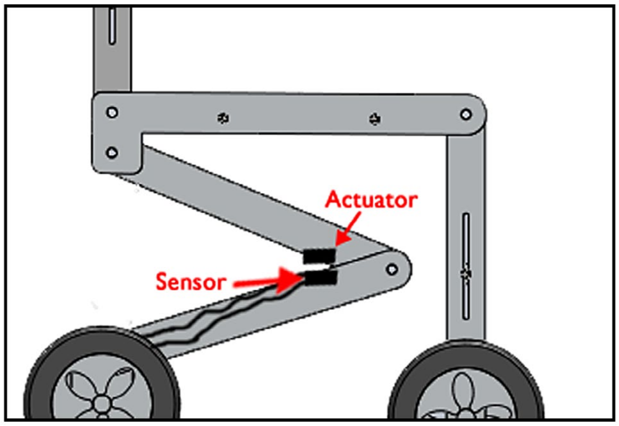
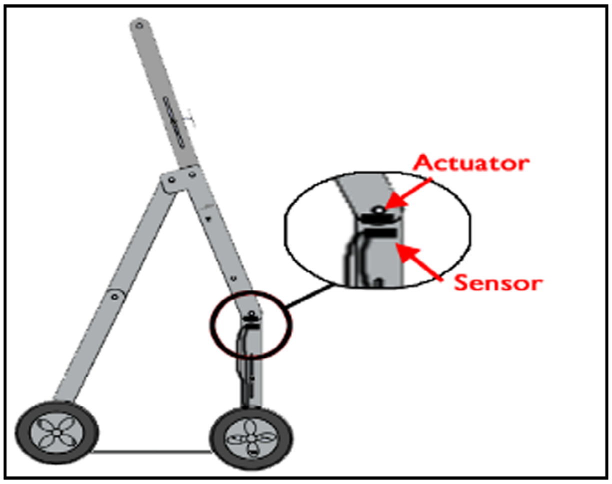


Figure 22. Magnetic sensor for sensing the standing position.

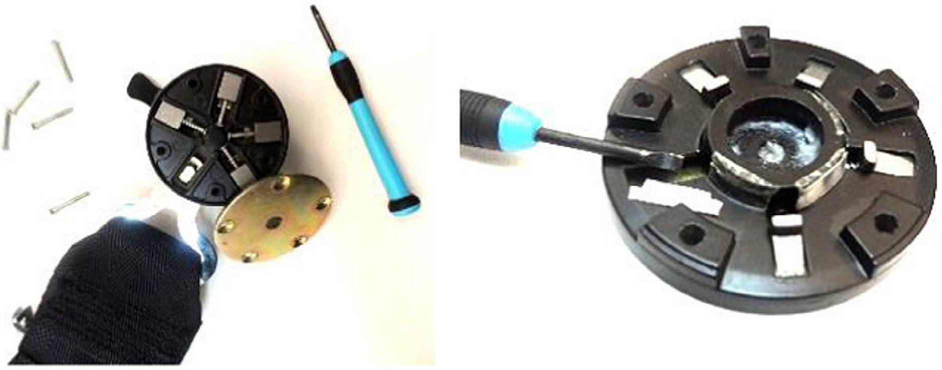


adds a value to the design of this wheelchair as it concerns about the users safety and avoid slipping or falling accidently. The system consists of a simple open circuit made by thin aluminum sheets. The circuit is opened were the end members of the belts enter. When all the end members are fastened, the circuit closes and gives a high signal. This signal is added to the program to control when the lifting motors can start moving. In addition, two LEDs were programmed; green to indicate that the seatbelt is fastened and red to indicate that it is not.

5.2.1. Seatbelt safety circuit

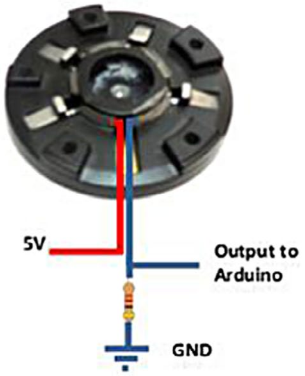
First, the seatbelt buckle was opened to fix the connections Figure 23(a). After that, aluminum sheets were fixed in the buckle as shown in Figure 23(b). One end of two aluminum sheets was connected to a flexible wire to power the circuit and make it work. These two sheets were fixed one in the beginning and one in the end of the aluminum sheets loop and were connected as shown in Figure 23(c) and finally the buckle was re-assembled again.

Figure 23. Seatbelt wire connection.



(a) Seat Belt Buckle Un-Assemble

(b) Fixing Aluminum Sheets in the Buckle



(c) Seat Belt Wire Connection

6. Conclusion and future work

In order to design the wheelchair with a STS facility; number of design options have been proposed and investigated in terms of stability, energy consumption and the occupied workspace. The design with better evaluation has been refined while ensuring ease of manufacturability, functionality, ease of use and less energy consumption. The realized wheelchair has the capability to support the weight of a 25 kg child and is equipped with a built-in mechanism that transforms the wheelchair user between sitting and standing modes as per his/her desire. The design has also considered number of design safety issues which ensure the safety of the user. The STS and back seat adjustments are the main features added to the design. Those features will help the user to make regular exercises for his back and the whole body. This will help in enhance blood circulation and muscle strength.

Numbers of problems have been observed while working on the first generation of the wheelchair. The following are examples of problems that yet need to be investigated:

- *Controlling the linear actuators*: The back seat was not able to reach the proposed position because of the lack of power supply that they are powered and excited together with the lifting motors. A feedback system will be required to get the current position of the back support of the wheelchair and accordingly adjust the posture of the patient at all times.
- *Manoeuvring problems:* Since the wheelchair is small in size and the wheels are relatively large; this affects its manoeuvring capabilities the due to the high frictional resistance with the floor. The optimum size of the wheels needs to be more investigated.

- *Resizing the skeleton:* More investigation needs to be done on resizing the skeleton material. The wheelchair skeleton comprises Aluminum bars with 12 mm thickness; reducing the links thickness to 8.0 mm will allow reduction of the wheelchair weight by 30% which in turn will reduce the energy consumption.

Future work of the project includes: control of the wheelchair of the STS speed in order to regulate the power consumption, control of the back seat which reconfigure the wheelchair to a full laying mode, taking care of the high jerky behaviour noticed while transition between STS and during manoeuvring by regulating the control input and testing the wheelchair on different terrains. As a further improvement for the wheelchair, two main features are underway including the swinging of the back seat that allows the user to adjust his back and a lower leg rehabilitation mechanism which can be used to exercise lower legs and ankles.

In addition, there are other technical areas of research that need to be addressed including the following:

- Arduino is a simple controller with limited computing power and has been used at the initial development and testing of the device. However, it is not well suited for the final application. We intend to use other controllers with more computing power.
- No research has been carried out yet to ensure that CPU works properly. Safety system directly connected to the motors will be considered. We think that it may be not enough to control power bridge by CPU only; additional circuit based on electrical contactors may be used to increase safety level. More advanced safety system need to be used to ensure safe operation of the device.
- In initial development we used skid-steering locomotion system. However, fixed wheels may be used instead of the caster wheels.

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