March 06, 2008

Patrick Leung
School of Engineering Science
Simon Fraser University
Burnaby, British Columbia
V5A 1S6

Re: ENSC 440 – Design Specification for a Wheelchair Stability and Pressure Relief System

Dear Mr. Leung:

The enclosed document, *Design specification for a Wheelchair Stability and Pressure Relief System*, outlines the set of technical requirement for design of our product. The goal of our team is to design a system that has the ability to move the body sideways and out of danger in a tipping situation and provides substantial and effective controlled pressure relief for disabled people with limited upper body mobility.

This document is dedicated to the detailed discussion of design specification of our product. The specification described in this document only applies to our first stage of development which is proof of concept model.

Safe Sense Technologies consists of three fifth-year engineering science students: Jamie Westell, Arash Jamalian, and Shadi Agha Kazem Shirazi. Please feel free to contact me with any questions or concerns regarding our design specification. I can be contacted by phone at (778)889-2310 or by email at saghakaz@sfu.ca. Our team can also be contacted via email at ensc440-spring08-safesense@sfu.ca.

Sincerely,

Shadi A.K Shirazi
President and CEO
Safe Sense Technologies

Enclosure: *Design specification for a Wheelchair Stability and Pressure Relief System*

DESIGN SPECIFICATION FOR A WHEELCHAIR STABILITY AND PRESSURE RELIEF SYSTEM

Project Team: Shadi A.K. Shirazi
Arash Jamalian
Jamie Westell

Contact: ensc440-spring08-safesense@sfu.ca
saghakaz@sfu.ca

Submitted to: Patrick Leung
Steve Whitmore
School of Engineering Science
Simon Fraser University

Date: March 6th, 2008

Version: 1.0

EXECUTIVE SUMMARY

The stability and pressure relief are two vital issues wheelchair users with impaired upper body balance are facing every day. *Equipoise* is an active system which has the ability to move the body sideways and out of danger in a tipping situation and it can also alleviated the development of pressure sores. Safe Sense technologies is confident that *Equipoise* will provide its users a higher degree of comfort and security, and allow incapacitated individuals to engage in their day to day activities with a greater sense of comfort and liberation.

This document outlines the design of the *Equipoise* system. It provides the set of detailed description for the first stage of development, the operational prototype for proof of concept. Therefore, only the design of functions related to functional requirement marked (I) as specified in the document, *Functional specification for wheelchair stability and pressure relief system* will be discussed.

The proof of concept model of Equipoise system consists of 5 main components:

- A linear actuator for moving the upper body of the user
- A linear encoder for positioning adjustment and speed detection
- An Inclinometer for detecting the tilt angle of the wheelchair from the ground
- An H Bridge for controlling the speed and direction of the Linear actuator
- A Microcontroller to read system inputs, apply control algorithm and produce commands for the linear actuator.

The detailed description of each component and their related functions, system overview, system structure, power and signal processing circuitry and user interface and general software program flow are provided in this document. A description of test plans for the system is also provided at the end of the design specification.

Safe Sense Technologies is committed to the production of *Equipoise* by the scheduled date, April 6th, 2008. By this date the design of the first stage of development of the *Equipoise* system will be completed.

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GLOSSARY

Equipoise The product name of the Wheelchair Stability and Pressure Relief System outlined in this document

PRM *Pressure Relief Mode*. This mode of operation is used to relieve the pressure from the user's seat and to enhance blood flow. Pressure relief leads to a lower risk of developing pressure ulcers (bed sores) and greater overall health of the user.

PWM *Pulse Width Modulation*. This type of signal is used to control a DC motor. A square wave is generated from a DC signal with a specific duty cycle. Increasing or decreasing the duty cycle (modulating the signal) increases or decreases the speed of the motor respectively.

WSM *Wheelchair Stability Mode*. This mode of operation is used to protect the user from a potential tip situation. When a dangerous position is sensed based on the angular tilt of the wheelchair and the position of the users body, the WSM will react to pull the body away from danger in order to avoid a fall or lessen the impact of the fall.

1. Introduction

Equipoise is an active system which has the ability to move the body sideways and out of danger in a tipping situation. It is common for wheelchair users with limited upper body mobility to be involved in tips and falls. Tipping occurs when navigating over sidewalk curbs, when meeting an immovable obstacle, when the user is reaching awkwardly and when the user suffers from sudden muscle spasms. In any one of these circumstances, the individual is rendered helpless and the accident inevitably follows. *Equipoise* will reduce these innate dangers by moving the person in the opposite direction of the tip and in so doing, help prevent the fall.

Equipoise, over the longer term, provides substantial and effective, controlled pressure relief. Pressure relief comes naturally to able bodied individuals. By moving the helpless individual's body, very gently, from side to side, *Equipoise* can help prevent skin break down, as well as keep the skin tissue healthy.

Equipoise requires less power than products currently on the market which are designed on the tilt and interpolation of the chair itself. The latter are large and heavy and require an excessive use of power. *Equipoise* simply moves the body rather than the chair and therefore does not consume as much power as its rival designs. The *Equipoise* apparatus is much smaller and lighter than any other present design; as a consequence, *Equipoise* has proven to be far more cost effective for both the manufacturer and the consumer.

1.1 Scope

The task of developing *Equipoise* is divided in to two main stages: the proof of concept stage and the production model stage. This document is intended to describe the design specification for the proof of concept model of *Equipoise*. Some minor design consideration for production model is included. The design and technical information outlined in this document will be used in implementation and testing process of *Equipoise.*

1.2 Intended Audience

This document is intended for use by Safe Sense technologies members only. It is intended to ensure that the development of *Equipoise* is following the correct design path.

Design engineers will use this document to assure that the implementation of *Equipoise* will meet all of the requirements set out in functional specification document. The testing team will use it to verify the functionality of the system. Project manger will use this document for project performance estimation and milestone scheduling.

In future, this document can also be used by marketing and sales personals to arrange sales strategies.

2. System Overview

In this section of the document, a general system overview of *Equipoise* will be discussed. As it has already been mentioned the two main functions of *Equipoise* system are Tipping stability and pressure relief.

In pressure relief mode, the user's upper body will be moved by a linear actuator from natural to the sides every 15 minuets. In this mode of operation, the movement begins from natural position and end when the upper body is moved 12 centimeters to one side. Each time, the upper body will be kept at leaning position for 2 minutes and then moved back to natural position. The duration to move the person form natural to sides or vice versa will be between 20 seconds to 1 minute. During the movement, the control system within *Equipoise* will keep the speed constant and very slow so that it is unobtrusive and independent of user's mass or any external disturbances. After power reset, the system will start again from natural position.

In tipping stability mode, The *Equipoise* system will obtain the wheelchair tilt angle from the ground by an inclinometer which is fixed to the body of the wheelchair. Once the wheelchair tilt angle is greater than certain threshold value, the user's body mass will be shifted to the opposite side by X centimeters, where X is proportional to the tilt angle. The upper body will be kept at that location until the danger of tipping is removed. In so doing, the *Equipoise* system will help to keep the wheelchair's centre of mass within the wheelchair foot print. The speed of movement will be proportional to the tilting speed of the wheelchair and the response time will be sufficient enough to prevent tipping or injury from tipping.

In the proof of concept model, the tilt angle is specified only for the certain type of wheelchair which will be worked with, but in the second stage of development, threshold angle will be adjustable to take into account the person's height and the wheelchair's structure.

The three fundamental inputs of *Equipoise* system are orientation of the wheelchair (tilt angle), the position of the body within the wheelchair and user inputs. These informations will be provided to the system through inclinometer, linear encoder, and user interface respectively.

The power to the system will be provided by a 12 volt battery. The power consumption of *Equipoise* system will be always kept at minimum when the linear actuator is not active.

The *Equipoise* system provides it's users a user interface consisting of four switches. These switches can be easily integrated to other kinds of user interface such as sip/puff control, voice recognition control or head movement control.

3. Structure Overview

Figure 1 and Figure 2 depict the structural design of *Equipoise* in the first stage of development. In this stage, the wheelchair that will be worked with is a manual wheelchair which was donated to Safe Sense Technologies from GF Strong Rehabilitation Centre. This wheelchair is similar to the wheelchair shown in these figures.

The main components of *Equipoise* system are: Linear actuator, Linear Encoder, Inclinometer, H Bridge, microcontroller and 12v battery. The linear actuator and linear encoder are mounted on the back seat of the wheelchair as is shown in figure 1. A battery box is designed to be mounted underneath the seat and the circuit box containing the H Bridge, microcontroller and inclinometer is located at the lower back of the wheelchair.

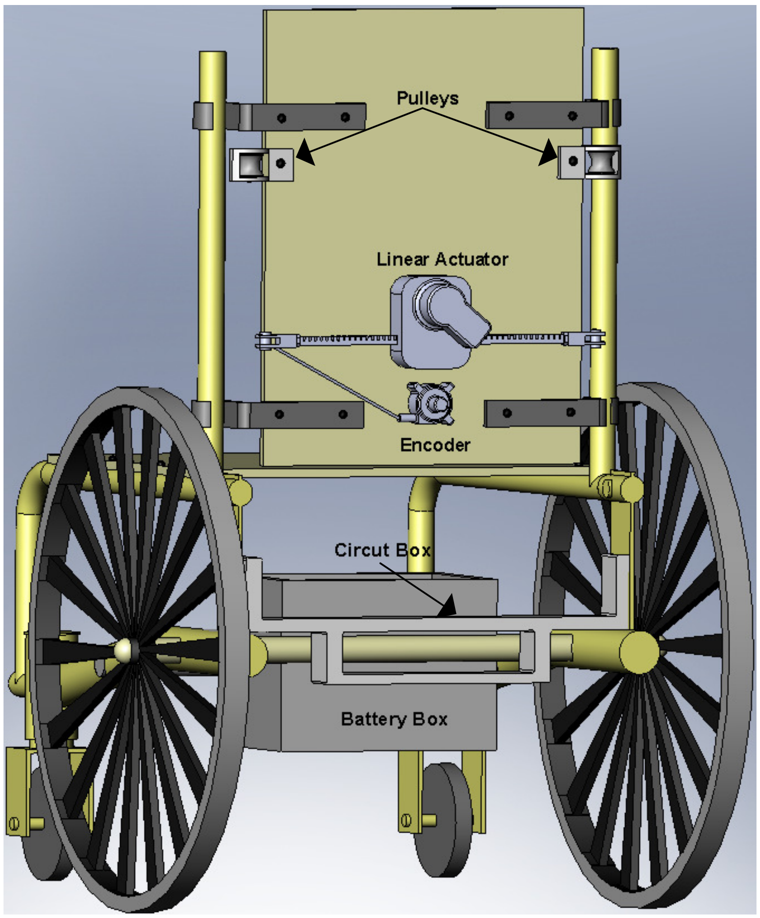

FIGURE 1 STRUCTURAL DESIGN (BACK VIEW)

The purpose of the linear actuator is to move the upper body of the user sideways. *Equipoise* system uses a DC motor coupled to the rack and pinion as a linear actuator. The two ends of the rack are connected to the chest harness by means of thin but strong ropes. The purpose of two side pulleys shown in figure 1 are for imposing a horizontal force on user's upper body. As the DC motor actuates the rack to the right the body will be moved to the left and as the rack is moved to the left the body will be moved to the right.

The two critical objectives of using linear encoder are to obtain information about the position of the body within the wheelchair and detect the motor speed in pressure relief and wheelchair stability mode. For the user's comfort and safety, it is important to run the motor proportional to the tipping speed in stability mode and at constant speed in pressure relief mode.

H Bridge and inclinometer are for controlling the speed and direction of the motor and obtaining tilt angle of the wheelchair from the ground respectively.

The Microcontroller is the brain of the system. It reads the system inputs, apply control algorithm and generates appropriate commands for the linear actuator.

Please refer to the following sections for the detailed description of each of these modules and their related functions.

As it has been mentioned before, *Equipoise* system also provides it user a user interface. This user interface consists of four switches which is located in front of the wheelchair. Figure 2 shows the front view of the wheelchair.

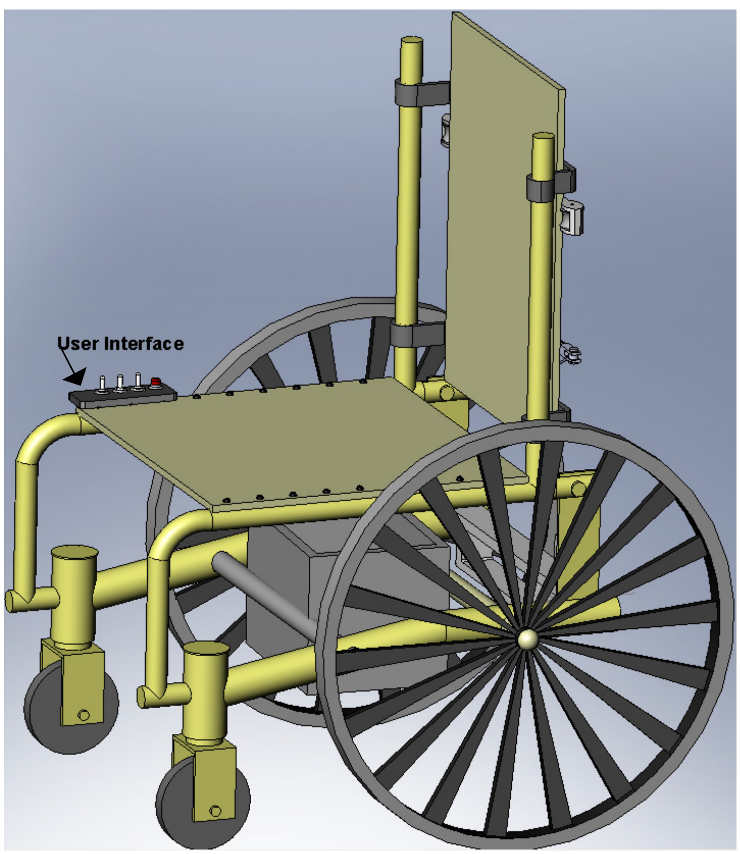

FIGURE 2 STRUCTURAL DESIGN (FRONT VIEW)

4. ACTUATION

A rack and pinion coupled to a DC motor is used for the actuation of the system. Figure 3 shows where the rack and pinion is mounted on the wheelchair. The rack and pinion is required to turn the rotary motion of the motor into linear motion.

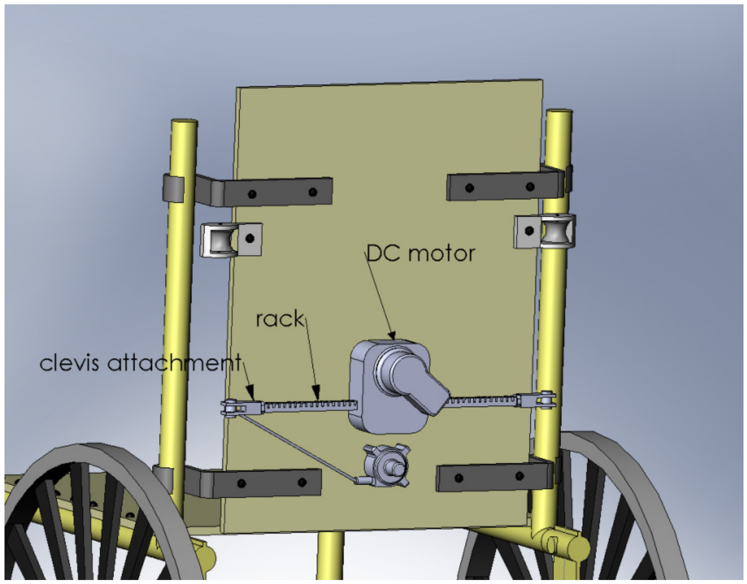

FIGURE 3 ACTUATOR MOUNTED ON THE BACK OF THE CHAIR

The actuator is mounted on the back of the chair to provide efficient output linear force without extra mechanical linkages. The total weight of the actuator is 5 lbs. The light weight is necessary to prevent instability when the wheelchair is moving up a ramp. If the motor was heavy, the centre of mass of the wheelchair would be moved too much to the back causing accidents for the user.

4.1 RADIUS OF THE PINION

Radius of the pinion is chosen based on the requirement to output 100lbs of linear force. At maximum load, the motor will be run at 13 Amps to have sufficient rpm. The complete calculations for the motor are shown in the next section. At 13 Amps, the motor output torque is 5.1 Nm. Therefore,

$$F = \frac{T}{R} \tag{1}$$

$$F = \frac{5.1Nm}{0.0114m} = 446.19\ N = 100.31\ lbs \tag{2}$$

where

F = Linear output force required

R = Radius of the pinion from center of drive shaft to contact point on rack = 0.45 inches = 0.01143 meters

T = Motor output torque (from the motor current/torque plot shown in the next section).

4.2 Cross sectional area of the rack and pinion

To ensure the safety of the user, the cross section area of the rack and pinion should be large enough to withstand the output linear force. The rack and pinion is made of steel. The compressive yield strength for this material is around 275MPa. For this design, with a safety factor of 1.5, the allowable compressive yield strength will be

$$\sigma_{alloable} = 183\ MPa \tag{3}$$

The compressive stress on the rack caused by the linear force tangent to the pinion is

$$\sigma = \frac{F}{A} \tag{4}$$

where A is the cross sectional area. Therefore,

$$\sigma_{actual} = \frac{446.19N}{2.1 \times 10^{-5} m^2} = 21\ MPa \tag{5}$$

$$\sigma_{actual} < \sigma_{allowable} \tag{6}$$

4.3 Length of the rack

Figure 4 shows the rack and pinion in centre position.

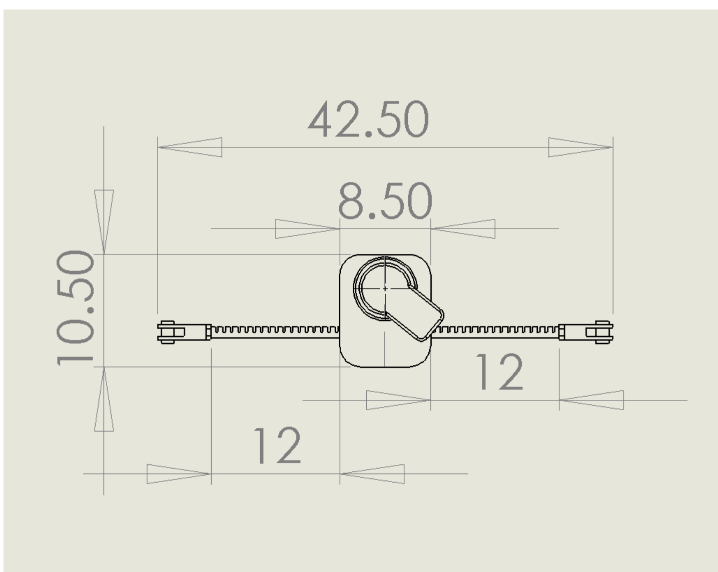

FIGURE 4 ACTUATOR IN CENTER POSITION (DIMENSIONS IN CENTIMETERS)

The stroke of the rack is chosen to be 12 cm based on Dr. Andrew Rawicz. Since the rack has to travel 12 cm to each side, the total length of the rack required is:

$$Total\ length\ of\ the\ rack = 2 \times stroke\ length + Length\ of\ the\ motor\ case \quad (7)$$

$$Total\ length\ of\ the\ rack = 2 \times 12cm + 8.5cm = 32.5cm \quad (8)$$

Note that the total length of the rack is chosen not to exceed the width of the wheelchair.

4.4 End joints

To connect the ropes to the rack, there are two clevises attached to both ends of the rack. The clevis attachments are made of aluminum with flexural strength of 173MPa. For our design, with a safety factor of 1.5, the allowable flexural strength will be

$$\sigma_{alloable} = 115\ MPa \quad (9)$$

The flexural stress on the clevis bar is

$$\sigma_{flexural} = \frac{3Fl}{D^3 \pi^{3/2}} \quad (10)$$

Where

F = Linear output force

D= Diameter of the clevis bar

L = length of the bar

Therefore,

$$\sigma_{actual\ bearing} = \frac{3 \times 446.19N \times 0.016m}{\pi^{3/2} \times 0.009^3 m^3} = 5.28MPa \quad (11)$$

$$\sigma_{actual} < \sigma_{allowable} \quad (12)$$

4.5 Locking

The rack and pinion is self locking by virtue of mechanics of the drive. The lock can not be removed with manually pushing or pulling rack. The locking mechanism is required to safely remove the motor power when the user is at a desired position. When the wheelchair is tilted, the motor does not have to stay engaged once the upper body is at a safe position. In pressure relief mode, it is necessary to keep the body at the desired position for effective pressure relief. By having the self locking mechanism, we can turn off the motor between posture changes to save power.

Note that, the user can always manually adjust the position of the rack using a joystick.

4.6 DC motor characteristics

Figure 5 shows the speed/torque and current/torque characteristics of the 12 V DC motor.

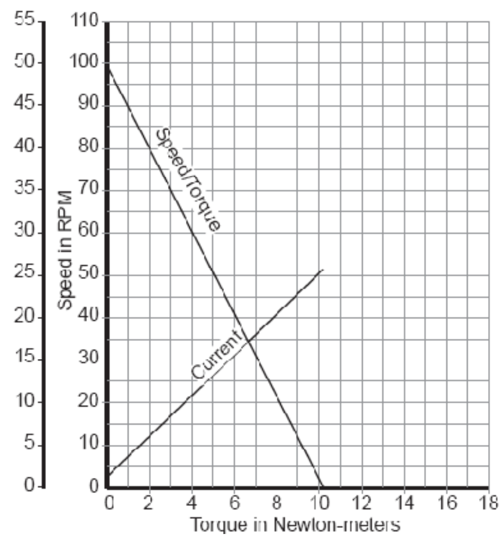

FIGURE 5 CHARACTERISTICS OF AM EQUIPMENT 12 V DC MOTOR

Experimental results show that the maximum speed of the rack with no load is 11cm/sec. The motor speed on RPM at that speed will be

$$speed(RPM) = \frac{speed(m/sec)}{2\pi \times R} \times 60\ sec/min \tag{13}$$

$$speed(RPM) = \frac{10}{2\pi \times 0.01143} \times 60 = 91.9\ RPM \tag{14}$$

Based on the speed/torque characteristics plot, the motor has to overcome an internal 0.5 Nm torque. The internal torque is due to the friction between rack and pinion, and the inertia of the pinion.

The operating point of the motor depends on the torque required (user's weight and acceleration), and the speed of the operation. For the pressure relief mode, the motor is running at very low speed providing a maximum of 5.1 Nm torque to move the user (100 lbs of linear force). The current required by the motor will be 13 Amps. In this mode, we design the system to move at a constant speed of 1 cm/sec independent of the weight of the user. The motor speed in RPM will be

$$speed(RPM) = \frac{0.01}{2\pi \times 0.01143} \times 60 = 8.355\ RPM \tag{15}$$

Based on the speed/torque plot, for pressure relief mode, the motor operating point of the motor is well within the operating region.

In stability mode, the speed of the motor will depend on how fast the wheelchair is tilting. The maximum current supplied to the motor is 20 Amps. Since the motor gets engaged for stability in few seconds, it is reasonable to draw 20 Amps from the H-bridge driver if needed. The motor can provide 7.8 Nm torque at 20 Amps with a speed of 40 RPM (4.79 cm/sec). In this case the maximum output linear force provided by the motor will be:

$$F = \frac{T}{R} \quad (16)$$

$$F = \frac{7.8Nm}{0.0114m} = 684.21N = 153.8\ lbs \quad (17)$$

Note that, in this mode the system must have relatively high acceleration to compensate the tipping acceleration; therefore, there will be a limit on the controllable tipping accelerations depending on the weight of the user ($F = ma$). On the other hand, the motor not only has to provide enough acceleration, but also enough speed to safely bring the upper body to a safe position; therefore, the maximum controllable tipping speed decreases as the torque required increases; When the motor is delivering the maximum torque (7.8Nm), the maximum speed of operation is 22.5 RPM. The following sample calculations show the maximum tipping speed for a particular user:

User's upper body mass: *50Kg*

Tipping acceleration: $10m/s^2$

The stability mode becomes active above a certain threshold angle; therefore the actuator gets engaged when the upper body is at that angle with respect to the ground. The threshold angle is chosen to be 15 degrees for the calculation.

$$F_{required} = 50Kg \times (9.8 + 10)m/s^2 \times \sin 15 = 256\ N \quad (18)$$

$$T_{required} = F_{required} \times R_{pinion} + T_{inernal} \quad (19)$$

$$T_{required} = 256N \times 0.0114m + 0.5Nm = 3.421\ Nm \quad (20)$$

$$I_{required} = 10\ Amps \quad (21)$$

Based on the speed/torque plot, the maximum speed of motor will be 65 RPM; therefore the maximum speed of the rack will be

$$speed(m/sec) = speed(RPM) \times 2\pi \times R_{pinion}/60 \quad (22)$$

$$speed(m/sec) = 65 \times 2\pi \times \frac{0.01143}{60} = 0.0778\ m/sec = 7.78\ cm/sec \quad (23)$$

Table 1 summarizes the operating parameters of the motor in pressure relief and stability mode

TABLE 1 DC MOTOR OPERATING PARAMETERS

Mode	Maximum output torque(Nm)	Maximum output linear force(N)	Maximum operating current(A)	Maximum speed of the motor (rpm)	Maximum speed of the rack (cm/sec)
Pressure Relief	5.1	446.19	13	8.4	1
Stability	7.8	684.21	20	22.5(max torque)	2.69(max torque)

5. Sensors

The equipoise system requires two physical quantities to be sensed and processed in order for it to respond properly: the lateral angle of inclination of the wheelchair and linear position of the rack & pinion motor.

5.1 Inclinometer

To obtain the lateral angle of inclination, an inclinometer is required. The Equipoise system uses the VTI Technologies SCA1T inclinometer. This is a 3D-MEMS based single axis inclinometer which features low temperature dependence and low noise output. Although this inclinometer features a serial peripheral interface (SPI), the Equipoise system utilizes only the ratiometric analog output included on the chip. The inclinometer is an 8-pin surface mount chip which for prototype reasons has been soldered to a proto-board and mounted to the wheelchair level to the axis of the wheels. Three of the pins are used to generate the analog output. The VCC and GND pins are connected to 5V and 0V respectively and the output pin provides an output voltage proportional to the tilt angle of the chip. For example, when the chip is level, the output is 2.5V, when the chip is tilted by 90 degrees, the output voltage increases to 5V and when the chip is tilted by -90 degrees, the output voltage decreases to 0V. Figure 6 shows the physical appearance of the SCA1T inclinometer.

FIGURE 6 VTI TECHNOLOGIES SCA1T SINGLE AXIS INCLINOMETER (WWW.VTI.FI)

The output signal of the inclinometer is connected to a 10 bit Analog/Digital converter on the microcontroller which converts the voltage to an integer value between 0 and 2^{10} (1024). Thus, the angular reading of the inclinometer is accurate to

$$\frac{180°}{1024} = 0.176°. \tag{24}$$

5.2 Linear Encoder

Part of the Equipoise system requires velocity control for the rack & pinion motor. In order to control the motor, the system must know the position and velocity of the motor and thus a linear encoder is required. There are several options for encoding the movement of the motor. The most commonly used sensor is a rotary encoder attached to the axis of rotation of the motor. With this application, a change in position of the motor generates a series of pulses which the microcontroller can use to calculate position change and velocity. One critical requirement of the Equipoise system is that the user may turn off and on the system at any time if they feel uncomfortable. With a rotary encoder, however, once power is lost and regained, there is no memory of the current position of the motor. This creates the requirement for an absolute encoder, one which outputs an accurate position value immediately after turning on.

The equipoise system uses the Celesco SP1-25 String Potentiometer. Also known as a draw-wire sensor or a cable extension transducer, a string potentiometer provides a ratiometric output voltage proportional to the extension of the cable. Figure 7 shows the physical appearance of the SP1-25 string potentiometer.

FIGURE 7 CELESCO SP1-25 STRING POTENTIOMETER (WWW.CELESCO.COM)

The string potentiometer has three terminals similar to the inclinometer. The VCC and GND terminals are connected to 5V and 0V respectively and the output terminal provides an output voltage proportional to the extension of the cable.

The SP1-25 contains a 25-inch stainless steel cable. On full extension of the cable, the output voltage is 5V while when the cable is fully retracted, the output terminal provides a voltage of 0V. The SP1-25 is therefore accurate to

$$\frac{25"}{1024} = \frac{63.5cm}{1024} = 0.062cm. \quad (25)$$

Figure 8 shows the schematic of the rotary potentiometer within the SP1-25 linear encoder.

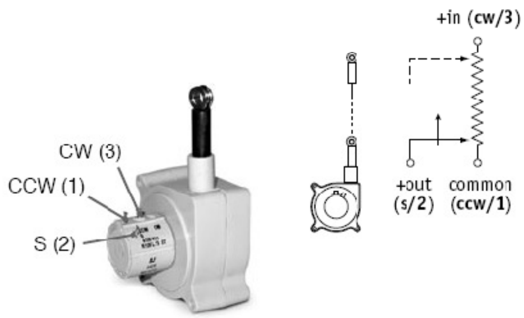

FIGURE 8 POTENTIOMETER SCHEMATIC OF THE SP1-25 (WWW.CELESCO.COM)

Due to physical limitations with the dimensions of the back of the wheelchair seat, the extension of the cable from the encoder will be at an angle to the direction of travel of the rack & pinion. This means that the output of the encoder is not linear with the position of the motor. To correct for this, the Pythagorean Theorem is used to calculate an accurate value for the position. Figure 9 shows the mounted position of the linear encoder as well as the right angled triangle which is formed between the rack & pinion motor structure and the cable extended from the encoder.

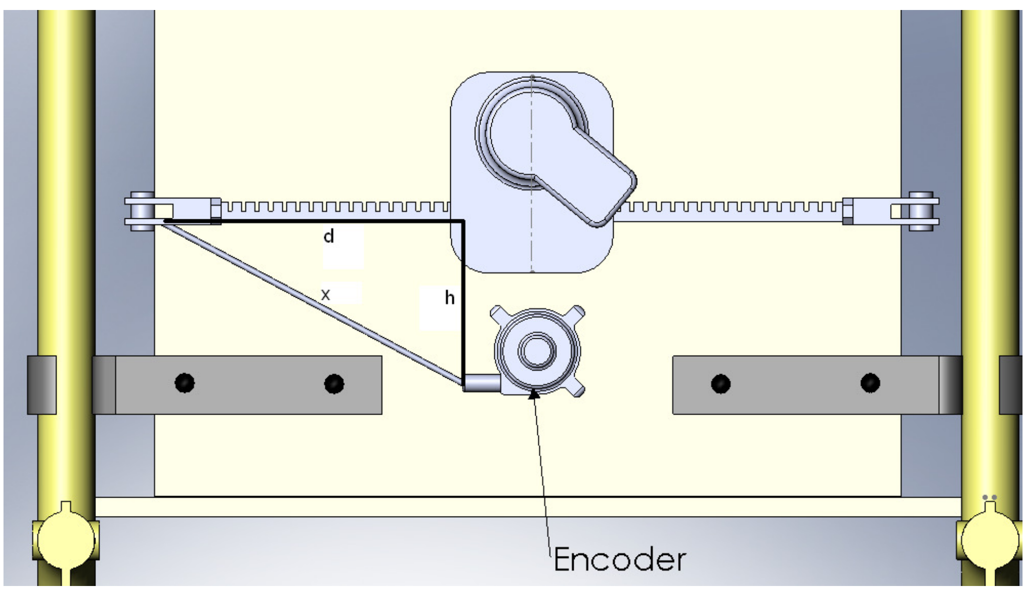

FIGURE 9 MOUNTING OF THE LINEAR ENCODER

From the above figure, it is seen that *d* is the distance required by the microcontroller for an accurate description of displacement. The value, *x*, however is the value which the encoder reads. Since *h* is a constant height value defined by the structure of the apparatus, the displacement value can be obtained as follows,

$$d = \sqrt{x^2 - h^2}. \quad (26)$$

6. User Interface

The user of the wheelchair equipped with the *Equipoise* system will be provided with a user interface consisting of three switches and an emergency stop button. Of the three switches, one turns on and off the Pressure Relief Mode (PRM), one turns on and off the Wheelchair Stability Mode (WSM), and one performs manual control on the body position by means of a left/right joystick control. One issue that arises is the usability of these buttons for the disabled. As the Equipoise system is designed for paraplegic and quadriplegic users, buttons and switches are undesirable for those with limited upper body movement. However, these inputs are designed to output binary signals which can be easily made more accessible for disabled users through such technology as sip/puff control, head movement control, or voice recognition in future developments.

6.1 PRM/WSM Switches

The PRM and WSM switches are basic two position switches. The switches have two terminals and when flipped in the on position, the switch conducts the signal between the two terminals. When flipped to the off position, the output of the switch is high impedance. To ensure that the output of the switch provides a logic low signal when in the off position, a pull down resistor is placed between the output terminal and ground. Figure 10 shows the schematics of these on off switches with pull-down resistors.

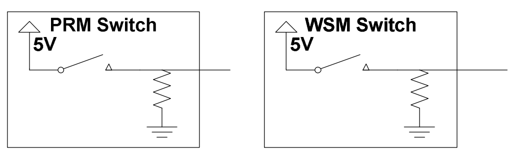

FIGURE 10 PRM AND WSM SWITCHES SCHEMATICS

The PRM and WSM switches produce logic level changes on two ports of the microcontroller. These logic level changes trigger interrupts which will turn on or off the respective modes of operation accordingly.

6.2 Manual Control Switch

The manual control switch is a three position switch with one input and two outputs. When pushed to the left position the input will be connected to one output and when the switch is pushed to the right, the input will be connected to the other output. Again there is the problem of pins left in the high impedance state. In order to clamp these pins to logic low pull-down resistors are used once again. Figure 11 shows the schematic of the two-output manual switch with pull-down resistors.

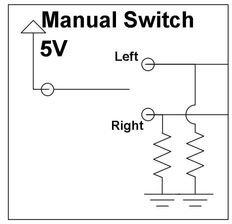

FIGURE 11 MANUAL SWITCH SCHEMATIC

The manual control switch changes logic levels on two separate pins which will trigger interrupts on two different ports of the microcontroller. Correspondingly the interrupt service routine will control the motor to move left and right according the direction of which the switch is pushed. When left untouched the switch springs back to the center position, pulling both outputs low and turning off the manual control of the motor

6.3 EMERGENCY STOP

A highly visible emergency stop button is also placed on the user interface console. The emergency stop button is a two terminal switch which connects and disconnects the two terminals on consecutive presses of the button. All components of the Equipoise system are powered by a 12V line from the wheelchair battery. This emergency stop button connects and disconnects this line so that in the case of a malfunction during testing or an emergency situation during use, the user can press the button and disconnect the power. Figure 12 shows the placement of the emergency cutoff button with the Equipoise system along with the placement of a 30A fuse. The fused is used for protection for the rack & pinion motor which can draw up to 30A.

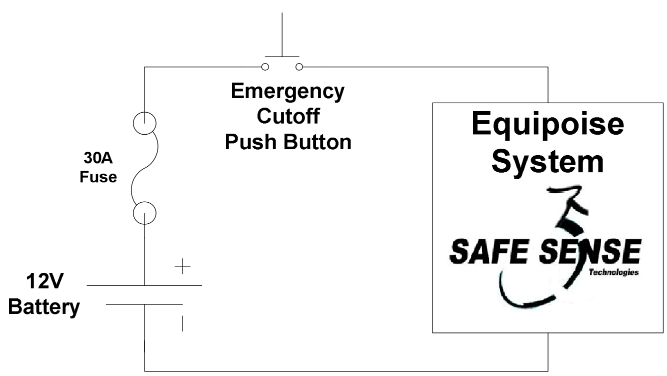

FIGURE 12 PLACEMENT OF EMERGENCY CUTOFF BUTTON

7. Programming

The AVR Butterfly Evaluation Kit is used to generate the required control signals for the Equipoise system based on user and sensor inputs. The AVR Butterfly serves as a development board for the AVR ATmega169 microcontroller. The features of the development board which are used with the Equipoise system are:

- 512kb External Flash memory
- UART communication interface
- 32kHz Crystal Oscillator
- Timers/Counters
- 10 bit Analog/Digital Converter (ADC)

Program code is transferred to the microcontroller via the UART communication interface and then stored in the external flash memory. The 32kHz crystal oscillator is used as the system clock and is pre-scaled for use with timers, counters. The ADC is used to retrieve input signals from the analog outputs of the inclinometer and linear encoder.

The Equipoise system must react sufficiently fast to external inputs in order to generate an effective output. Specifically, depending on the current tilt angle and tilting speed of the wheelchair along with the body position of the user, the Equipoise system must sense danger and correct the body position accordingly. In order to control the velocity of the body movement, the system must also have current motor position and motor speed values for the feedback controller to react sufficiently fast. To satisfy these criteria, the program is designed to be both timer interrupt as well as pin change interrupt driven.

To ensure that sensor inputs values are gathered consistently and uniformly a timer interrupt is generated after a certain period of time. After testing with several periods, it is found that too short of a time interval results in noisy readings while too slow of time intervals results in slow response time. An optimal value of 7.8125ms (128Hz) was found during testing to be the most effective interrupt timing.

7.1 Timer Interrupt

After gathering the sensor data during these timer interrupts, decisions must be made accordingly. The following diagram shows the program flow within the timer interrupt. Figure 13 shows the program flow within the timer interrupt occurring every 7.8125ms.

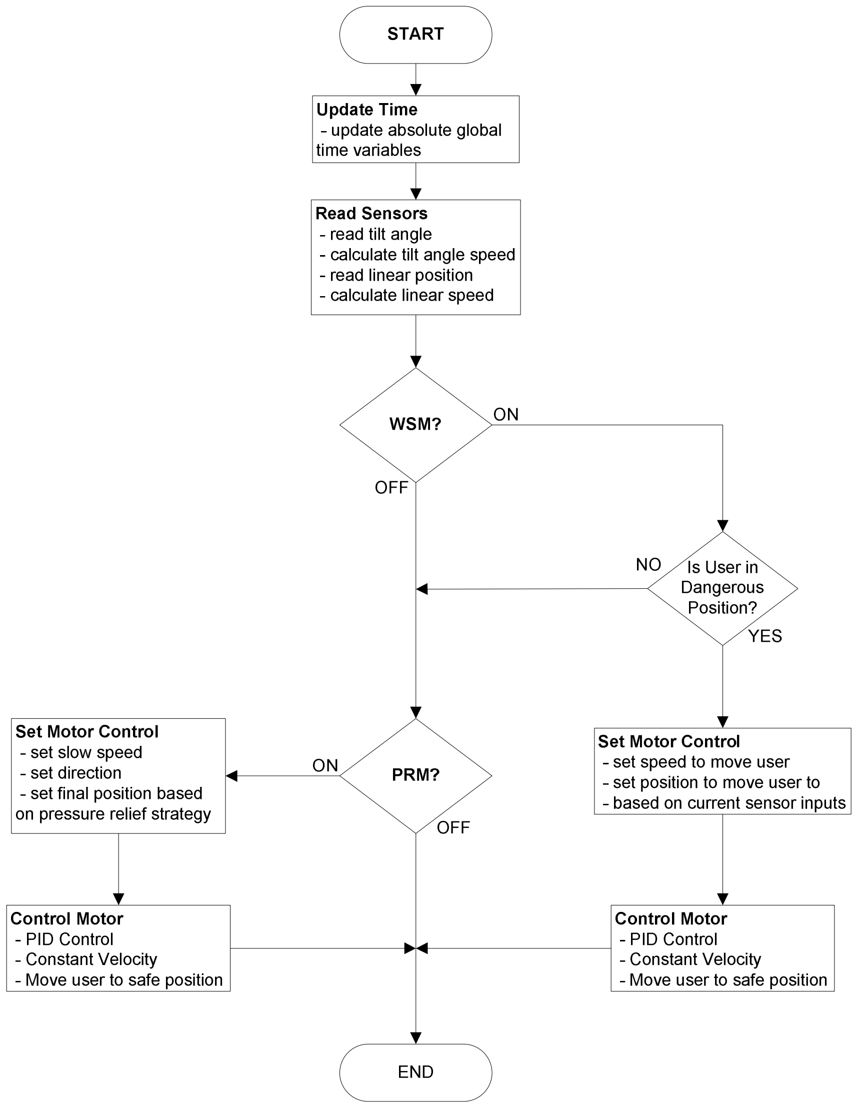

FIGURE 13 TIMER INTERRUPT PROGRAM FLOW

7.1.1 Wheelchair Stability Mode

The most critical process in the timer interrupt is the check for user safety. If the user has flipped the WSM switch on, the timer interrupt will check to see if the user is in a dangerous position. This decision is based on certain thresholds for position, tilt angle, and tilt angle speed. If it is found that the user is in a dangerous position, the motor controller will move the person to a final position away from the danger. Figure 14 shows an example situation in which WSM is turned on and a dangerous situation is sensed.

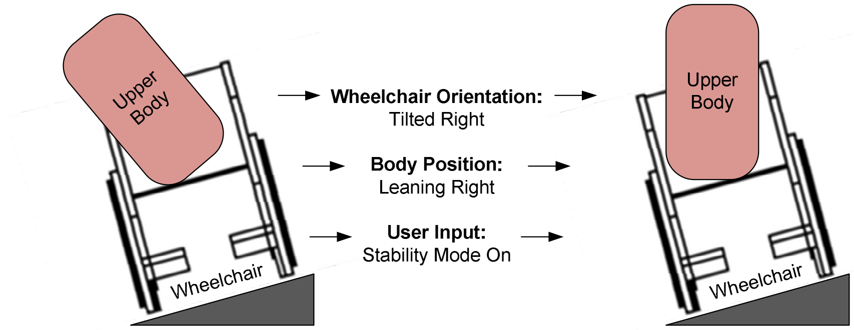

FIGURE 14 WHEELCHAIR STABILITY MODE EXAMPLE SITUATION

7.1.2 Pressure Relief Mode

If the PRM switch is flipped on by the user, then a pressure relief strategy begins. This strategy follows these steps:

1. Move the user at a very slow speed to the right.
2. Keep the user at this position for two minutes.
3. Move the user back to the center position at a very slow speed.
4. Keep the user at this position for fifteen minutes.
5. Move the user to at a very slow speed to the left.
6. Keep the user at this position for two minutes.
7. Move the user back to the center position at a very slow speed.
8. Keep the user at this position for fifteen minutes.
9. Repeat steps 1 to 8.

This is an infinite loop which is only exited when the user turns off the PRM switch or when a dangerous position is sensed while in the WSM mode. Alternatively, the user can exit the PRM mode by using the manual control switch to move to a desired position. Figure 15 shows the example of how the user's upper body changes with the pressure relief mode operation.

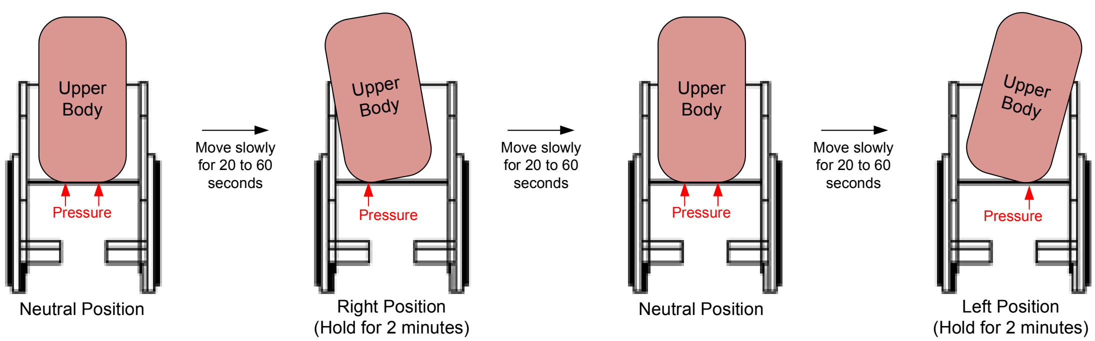

FIGURE 15 PRESSURE RELIEF MODE

7.1.3 Update Time

Each time this interrupt occurs, a global variable which holds a time value is incremented by 7.8125. This variable holds millisecond count of the program and when it is incremented past a multiple of one thousand, a variable holding the seconds count is then incremented. Using this process a series of variables hold time values is accessible to all functions in the program. Specifically, it is used in the pressure relief strategy in order to move the person left and right for precise periods of time.

7.1.4 Read Sensors

This process gathers the sensor data from the ADC. In order to reduce noise, an average value is calculated every three samples. This prevents sharp increases and decreases due to electrical interference from affecting the tilt angle and linear encoder values. Since tilt angle speed is used for the wheelchair stability criteria and the linear encoder speed is used for the motor controller, this process also calculates velocity values for the corresponding sensor inputs. To generate a discrete derivative the difference between two successive samples is calculated and then divided by the time difference, in this case 62.5ms.

7.1.5 Set Motor Control

This process sets up the variables to be used for the motor controller. Depending on the mode of operation, PID variables are adjusted in this section to adjust the rise time of the controller. For example, in PRM the user is to be moved slowly and unnoticeably so a longer rise time is needed in comparison with WSM where fast response time is required and thus a smaller rise time. Also, a final position value is set in order to tell the motor controller where to move the user to. When the linear encoder position value matches the final position value, the motor is turned off.

7.1.6 Control Motor

A basic PID motor controller is used to ensure that the person is moved with constant velocity. This implementation makes the movement of the motor independent of the load which the motor is carrying (below the maximum load). The motor controller increases the PWM duty sent to the motor driver until the motor is moving at the set speed. If the motor is moving higher than the set speed than the PWM duty is decreased accordingly. Figure 16 shows the PID velocity controller diagram that is implemented in the Equipoise system.

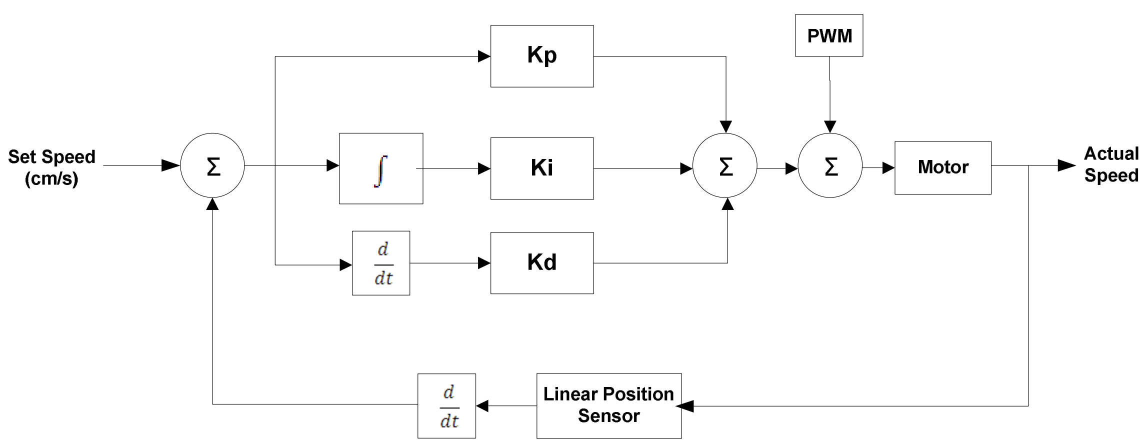

FIGURE 16 PID VELOCITY CONTROLLER

One consideration for a high power motor such as the rack & pinion DC motor used in this application is current rush. Starting the motor at a high PWM duty cycle will cause a large starting current to be drawn to the motor. Consequently, with a DC power source such as the 12V battery, a voltage level in the logic and signal processing devices will drop. Equipoise protects against this in two ways. First, a PID motor controller such as the one described previously will inherently have a finite rise time for the motor to get up to speed. This causes the PWM ratio to increase gradually thus giving the back EMF of the motor a chance to rise correspondingly. Also, voltage regulators are used so that if the 12V DC battery does drop in voltage, the 5V logic supplies are maintained.

7.2 Pin Change Interrupt

As mentioned earlier, the program must respond to user interface pin changes. The butterfly is initialized to generate interrupts any time a logic level changes on any of the pins on one port. As there is only one interrupt service routine for all logic level changes on the port, the ISR must check the level of all pins and generate outputs or set/reset variables accordingly. Figure 17 shows the program flow of the pin-change interrupt service routine.

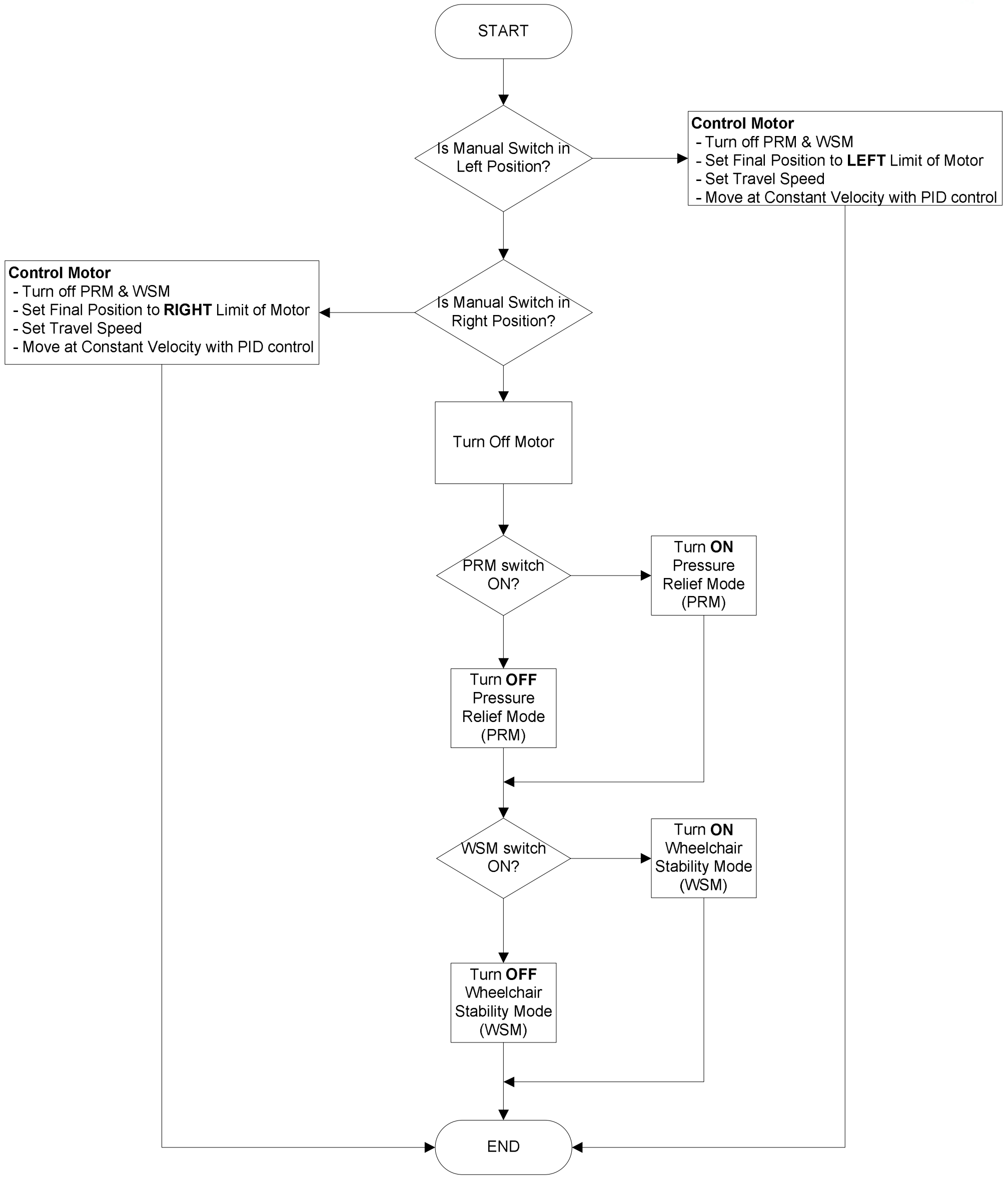

FIGURE 17 PIN CHANGE INTERRUPT SERVICE ROUTINE

7.3 Main Function

The main program loop runs an initialization function, moves the motor to the home position, and then enters an in finite program loop in order to wait for interrupts to occur. Figure 18 shows the program flow of the main function running on the Equipoise system.

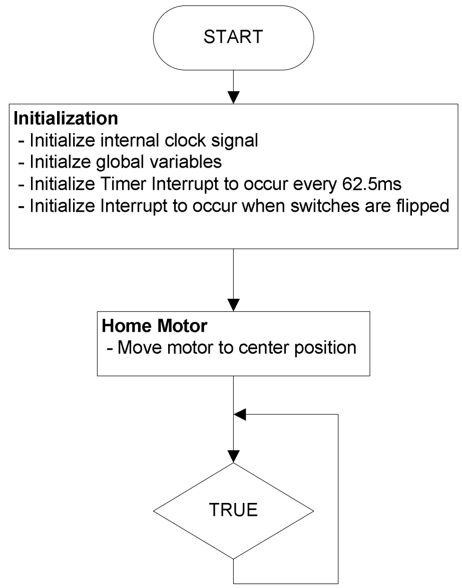

FIGURE 18 MAIN PROGRAM LOOP

8. Signal Processing Circuitry

The AVR Butterfly reads in 6 signals and outputs 3. The six input signals described in previous sections are:

- PRM switch
- WSM switch
- Manual Control switch (LEFT)
- Manual Control switch (RIGHT)
- Inclinometer Signal
- Linear Encoder Signal

The 3 output signals are:

- Pulse Width Modulation (PWM)
- Motor Direction
- Output Enable

Figure 19 shows the block diagram of the complete signal processing circuitry including the external inputs (switches and sensors), the AVR Butterfly, the PWM signal logic, the H Bridge motor controller, and the Rack & Pinion Motor.

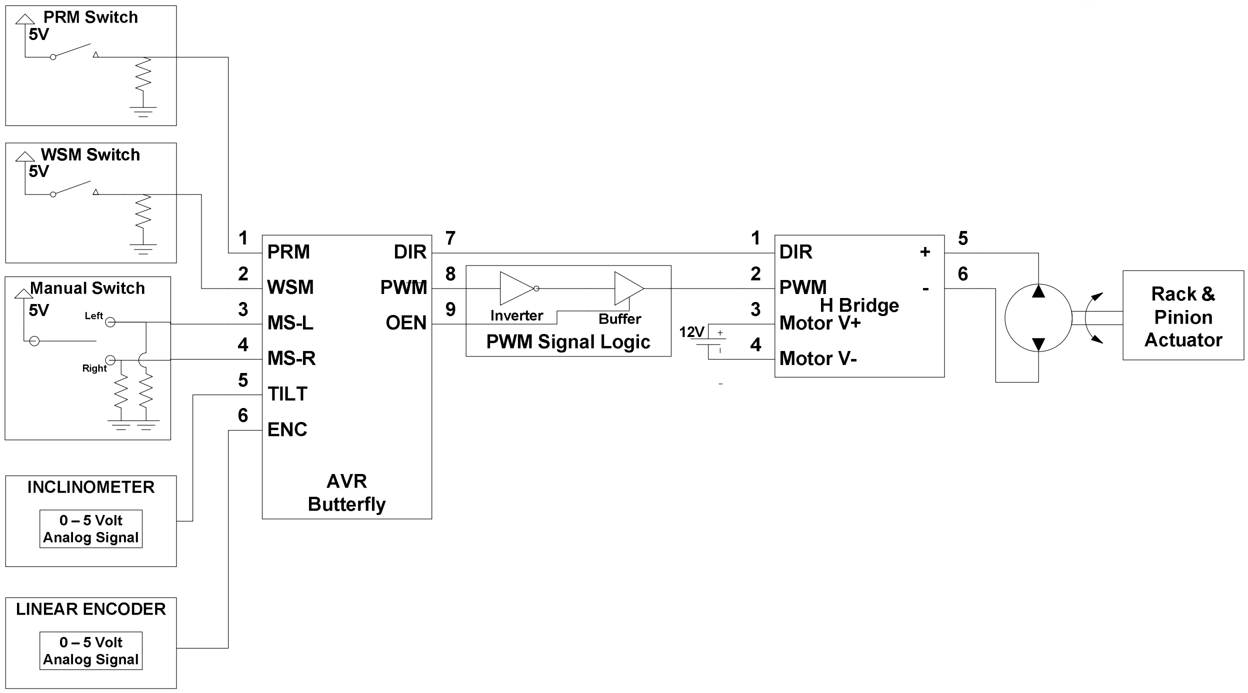

FIGURE 19 SIGNAL PROCESSING DIAGRAM

After the AVR Butterfly, the signals are conditioned with some PWM signal logic consisting of an inverter and a buffer. To ensure that PWM signals are only sent to the motor controller when the program desires, an output enable pin enables or disables a tri-state buffer connected to the motor controller. The inverter is necessary because the PWM signal generated in the Butterfly is opposite that of what is used by the motor.

9. Power Circuitry

The power of the system is provided by a 12 Volt 35 AH wheelchair battery. The battery provides power for all the components of the system. The inclinometer, linear encoder, buffer, inverter, and the H-Bridge logic are connected to the main 12 Volt line through a 5 Volt voltage regulator. Similarly, the AVR butterfly is connected to the main line through a 4.5 V adjustable voltage regulator. Since the H-bridge is handling high currents, a 50 mA slow blow fuse is placed in line with 5V logic supply. The motor is powered by the drive circuitry inside the H-Bridge drive. The driver is capable of supplying up to 20 A of current to the motor. The driver has an input voltage line which is connected to the battery through a 30 Amp switch breaker. The output lines of the driver are connected to the motor. Figure 20 illustrates the power circuitry of the *Equipoise* system.

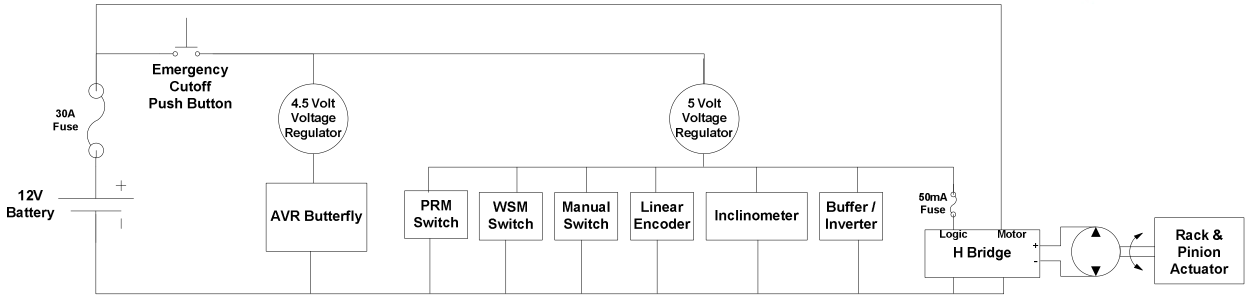

FIGURE 20 POWER CIRCUTRY DIAGRAM

9.1. H BRIDGE

H Bridge is required for controlling the direction and speed of the DC motor. *Equipoise* system uses Devantech MD03 H Bridge (50V, 20 Amp), since it can supply enough power to drive a medium power DC motor. The Main feature of this motor driver is that it can handle high currents. Figure 21 shows the picture of the Devantech MD03 H Bridge.

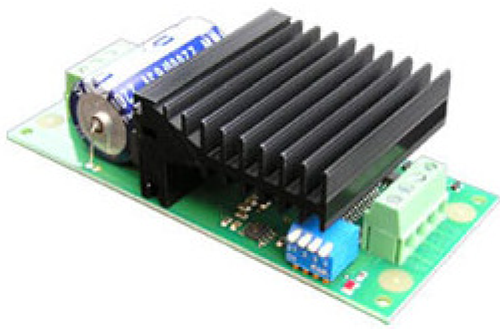

FIGURE 21 DEVANTECH MD03 H BRIDGE (HTTP://WWW.ACTIVE-ROBOTS.COM/PRODUCTS)

This H Bridge has a Built-in charge pump to overcome the voltage drop problem. This charge pump uses arrays of capacitors to increase voltage in the module. This higher voltage can then be used to trigger the bases of the transistor arrays in an H bridge. In this way, the logic voltage need not be higher than of the high current load being driven.

The on board charge pump generates 15V MOSFET drive voltage. So the module requires only two supply voltages:

1. A standard 5V supply voltage for the control logic. Only 50 mA current is required.
2. Motor Voltage (any voltages between 5V up to 50 V DC)

The other advantage of this motor driver is that it allows the high-current load to not only be reversed (using inverted voltage) but also it allows very fast switching of the motor current. This rapid switching can be used to control the speed of the motor by PWM signal generated from microcontroller. There is a simple resistor/capacitor filter on the module which will generate the analog voltage from the incoming PWM signal. The 0% duty cycle will represent 0V and a 100% duty cycle will represent 5V.

In addition, this motor driver has over temperature protection and over current shut down. The temperature sensor limits the motor current if the module gets too hot and the current limiter limits the motor current to 20A.

In overall the inputs to H Bridge motor driver are as follows:

- Logic level direction control (logic 0 for reverse direction, logic 1 for forward direction)
- PWM Input from Microcontroller
- 5V logic supply voltage
- 12V motor battery

Since the module is handling high currents, a 50 mA slow blow fuse has be placed in line with 5V logic supply voltage and 30 Amp switch breaker in line with 12V motor battery.

10. Force Transfer

The linear output force of the actuator gets exerted on two sides of the user's chest, moving the upper body sideways. To transfer the force from the rack and pinion to the user, aluminum ropes with sufficient tensile strength are used. The use of ropes instead of rigid links has the following advantages:

1. Ropes make the mechanical system lighter and stiffer.
2. Ropes are more efficient since they minimize the friction when transferring the force.
3. Using ropes eliminate the need to manufacture extra linkages and joints.
4. Rigid links require extra maintenance such as lubrication and they wear out faster than ropes.
5. Rigid links change the appearance of the wheelchair which is undesirable.

The ropes are connected to the sides of a chest harness wore by the user. The chest harness is easy to wear, adjustable for different sizes, and gives the user a sense of safety. The joints used to connect ropes to the chest harness are chosen based on comfort and shear strength. Figure 22 shows the chest harness.

FIGURE 22 CHEST HARNESS (HTTP://WWW.URBANHART.COM)

As suggested by Ian Dennison, physiotherapist and equipment evaluator in GF strong rehabilitation centre, any force exerted on the user should be in horizontal direction. The vertical component of the force must be minimized to avoid developing more downward pressure on the user. Two pulleys are mounted on the sides of the chair at the same height as the user's chest. The ropes are passed through these pulleys so that only the horizontal components of the tension in the ropes are exerted on the user's chest.

As mentioned in the actuator section, the rack can travel 12 cm to each side from the centre position. In order to move the upper body 12 cm to each side from the centre position, the ropes coming from the two ends of the rack were connected to the chest harness as shown in Figure 23. Note the use of pulleys on the sides of the chair to eliminate the vertical force components.

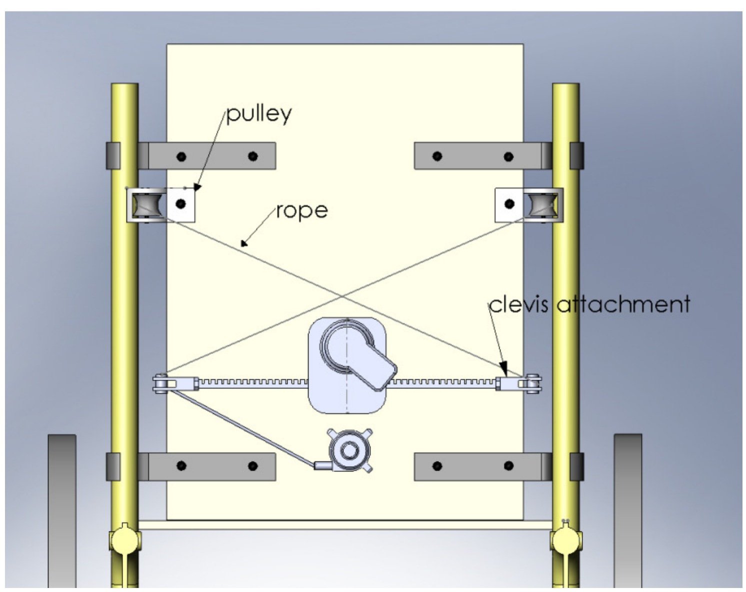

FIGURE 23 ROPES ATTACHMENT

The mechanical system shown above has another important advantage: The position of the upper body is always the same as the position of the rack. As a result, the control software can find out the body posture simply by reading the rack position.

13. System Test Plan

Equipoise system's two main functions, pressure relief and stability, will be tested separately based on the functional requirements of each mode. The goal of the following test procedures is to ensure the safe operation of the system for any user.

13.1 Pressure Relief mode

Users with different upper body weight and muscle strength will be asked to test the pressure relief mode. The system should be able to move any user at the same constant velocity.

The effectiveness of the pressure relief mode will be tested by placing a pressure mat on the seat and measure the change in pressure as the upper body is moving sideways.

13.2 Stability mode

The response time of the system and the speed torque capabilities of the DC motor will be tested for this mode. To test the response time, the time difference between the detection of danger and moving the upper body to opposite direction will be measured.

In addition, for a particular user and threshold angle, different tipping accelerations are tested. The system must be able to bring the upper body to a safe position at a comfortable speed. For this mode, the maximum controllable tipping acceleration and tipping speed varies for each user as discussed in section 4.6.

13.3 Safety and Comfort

Manual adjustment has the highest priority when the system is running. The manual switch will be pressed while the system is in pressure relief or stability mode. The system should stop its current operation and switch to manual mode.

Different users will be asked to wear the chest harness to ensure it is comfortable and acceptable.

12. Conclusion

For the design of *Equipoise*, an interdisciplinary knowledge from mechanical, electronic, and control engineering was required. The prototype of the *Equipoise* system will be made based on the proposed design specifications. The objective is to meet all the functional requirements of the system by April 6th.

13. References

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