Standing Paraplegic Omni-directional Transport (SPOT)

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Abstract

Dr. Garrett Cuppels is an orthopedic surgeon who suffered a tragic injury in 2010 leaving him paralyzed from the waist down. To return to the operating room and once again perform standing surgeries, Dr. Cuppels requires a dynamic robotic system that will secure him in the standing position and allow him to move around the operating room quickly and efficiently. For this purpose, we designed and fabricated a four-wheeled, joystick-controlled robotic platform utilizing omni-directional mecanum wheels. A modified off-the-market paraplegic leg bracing system called the EasyStand 5000 was then mounted to the top of this four-wheeled platform to enable Dr. Cuppels to stand during surgeries. Together these devices form the basis of the Standing Paraplegic Omni-directional Transport (SPOT). SPOT was designed to mimic natural standing movement and to minimize time spent in the operating room, making it safer for patients. Several aspects of SPOT's design, including its waterproofing, battery charging system, and EasyStand must be modified or installed before the device is ready for the operating room. Through testing we found that the device requires higher torque motors to achieve omni-directional movement when fully loaded. Once these improvements are made and the device is tested with Dr. Cuppels, SPOT will greatly increase the client's chances of returning to orthopedic surgery.

1 Introduction

1.1 Background

In the United States, approximately 3.3 million people use wheelchairs [1]. Of those 3.3 million, only 17.4% are employed. A Wisconsin area hospital approached the Biomedical Engineering Department at the University of Wisconsin-Madison with a request to design a device which would allow a T12 paraplegic to return to work as an orthopedic surgeon. Orthopedic surgeries requiring the physician to stand would not be possible for a paraplegic using a standard wheelchair.

This device required a specific set of design constraints and objectives. First, the device must be capable of holding the user in a standing position for up to three hours (the length of longer orthopedic surgeries). Second, the standing mechanism needs to be both highly safe and sturdy with no chance of harming the surgeon, patient, or hospital staff. Third, the device must move quickly and accurately around the operating room table. Forth, due to the large risk from increased time under anesthesia [2], the device must not increase the time it takes for the user to move as compared to an able bodied surgeon. Finally, this device must comply with the standards of the hospital where it will be used. For example, the device has to be sterilized with Virex and be powered with batteries.

Figure 1. Picture of fully assembled SPOT prototype.

After nine months of research and design a prototype device was built to meet the design requirements. This device was named the Standing Paraplegic Omni-directional Transport (SPOT). SPOT consists of an EasyStand 5000, to support the user, mounted on a robotic three ft by three ft base utilizing four independently controlled mecanum wheels to move about. Through vector addition the mecanum wheels, when moved at different speeds and directions, were able to provide net translation in any direction as well as rotation. A medical grade joystick allowed for precise input to control the movement. Furthermore, safety factors were incorporated, such as brakes, an emergency stop button, and an enable button. This device was capable of running on external batteries. A picture of the SPOT prototype can be seen in Figure 1.

1.2 Alternative Devices

Current alternative devices include motorized wheelchairs, standing wheelchairs, such as the LEVO C3, and even nonmedical commercial products, such as the Segway, to help transport paraplegic people. These products could be useful for our client for the purpose of everyday mobility. However, a design to fulfill specific operating room needs was required. The surgical operating room environment requires cleanability, sterilization, a low profile, great stability, and omni-directional movement.

2 Materials and Methods

2.1 Design of Motor and Wheel Assembly

We determined base dimensions using a base-tipping model shown in Figure 2. We determined a minimum base weight of 269 lbs to ensure that SPOT did not tip when the mecanum wheels were mounted in a 27.5” × 27.5” square. The wheels were aligned in a perfect square to allow for optimum vector addition by the mecanum wheels. The mecanum wheels allowed for omni-directional movement through the rotation of fifteen 45° passive rollers mounted around each wheel. These rollers changed the direction of the movement vector by 45°. The direction of the entire four wheeled platform was determined by adding each separate diagonal wheel vector to form one large movement vector as shown in Figure 3.

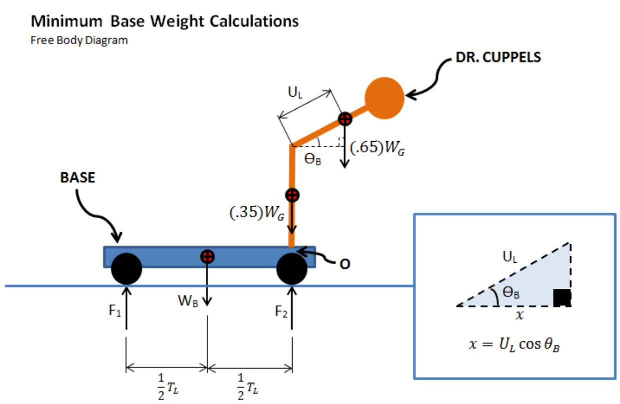


Figure 2: Free body diagram of SPOT when used in the operating room.

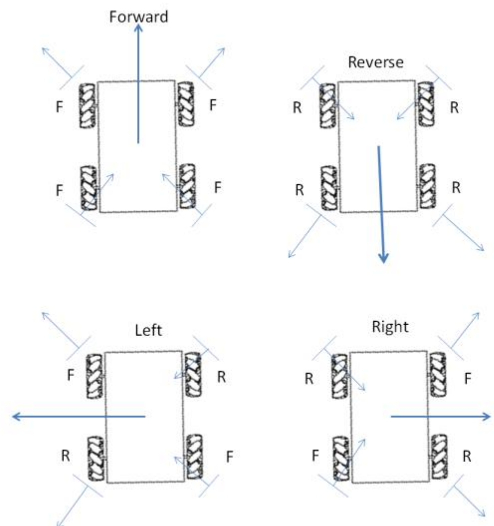


Figure 3: Mecanum wheels, when rotated in different directions, can create any net direction of motion.

Labels:

WB	Total weight of the base
F1	Friction force on both the back wheels
F2	Friction force on both of the front wheels
TL	Length of the base from the center of the back wheels to the center of the front wheels
UL	Distance from user’s hips to his upper-body center-of-mass
ӨB	User’s angle of inclination
WG	User’s total weight
X	Horizontal distance from user’s waist to his upper-body center-of-mass
O	Position directly below user’s feet

The base served as the support system for the entire device and also housed the circuitry, motors, and brakes. It featured eight steel reinforcement rods, two aluminum C-channels, a central aluminum I-beam, two AndyMark Toughboxes, four mecanum wheels and an EasyStand mounting system as shown in Figure

4. A 7” long, 0.5” diameter solid steel shaft was used for each axel between an outer flange bearing and inner linear bearing. Each motor shaft was connected directly to an axel in a 1:1 ratio, to allow for sufficient torque and power for movement as shown in Figure 5. By placing bearings and support systems on either side of the mecanum wheels, the design created little to no stress on the motor shafts, and produced a very strong axel to chassis configuration.

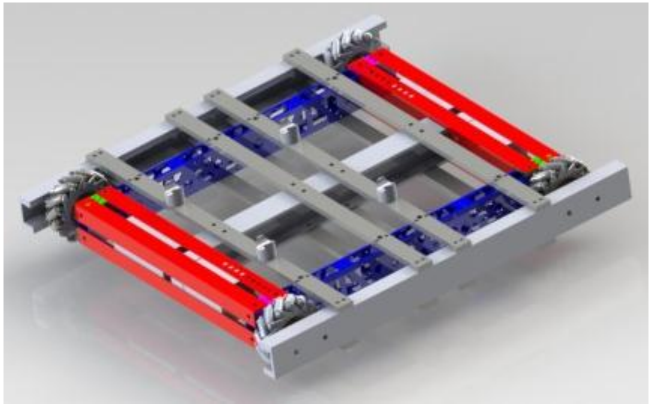


Figure 4. SolidWorks diagram of base design.

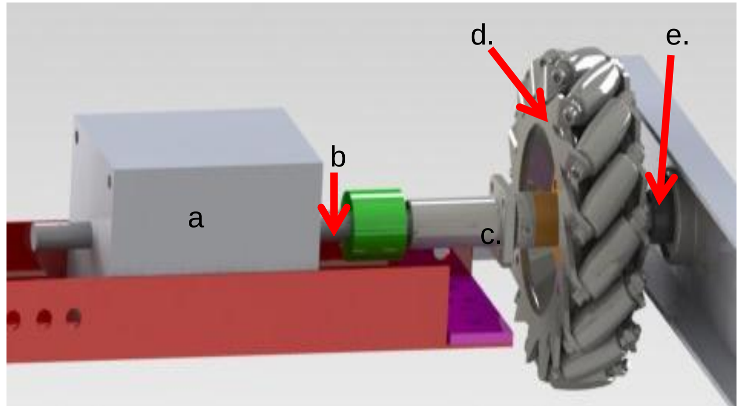


Figure 5. Shows motor (a), shaft (b), linear bearing (c), mecanum wheel (d), and flange flush bearing (e) all attached into a single assembly. The Toughbox not shown in the figure will surround the linear bearing. The motor will be attached to the shaft by a flexible coupling.

2.3 Design of Standing Mechanism

The device required a stable and modifiable standing mechanism to secure a paraplegic person into the device. The EasyStand 5000 was slightly modified and mounted securely to the base of the device using bolts and custom mounting attachments as shown in Figure 1. The user can mount, raise and lower the EasyStand 5000 independently. The EasyStand 5000 has been proven over thousands of hours of use by paraplegic patients and was well suited for the device.

2.4 Circuit Layout

SPOT is controlled by a Galil 4-axis DMC 41×3 motion controller. This controller is connected to the four other main elements of SPOT’s electronics; the user-interface, motors, brakes, and batteries. SPOT will also be outfitted with professional waterproof cables to ensure adequate circuit protection between electronic elements. Following sections explain the device electronics along with a circuit diagram in Figure 6.

Figure 6. (a) Circuit diagram key to the right, (b) Complete circuit diagram of SPOT below.

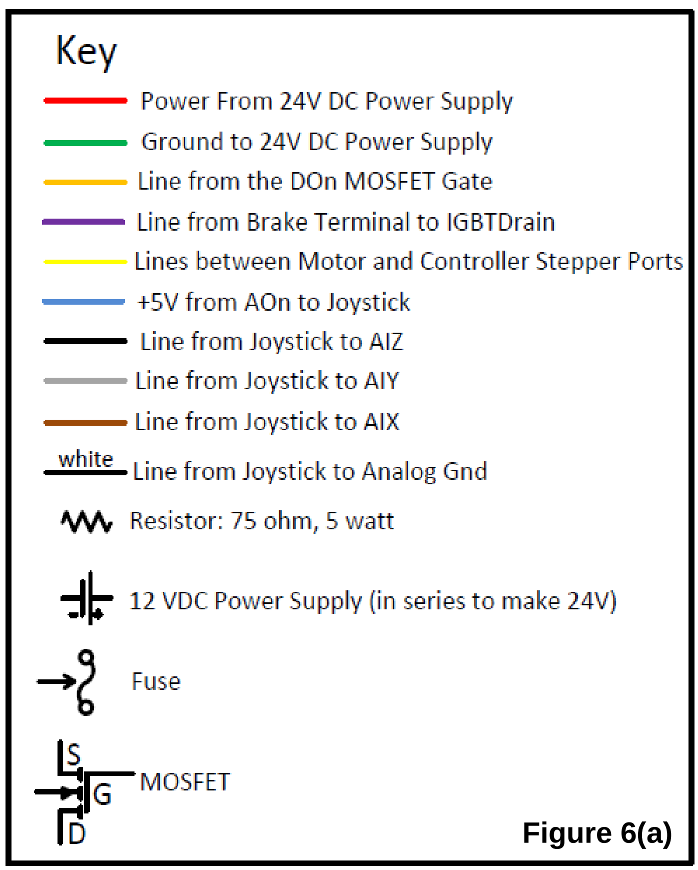
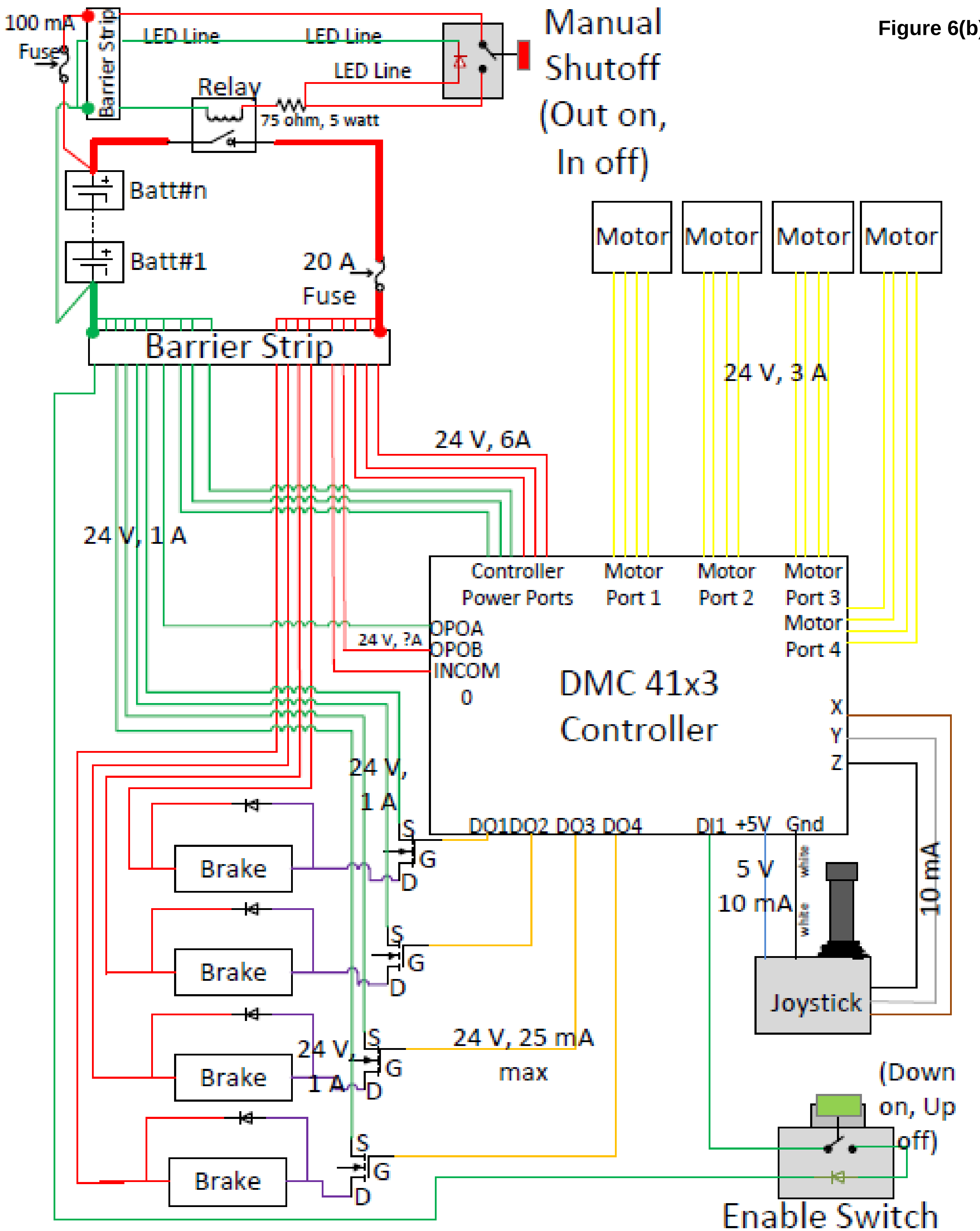


Figure 6(a)

Figure 6(b)


100 mA
Fuse
Barrier Strip
LED Line
LED Line
LED Line
Relay
75 ohm, 5 watt
Manual Shutoff (Out on, In off)
Batt#n
Batt#1
20 A Fuse
Barrier Strip
Motor
Motor
Motor
Motor
24 V, 3 A
24 V, 6A
24 V, 1 A
Controller Power Ports
Motor Port 1
Motor Port 2
Motor Port 3
Motor Port 4
OPOA
OPOB
INCOM
0
24 V, ?A
DMC 41x3 Controller
X
Y
Z
DO1DO2 DO3 DO4
DI1 +5V Gnd
24 V, 1 A
Brake
Brake
Brake
Brake
S
G
D
5 V 10 mA
white
white
10 mA
Joystick
24 V, 25 mA max
24 V, 1 A
(Down on, Up off)
Enable Switch

2.5 User Interface

The user-interface of the circuit is defined by three components: an emergency stop button, an enable button, and a joystick. The device is powered by twisting the red emergency stop button clockwise. When activated, a red LED will illuminate the emergency stop button to indicate that the system is powered as shown in Figure 7. The twisting action allows current from the batteries to flow through a relay to power the rest of the device. As a safety precaution, the emergency stop button can be hit at any time to block the flow of current to the device. It is a “hard” on/off switch.

The enable button serves as a “soft” on/off switch. When pushed it allows current to flow from INCOM0 through digital input 1 to ground. The controller can detect when this circuit is closed which allows the controller to read the position of the joystick and enable the device for movement. As a result, the inactivation of the enable button stops the controller from reading the joystick’s output positions, allowing the surgeon to deactivate SPOT’s movement during mounting and demounting or during times of an orthopedic surgery that may result in an accidental bump of the joystick.

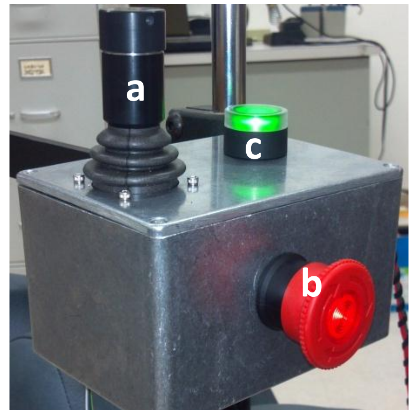


Figure 7. (a) User Interface with joystick, (b) emergency stop/power button and (c) enable button.

2.6 Stepper Motors

SPOT’s stepper motors, operating at 3 amps per phase, were selected for each wheel because they do not require feedback to the controller as opposed to servo motors. Each stepper motor is controlled directly by the motion controller through user-input from the three-axis joystick. Upon stimulation by user-inputs, the controller will send 24 V to the motors, causing them to micro-step. Each motor has four wires corresponding to four terminals on the controller. Internal amplifiers on the controller supply the correct pattern of current to turn the motors.

2.7 Brakes and Brake Circuit

The brakes of SPOT are electrically released spring (ERS) brakes as shown in Figure 8a. The brakes are engaged in the resting state, without power, and released when the power is supplied. This makes them ideal for power conservation because SPOT will be stationary most of the time during surgery. These powerful brakes will give the surgeon great stability while in the stationary position. The brakes are controlled by the digital outputs of the controller and a simple MOSFET switching circuit as shown in Figure 8b. During movement four separate digital 24 V signals are sent to four separate MOSFET gates, each connected to a separate brake. This allows about 0.9 A to flow through each brake, causing them to release the motor shaft. After movement is completed this signal is terminated and current ceases to flow, re-engaging the brakes. Diodes have been placed in parallel with the brakes to suppress large voltage spikes.

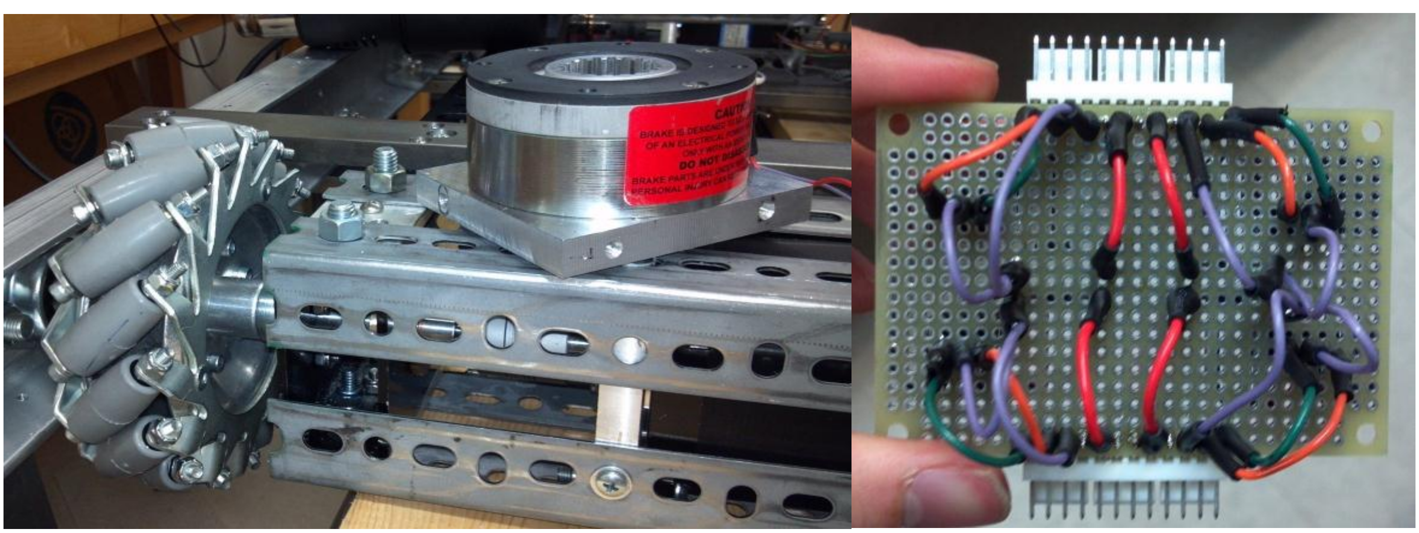


Figure 8. (a) Electrically Released Spring (ERS) brake with (b) MOSFET braking circuit.

2.8 Batteries

SPOT is powered by two 12 V, 8 A-hr batteries in series with one another to create a total battery source of 24 V. This was done for demonstration purposes. Further research into charger design and battery mounting is required before implementation in the operating room.

2.9 Programming

SPOT is controlled using a Galil 41x3 motion controller. This controller has been programmed using Galil's DMC code. When powered ON, the program will automatically start execution and begin reading the position of the joystick. If the enable button is pushed and the joystick is moved outside the neutral threshold range, the base will begin the motion process; the brakes are powered and then release, the motors turn ON, appropriate speeds are given to each motor, and each motor's motion begins. When both the Z-axis and X(or Y)-axis of the joystick are moved outside the neutral range, rotation is given priority over translation. This is to help overcome the difficulty of twisting the tip of the joystick without accidentally deflecting it as well. Once the joystick is returned to the neutral range, motion is stopped and the motors are powered OFF, and the brakes lock. This information control loop is repeated as long as power is given to the controller. A flowchart outlining the program functionality is shown in Figure 9.

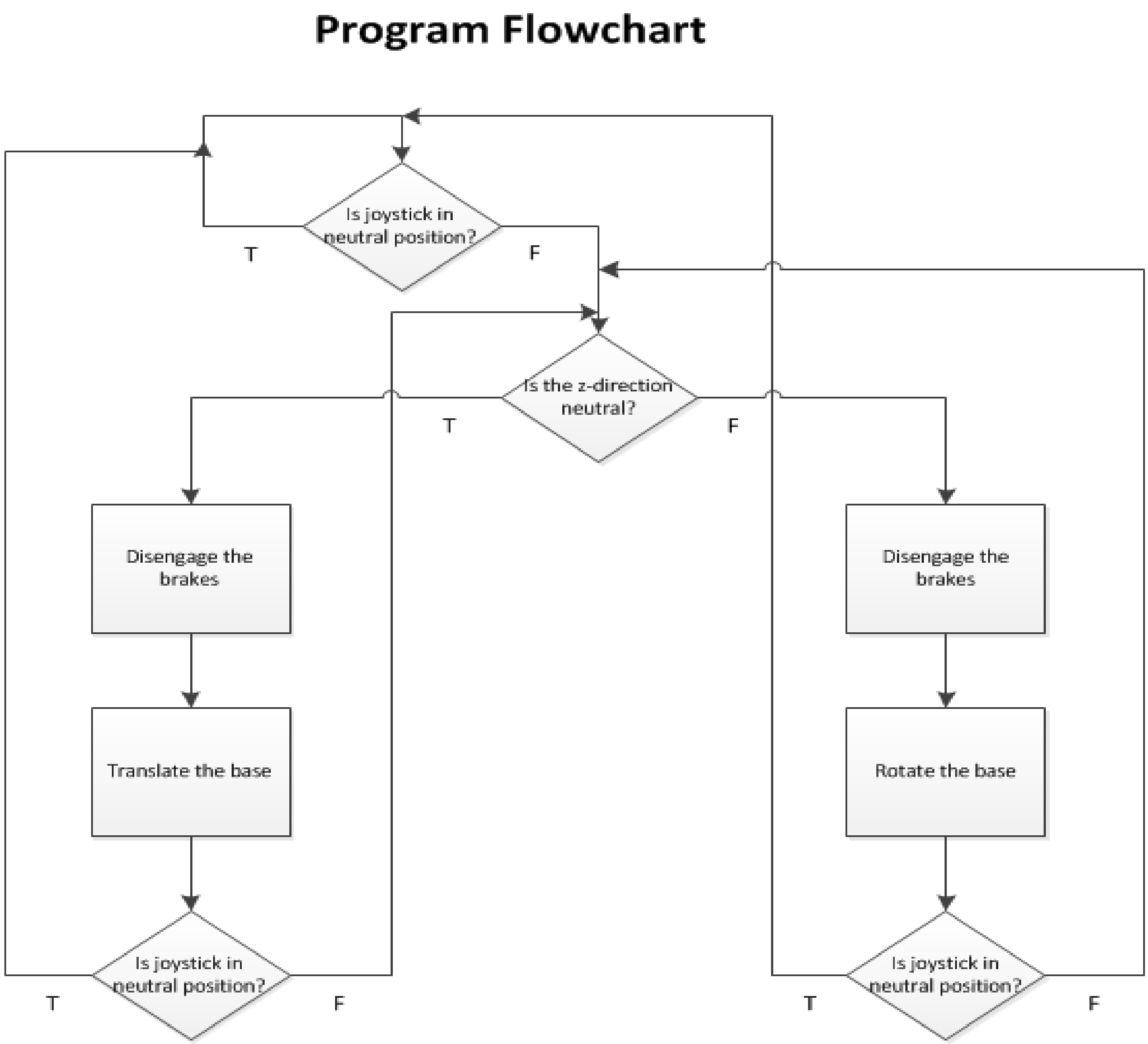


Figure 9. Program process modeled as a flowchart. Assume the enable button is ON, pushed.

3 Results and Discussion

Through an intense nine-month period of planning and subsequent development, as well as through the generous support of individual donors and corporate sponsors, SPOT was designed and fabricated. Its movement, programming, weight bearing ability and ergonometric qualities were evaluated. While demonstrating success in most of these areas, the design still requires improvement before it is ready for its intended use. Areas such as battery design and waterproofing will be completed in Fall 2012. This will require the future installation of professional waterproof cables, an easily cleanable plastic shell and an off the shelf battery charging unit. The Easystand 5000 will also be modified for comfort and functionality after user testing with the surgeon. One area that was intended to be complete at this point was motor selection. Upon testing it was discovered that the selected motors, which included a safety factor of six from initial theoretical calculations, were not strong enough to adequately move the base sideways when fully loaded to 235 kg as shown in Figure 10. This was due to the complex mechanics of the mecanum wheels, resulting in larger forces needed to move the base than theoretically predicted. Therefore, we will select new motors that draw more current and have a larger constant torque range. These motors, combined with gear boxes will increase the torque of the base to provide the required movements of SPOT.

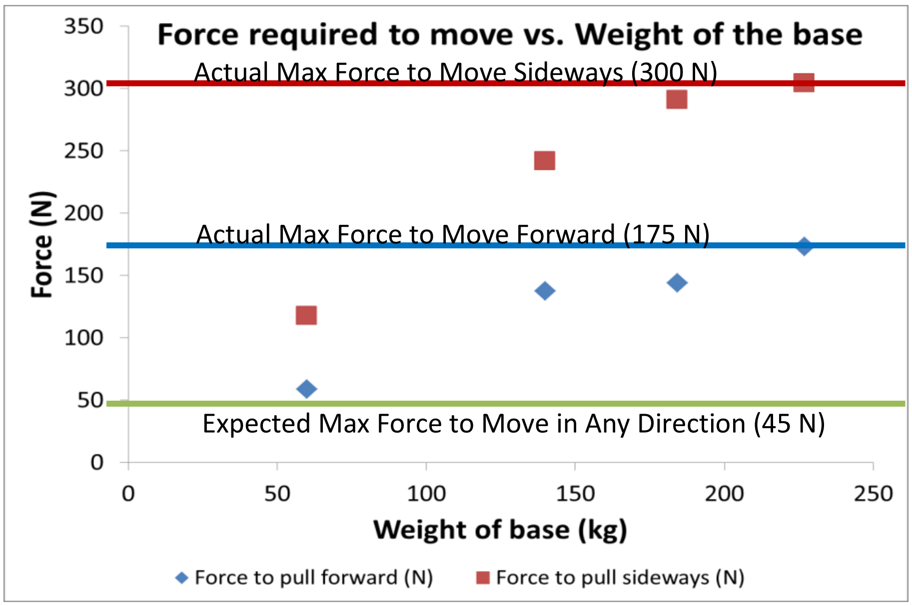


Figure 10. Theoretical vs. observed Total Force (N) required for SPOT movement in the forward and sideways directions. The observed required force to move the base was much greater than predicted due to the complex mechanics of the mecanum wheels.

4 Conclusion

Once additional components are installed and tested with Dr. Garrett Cuppels, SPOT will be ready for use in the operating room. Not only will SPOT enable Dr. Cuppels to regain his dream of practicing orthopedic surgery, but it will enable him to help thousands of patients throughout the rest of his career. Considering the investment society has already made in his education and training, SPOT's $10,000 price tag is minimal. If used successfully for its intended purpose, SPOT's design could potentially be used to help other disabled medical students or professionals return to work. Beyond this SPOT could potentially help thousands of other paraplegics who require stable precise standing mobility, whether its purpose is for work or leisure. Even if SPOT is not an ideal mobility solution for all paraplegics, the story of SPOT and its use by Dr. Cuppels alone will further shed light on this underserved population of disabled individuals. There are many solutions to the difficulties facing paraplegics in America and around the world. It is our hope that this story will inspire more students and professionals to take on the challenge of making these solutions a reality.

References

[1] BraunAbility. (2011, Dec 1). Disability in America Infographic. Retrieved from http://www.disabled-world.com/disability/statistics/american-disability.php

[2] Fecho, K. et al. Postoperative mortality after inpatient surgery: Incidence and risk factors, 2008. Ther Clin Risk Manag. 2008 August; 4(4): 681–688.

Additional Information

Additional information about SPOT, Dr. Cuppels and the UW-Madison SPOT Design Team can be found at: http://fundly.com/uwbiomedicalengineeringdesign

Acknowledgments and Thank You!

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Red Lion Controls,
Turck,
MTECH Wisconsin and
Warner Electric.

Special thanks to Matty Neikrug for preparing the audio/visuals for this project.

Finally we would like to extend our most heartfelt thanks to all our donors for their financial contribution through fundly.com.

NIBIB DEBUT Challenge Certification Form

Instructions:

Each and every member of a Student Team participating in the NIBIB DEBUT Challenge must read this Certification Form and complete it by providing the date and his/her printed name and signature where indicated below.

A Student Team can include only one Certification Form with its entry, which will be submitted by one member of the Student Team appointed to do so by that Student Team (e.g., the "captain" or "submitting participant" of that Student Team).

Entries that fail to include a completed Certification Form will be disqualified from the Challenge.

FOR FURTHER INFORMATION CONTACT: Dr. Zeynep Erim at (301) 451-4797 or Zeynep.Erim@nih.gov.

I have read and understand the Challenge.gov Terms of Participation ("Terms") located at http://challenge.gov/terms and the NIBIB DEBUT Challenge Rules ("Rules") located at http://debut.challenge.gov/. I hereby agree to abide by such Terms and Rules.

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Student Team Member Name	Student Team Member Signature	Date
Bret Olson		5/25/12
James Madsen		5/25/12
Michael Konrath		6/2/2012
Blake Marzella		5/30/12
Justin Cacciatore		6-1-2012

To,
Whom It May Concern

From,
Amit Nimunkar
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Madison, WI, 53706

Subject: University of Wisconsin-Madison students participating in DEBUT challenge.

Hello Sir/Madam,

This letter is to verify that the following students participating in the Design by Biomedical Undergraduate Teams (DEBUT) challenge are enrolled full-time in the Biomedical Engineering Department undergraduate curriculum during the academic year 2011-2012 at the University of Wisconsin Madison.

Participating students:

Justin Cacciatore
Michael Konrath
James Madsen
Blake Marzella
Bret Olson

Please feel free to contact me for more information.

Sincerely yours,

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