TUX 2 – A Balancing Wheelchair

First Semester Report

by
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Prepared to partially fulfill the requirements for
ECE401

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Abstract

Wheelchair design has been slow to harness new technologies for improving the mobility of persons with disabilities. Since the invention of the basic wheelchair in the 1890's, the overall mechanical design of wheelchairs has largely gone unchanged. Advancements have been made in the materials, construction, power and portability of wheelchairs but the underlying assumption that the device must be statically stable has hindered further innovation. Requiring static stability immediately demands a large footprint which makes a classic wheelchair bulky and awkward in real environments.

TUX2 is a prototype built around the idea that modern embedded systems and MEMS devices can be used to overcome the stability pitfalls of an otherwise purely mechanical system. The TUX2 wheelchair consists of two co-axial wheels on which the rider is balanced, similar to a Segway but with some important control differences. By eliminating caster wheels, the footprint of TUX2 is reduced down to less than 25% of a standard wheelchair. The reduction in footprint allows for a substantial increase of mobility in tight areas and improved agility. To achieve stability, a novel control system consisting of several inexpensive MEMS gyros and accelerometers, similar to those found in cell phones has been designed and implemented. A major difference between the TUX2 system and previous inverted pendulum systems such as the Segway is the ability of the control system to manipulate the riders center of mass. A disabled passenger is not able to lean on the device to control direction, therefore the control system must not only balance but also move the passengers center of mass in order to accelerate and turn.

This paper discusses the second of two prototypes that have been built, TUX and TUX2. More information, videos and full size pictures can be found at http://www.tuxrobotics.com.

Introduction

With a few exceptions such as the iBOT® and the Standing Wheelchair®, attempts to improve the mobility of persons with physical disabilities have been focused almost entirely on improving the traditional four-wheel wheelchair. Advanced materials, manufacturing, and computer aided design have brought the modern wheelchair a long way since it's inception in the 1890's but this approach has caused innovations on the fundamental design to be neglected. The wheelchairs in use today have the same basic four-wheel design that has been used for over 100 years, just with upgraded materials and possibly motorized.

The TUX project is aimed at radically redesigning the wheelchair from the ground up using modern technologies to take mobility to a new level. A basic four-wheel wheelchair suffers from several fundamental limitations which cannot be overcome with a classical design. These limitations include:

- A low center-of-mass is required which forces the wheelchair to be low to the ground
- A large footprint is required which makes the wheelchair inefficient in small spaces
- A large frame is required which makes portability difficult
- Access to items over five feet off the ground is not possible
- Eye to eye contact during a conversation is not possible
- Many types of doors are inaccessible

To solve these problems, it was decided that a balancing wheelchair would provide an optimal solution. By using electronics and sensors to balance, the size of the base can be drastically reduced while at the same time the device can be much taller. Because the base is now smaller, the device mobility also substantially increases.

The development process was broken down into three prototypes. TUX, the first prototype, was designed to be a simple proof of concept. TUX2, the second prototype, was designed to carry a passenger in a standing position by including a support structure that holds them up. TUX3, the final design will have the passenger strapped to a support structure that can change between a sitting and standing position while balancing.

Special note should be given to the fact that although the passenger will be in a standing position, the support structure will bear the entire weight of the passenger. The support structure is specially designed to support someone in a standing position without any muscle control. Computer drawings of the first two prototypes are shown below. At the time of writing, both prototypes are functional and software development is ongoing for TUX2.

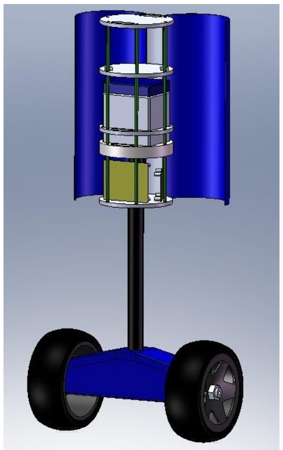

Figure 1: TUX – Proof Of Concept

Figure 2: TUX2 – Basic Standing Wheelchair

I. TUX – A Proof Of Concept

A. Introduction

The first step in the design process was to build an inexpensive prototype that could be used as a platform for software development, TUX fulfilled this purpose. TUX is now a completed project and is no longer being developed. It is being mentioned here as a lead-in to the discussion of TUX2 and therefore this section is intended to be a basic overview of TUX. For more information and videos on TUX, please see http://www.tuxrobotics.com/tux1.php

B. Mechanical Hardware

The basic requirements for the platform were the following;

- Rugged - will not be damaged by falling over
- Rigid – The platform must be extremely rigid to simplify the control system
- Easily Modifiable – All the electronics and mechanical components are easily accessible to allow modification and testing. No adhesives, tapes or one-time fasteners can be used
- Repairable – Any component used must be replaceable if broken

Everything used to build TUX is low cost off the shelf hardware, with the exception being the electronics which were custom manufactured. The entire project cost under $350. The base and electronics enclosure was manufactured using folded aluminum sheet-metal that is bolted together at the seams. The center support tube contains the wiring for the motors and runs through the entire base and half of the body to provide rigidity. The body of TUX is built in layers connected using threaded rod. Each layer was cut from a sheet of polycarbonate on a CNC machine, with the exception of the middle layer which was machined out of high density polyethylene.

C. Electronics

There are two main systems that work together to control TUX, the motor drivers and the main control board. There is one motor driver per wheel, each of which are identical and connected via a serial bus to the main board. Each motor driver is responsible for closed-loop control of a wheel and has a single processor running a PID control loop. The main control board is responsible for collecting sensor data and implementing the balancing software. Figure 1 below shows the basic layout.

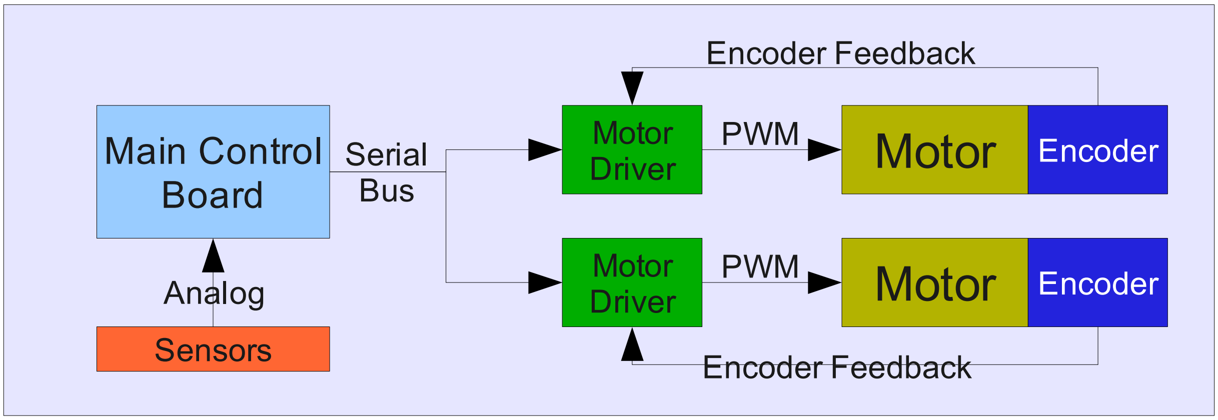

Figure 3: TUX Electronics Layout

D. Control System

The control system development was the entire reason for building TUX. Several methods of implementing the control system were considered but a modular control system was decided on due to its ease of development and debugging. Figure 4 shows the basic structure of the system. Each block in the diagram was developed and tested individually and then connected together as a system.

E. Software

The software for TUX was written almost entirely in C, with the exception of a few routines that were done in Assembly to optimize efficiency. The Microchip C30 Student Edition compiler was used to compile all of the code for the project.

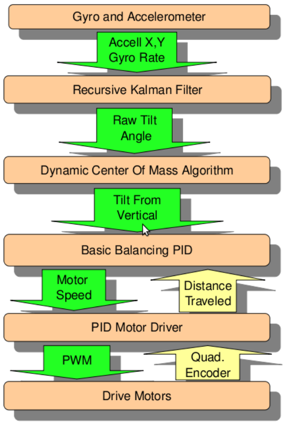

Figure 4: TUX Control System Diagram

II. TUX2 – Basic Balancing Wheelchair

A. Introduction

After building TUX, work began quickly to adapt the design to a full sized system. TUX2 is the next iteration in the design process, with the goal being to incorporate a human passenger. With this design, the goal was to make the system ridable by an average person in a similar fashion to a Segway and then gradually implement a higher level of control. The system has also been designed much more carefully for reliability.

B. Mechanical Design

1. *Base Design*

The base of TUX2 consists of two identical cast parts that are made out of an aluminum-magnesium alloy. The two sides are connected using common square tube aluminum bars. The choice to go with a custom casting was not trivial due to the amount of time and effort involved in the mold-making and casting process. It was decided to put forth the time into casting the part for several reasons. First, a cast part can be extremely custom, allowing for an efficient strength to weight ratio. Second, the cast sides can be machined easily to tight tolerances that are required for the drive components. Third, by casting the sides, part of the gearboxes could be integrated into the side which saves space. The three images below show the cast part and how it fits together to form the ends of the base. By connecting the sides with square tube aluminum, the entire base can be easily disassembled if necessary. This also leaves the option in the future to cheaply and easily make the base wider if it is determined necessary for a future support structure.

Almag, the aluminum-magnesium alloy used, was chosen because it has excellent characteristics for reducing the vibrations. It is much harder than a standard aluminum alloy which improves rigidity. In computer stress analysis tests, one side piece is able to withstand over 800lbs before reaching the yield strength of the material. This was confirmed by testing one of the failed castings. Several severe hits from a sledge hammer were required to cause the part to fail.

The dimensions of the base were determined by considering the size of typical places the platform would be required to operate. It is a total of 24" wide and 12" deep, small enough to fit through the smallest doors and skinniest sidewalks. Being small also means that the system is light, weighing around 35lbs with the batteries being the heaviest components.

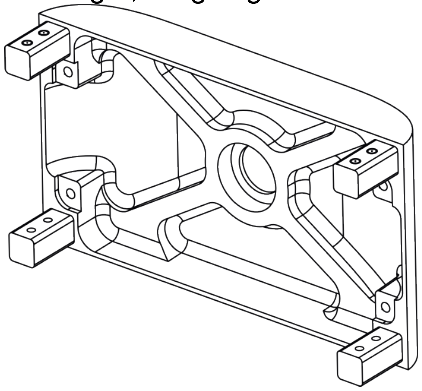

Figure 5: CAD Model for one side

Figure 6: Finished Side With Bearing

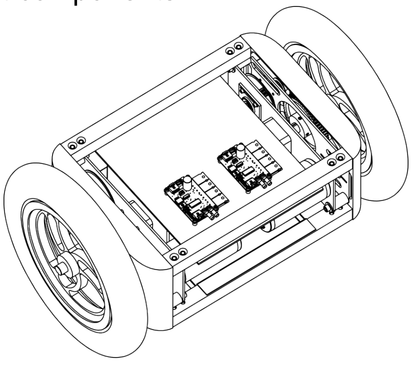

Figure 7: CAD Model of TUX2 Base

2. *Gearboxes*

A significant amount of effort was invested in designing the gearboxes for TUX2. It was learned from TUX1 that reducing the backlash in a system to a minimum was crucial in order to have an aggressive control loop. For TUX2, toothed pulleys were used to transfer power instead of gears because they offer almost zero backlash and do not need to be positioned as precisely as gears. The gearboxes are a two stage design that has an 11.5:1 ratio. Because there are two belts, a system had to be designed to tension each belt separately. To accomplish this the axle on the left in figure 7 can be moved to adjust the tension on the outer belt. The inner belt can be adjusted by moving the motor in slots that are cut in the plate. The shafts are retained using snap rings on either side of the bearings. Keys were used to connect the pulleys to the shafts. Keys alone have a significant amount of backlash so a setscrew was also added to each pulley to press on the key. The encoders for the motor drivers are also mounted in the gearbox. To increase the accuracy, the encoders were placed directly on the motor shafts. By placing them on the motors, the accuracy is multiplied by the gear ratio. In this particular design 2000 count per revolution encoders are being used with an 11.5:1 ratio which gives 23,000 counts per revolution of the wheel.

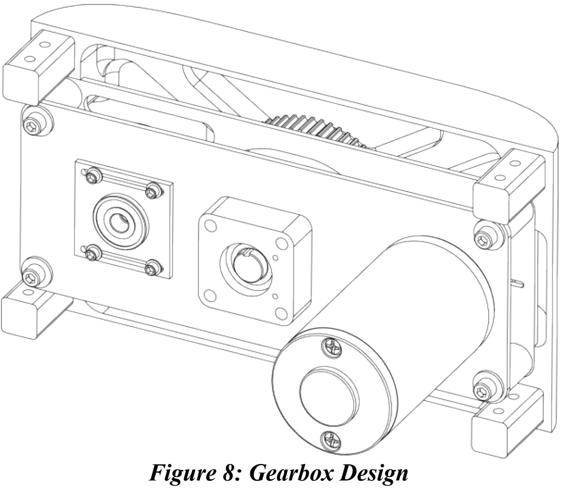

Figure 8: Gearbox Design

3. *Support System*

In order for a passenger to be able to ride TUX2, a support system had to be designed to fit the base and hold up a person. The TUX2 support is designed to take advantage of the passenger's bone structure. The passengers knees, hips and upper body are securely strapped to a steel frame using webbing. By supporting the knees and hips, the passengers bone structure is supported such that it feels like they are standing. This approach was used instead of a full harness because it produces many fewer pressure points on the passenger while still supporting their weight. The full restraints of the support system have not been implemented yet because the device is not reliable enough to risk being strapped in yet.

C. Control System Overview

1. Modular Design

The control system layout inherited many characteristics from TUX, including a design approach that sets it apart from most classical control systems; a modular design. By dividing the control system into several smaller systems, the complex task of balancing and driving an inverted pendulum platform became much more tractable. Individual modules allow the system to be designed and tested in sections, similar to the way software is written with functions that are completely independent. As long as each module in the system does what it is designed to do, the system works. If a module fails, the system can adapt and come to a safe stop.

2. Hardware Abstraction

Because the same processors are being used for the motor drivers and the main control board, it was decided that creating libraries for the hardware functions would save time in software development. A library was written for each hardware peripheral and a few were also written for common tasks such as serial communication and device initialization. The software created for the boards also has a file to define I/O. This makes the software extremely portable in case the hardware is redesigned in the future.

3. Theory Of Driving

The ability to control driving dynamics is a major feature that sets TUX2 apart. At first glance it seems like a simple thing to do once basic balancing has been accomplished but this is far from the truth. In order to drive without the passenger being able to lean requires the control system to be capable of manipulating the passenger's center of mass. This is done by leaning forward or backward to accelerate or stop. Figure 9 to the right shows the basic states during driving. Figure 10(1) shows how the device must lean forward in order to accelerate. Once at the desired speed, the platform must lean back to a vertical position. The same principle is applied in reverse to stop as shown in Figure 10(3) and (4). To accomplish this, a dynamic center of mass algorithm was created which allows the controller to manipulate the center of mass.

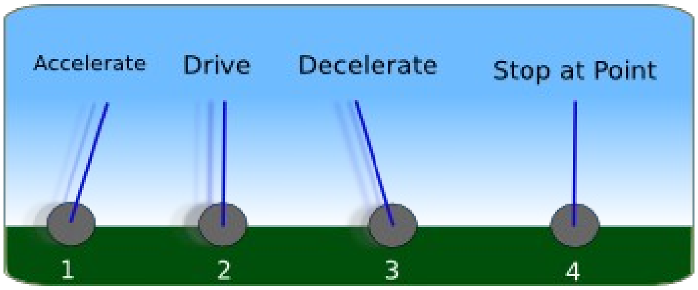

Figure 9: Driving Dynamics

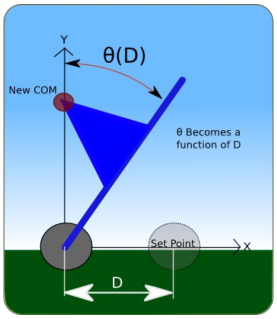

Figure 10: Dynamic Center Of Mass

Figure 10 depicts graphically how the device calculates where the center of mass should be. By knowing the distance that the device must travel to maintain balance, the angle necessary to move the center of mass over the base can be calculated. Once the angle is known, it can be adjusted in order to make the device lean forward or backward to accelerate. This solves two problems at once, it allows the device to drive as well as react to outside changes in center of mass such as the passenger extending an arm or lifting an object.

4. One Step Past TUX

The TUX2 control system improved upon the TUX system in several significant ways. The first and most basic is loop speed. On TUX2 the control bandwidth is around 250Hz as compared to a 100Hz design on TUX. As both models are using the same processors, this improvement can be credited to extensive code optimization to use the DSP instructions of the processors and a reduction in packet sizes on the serial bus.

The second major improvement over TUX is the improved motor control algorithm that the motor drivers are running. On TUX, the motor drivers used a basic PID loop. TUX2 uses a more sophisticated PID loop combined with a novel load prediction technique implemented after the PID output. Figure 2 shows the basic layout of a motor driver control system.

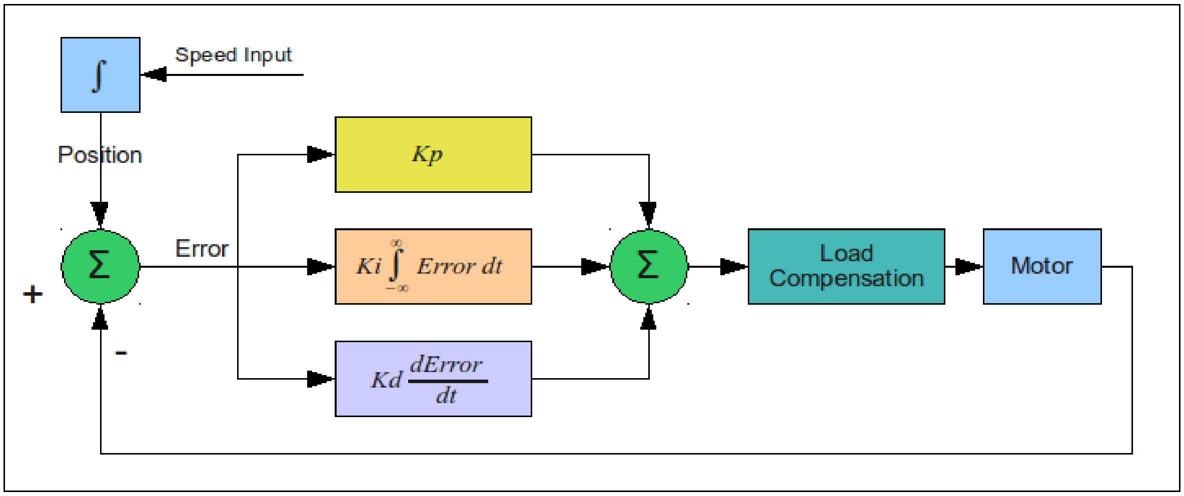

Figure 11: Motor Driver Control System

The motor driver load compensation system can adjust the output commanded by the PID to match the load on the motor. To do this, a linear model of the motor is used to compare the last several commands to the actual output position. To determine how much to amplify the output signal due to load, the controller keeps a short running average of the recent outputs compared to the feedback. It then compares this to the known linear model of the motor and uses the model to predict a new ΔD, the percent duty cycle at which the motor will start turning. ΔD is crucial because moving the motor very small amounts requires the controller to know very accurately at what PWM duty the motor will start turning. If the commanded duty is too low, the integral will wind up and cause oscillations. Conversely, if the commanded duty is too

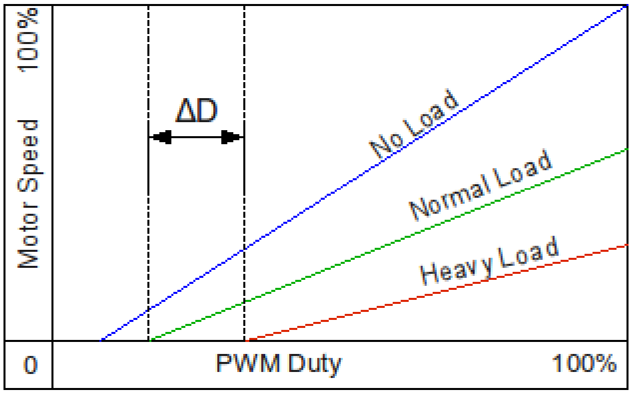

Figure 12: Load Compensation

high it will overshoot the setpoint. The compensation routine will also multiply the output to the motor by a constant relating to the slope of the adjusted model. Because motors are inherently non-linear devices, outside a certain operating range the compensation is set to saturate to a maximum or a minimum to allow the PID to correct for the non-linearities. The load compensation is calibrated using a routine programmed into the motor drivers which drives the motor from stop to full speed and then calculates the linear model for the no-load condition. A second test is then conducted with a normal load to allow the controller to calculate a scale coefficient for the system.

The third and likely significant change to the control system is the added use of the accelerometer on the main control board for damping oscillations. Because the accelerometer on TUX2 is in the base instead of at the top near the center of gravity like TUX, it can be used to actively dampen oscillations.

C. Software Design

1. Motor Controllers

The software for the motor controllers is extremely time crucial so several different levels of interrupts are used to assure predictable timing. The basic design consists of a main loop which is interrupt driven to execute at exactly 250Hz. There are also several other lower priority interrupt routines for serial communication. At the end of the main loop there is a check to ensure that the serial interrupts have not caused the execution of the main loop to take too long. If this happens, the controller will continue to operate but a red LED on the board will light to announce that there is a timing error. The motor controller also does a significant amount of error checking. If a serial signal is not received within a certain time limit the board goes into standby mode. The serial communications are checked using checksums to prevent serial errors from causing disturbances. Also, if the position error on the PID controller becomes too high, the controller has a fatal error and halts until reset. This is caused by the motor reaching stall torque and not being able to do what the driver is commanding.

2. Main Control Board

The software for the main control board is very similar to the motor drivers but the timing emphasis is placed on the balancing algorithm. A main control loop set by hardware timers to execute at exactly 250Hz is responsible for computing the control algorithms. The A/D conversion is also synchronized with the main control loop but it is 32x faster and samples at 8kHz. This allows for filtering of the sensor inputs between each main loop iteration. Because C does not support objects, each filter and control block is implemented using a struct and a function. The struct which contains the data is passed to the function using a pointer, reducing the amount of memory and number of clock cycles the processor needs to perform the task.

D. Electronics

1. Motor Drivers

The motor drivers for TUX2 project presented a significant challenge due to the tight specifications they had to meet. High current combined with a fast switching speed meant that the control MOSFETS would have to have an extremely high switching current to overcome the parasitic capacitance on the gate. To my knowledge, the driver specifications on the right beat any commercially available motor controller in the price range. The motor drivers are based on a 30MIPS dsPIC

<u>TUX2 Motor Driver Ratings</u>

Max Current: 200A

Voltage: 12-36 Volts

PWM Frequency: 15kHz

Control Bandwidth: 250Hz

Cost: ~$50 Each

processor that has a special hardware module for quadrature encoder inputs.

The motor drivers went through several revisions before reaching their current state. The first version of the driver was manufactured using the photo-transfer method in a few hours. Because it is a fairly complex design, the board had to be two layers to accommodate the connections. Manufacturing a two layer board manually requires that the vias are very large and accessible (not under chips) to allow wires to be soldered through. This led to a working design but it was very large. The second version was sent out for manufacturing and worked very well as a test platform for the software. The second version was also used for current testing to insure it indeed met specifications.

As with any device that dissipates large amounts of power, the motor drivers needed to be cooled. Instead of adding a heatsink to the board which would have been heavy and bulky, the boards were mounted to an aluminum plate. The MOSFETS are connected with thermal pads to the plate so that the frame can be used to dissipate the heat.

High current was another challenge that had to be overcome in the design because a standard PCB trace cannot handle the necessary current. To solve this problem, the high current traces on the board were left exposed so thick copper wires could be soldered directly onto the board. These wires can be seen in Illustration 3 below. Screw terminals were also used so that crimp terminals could be used on all the wires. This allows easy disassembly if necessary and is far more secure than rectangular connectors.

To ensure that the motor drivers would fit in the mechanical system, the boards were modeled in SolidWorks by importing the Cadsoft Eagle layout and placing the parts on the board. The final placement of the boards can be seen in Drawing 3 above.

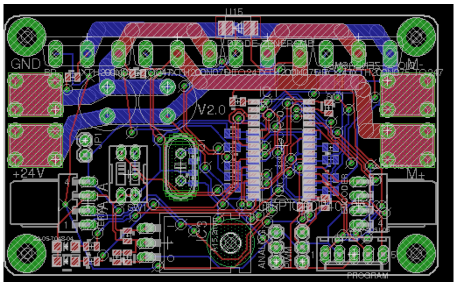

Figure 13: Motor Driver Layout

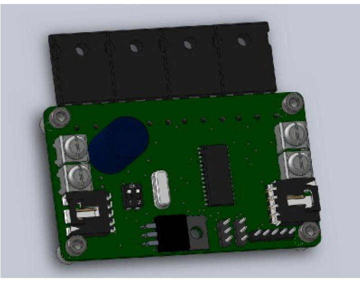
Figure 14: Motor Driver Model

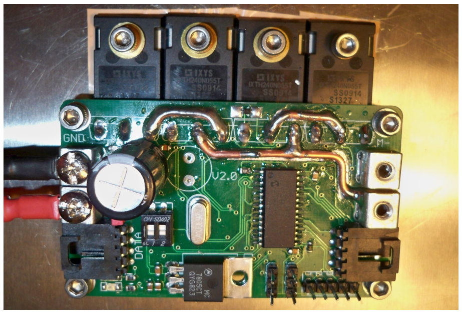

Figure 15: Final Motor Driver

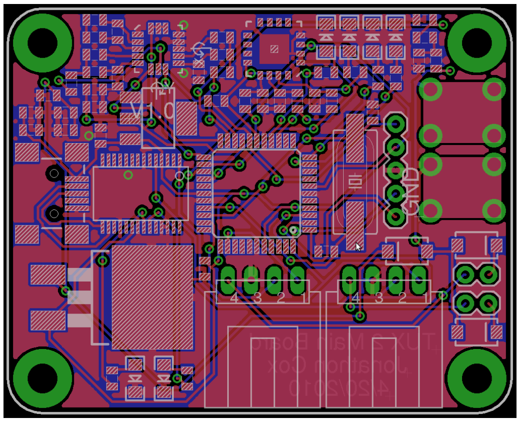

Figure 16: TUX2 Main Control Board

2. Main Control Board

The main control board is a relatively simple design compared to the motor drivers. It is based on a dsPIC processor which is capable of high speed analog-to-digital conversion. The sensors for TUX2 are soldered directly onto the main board along with some hardware filters to enhance the signals as much as possible. Much care was also taken in the analog design to reduce the closed loop area of the traces in order to reduce electromagnetic interference. The entire main board is a surface mount design which produced another significant challenge. The schematic and board layout are shown below in figure 16. The board is designed with a USB port to allow easy debugging and programming. Later the USB port will be used to monitor statistics about the operation.

Because all the parts are surface mount, soldering them became much more sophisticated. The accelerometer and gyroscope are especially difficult to solder because they are QFN packages that do not have leads. To solve this problem, a cheap reflow oven was built using a toaster oven. The toaster oven was dissembled and all the control circuitry was replaced with a custom built board. The custom board uses a relay and a thermocouple to regulate the temperature inside the oven, allowing it to be used for reflow purposes. In tests, the oven was able to reach 800 degrees Celsius, far higher than what is required for reflow soldering. Pictures and details about the reflow oven can be found in Appendix A.

3. User Interface

The user interface is crucial to creating a successful device that is easy to use. If the user interface is not well designed, regardless of the merit of the device, the user will not be satisfied and therefore sales will be hurt. The user interface for TUX2 has not been built yet as it is on the schedule for next semester but several designs have been considered. An LCD with information on battery levels and other important statistics will absolutely be included in the design. To control the device a simple joystick for passengers that are paraplegic will probably be used. For quadriplegic passengers, a more complex MEMS based head position sensing system is being considered due to the ease of integrating it with the overall design of TUX2.

E. Results

1. Testing

Several forms of testing were used throughout the development process to ensure that each component operated correctly. The most extensive testing was done on the motor drivers. To increase reliability of the system, the motor drivers are designed to be able to handle the motors at full stall, continuously. That means 166A at 12V continuously. To test this without having to place the drivers in the frame, a heatsink was used with a fan. It turned out that the weakest link were the traces on the board. The first version had been constructed by heavily plating the traces with solder to increase the current handling ability. As the picture below shows, this didn't work for more than about 60A. The solution to the problem was to coat the traces with copper wires. After this, the motor driver was able to maintain 170A continuously with proper cooling.

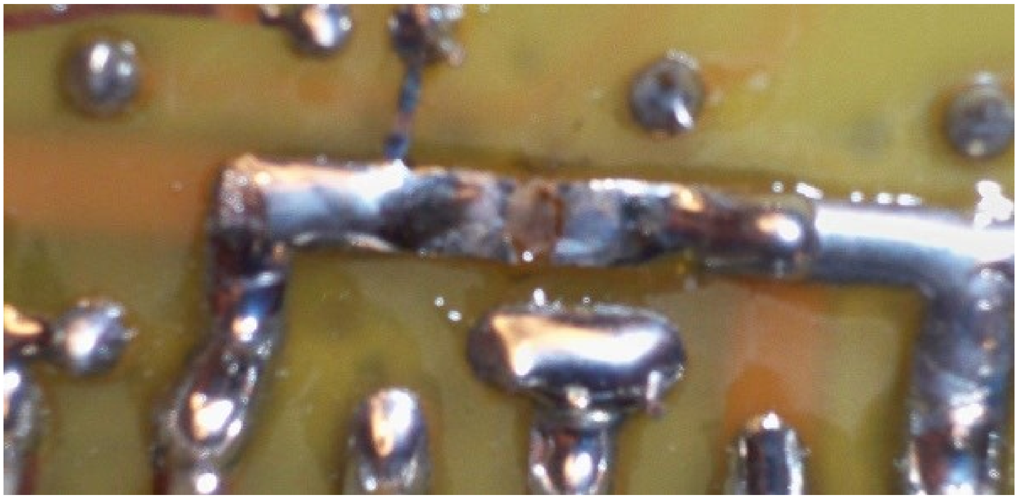

Figure 17: Blown PCB Trace

To test the entire system, a hand-held remote was built that had a joystick for turning and a spring-loaded switch to turn TUX2 on and off. If the remote was dropped, the power was turned off. This allowed the platform to be safely ridden and tested without worrying about it running away.

2. Reliability
   A very high rate of reliability is an obvious requirement for this project because people are in danger of being hurt or killed if the device fails. To improve reliability, redundancy has been incorporated into the design wherever it was economically sound to do so. All the power wires in the device are redundant and the software is designed to maintain balance even if an entire motor driver dies by using the remaining motor driver. The two sealed lead acid batteries on-board are wired such that if one fails, the other can still function. The reliability of the system was tested by simulating the failure of different components and determining if the platform was still stable. This testing is still very early and will be continued throughout the project.

III. TUX3 – Standing/Sitting Wheelchair

The next step toward making the TUX project a viable wheelchair design will be started next semester with a more advanced prototype, TUX3. TUX3 will build upon the same systems that have been created for TUX and TUX2 with the addition of a much more advanced restraint system.

The new restraint system will be designed to allow the passenger to be in a standing or sitting position on the device and it will use motors to change the passenger's position on command. Because the control system is capable of dealing with a change in the center of mass of the passenger, the base should not need to be modified at all.

Another area that will be refined is the user interface. Because the control system has the ability to tell where it is in space, an inertial measurement control system would be an excellent fit. The system will involve a device that the passenger wears on his/her head that can sense their movements. Essentially, all they will have to do is look where they want to go and TUX3 will sense the movement and execute it.

IV. Conclusion

After a considerable amount of effort and time, the TUX project is making progress. With the completion of TUX2, the applicability of a balancing wheelchair has been proven and many of the barriers that existed with TUX have been overcome. That being said, there are still a lot of problems to solve before TUX2 is viable for actual use. Next semester will push the project even further with TUX3 and a more advanced support system. TUX3 will hopefully become a fully functional balancing wheelchair that can be tested by someone with a severe disability.

Appendix A – Abbreviations

EMI – Electromagnetic Interference
PCB – Printed Circuit Board
TUX – First Prototype
TUX2 – Second Prototype
MEMS – Micro Electromechanical System
MIPS – Mega Instructions Per Second
MOSFET – Metal Oxide Semiconductor Field Effect Transistor
QFN – Quad Flan No-Leads Package

Appendix B – Budget

Electronics	
Boards	$138.20
Components	$555.31
Solder Paste	$42.04
Mechanical	
Drive Parts	$167.64
Hardware	$23.70
Raw Metals	$91.76
Total:	$1,018.65

Appendix C – Reflow Toaster Oven

In order to solder the main board for TUX2, a custom reflow oven was built using a common toaster oven. The oven is shown below with the controlling PCB. The reflow oven worked very well for the TUX2 board.

Appendix D – Proposal For Funding

TUX 2 - Inverted Pendulum Wheelchair
Proposal For Senior Design Funding
Jonathon Cox

Overview

The TUX project was started almost a year ago with the goal of creating a new control system capable of balancing a two wheeled inverted pendulum platform. Inverted platforms such as the Seguay Personal Transporter, have proven to be an efficient means of transportation and a marketable design. The TUX project takes the idea one step further by advancing the control system and hardware such that a paraplegic or quadriplegic person can operate the device as a wheelchair replacement.

Invariably the first question is "How is this project different than a Segway?" The TUX platform can maintain balance when the center of mass of the passenger changes, a Segway cannot. The answer, while subtle, leads to a tremendous increase in control system complexity and capability. By allowing the center of mass to change, the platform can balance a person without any muscle control. On a Segway, a person is required to be able to lean in order to accelerate, with TUX acceleration can be achieved through any kind of input such as a puff control or head movements.

Current Status

Over the last year, two working prototypes have been developed as test platforms for the control system. TUX 1, the first prototype, was a successful proof of concept which was completed in three months at a cost of about $350. It was privately funded and built as a project for an embedded systems class. It is a four foot tall platform that weighs about 20 lbs. Everything on the platform is custom designed and built, including all the circuit boards. The software was also written from scratch. The control system exceeded project goals and is capable of maintaining balance even when the center of mass is dramatically changed. Starting from vertical, weight can be applied to a horizontal lever arm and the platform adjusts automatically without any human intervention. In testing, it can reliably support it's own weight on a horizontal lever arm of 3 feet, requiring it to lean almost 45 degrees from vertical. This prototype has been featured in several publications and was awarded the grand prize at the 2009 Colorado Space Grant Symposium in Boulder, CO. Although very successful, it is too small to actually support a person.

TUX 2 was started during the summer of 2009 and with funding provided by the Colorado Space Grant program and continued through the fall with personal funds. TUX 2 is designed to carry a 400 pound person using the same balancing system as TUX 1. With the support of the mechanical engineering department, a custom platform was built with a sand cast aluminum frame and custom power train capable of 700Watts of power. High power motor drivers were custom designed and built in order to achieve a control system bandwidth of over 200Hz and a PWM frequency of 20kHz. The high PWM frequency is important because it makes the platform virtually silent. The drivers also save space by using the cast aluminum frame for heat sinking. Currently, the platform is completely operational and can be ridden by an able bodied passenger. The next step of the project is to fit the platform with a restraint system capable of supporting a person who is paraplegic or quadriplegic and perfect the control system.

Project Goals

By the end of the semester, the platform will be capable of safely transporting a disabled passenger using a joystick. To accomplish this, the following systems will be designed and built:

- A MEMS sensor system will be designed which incorporates redundancy and fault tolerance.
- A support Structure will be designed that allows a disabled person to ride the device.
- A user interface will be designed and built to display relevant information to the passenger
- Add wireless capability to the control system to aid in debugging and data logging

Budget

Item	Description		Cost
Sensor System			
Sensors	Accelerometers and Gyros		$150.00
Processors	dsPIC30F4011 (x2)		$20.00
Board	PCB and Chemicals		$10.00
Components	Resistors, Capacitors ... etc		$20.00
		Total:	$200.00
Restraint System			
Linear Actuators	Used to adjust Tilt		$200.00
Raw Metal	Aluminum Tubing		$20.00
Fasteners	Screws/Bolts/etc		$5.00
Webbing	Used to make harness		$20.00
		Total:	$245.00
User Interface			
LCD	Standard LCD		$15.00
Board	PCB Board and Chemicals		$10.00
Buttons/Controls			$5.00
Mounting Hardware	Box, Screws, Standoffs		$10.00
		Total:	$40.00
		Sub Total:	$485.00
		Tax/Shipping:	$20.00
		Grand Total:	$505.00

Conclusion

This project includes a substantial amount of digital signal processing and I believe it will be a very innovative system when it is complete. Thank you for your time and consideration, for more information and videos of the project in action see **http://www.tuxrobotics.com**.

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Sponsors

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