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M. Eng – Mechanical Engineering
MAE 6900-742: 3 credits

October 12, 2014

Autonomous Bicycle Project
Team Leader and Mechanical Sub-Team

Goals and Objectives

The autonomous bicycle project team has a few different goals that we would like to accomplish. The priority is balance; we decided to design and build a bicycle that can balance itself (with no rider) while moving in a straight line. At first, we will try to do this at a running speed, approximately 5 - 10 miles per hour, but eventually we would like it to balance at slower speeds than the average person can ride. Once we accomplish this, we want to automate other kinds of motion. This includes the possibility of doing a trackstand, which is when the bicycle balances with zero forward velocity. Another prospect is to make the bike ride in a circle of constant radius.

Our secondary objective is to create a fly-by-wire bicycle. This would have a human rider that can control steering, but the bicycle still balances itself. The handlebars controlled by the person riding would not have a direct mechanical link to the fork, but rather would electrically signal a motor to turn the fork. A controller would read the input signal from the handlebars and decide if it is acceptable to keep the bike stable, and then send its own signal to a steering motor. Essentially, the controller would correct the error of the human. Eventually, the end goal is to satisfy the first two objectives, while also making it more comfortable/easier to ride than a normal bicycle.

Purpose

The application of this research extends into more than just a fancy robotic bicycle. The most obvious is its use in teaching people to ride. A bicycle that corrects user error would make it much easier for children and adults to learn how to ride, and much safer as well. While training wheels are often used for children too young to balance, this system can help bridge the gap between training wheels and riding normally.

Another reason for doing this research is to provide a more economical and environmentally friendly form of transportation. If a commercially produced version were created, it would be safer and easier to ride bikes in cities, where car traffic is heavy. This would mean more people riding bikes instead of driving, and could save commuters gas money and reduce carbon emissions.

Finally, a successful autonomous bicycle design would open the door into other autonomous vehicles. Although autonomous cars are already being researched and produced by companies like Google, autonomous motorcycles and motorized scooters have yet to be produced. Like bicycles, they are more economical and environmentally friendly and could become safer with feedback control systems like ours.

Division of Work

As team lead, it is my job to ensure that everyone on the team is completing their work on a weekly basis and are truly contributing to the team's progress. In addition, I need to make sure people are working on things that keep them engaged and excited. At the beginning, this meant looking at everyone's major and fields of expertise and assigning work that pertained directly to their interests. Marvin Lao, as our only computer science major, was assigned to coding. Jay Jiang and Shihao Wang both had a strong interest in dynamics, and therefore were assigned to modeling the dynamics of the bicycle and designing a controller in MATLAB. They worked together with their simulations and finding the equations of motion, but used two different approaches to design a controller. Rany Megally, with a strong background in systems and controls, was assigned to working with Marvin to get the hardware working with the microcontroller. As a graduate student with a mechanical engineering degree, I took on the role of designing and executing the mechanical aspects of the bicycle. Two members joined the team partway through the semester, Ariam Espinal and Ellen Yu. Ariam had worked on the project over the summer, focusing on the electrical circuits and coding required for the hardware, so he was assigned to work with Marvin. Ellen was assigned to work with them, but focused on the drive motor rather than the steering motor and the potentiometer.

Previous Work

The autonomous bike project began in the Spring 2014 semester, and continued through the summer. At the beginning of the semester, we had an almost complete steering tube assembly, including a steering motor and potentiometer as well as a drive motor. The bike selected was one that had been donated to the lab, the Dahon Classic III. Although it is a small bike, the steering tube and assembly is tall enough that it should be easy to balance with a good controller. The motor we had was the Yasakawa Minertia Type JO2L, but it would later prove to be too weak to move turn the wheel and fork. The potentiometer being used is the Bourns 6639S-1-103, and the hub motor is the MagicPie 2x brushless hub motor. The microcontroller we’re using is the BeagleBoneBlack, and our sensor for measuring the lean angle of the bike is an Inertia-Link IMU. A small amount of the circuitry was also complete, along with a small portion of the code for the hardware. However, the bike was still far from complete, and there would prove to be problems with what had been done so far.

Summary of Work

One of the first main steps of completing the steering assembly was designing and fabricating a shaft to connect the fork to the motor coupling. The one that had been previously used was for the drive belt assembly, not the steering tube assembly, and therefore did not fit the setup we were using. After modeling the shaft in SolidWorks, I used scrap aluminum from the lab and machined the part.

Once this piece was complete, we were able to test the steering assembly with the bicycle to see if the motor was strong enough to turn the front wheel. With a 24V and 2.5A input, the wheel barely moved with just the weight of the bicycle and no rider. Therefore, we needed to find a new motor or gearbox to provide enough torque to turn the wheel quickly. To determine the torque and angular velocity required, I attached my phone to the handlebars of my own bicycle and rode at approximately walking speed, 2-3 mph. I took a video and measured the angular velocity and acceleration of the wheel turning while trying to balance. The angular velocity was measured as 23.9 rad/s (228 rpm) and the acceleration was 87 rad/s^2. Using I = .0333 kg*m^2, the moment of inertia calculated from the geometry of the fork and wheel, I determined the torque required to be 2.901 N*m. The motor and gearbox combination we decided to buy was the Maxon 80W 2260-885-51.216-200. With a torque rating of 8.9 N*m and a top angular velocity of 457 rpm, it would be sufficiently powerful to turn the wheel fast enough.

Getting a new motor and gearbox presented a few new issues that needed to be addressed. First, in order to measure the motor angle, we would need either a new encoder or a new mechanical setup with the potentiometer. Since using an encoder would require a significant amount of research, coding, and testing, we decided to use a new mechanical setup with the potentiometer we already had and knew how to use.

Since the new motor and gearbox only had one output shaft, the potentiometer needed to rotate at the same rate as the motor without interfering with the rotation of the fork. This involved a new shaft to connect the gearbox output to the coupling for the fork shaft. This shaft needed a gear on it to connect to another gear of the same diameter and number of teeth around the potentiometer. In order to make all this fit with the tube assembly, the plates were modified as well. A new adapter plate was necessary to fit the top end of the motor the circular plate that fit in the tube. I chose to make an adapter plate instead of making a new circular plate because a circle would need to be machined with the CNC machine, requiring code that no one currently on the team was familiar with. In addition, the potentiometer plate needed to be modified to fit the new potentiometer and motor shaft setup.

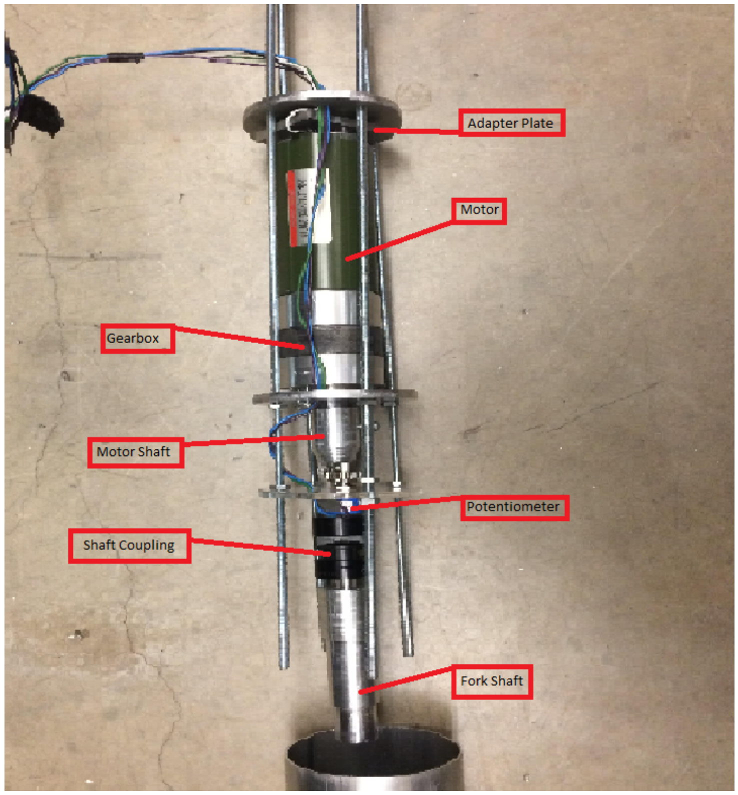
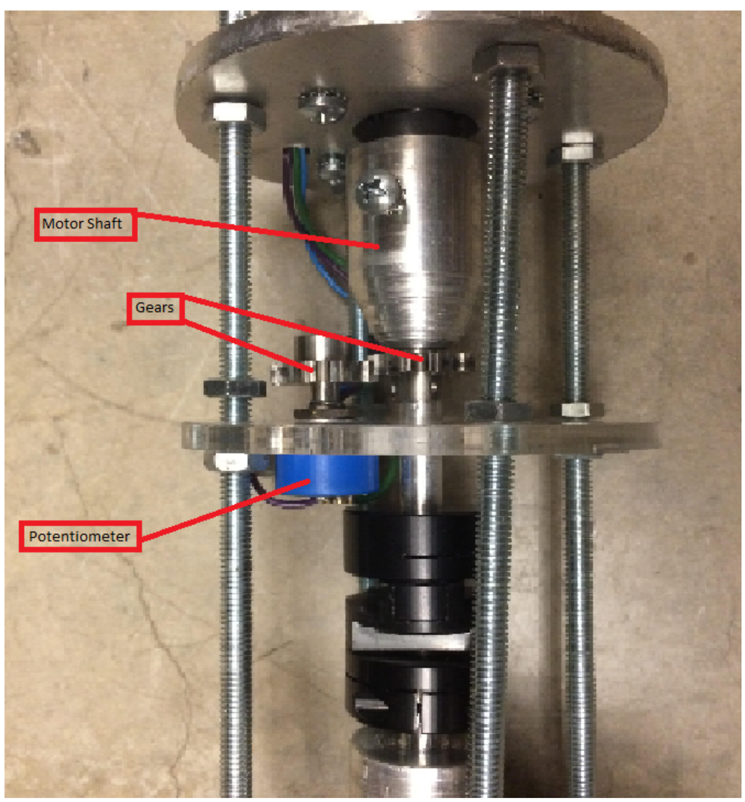


Diagram of the Steering Assembly



Close-up of the Potentiometer Gear Setup

After all of the machining was done, we tested the new steering setup with the power supply in the lab. We decided to switch the hub motor to the back wheel instead of the front since it is much heavier than a normal wheel, and therefore the motor would be able to turn a normal wheel much more quickly. With a 24V input, the motor was able to turn the wheel more than fast enough for our application.

With the mechanical setup complete, I completed the wiring for the potentiometer and steering motor and drilled holes in the electrical box to connect it to the BeagleBone. I also mounted the IMU in the electrical box so that it could accurately measure the lean angle while still being protected from a collision. With the ambition of testing before the end of the semester, I determined what additional electrical components we would need to get all of the hardware working together. After discussion with Ariam and Jason, we ordered a DC/DC converter to limit the voltage input to the IMU.

Future Work

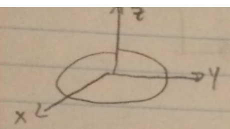
One unforeseen problem that arose before testing was that the electrical team had coded and wired for an angular position controller for the steering motor early in the semester, but the control models that Jay and Shihao developed required angular velocity control. Therefore, Ariam and Marvin needed to work on a differentiator circuit and the code to go with it, but ran out of time by the end of the semester. This will be a priority to finish at the beginning of next semester, and once complete, the bike will be ready for testing. Although we don't expect the controller to work first try since we made many approximations in our moment of inertia calculations, we predict that it will be relatively easy to adjust our control constants in a trial and error process to balance the bike.

Once we successfully get the bike to balance in a straight line, the next objective will be a fly-by-wire implementation, as stated in our goals and objectives. This will require a mechanical setup for the handlebars, a potentiometer to measure desired steer angle, and a new controller to incorporate the user input. It will likely be a significant challenge, but I am confident that our team will be able to accomplish it before the end of the year.

As another goal for next semester, I would like to make the autonomous bicycle team an official Cornell University project team. This would help generate publicity for the team to attract new members, and also possibly give the team and lab more funding, opening even more possibilities for the future.

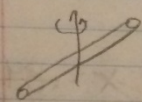
Appendix A: Handwritten Notes/Calculations/Sketches

Moment of Inertia Calculation



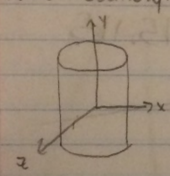
$$I_x = I_y = \frac{mr^2}{4} = (.702)\frac{(.203)^2}{4} = .00723$$

Handlebars: $L = 19" = .483\,m$ $m = .76\,kg$



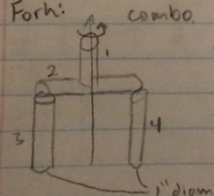
$$I = \frac{mL^2}{12} = \frac{(.76)(.483)^2}{12} = .01477$$

Tube Assembly: $r = 2" = .051\,m$ $m = 3.60\,kg$



$$I_y = \frac{mr^2}{2} = \frac{(3.6)(.051)^2}{2} = .00468$$

Fork: combo. of 4 moments: assume each of 4 parts $= \frac{m}{4} = \frac{.7\,kg}{4} = 1.75\,k$



$$I_1 = \frac{m_1 r_1^2}{2} = \frac{(1.75)(.019)^2}{2} = .00315$$

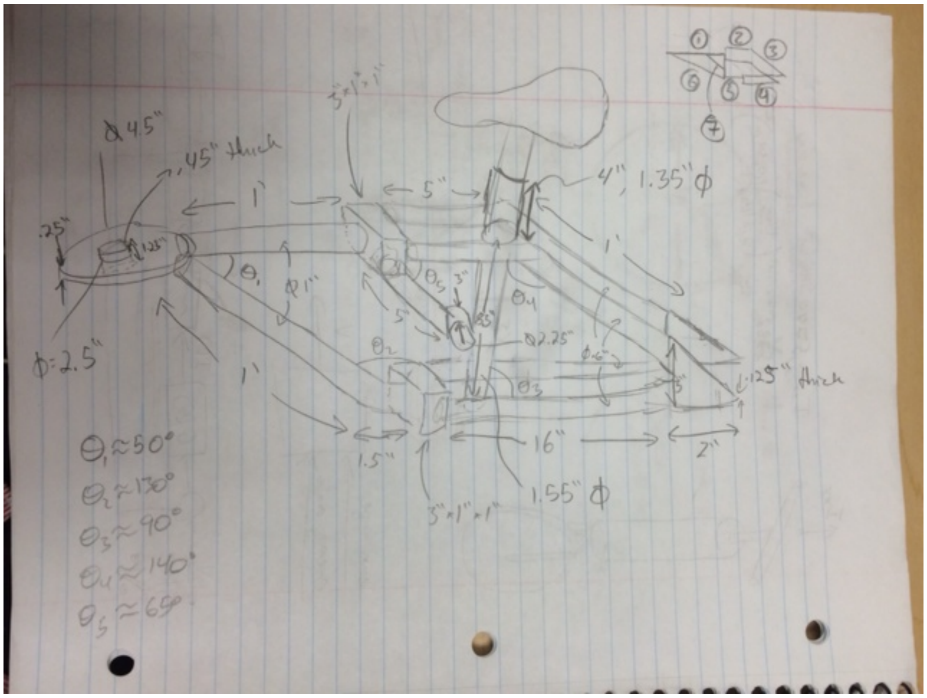
$$I_2 = \frac{m_2 L_2^2}{12} = (1.75)\frac{(.076)^2}{12} = .000842$$

$$I_3 = I_4 = \frac{m_3 r_3^2}{2} + m_3 d_3^2 = (1.75)\frac{(.013)^2}{2} + (1.75)(.038)^2 = .00267$$

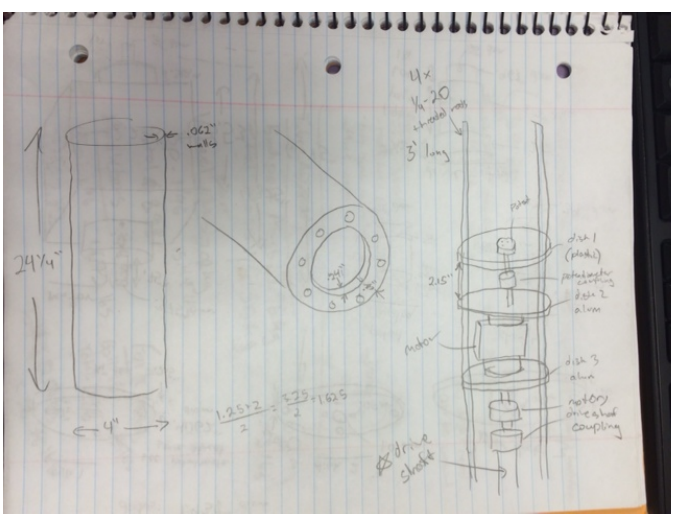
$$I = .00723 + .01477 + .00468 + .00315 + .000842 + .00267$$

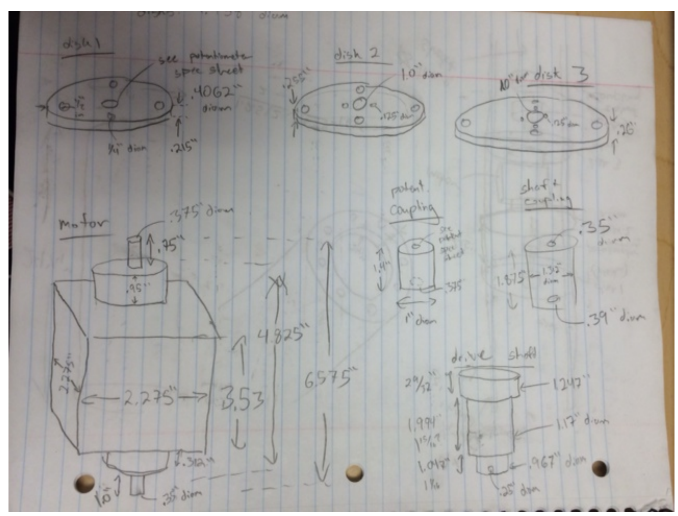
$$\boxed{I = .033342\ kg \cdot m^2}$$

Bike Frame

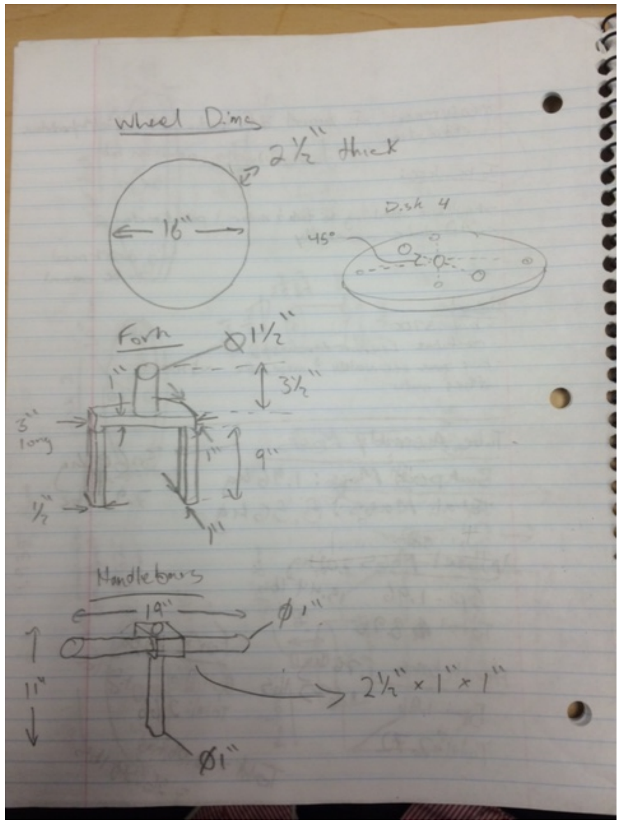


Tube Assembly

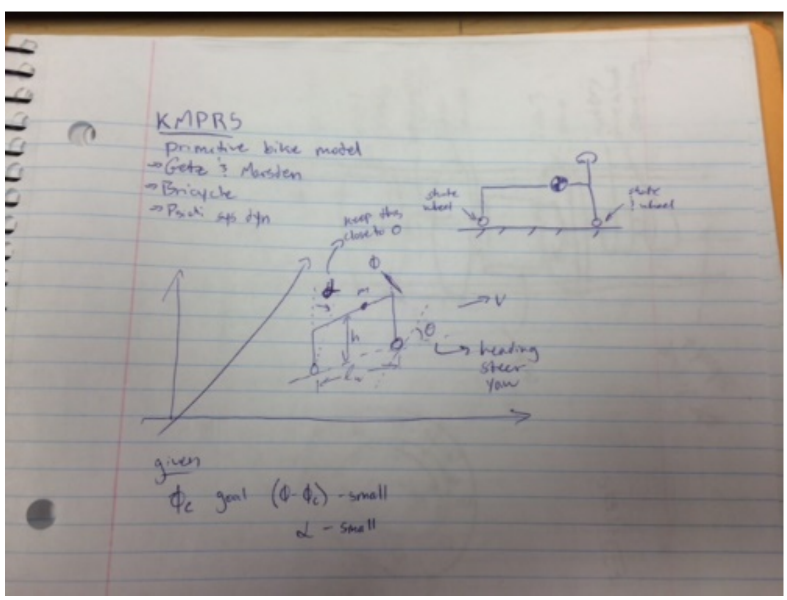




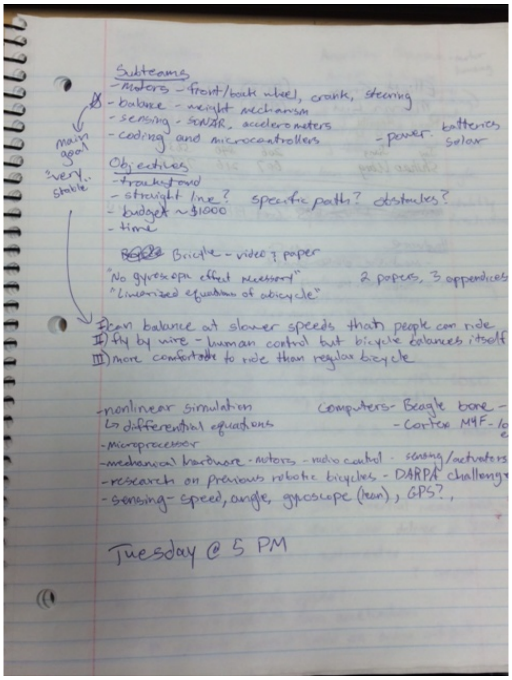
Front End



Bike Dynamics Diagram



General Misc. Notes



Subteams
- Motors - front/back wheel, crank, steering
- balance - weight mechanism
- sensing - SONAR, accelerometers
- coding and microcontrollers

- power. batteries
solar

main goal
"very stable"

Objectives
- trackstand
- straight line? specific path? obstacles?
- budget ~$1000
- time

Bricyle - video & paper

"No gyroscopic effect necessary"
"Linearized equations of a bicycle"

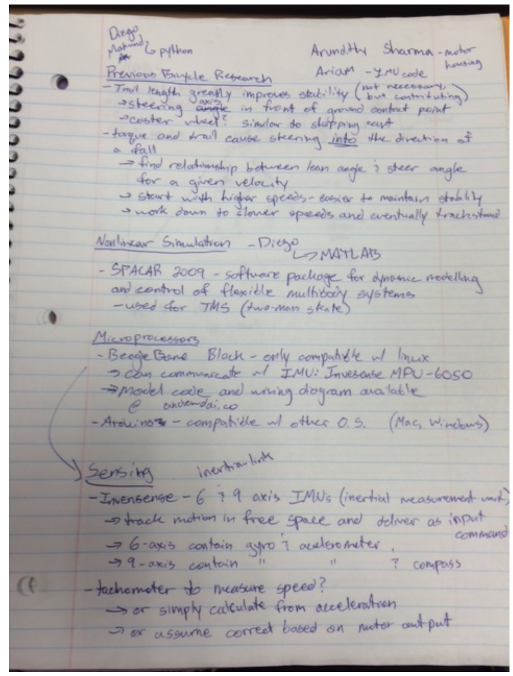
2 papers, 3 appendices

I) can balance at slower speeds than people can ride
II) fly by wire - human control but bicycle balances itself
III) more comfortable to ride than regular bicycle

- nonlinear simulation
↳ differential equations
- Microprocessor
- mechanical hardware - motors - radio control - sensing/actuators
- research on previous robotic bicycles - DARPA challenge
- sensing - speed, angle, gyroscope (lean), GPS?,

Computers - Beagle bone -
- Cortex M4F -

Tuesday @ 5 PM



Diego
Mahmud
↳ python

Arundhy Sharma - motor housing
Ariam - IMU code

Previous Bicycle Research
- Trail length greatly improves stability (not necessary, but contributing)
→ steering axis in front of ground contact point
→ caster wheel? similar to shopping cart
- torque and trail cause steering into the direction of a fall
→ find relationship between lean angle & steer angle for a given velocity
→ start with higher speeds - easier to maintain stability
→ work down to slower speeds and eventually trackstand

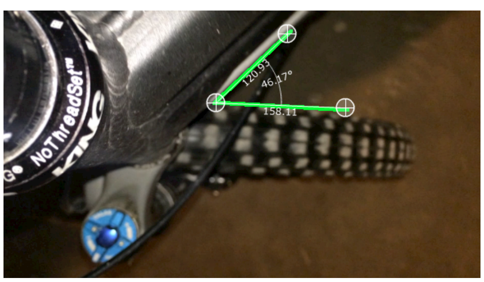
Nonlinear Simulation - Diego
↳ MATLAB

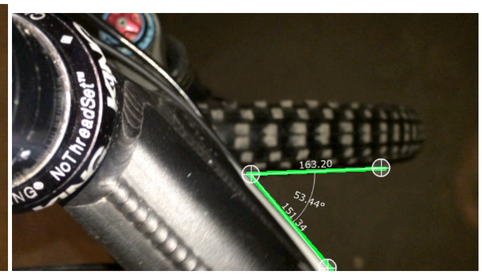
- SPACAR 2009 - software package for dynamic modelling and control of flexible multibody systems
- used for TMS (two-mass skate)

Microprocessors
- BeagleBone Black - only compatible w/ linux
→ can communicate w/ IMU: Invensense MPU-6050
→ model code and wiring diagram available @ embedded.co
- Arduino - compatible w/ other O.S. (Mac, Windows)

Sensing inertia-link
- Invensense - 6 & 9 axis IMUs (inertial measurement unit)
→ track motion in free space and deliver as input command
→ 6-axis contain gyro & accelerometer.
→ 9-axis contain " " & compass
- tachometer to measure speed?
→ or simply calculate from acceleration
→ or assume correct based on motor output

Angular Rate Calculation





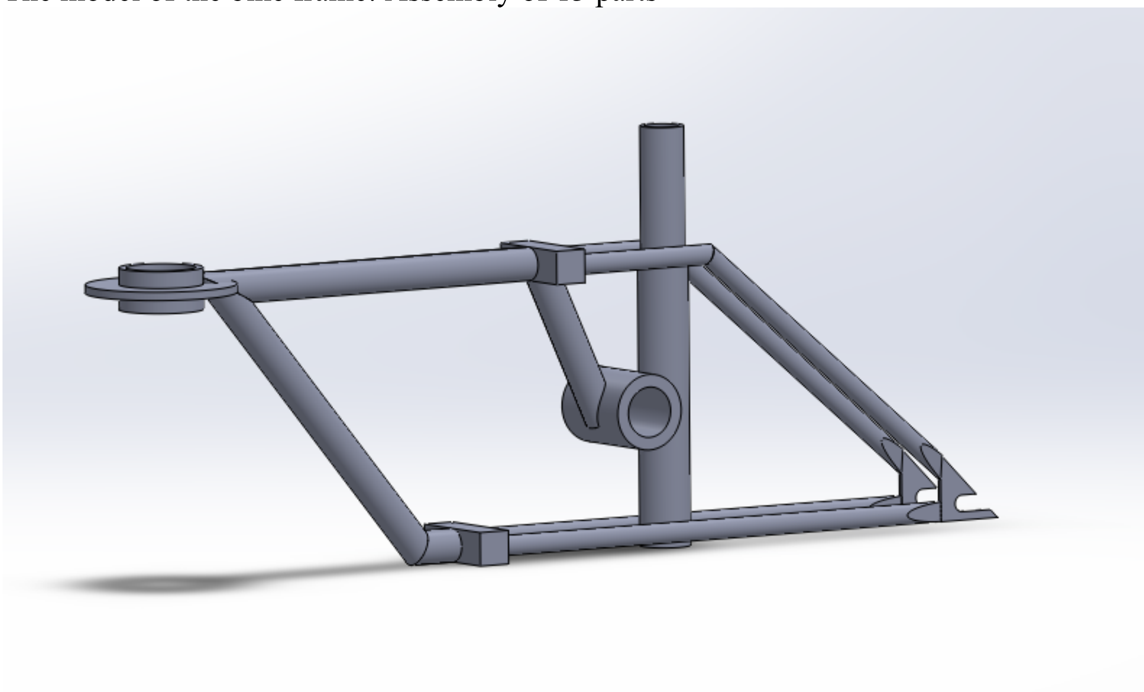
$$t = .4 \text{ seconds}$$
$$\Delta\theta = 46.2° + 53.4° = 99.6° = 1.74 \text{ rad}$$
$$\omega = \Delta\theta/t = 1.74/.4 = 4.35 \text{ rad/s} = 41.5 \text{ rpm}$$

$$\Delta\theta = \omega_0 + ½\alpha t^2$$
$$1.74 = 0 + ½\alpha(.2)^2$$
$$\alpha = 87 \text{ rad/s}^2$$

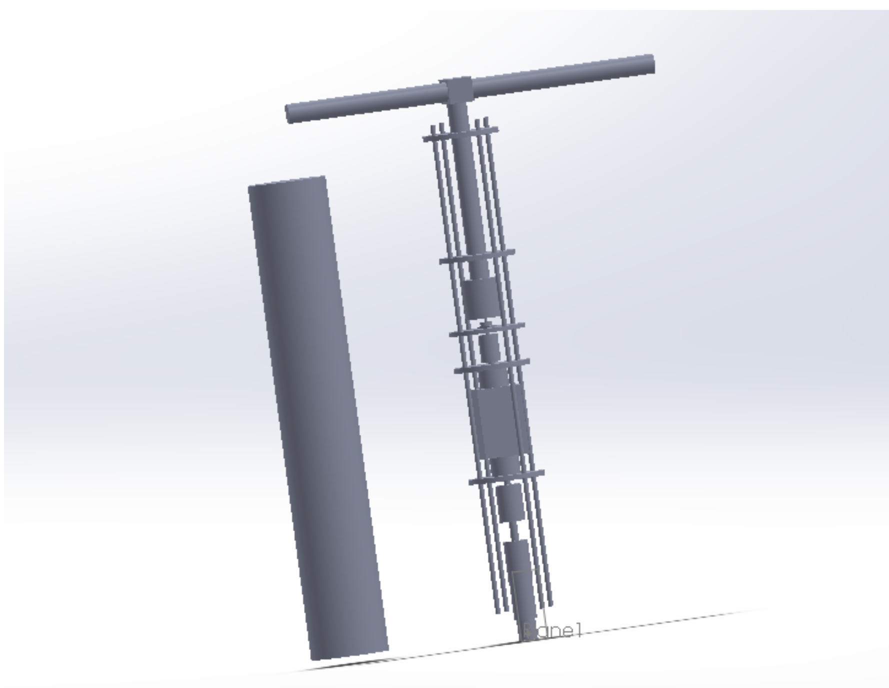
$$I_x = .033342 \text{ kg*m}^2$$
$$T = I_x\alpha = (.033342)*(87) = 2.901 \text{ N*m}$$

Appendix B: SolidWorks and ANSYS Models

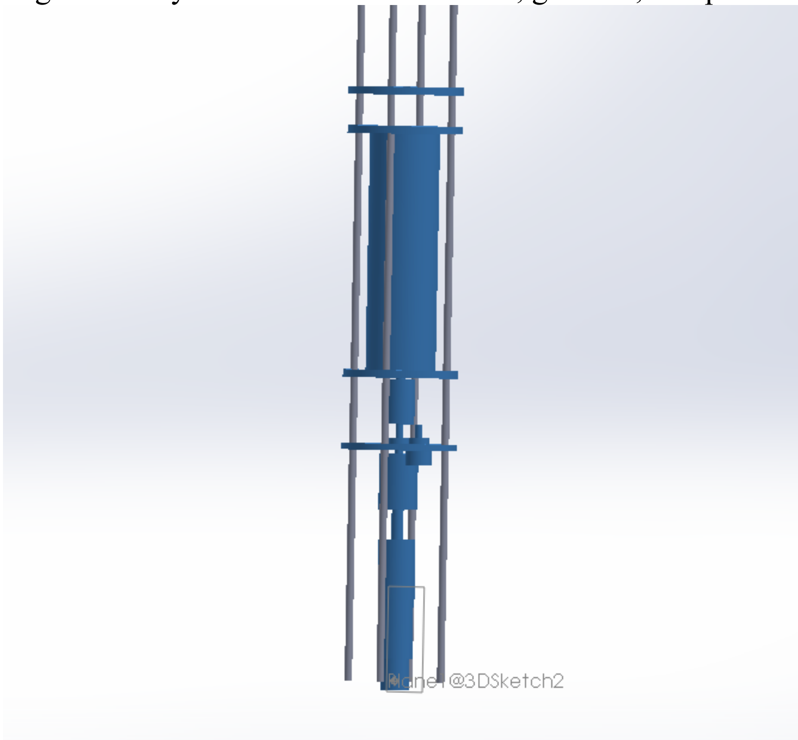
The model of the bike frame: Assembly of 13 parts



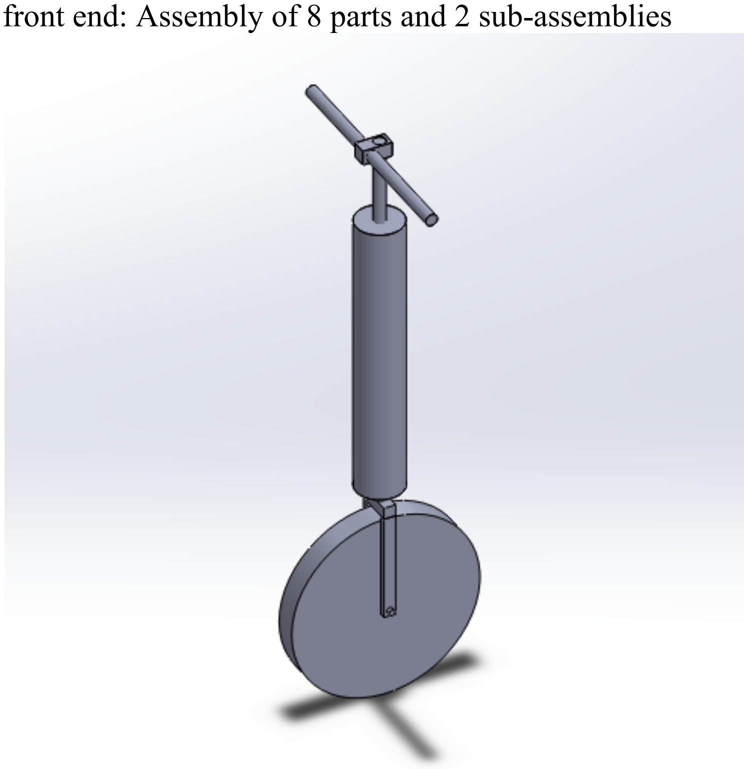
The model of the tube assembly with the handlebars attached and new potentiometer: Assembly of 16 parts and 1 sub-assembly



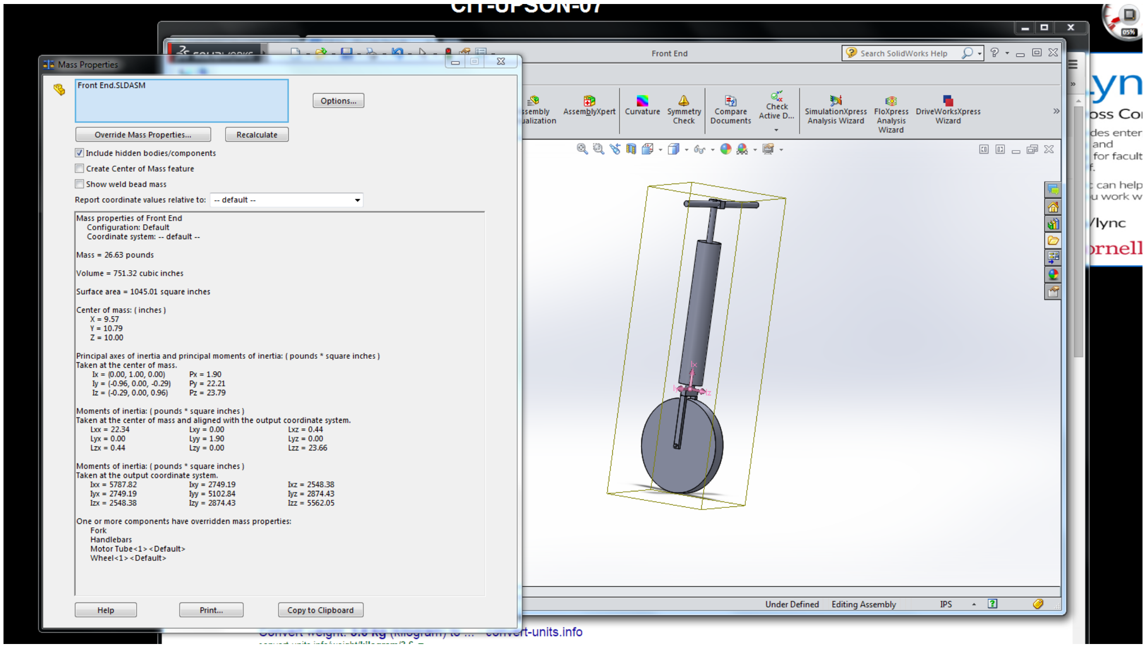
Updated Steering Assembly CAD Model: New motor, gearbox, and potentiometer setup



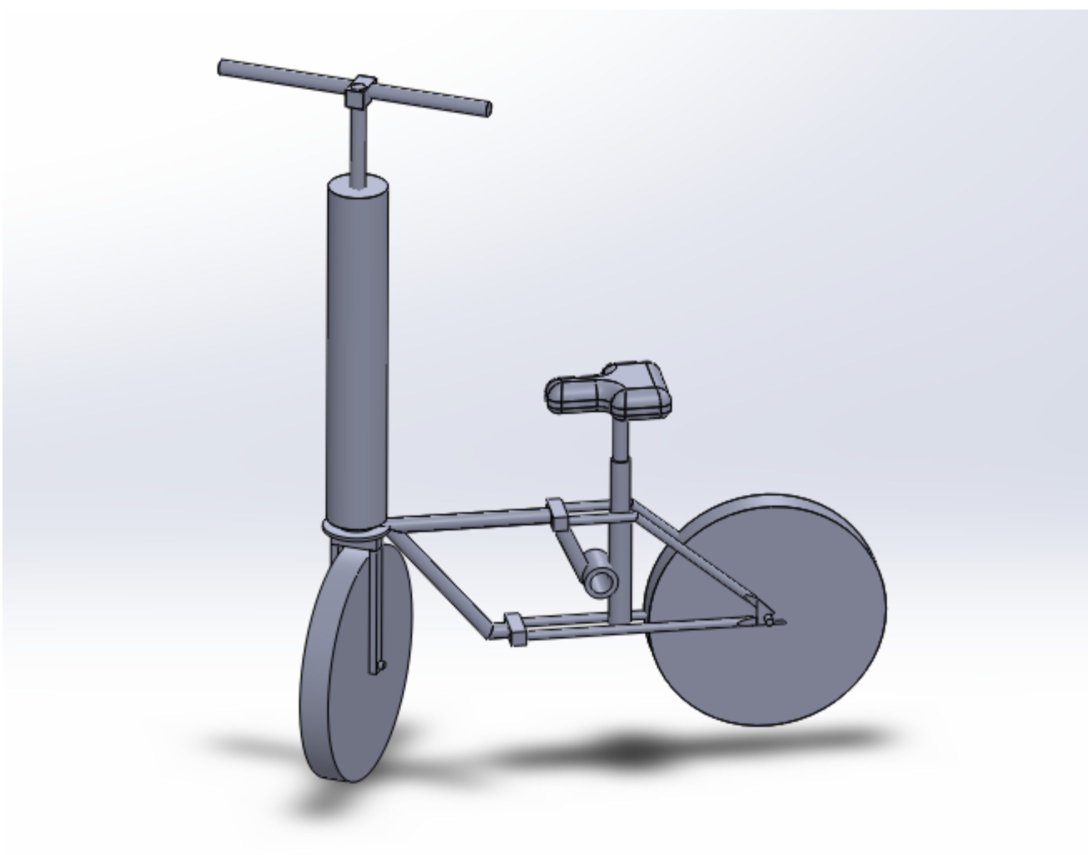
A model of the front end: Assembly of 8 parts and 2 sub-assemblies



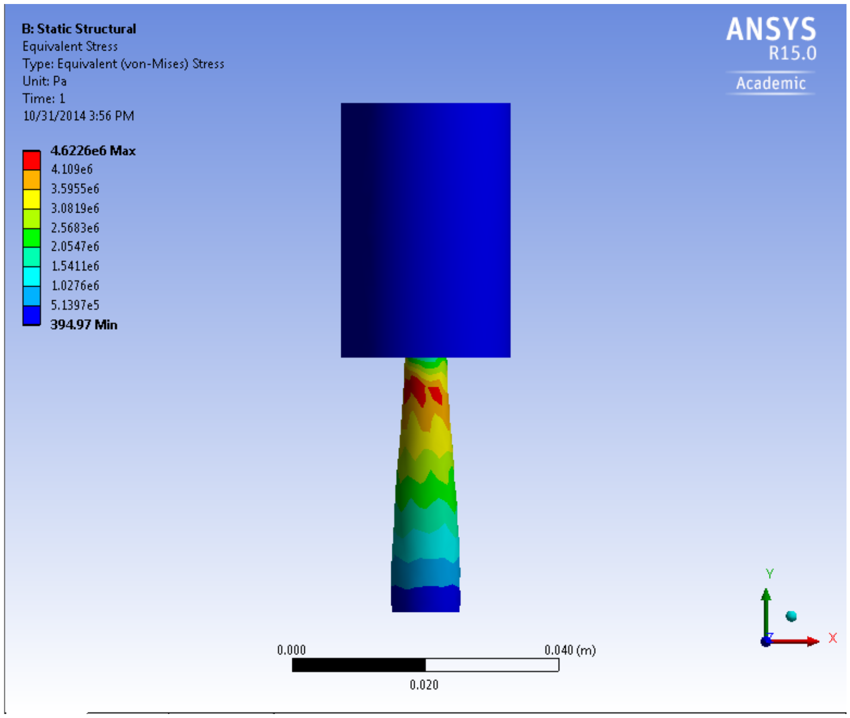
Moment of Inertia Calculation of Front End



Model of the entire bike: Assembly of lots of parts and sub-assemblies



Stress Analysis of Potentiometer Shaft



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