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Autonomous Stability Control of a Moving Bicycle

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Buddy Michini

Advisor: Jaime Peraire
Partner: Sean M. Torrez

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1 Executive Summary

Bicycles have been a popular form of transportation and recreation for over a century. The physical dynamics of bicycles have been studied by scientists, mathematicians and engineers alike for almost as long. With the advent and evolution of computers and electrical sensors, the control of complicated dynamic systems becomes more feasible. The fully-autonomous stability control of a moving bicycle has not been extensively researched or achieved satisfactorily. In this experiment, we will assess the ability of an autonomous controller to maintain bicycle stability at various speeds with various impulse disturbances applied. Our findings will be pertinent to any application involving the control of a two-wheeled inline vehicle. One such application could be a ”learning bike” that would offer supportive control for an inexperienced bicycle rider.

A dynamic model of bicycles will be adapted from previous research. Computer tools will be used to numerically simulate the model to determine critical hardware requirements an autonomous bicycle. An autonomous bicycle will be fabricated and a control algorithm will be tested. Once a final controller is designed, the bicycle will be tested at various forward velocities with various impulse disturbances applied. Data taken will be analyzed, and the effectiveness of the stability controller will be assessed. Our results will aide the future development of assisted-stability controllers for bicycles and motorcycles and will evaluate the feasibility of a ”learning bike” with regards to cost and safety issues.

The project will be completed within 13 weeks during the Fall 2006 semester and has an estimated budget of $700.

2 Introduction

For over a century, bicycles have been a means of low-cost transportation as well as a popular form of recreation. Bicycle dynamics and stability have been extensively modeled in past research by mathematicians, scientists, and engineers alike. Smaller and faster modern computers and more reliable sensors have made possible the cheap and effective control of complicated dynamic systems. These factors make the design and implementation an autonomous stability control system for a bicycle possible. One particular application of this would be a ”learning bike”. This assisted-stability bicycle would have the ability to decrease the amount of supportive control as the rider becomes more skilled.

In this project, we will assess the abilities of a computer control system by implementing such a control system on a bicycle. The controller will take roll-angle and roll-rate data from onboard sensors as inputs and apply a control torque to the front fork via an electric motor. This will act to fully stabilize the bicycle while traveling at a constant speed.

Several researchers have studied the automatic control of bicycles. There have been attempts to implement such control systems, and some have even been successful at stabilizing the bicycle on a treadmill apparatus (see Literature Review for more details). To our knowledge, however, there have not been any successful attempts at stabilizing a moving bicycle. Our bicycle will be completely self-contained and able to move freely through a test course.

3 Hypothesis, Objectives, and Success Criteria

3.1 Hypothesis

An autonomous control system is able to maintain the stability of a bicycle traveling at 5 m/s after the application of a 15°impulse disturbance in roll-angle. The control system will return the bicycle to within 0.75°of the nominal 0°roll-angle a maximum of 4 seconds after the impulse disturbance.

3.2 Objectives

Derive a simple model of bicycle stability dynamics from a literature survey and design a stability controller based on that model. Implement the stability controller on a bicycle and measure its response to a 15°impulse disturbance in roll-angle while traveling at 5 m/s.

3.3 Success Criteria

Assess the ability of an autonomous controller to maintain bicycle stability after a 15°impulse disturbance in roll-angle while traveling at 5 m/s. If such a controller cannot maintain stability, identify the phenomena and/or limiting factors that prevent it from doing so.

4 Literature Review

There are two general categories of research that pertain to this project. The first is research that has been done on the dynamics of the bicycle itself. The second is research done on control systems and controlling a bicycle specifically. Pertinent literature will be discussed herein, roughly in the order above.

4.1 Dynamic Models of Bicycles

An IEEE article pertaining to bicycle dynamics by Åström, Klein, and Lennartsson[1] includes discussion of linear modeling, measuring bicycle dimensions and physical parameters, and stabilization considerations. Second-order and fourth-order linear models are presented clearly, and these are being considered for use in our project. The article also cites a list of over 70 references that pertain to bicycle dynamics and control which were researched accordingly.

The fourth-order linear model presented by Åström et al.[1] was originally developed by Franz Whipple[2] in 1899. Over the past 20 years the model has been further developed and explained by Papadopoulos[3,4]. His helpful publications have made it possible to further understand this model such that we can utilize it in our project. The fourth-order model has been validated experimentally in two separate studies by Schwab et al.[5,8] This makes us confident that, if applied correctly, the fourth-order model will be adequate for our needs.

4.2 Control Approach

Investigation of these dynamic models brings to light a critical design issue. Our experiment relies on the control of the front fork to stabilize the bicycle. However, the front fork can be controlled in two ways, either by commanding a steering torque to be applied to the fork or by commanding an absolute position (i.e. steer-angle) of the fork. This has many design implications on our bicycle, such as whether we need only mount a DC motor directly to the front fork or a more complicated servo motor (see Technical Approach for details).

Åström et al.[1] develop the second-order linear model by considering torque to be the control variable. This approach confirms the fact that the design of the front fork has a major impact on the stability of the bicycle. This indicates that applying a steering torque on our bicycle would be a very natural means of control as far as the fourth-order dynamic model is concerned.

In his summary report, Papadopoulos[3] includes an appendix pertaining solely to the application of the fourth-order model mentioned earlier. He states that the equations of motion may be manipulated to study the effects of either a steer-torque controller or a steer-angle controller. He specifically notes that a steering torque could be applied by a "balance controller" that applies a torque based on the roll angle of the bicycle, indicating that controlling the fork via a steering torque is a sound approach for our stability controller.

4.3 Previous Experiments and Current Research

As mentioned earlier, ours is not the first attempt at creating a bicycle stability controller. In his Ph.D. thesis in 1975, Van Zytveld[6] designed and implemented a ”lean controller” that attempted to control the bicycle much like an operator riding without handlebar control would lean to achieve stability. The bicycle used a gas motor to maintain forward speed, an outrigger fitted with a potentiometer to measure roll angle, and a DC motor that controlled a shifting weight (providing the ”leaning” effect). Batteries, amplifiers, and other electronics needed to implement the control law were also mounted on the bicycle.

The bicycle never achieved satisfactory operation, and could only maintain stability for a few seconds at a time. Despite this fact, several aspects of the thesis are pertinent to our experiment. Firstly, a proportional plus derivative control law was chosen for its relative ease of implementation and its effectiveness in stabilizing the system (at least in theory). This can possibly be used as a starting point for our control law. Second, Van Zytveld concludes that the main factor in the controller’s inability to maintain stability was a deficiency in the power converter. This is a hardware problem not related at all to the dynamics or control theory. Thus, hardware design, not just dynamics and control theory, should be considered in our experiment.

Murakami and Tanaka[7] designed and implemented a steering controller for a bicycle robot. In this experiment, the steer angle was controlled via a servo motor, and an electric motor was used to maintain forward speed. The bicycle was tested on a treadmill apparatus and the controller demonstrated the ability to stabilize the bicycle effectively.

Unfortunately, it seems as if the study was translated from Japanese, and the model derivation among other things is at times hard to follow. Even so, there are several aspects of the study that are pertinent to our experiment. Again, a proportional plus derivative control law was implemented. This confirms that such a control law will be a good starting place in our design. More importantly, this study demonstrates that steering control is adequate in the stabilization of a bicycle. Unlike the lean controller discussed above, the steering controller in this experiment is proven to be able to control the roll angle of the bicycle and maintain stability.

4.4 Summary

We believe that our experiment will add three key aspects to the body of research described above. First, our experiment will evaluate the ability of a steering torque control method to stabilize the bicycle. As discussed above, steering angle and lean controllers have been tested, but not a steering torque controller. Second, our experiment will evaluate the feasibility of building an autonomous bicycle that is self-contained and free to move. While Murakami and Tanaka demonstrated that their controller works on a treadmill apparatus, our bicycle will be completely self-contained and be able to move unconstrained through a test area. Third, our experiment will act as a starting point for further research into the applicability of such a steering controller to a "learning bike" with regards to cost and safety issues.

5 Technical Approach

5.1 Objectives

Again, our objective has two major components: 1) Derive a simple model of bicycle stability dynamics from a literature survey and design a stability controller based on that model and 2) Implement the stability controller on a bicycle and measure its response to a roll-angle disturbances.

5.2 Model Derivation

The dynamic model will be selected from the literature and appropriately tailored to our project with the guidance of faculty advisors. The model should be simple enough to analyze relatively easily but accurate enough to design an initial control law. As mentioned above, we are currently considering either the second-order or fourth-order linear models presented by Åström etal.[1]

Once a model is selected, a bicycle must be obtained. The bicycle should have good stability characteristics based on considerations discussed in the referenced literature. It must then be measured for relevant dimensions, moments of inertia, etc., so that the model can be numerically analyzed for the case of our specific bicycle.

5.3 Controller Design

MATLAB will be used to analyze the model and design an initial control law. As explained above, both Van Zytveld[6] and Murakami[7] implemented proportional plus derivative stability controllers in their experiments. This type of controller is relatively easy to implement digitally, which makes it appealing for our project. Also, Murakami has proven this type of controller successful in stabilizing a bicycle. These factors lead us to believe that a proportional plus derivative controller will be a good place to start.

We will model our closed-loop system, including the controller, model, and feedback loop, with the Simulink toolkit. Various disturbance inputs will be simulated, allowing us to tune the controller until a satisfactory response is attained. While numerical simulations using Simulink will provide a means for us to verify our control law theoretically, the controller will surely require tuning upon implementation on our bicycle.

5.4 Hardware Selection and Bicycle Modification

Using results from the numerical simulation, hardware will be sized and chosen as described in section 5.2, "Apparatus". The bicycle will then be modified as described in 5.3, "Construction".

5.5 Measurements

The bicycle will be tested on a flat, open test area such as an empty parking lot or large gymnasium. Initial runs will be used to tune the controller gains in an effort to optimize stability and robustness. This will most likely be a trial-and-error process. During every run the laptop computer will be logging roll angle, roll rate, and commanded control torque along with appropriate timestamps. Initially this data can be used to analyze each run and tune the controller appropriately.

Once a satisfactory controller is decided upon, formal test runs will be performed. Independent variables are forward velocity V [m/s] and magnitude of roll impulse disturbance ? [degrees]. The dependent, measured variable is roll angle response with time. From this response several performance characteristics will be determined such as time to return to 0 nominal roll angle, percentage overshoot, and overall stability. Trials will be performed to complete a test matrix similar to Table 1.

6 Experimental Design

6.1 Modeling and Numerical Simulations

Modeling the dynamics of the bicycle is critical for sizing hardware and designing the stability controller. The linear fourth-order model presented in Section 3.1 was used to

Table 1: Test Matrix Format

		Magnitude of Impulse Disturbance (degrees)			
		δ_1	δ_1	...	δ_n
Forward Velocity (m/s)	V_1				
	V_2				
	$\vdots$				
	V_n				
		Roll Angle Response with Time (degrees)			

simulate bicycle dynamics. The model has several input parameters including dimensions, masses, and moments of inertia. Instead of measuring our bicycle for these, we used values provided in the experimental validation of the model by Schwab et al.[8] While these values do not represent our bicycle exactly, they should be very similar since the bicycle used by Schwab is very similar in size and dimension to our bicycle.

The Simulink toolkit in Matlab was used to run numerical simulations of the model. Appendix A explains how the model was coded into Simulink and gives a general overview of the numerical simulation process. These simulations were used to determine critical pieces of information necessary to size the experimental hardware. For example, one output of the model is the torque that the steering motor must provide. This allowed us to determine the specifications that a candidate steering motor must meet. Other specifications determined from the model included steering motor rotation rate and rate gyro measurement range.

6.2 Apparatus

Figure 1 is a conceptual sketch of the experimental apparatus. The drive motor will be fitted to the frame and attached to the drive chain, essentially taking the place of the pedals. After the handlebars are removed, the front fork must be mechanically linked to the steering motor. Motor driver electronics will be mounted near the steering motor (not shown in Figure 1). The rate gyro and inclinometer, which measure roll rate and roll angle, respectively, will be attached rigidly to the frame of the bicycle. The laptop computer and micro-controller must be mounted within the frame and properly protected should the bike fall over. Safety outriggers (much like raised training wheels) will be mounted on either side of the back wheel to catch the bicycle if the roll angle exceeds a maximum tolerance. Battery cells must be mounted strategically to adjust the center of gravity to a desired location. Finally, a device will be mounted that will apply a desired impulse disturbance in roll angle. The method of disturbance has not yet been determined, but could be as simple as launching a mass perpendicular to the path of motion thereby rolling the bike in the other direction.

The finished autonomous bicycle will be a complicated apparatus with many components. The following sub-sections discuss each of these components in detail in terms of their specifications and the reasons they were chosen.

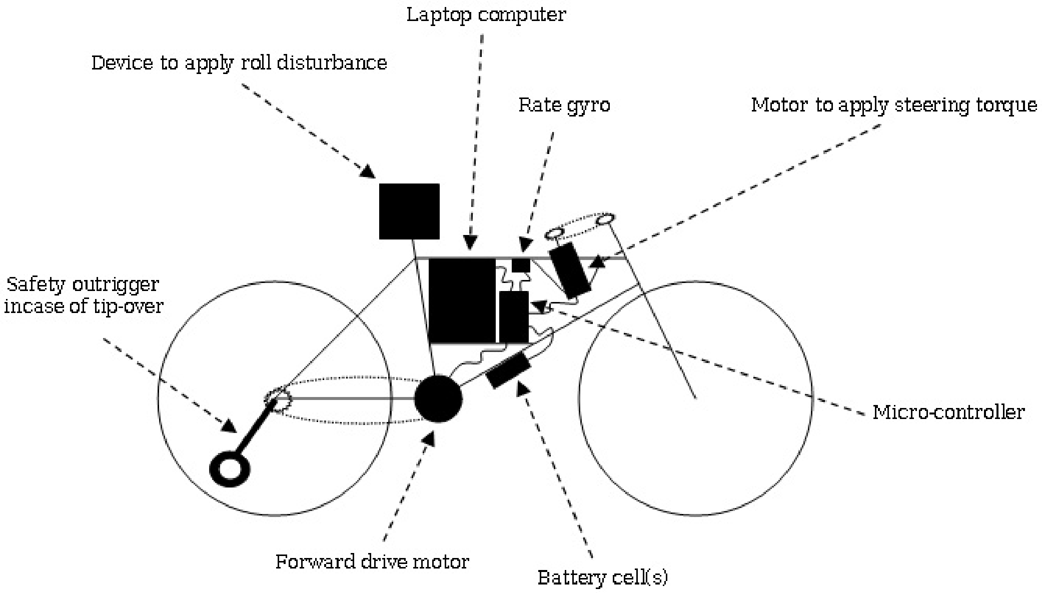

Figure 1: Sketch of experimental setup

6.2.1 Bicycle

The bicycle being used is a fairly standard men's mountain bike. The bicycle, donated to us by Prof. Willcox, is a Motiv Backcountry HP (18.5 inch frame, 26-inch tire diamter) with a rigid frame (no suspension). While the bicycle was previously used, the critical moving parts (such as bearings, wheels, etc.) are in good working condition. Non-critical elements (such as pedals, handlebars, etc.) will be removed in the construction process.

6.2.2 Rate Gyro and Inclinometer

From the numerical simulations, it was determined that the rate gyro must have a measuring range of at least ±60°/sec. Since the rate gyro is perhaps the most critical sensor in the experiment, it was important to choose a reliable and accurate device. We decided to go with the same gyro that Schwab et al.[8] used on their instrumented bicycle. The CRS03-01 made by Silicon Sensing has a ±100°/sec range and an excellent scale factor of 20mV/°/sec. Its power supply requirements and output signal are also compatible with the OrcBoard Controller being used.

To obtain roll angle, we will be integrating the roll rate signal from the rate gyro. This will lead to drift over time and must be corrected. To do this, we are using a 3-axis linear accelerometer. The accelerometer will essentially be used as an inclinometer, or device that determines the bicycle's absolute angle relative to the ground by measuring gravity forces. This will be used to correct any drift in the rate gyro integration. Dick Perdichizzi has provided us with a Crossbow CXL04M3 3-axis Accelerometer free of charge. The device has a ±4g measuring range and a 500mV/g sensitivity, making it more than adequate for our purposes. It is also compatible with the OrcBoard Controller.

6.2.3 Motors

Two motors are needed for this experiment, the drive motor to propel the bicycle forward and the steering motor to apply control torque to the front fork. From the numerical simulations, it was found that the steering motor must be able to apply a stall torque of 1 Newton-meter. The motor must also have an encoder so that steer angle and steer rate can be measured. Dave Robertson provided us with a Matsushita GMX-6MP009A DC brushed motor free of charge. The motor provides 1.4 Newton-meters of torque, runs at 24V, and has a 500-pulse encoder, making it adequate for our purposes.

The drive motor is less critical than the steering motor. It must be able to maintain a roughly constant speed of rotation such that the bicycle moves forward at a constant speed. A 24V DC motor has been provided for us by Dave Robertson. The manufacturer is unknown and the part number listed on the motor is 70071906-5. Testing indicates that the motor has enough torque to drive the bicycle forward. We will mount an optical encoder on the drive motor with the help of Dave Robertson to measure the speed of rotation of the motor and thus the forward speed of the bicycle. This will allow us to implement feedback control to keep the bicycle moving at a constant forward velocity.

6.2.4 Motor Drivers

Our controller will be commanding a torque to be applied by the steering motor. In DC motors, torque is roughly proportional to current (amps). While the OrcBoard does have motor output ports with current-sense, it does not provide enough power for this application. This brings about the need for a motor driver, or a device that amplifies a motor command signal to actually power the motor. Since we are commanding torque (and thus current), a current-amplifying device is required. The Advanced Motion Controls Z6A6 Servo Amplifier provides exactly the functionality needed. It has a current-amplification (torque) mode, 3-amp continuous output, and a current-sense output that would allow us to implement closed-loop torque control if needed. The device is compatible with the OrcBoard and can accept a 24-volt DC power supply, which is the output of our batteries.

For the drive motor, we will be commanding a speed of rotation (and thus forward bicycle velocity). In DC motors, speed is roughly proportional to voltage. The Z6A6 described above also has a voltage-amplification (speed) mode. This, in conjunction with the speed of rotation measurement from the drive motor encoder, will allow us to implement feedback control to keep the bicycle moving at a constant forward velocity. Thus we will order another Z6A6 to power the drive motor.

6.2.5 OrcBoard Controller and Laptop

We have chosen the OrcBoard Controller to interface with the sensors and send output signals to the motors. The OrcBoard was originally designed for the MIT Maslab Robotics Competition with ease-of-use and flexibility in mind. More information can be found at www.orcboard.org. The board interfaces with a computer via a USB connection.

The laptop we will use is a Dell Lattitude D800 with a 1.7GHz Intel Pentium M processor. A Java API provided for the Orcboard allows the laptop to read Orcboard sensor inputs, do appropriate computations, and command motor output signals. Simple controller logic will be coded in Java and run on the laptop in real-time throughout each experimental trial. We are in possession of both the OrcBoard and the laptop and thus do not need to purchase them.

6.2.6 Batteries

The OrcBoard requires a 12V power supply to power itself and the sensors, and draws very little current. We will use a B.B. Battery BP4-12 12V sealed lead-acid battery, and already have two in our possession.

The motor drivers and motors require a 24V DC power supply. Numerical simulations indicate that both motors combined will require roughly 6 amps of continuous current. To accommodate this power requirement we will use two B.B. Battery BP10-12 12V sealed lead-acid batteries. The batteries will have about a 1-hour life per charge, are readily available, and are relatively inexpensive, making them ideal for our needs.

6.2.7 Safety Devices

The bicycle will have two safety outriggers, much like raised training wheels, to prevent a complete tip-over and absorb any large shocks. The laptop and Orcboard will be housed in aluminum frames with interior padding to protect them from excessive vibration and from damage in the event that the bicycle flips over. Fail-safe logic will be embedded in the controller code that prevents the steering motor from forcing the front fork to turn too far (and thus causing the bicycle to flip).

6.2.8 Various Fittings and Brackets

With the large amount of hardware that must be mounted to the bicycle, the exact design of various fittings and brackets cannot be determined at this time. Due to time constraints, we were not able to design each and every small fitting that will be needed. However, we will manufacture these parts as we need them during the build with the help and expertise of the technical staff, especially Todd Billings. The extra time needed to do this has been allotted in the proposed timeline.

6.3 Make/Buy Decisions

Table 2 summarizes the hardware needed for the project, and indicates whether the equipment will be bought, made, or is already obtained. The only pieces of equipment that must be bought are the rate gyro, motor drivers, and batteries.

6.4 Construction and Final Controller Design

6.4.1 Construction

A dimensioned schematic showing the locations of motors, sensors, batteries, electrical components, and safety devices onboard the bicycle can be found in Appendix B. As mentioned above, small fittings and brackets are not shown. Components will be mounted to the bicycle with the advice and expertise of Todd Billings. Step-by-step construction methods are not listed herein since the measured experimental outcomes will not depend on the exact method of construction. The apparatus should be constructed such that the moving parts all function properly and the sensors are mounted with the proper geometry. If

Table 2: Hardware Summary with Make/Buy Decisions

Type of Hardware	Obtained	Make	Buy	Manufacturer/Model	Price
Bicycle	✓			Motiv Backcountry HP–	
Rate Gyro			✓	Silicon Sensing CRS03-01	$300
3-Axis Accelerometer	✓			Crossbow CXL04M3	–
Steering Motor	✓			Matsushita GMX-6MP009A	–
Drive Motor	✓			24V motor, P/N 70071906-5	–
Motor Driver			✓	Two Adv. Motion Control Z6A6	$175 each
Controller Board	✓			OrcBoard Robot Controller	–
Laptop	✓			Dell Latitude D800	–
OrcBoard Batteries	✓			B.B. Battery BP4-12 12V	–
Motor Batteries			✓	Two B.B.Battery BP10-12 12V	$25 each
Safety Outriggers		✓		–	–
Fittings/Brackets		✓		–	–

these two criteria are met, variations in construction methods should not affect experimental outcome. An electrical diagram showing wiring schematics and electrical connections can be found in Appendix C. All electrical components will be wired and tested with the advice and expertise of Dave Robertson.

6.4.2 Measurement of Bicycle Parameters

As mentioned earlier, we've used bicycle parameters from a bicycle similar to ours for modeling and numerical simulations up to this point. However, with so many new components added, our final bicycle will most likely have substantially different parameters. Once all of the final hardware is mounted, the bicycle will need to be measured for masses and centers of gravity. This new information will be used to update the dynamic model, making the numerical simulations more accurate for our particular bicycle.

6.4.3 Final Controller Design

The updated dynamic model, which will represent our bicycle more accurately, will then be used to design the control algorithms. We are using a simple full-state-feedback design that assigns a gain to each state (roll angle, roll rate, steer angle, and steer rate) and feeds that signal back to the torque command. These gains will be optimized either with LQR (Linear Quadratic Regulator) techniques, or by trial-and-error using Simulink. We have been in contact with Professor Paduano and will continue to draw upon his expertise as we design our controller.

The fact that the dynamics of the bicycle change drastically with velocity must be accounted for. To do this, we will calculate an optimal set of gains for various forward velocities (e.g. a set of gains for 5.0m/s, a set of gains for 5.1m/s, etc.). These gains will be stored in a table on the laptop and will be accessed in real time during experimental trials. Thus, for a given forward bicycle velocity, the controller will use the appropriate set of gains.

6.5 Testing Protocol

6.5.1 Measurement Devices

Our hypothesis requires that we measure roll angle and forward velocity with time. As mentioned earlier, we will be measuring roll angle using the CRS03-01 rate gyro. The rate signal will be integrated on the OrcBoard and read by the laptop at a sample rate to be determined. Drift in this signal will be corrected by the CXL04M3 3-axis Acceleromter, which will use gravity measurements to determine absolute roll angle. Forward velocity, measured by the rate sensor on the drive motor, will also be read by the laptop. These two values will be timestamped and stored on the laptop for later analysis.

6.5.2 Testing Procedure

The following is a step-by-step procedure that will be followed for each experimental trial. A specific protocol will limit the variability between trial runs and thus minimize any error due to variations in testing procedures.

1. Set the pivot angle of the roll disturbance device appropriately such that the desired roll angle disturbance will be achieved.
2. Power up and initialize the OrcBoard and laptop.
3. Start the Java program on the laptop, then close and secure the laptop's protective case on the bicycle.
4. Ensure that the bike is held still at a constant roll angle for at least 5 seconds while the initial roll angle is calculated using the 3-axis Accelerometer.
5. Run along side the bicycle and help stabilize it as a constant forward velocity is attained.
6. Once the bicycle is moving forward at a constant velocity in a relatively stable manner, apply the roll disturbance by pulling sharply on the cord of the disturbance device in a horizontal direction.
7. Monitor the bicycle as it recovers (or does not recover) from the disturbance. The drive motor will automatically shut off should the maximum roll angle tolerance be violated (the angle at which the safety outriggers touch the ground).

Table 3: Experimental Test Matrix

		Magnitude of Impulse Disturbance (degrees)			
		1°-3°	5°-7°	9°-11°	14°-16°
Forward Velocity (m/s)	4				
	4.5				
	5				
	5.5				
	6				
		Roll Angle Response with Time (degrees)			

8. Rename data file as appropriate for later analysis.

6.5.3 Range of Velocities and Disturbances to be Tested

The experimental test matrix (Table 3) has the format of the matrix shown in Table 1. However, since the disturbance device cannot be expected to produce exact roll angle disturbances, a range is used for the roll angles to be tested as opposed to discrete values. Thus, for the cell corresponding to a forward velocity of 5m/s and a 5°-7°roll angle disturbance, an actual roll angle disturbance of 6.4°would suffice. For each cell in the test matrix, three trials will be performed to obtain average response characteristics.

6.6 Safety Concerns

The apparatus poses no real threat to human safety. The power cables connecting the motor drivers to the motors will be well-insulated to minimize the risk of electrical shock. It is unlikely, however, that voltages in these lines will grow high enough to cause serious harm.

We are mainly concerned with the safety of the expensive equipment aboard the bicycle. The laptop, OrcBoard, and sensors will be protected as described in section 6.2.7 above. Both the laptop and the OrcBoard will have a protective metal case around them, and the sensors will be mounted such that they are not damaged in the event of the bike flipping over. There are safety outriggers to prevent the bike from tipping over completely, as well as fail-safe logic embedded in the control logic that prevents the front wheel from turning too far and thus flipping the bicycle over.

7 Data Analysis

7.1 Sources of Error

Our hypothesis only requires measurements of roll angle and velocity with time. Roll angle will be obtained by integrating the roll rate signal from the rate gyro. As mentioned above, this can cause drift in the measurement over time. To minimize this error we will be correcting the measurement periodically with the 3-axis accelerometer. The accuracy ratings of both the rate gyro and the accelerometer (provided by the manufacturer) will be used in quantifying error.

There will also be error in the velocity measurement from the drive motor encoder. Since drift is not a factor in this measurement like it is for the roll angle measurement, the error in velocity should be relatively small. Still, specifications from the encoder will be used to quantify the error and factor it into our analysis.

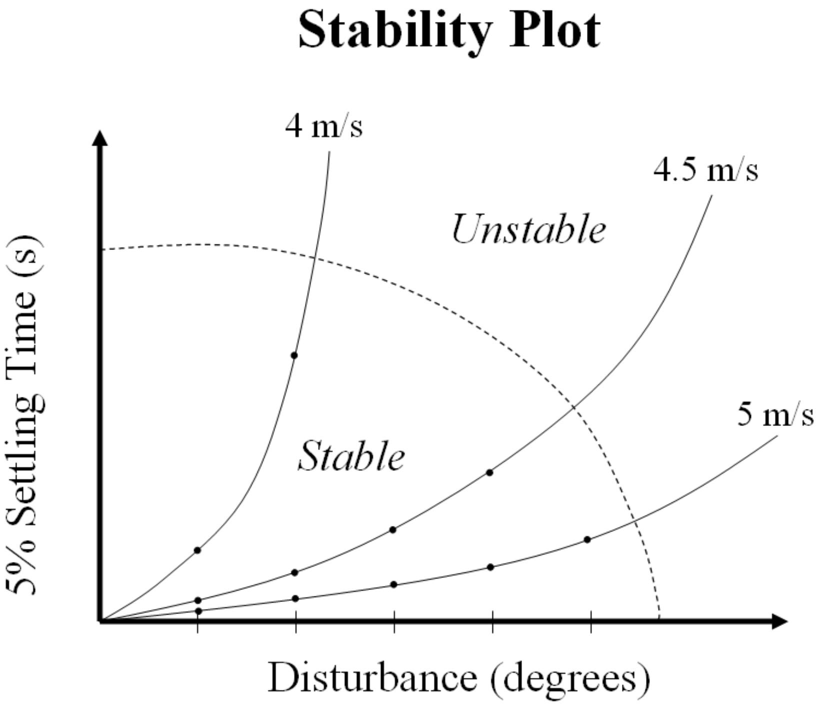

Figure 2: Example of Stability Plot Combining Trial Data

7.2 Data Reduction

For each cell in the test matrix, three trials will be performed. For each trial, the roll angle data will be used to calculate the 5% settling time. This simply the time at which the roll angle first drops below 5% of the disturbance magnitude and stays below that value. The mean settling time of the three runs will be calculated as well as the standard deviation. This will essentially provide us with a set of settling times corresponding to different disturbance magnitudes and different forward velocities. This data can then be used to create a plot similar to the one shown in Figure 2 that will generate a ”region of stability” for the bicycle with our controller. This can then be compared to the theoretical region of stability of an uncontrolled bicycle using data from numerical simulations of our model.

7.3 Hypothesis Assessment

Our hypothesis simply states that the control system can maintain the stability of a bicycle traveling at 5 m/s after the application of a 15°impulse disturbance in roll-angle. Further, the control system will return the bicycle to within 0.75°of the nominal 0°roll-angle a maximum of 4 seconds after the impulse disturbance. In this case, 4 seconds is simply the 5% settling time. Thus we will need only reference the stability chart (like the one in Figure 2) to determine whether or not the hypothesis is correct.

8 Project Planning

8.1 Budget

Table 2 (above) shows the costs of the components that will need to be purchased (the rate gyro, motor drivers, and batteries). These combined total just over \$700. The extra \$200 over the \$500 62x budget will be funded through our advisor, Professor Peraire.

8.2 Schedule

Figure 3 shows the project timeline. The build schedule in particular is very aggressive. It will rely on the hardware being available at the very start of the semester. We have allotted an entire month of October to test the bicycle, work out any bugs, and design the final controller. This is a conservative estimate and allows for build time to spill over into October should construction go slower than planned. Data will be taken throughout the entire month of November, which is also a conservative estimate. Should the data take longer to collect than planned, it is possible to reduce our test matrix to include a smaller velocity range (recall that our hypothesis only requires that we measure responses at 5 m/s).

Task	Sep-06				Oct-06				No	
	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2
Build Bicycle	▨	▨	▨	▨						
Bicycle Completely Built					X					
Test Bicycle					▨	▨	▨	▨		
Measure Bicycle Parameters					▦					
Final Controller Design Finished									X	
Take Data									▨	▨
All Data Taken										
Analyze Data										
Write Final Report										
Final Report Finished										

Figure 3: Project Timeline

8.3 Technical Support and Facilities

As mentioned earlier, we will draw upon the expertise of Todd Billings while constructing the bicycle and the expertise of Dave Robertson while integrating the electrical components. Questions about hardware such as sensors and motors will be directed to Dick Perdichizzi. Professor Paduano has already helped us a great deal with controller design, and we will continue to seek his advice as we design our final controller.

We will need a fairly large area with a smooth, flat surface to perform our experimental trials. This will be done on the first floor of the Johnson Athletic Center (W34) until the ice rink is constructed during the third week of October. After that, testing can be done on the 3rd floor of the Johnson Athletic Center (the indoor track). Both locations can be reserved through the CAC-DAPER Virtual Scheduling System. I have access to this site since I manage the MIT intramural hockey league.

In the worst case, if both of these facilities are unavailable (which is very unlikely), testing can be done in one of MIT's gymnasiums or on a large, flat parking lot. There are many such parking lots on the MIT campus. This contingency plan is, however, weather permitting

9 Conclusion

A model for bicycles dynamics will be derived and a stability controller will be designed based on that model. An autonomous bicycle will be constructed with the necessary sensors, motors, electronics, and computational devices. The autonomous bicycle will be tested at various velocities with various impulse disturbances applied to it. A stability plot will be created using the 5% settling times derived from raw data. This plot will be used to determine whether or not the bicycle can maintain stability after a 15°impulse disturbance in roll angle is applied while traveling at 5 m/s with a 4 second 5% settling time, as our hypothesis states. Data collected and analyzed in our experiment will aide the future development of assisted-stability controllers for bicycles and motorcycles and will evaluate the feasibility of a "learning bike" with regards to cost and safety issues.