ASSISTED-BALANCE BICYCLE

SENIOR DESIGN

FALL 2010

CYCLE 1 REPORT

Daniel Dunbar, Daniel Golden, Mason Nixon, Brett Smith, and Bryan Wall

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I. Introduction

The most difficult part of learning to ride a bicycle for many people is creating enough momentum through pedaling in order to allow the bike to stabilize itself. Once a rider learns how to mount a bicycle and distribute his or her weight, the rest is up to the natural physics of the wheels, seat, pedals, brakes and handlebars. Imagine if this most difficult task was eased by taking away the necessity of stabilizing oneself when learning to ride a bike by adding a device that helped the rider balance.

When an individual is first learning to ride a bicycle there is typically a device in place to help them called training wheels. The purpose of training wheels is to prevent the person learning to ride the bike from falling over if that person becomes unbalanced. Training wheels do not however teach a new rider how to balance since there is not generally even the capability of trying to balance when the two wheeled device is made into a stable four wheel device. This means that when the training wheels are removed after the rider learns about peddling and steering, that rider is suddenly introduced to an aspect of riding a bicycle that he or she has not had to deal with before; balancing. Our balance-assist can create the intermediary step and allow the rider to become more confident in their ability to control the bike and ultimately learn to ride the bike with no assist.

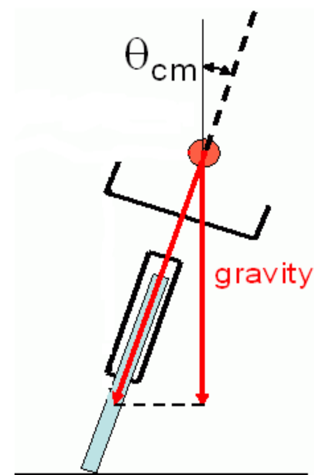
Before a device can be made to help assist with the balancing of a rider, an understanding of the physics of a bicycle, specifically the bike falling, is required. When a bike is falling out of balance, it is as if the bicycle is making a circle to the side of the fall, pulling the

bike towards the center of that circle, sometimes referred to as the "circle of fall." In order to keep from falling into the circle of fall, otherwise known as crashing, the rider has to create a counter-pull out of the fall. There are two ways a rider can create this counter-pull to overcome the fall. One choice is to quickly speed up the bicycle. The other is to quickly tighten the radius of the circle of fall by turning the front tire into the direction of fall. Experienced riders instinctively do both as required. What we propose to do is create the counter-pull necessary to allow for the rider to remain upright by using a third method.

Beyond teaching someone how to ride a bicycle, the balance assist also has application in rehabilitation of people with inner ear problems, which can cause a deficiency in the ability to self-balance, or other debilitating injuries and also in aiding the elderly who have lost their confidence in their ability to self-balance.

As a senior design project, this project encompasses many areas of engineering. General dynamic physics is involved in determining the motion of a bicycle. The problem of balancing a bicycle is directly comparable to the classic nonlinear control systems problem of the inverted pendulum. There is a great mechanical aspect of this problem in devising mounting methods and mass distribution of our balance assist. Lastly, there is a project management aspect of the project that involves time-management, money-management, and teamwork that are all well accounted for by our proposal.

II. Bicycle Physics and Equipment Placement **Bryan Wall**

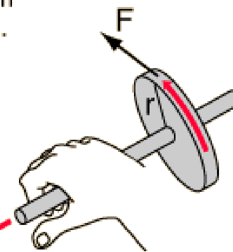


The primary principal that allows a falling object, such as a bicycle, to have its position and angular acceleration changed by an accelerating flywheel is something that is called "coupled forces". This essentially means that as long as the flywheel is fixed to the bicycle, the moment, also called torque, which is generated by the angularly accelerating flywheel, is transferred to the angular acceleration of the bicycle which is then used to rotate the bicycle back to the vertical position. There are many variables that must be calculated to determine what angular acceleration of the flywheel is need to counteract the falling motion of the bike due to gravity including the torque created by the bicycle falling as well as the moment of inertia of the flywheel.

To calculate the torque of the bicycle falling we must first calculate the center of gravity, also known as center of mass, of the bicycle. The reason for this is because the force of the gravity pulling the bicycle down can be represented by a single force that is applied to the object at its center of mass. This is not so simple a task when trying to calculate the center of mass for an oddly shaped object such as a bicycle. However, we can easily calculate the center of mass of simple geometric shapes such as discs and rods. This is helpful due to the fact that a bicycle is essentially made up of two discs and a few rods. Therefore, the process to find the center of mass for a bicycle becomes fairly simple. All that has to be done is to find the center of mass of all the individual pieces of the bicycle. Then, those individual centers of masses can

be added up using weighted averages to find the center of mass of the entire bicycle. Once that is done, the radial arm from the ground to the center of mass where the gravity acts on is known, and the torque of the falling bicycle can be calculated.

Once the torque of the falling bicycle is known, that force can then be compensated for by accelerating the flywheel in the opposite direction of the falling motion of the bicycle. The torque of the bicycle and the torque created by the flywheel are related by the equation



$$M_b \times {R_b}^2 \times \alpha_b = M_f \times {R_f}^2 \times \alpha_f$$

where M_b is mass of the bicycle, R_b is radius from the ground to the center of mass of the bicycle, α_b is the angular acceleration of the bicycle, and the terms on the right side of the equation are the mass, radius and angular acceleration of the flywheel. It thus becomes a matter of calculating the necessary variables to determine how much angular acceleration of the flywheel is needed to move the bike. As can be seen by the equation above, the primary variables we need to control to keep the flywheel angular acceleration as low as possible to keep it within the limits of the motor are to keep the center of gravity of the bicycle as low as possible, have the ratio of the center of mass of the bicycle to center of mass of the flywheel as large as possible without overweighting the motor, and making the radius of the flywheel as large as possible.

Using the above principle and concepts we can approximately model the falling of a bicycle and the effect that an angularly accelerating flywheel attached to the body of the bicycle will have on the bike. It is therefore possible to create a counter moment to the bicycle

falling using a flywheel while keeping the values within the capabilities of the motor and the stress limits of the materials for the flywheel.

In order to keep the necessary mass, radius, and angular acceleration of the flywheel as small as possible compared to the torque of the bike, it is necessary to do all we can with equipment placing to keep the torque of the bike as low as possible. Since the torque of the bike is represented by the equation $T_b = M_b \times R_b^2 \times \alpha_b$, and our goal is to keep T as small as possible, it is easy to see that to do this we need to keep the center of gravity and the total mass of the bike as low as possible. Keeping these goals in mind we placed the battery just above the pedals which is as low as we could reasonably mount it. For the motor and flywheel placement we were limited by the fact that they needed to stay together and that if the flywheel was too close to the ground then it would reduce the angle at which the bike could fall without the flywheel hitting the ground. We therefore chose to mount the motor, flywheel, and remaining circuitry on a platform above the back tire behind the seat.

III. Motor and Power Systems — Brett Smith

Motor

After considerable research, we chose a cordless drill motor for our design. We selected an 18V Bosch drill. This decision was beneficial for several reasons. For one, the drill motor is powerful. It is capable of spinning up to 1600 RPM and generating 500 in-lbs of torque. Secondly, it came with two lithium-ion batteries rated at 1.3 Ah so we would never have to wait on one to charge. Also, the drill came with a quick charger that can fully charge the battery in

30 minutes. Lastly, the drill has forward and reverse functionality built into it (more on that later).

Motor Controller

As mentioned earlier, the drill has forward and reverse functionality built into it. However, after purchasing the drill, we discovered that it has a mechanical switch that allows for the reverse to be activated. This is undesirable for a couple reasons. Mechanical switching is much slower than electrical switching. Also, to be able to switch directions in software we would have to have some sort of actuator to flip the switch which would just overcomplicate the circuitry. We looked into designing an H-bridge circuit using transistors to allow reversing the voltage applied to the motor on the fly. This would be a rather cheap and cost effective method. The problem with this solution is that all the MOSFET transistors we saw had low current ratings. Our drill has been measured at up to 12 amps. In the end, we settled on a premade motor controller ordered off the internet. It is rated up to 15 amps (21 amps if a heat sink is added). This saves us room since it is all contained on a printed circuit board. Plus, it is very easy to interface with the microcontroller.

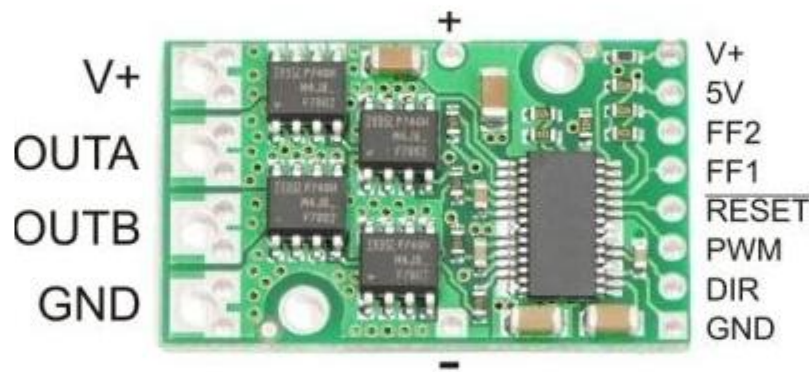


Figure 1 - Motor Controller Pinout

Wiring

As far as the wiring of everything, we have mounted most of the components on a breadboard that sits on a metal mounting plate positioned behind the bike seat. This is the best option for flexibility. The breadboard is attached to the plate by Velcro for easy removal. The motor controller, accelerometer, and microcontroller are all wired together on this breadboard. The 18V battery is mounted to a wooden shelf below the bike seat. We are also using a 9V battery to power the microcontroller, motor controller, and accelerometer. This battery is mounted beside the breadboard. Rather than, try to feed everything off the 18V battery, we felt it best to use a smaller battery. This keeps the motor circuit somewhat isolated from our other more sensitive devices. Since the motor does draw considerable current, we had to use thicker wires than the 22 gauge used on the breadboard. The wires inside the drill are 14 gauge. To be on the safe side we went ahead and wired the motor controller to the battery and motor using 12 gauge.

Figure 2 – Clockwise: Side View of Bike, Top View of Bike, Breadboard and Motor, Battery

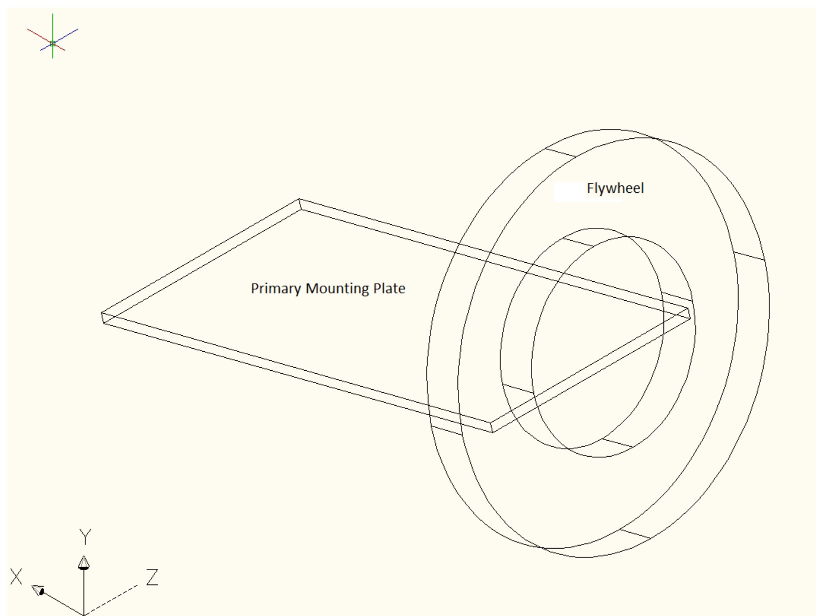
IV. Structural Design/Accelerometer — Mason Nixon

Structural Design

For the mounting hardware (See Figure 1 CAD below), we decided to use an in-house method for construction of the primary hardware mounting plate and mounting rods. We came up with the optimal dimensions for a primary mounting plate by taking into consideration the size of the flywheel and the amount of hardware we would need room for. Since the plate had

to be long enough to space the flywheel away from the bicycle wheel, it was necessary to add additional supports at the rear of the bike. Calvin Cutshaw assisted in the cutting and welding of the plate, and we assisted by rethreading the U-mounts and sought a bicycle seat to fit the seat pipe.

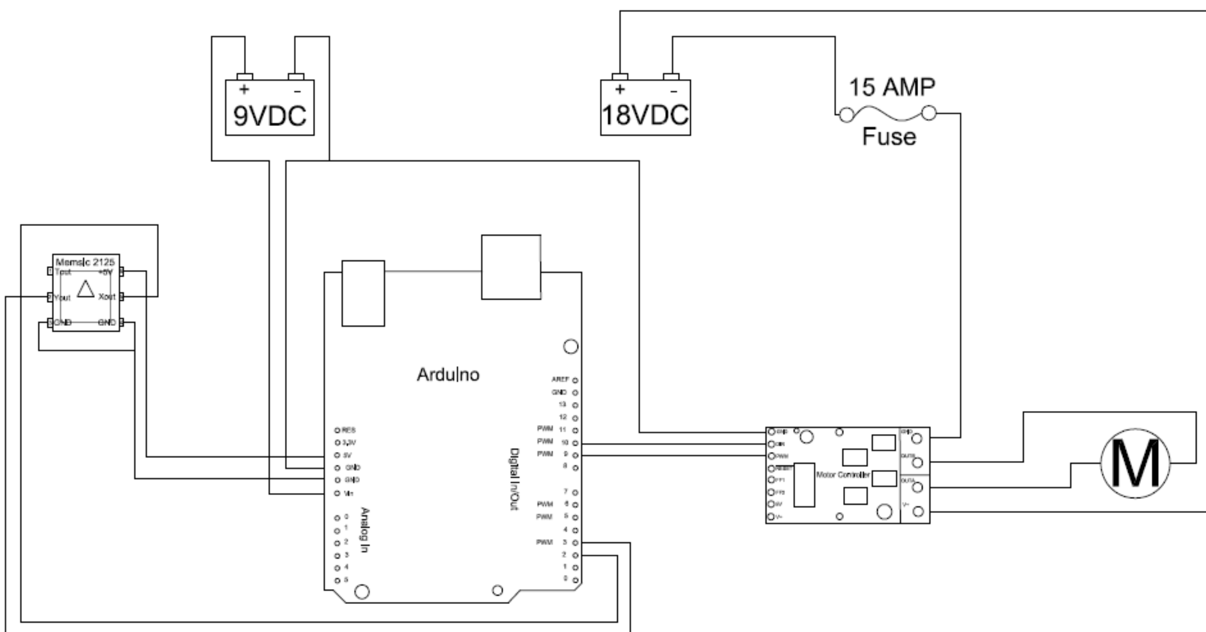
Figure 3 - Mounting Plate and Flywheel



Once the plate was fixed and level, we added the solder-less breadboard and the motor. Most of the mounting we did at this point is meant as a temporary solution, not intended for use on the final product design. We designed a wooden motor mount to affix the motor to the primary plate. We then used foam and Velcro to attach the solder-less breadboard to the primary plate. The foam is used as a damper to counter the vibration due to the motor.

We were able to design an electrical schematic in AutoCAD 2009, which allowed for ease of updates and offered a professional look. On the breadboard itself, using the schematic, we were able to wire all of our components using minimal space. It was necessary to use two different batteries because at this time we did not believe it was proficient to design a power system that would operate off of one power source. We mounted the accelerometer as far from the motor as we could to minimize the vibration caused by the motor. We also mounted it on the opposite support of the primary plate for the same goal.

Figure 4 - Electrical Hardware Schematic

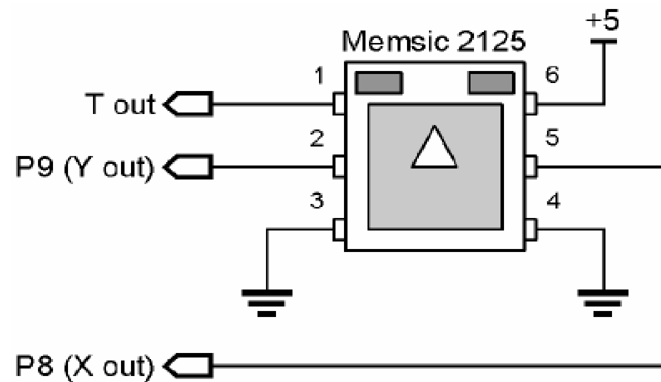


Accelerometer

For the accelerometer we decided to use the Memsic 2125, which is a low cost, dual-axis thermal accelerometer capable of measuring tilt, acceleration, rotation, and vibration with a range of ±2 g. The Atmel Atmega328 can be paired with this accelerometer to test for an

accurate readout and simulation of operation. The Memsic 2125 has a simple digital interface: two pins (one for each axis) emit pulses whose duration corresponds to the acceleration of that axis.

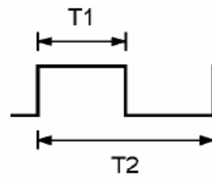
Figure 1. Essential Memsic 2125 Connections



Internally, the Memsic 2125 contains a small heater. This heater warms a "bubble" of air within the device. When gravitational forces act on this bubble it moves. This movement is detected by very sensitive thermopiles (temperature sensors) and the onboard electronics convert the bubble position [relative to g-forces] into pulse outputs for the X and Y axis.

The pulse outputs from the Memsic 2125 are set to a 50% duty cycle at 0 g. The duty cycle changes in proportion to acceleration and can be directly measured by the Atmel Atmega328 (using the Arduino Duemilanove bootloader). Figure 2 shows the duty cycle output from the Memsic 2125 and the formula for calculating g force.

Figure 2. Memsic 2125 Pulse Output



A(g) = ((T1 / T2) – 0.5) / 12.5%

The T2 duration is calibrated to 10 milliseconds at 25° C (room temperature). Knowing this, we can convert the formula to the following Arduino routine:

```
const int xPin = 2;                 // X output of the accelerometer
const int yPin = 3;                 // Y output of the accelerometer
 // variables to read the pulse widths:
 int pulseX, pulseY;
 // variables to contain the resulting accelerations
 int accelerationX, accelerationY;

 // read pulse from x- and y-axes:
 pulseX = pulseIn(xPin,HIGH);
 pulseY = pulseIn(yPin,HIGH);

 accelerationX = ((pulseX / 10) - 500) * 8;
 accelerationY = ((pulseY / 10) - 500) * 8;
```

In the above code, by dividing the raw pulse input pulseX - Y by 10 milliseconds and subtracting 1000 times 0.5 and then dividing the entire quantity by 1 over 0.125. The accelerationX - Y are in milli-g's (Earth's gravity = 1g. or 1000 milli-g's).

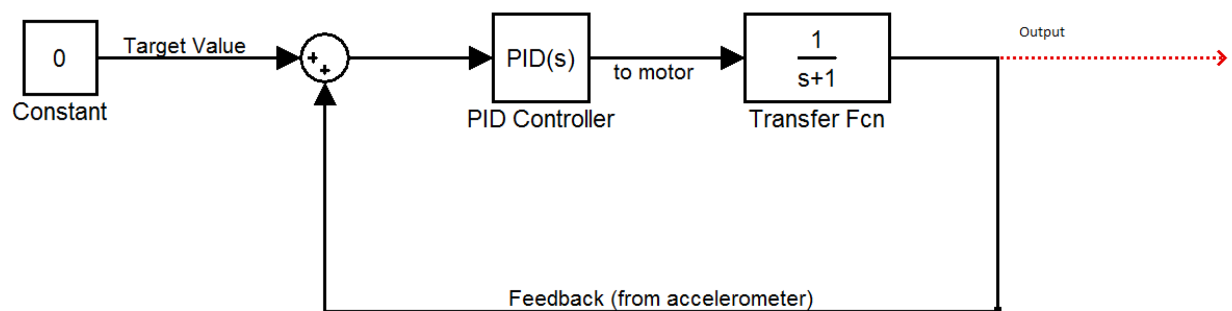
```
 z1 = (accelerationX * 9);
 z2 = (accelerationY * 9);

 //Calculate the angle to 2 decimal places by making a long into a float.

 tiltX = (float)z1 / 100.0;
 tiltY = (float)z2 / 100.0;
```

Since the output from the accelerometer is a number between 0 and 1 which corresponds to 0 to 90 degrees, one can multiply the acceleration calculated by 9 and divide by 100.0 and obtain an angle out to up to 4 digits. The Memsic should provide suitable resolution for our feedback since the output is accurate to 1 milli-g and the Arduino should provide a simple interface for implementing our control system.

V. Balancing Control System Theory — Daniel Dunbar

The goal of the control system is to balance the bicycle using feedback from the accelerometer. This creates a closed loop control system, which is controlled by a PID controller. There are two inputs into the system, the desired value of zero (a completely balanced system) and the feedback from the accelerometer. These two inputs are added together to get an error, which is inputted into the PID controller. The output from the PID controller determines the voltage applied to the motor, which affects the speed and acceleration of the flywheel, thus balancing the bicycle.

Figure 5 - Control Loop



To model the control system, SIMULINK was chosen. SIMULINK is a component of the MATLAB package and is used to build systems from a block component level. This allows the

user to create a complete system within SIMULINK using standard blocks used in control system theory. SIMULINK also has a PID tuner, which will automatically tune the gains for the P,I, and D parts of the controller. If an accurate model of the plant can be obtained or designed, this is an extremely effective tool that allows the user to look at the rise time, overshoot, etc. to find a controller that will suit the application best.

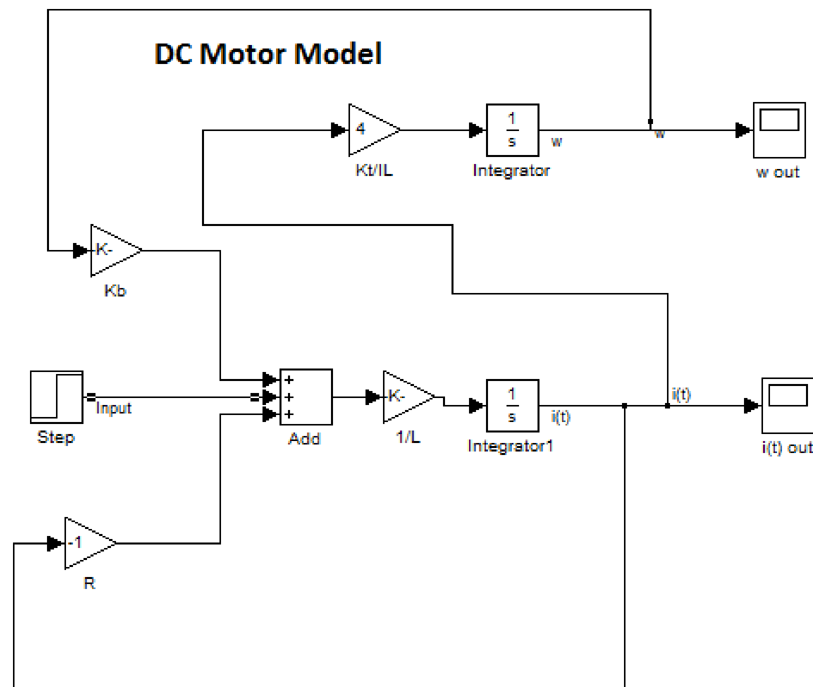
Also, SIMULINK allows the user to model certain components using differential equations. For example, a DC motor can be broken down to two differential equations:

$$\frac{d\omega(t)}{dt} = \frac{K_T}{I_L} i(t) \quad \text{and} \quad \frac{di(t)}{dt} = \frac{1}{L[V_s - Ri(t) - K_b\omega(t)]}$$

where K_T, I_L, R, L, and K_b are parameters of the motor.

From these equations, one can create a model using integrators, adders, and gain blocks. Thus, is on can obtain the motor parameters, one can create an accurate model of a motor within MATLAB and use the computational power of the program to do some useful analysis.

Figure 6



To model the control system initially in SIMULINK, an external simulated input had to be created. This input represents the external forces on the bicycle, such as a person leaning or simply gravity working on the system. This was added to the force created by the angular velocity of the motor to create the feedback portion of the system, which will be actualized by the accelerometer in the physical system. For the external input, several different patterns were created to try to accurately simulate some forces that might occur during physical testing.

In transition to the implementation phase of the control system, the original plan was to use MATLAB's built in Embedded C writer to write the code for the control system. However, when we tried this, the code was much too convoluted to be able to fine tune away from MATLAB, so we wrote the code ourselves. The SIMULINK model was not done in vain, though,

because we are using it as a theoretical basis for our control system, and we are working to develop an accurate transfer function that lines up with our actual motor under load. When we achieve this, we will be able to use the SIMULINK model to tune the control system to optimize performance.

The code, as seen below, was built as a function called from the main program. This allows the program to be modularized for ease of reading and helps in the debug process. Also, the K_P, K_D, and K_I constants are at the top for easy access when tuning the control system.

```
#include "ControlSystem.h"

void controlsys(int accel,int *dutycycle,unsigned char *direction)
{

int Kp = 1;         //Kp = Proportional Constant
int Ki = 2;         //Ki = Integrator Constant
int Kd = 3;         //Kd = Derivative Constant

int dt = 100;       //dt = sampling frequency

int integrator = 0;
int lasterror = 0;
int derivative;
int error;

*direction = 0;   // sets the output sign to positive
error = 0 - accel;
integrator = integrator + (error/dt);
derivative = (error - lasterror)*dt;
lasterror = error;
*dutycycle = Kp*error + Ki*integrator + Kd*derivative;

if (*dutycycle<0){
        *dutycycle = -1*(*dutycycle);
        *direction = 1;}
if (*dutycycle>255)
        *dutycycle = 255;
```

```
}
```

VI. Embedded System Architecture Daniel Golden

For our balancing system, we incorporated a control loop which reads accelerometer data, sends the data to the control system, and then sets a new corrective Duty Cycle and direction pin for use by our motor controller. This control loop is shown in Figure 7 below.

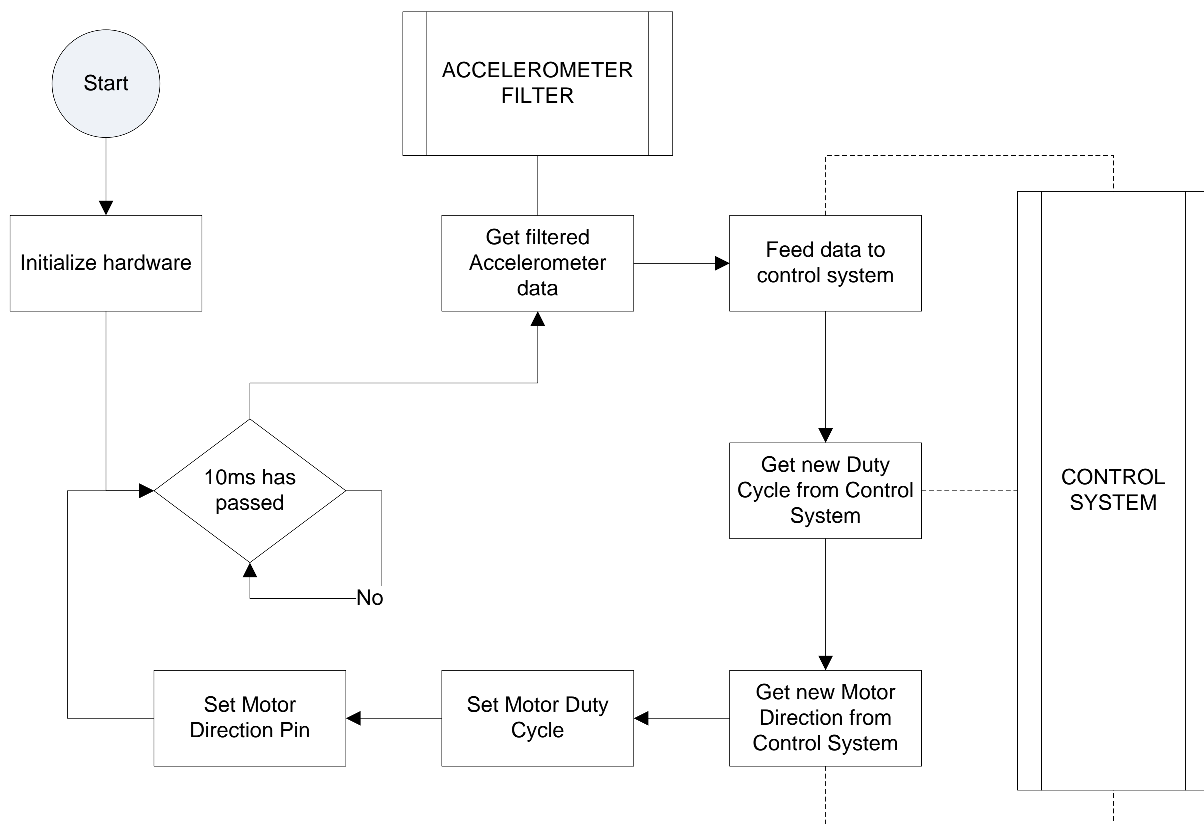


Figure 7 - Embedded System Control Loop

Accelerometer Filter

It has yet to be decided as to the best method for smoothing the data. At this moment, we are not implementing a filter. One goal for the next cycle is to implement an accurate filter.

Control System

To execute the control system we chose to simply encapsulate the entire system into a function that takes three arguments. One is the accelerometer data and the other two are pointers to variables in the calling method's scope which are updated by the control system function.

Hardware Initialization

Measuring a PWM signal on our ATmega1280 microcontroller required that we use a system timer and execute an edge-triggered pin Interrupt Service Routine (ISR) to measure and process the data. In order to achieve the best duty cycle resolution, we used one of the 16-bit timers and prescaled the timer clock so that our clock would count from 0 to as close to 65535 (2^16 – 1) as possible during one accelerometer's PWM period. To avoid dealing with counter rollovers, we simply reset the couter after every period of the accelerometer.

Hardware Initalization Routine:

```
/* Set up pin 11 for motor controller PWM output. */
DDRB |= 0x20;                //Set PB5 for output
PORTB |= 0x20;               //Set PB5 to Output High
/* Set up timer1 */
TCCR1A |= _BV(COM1A1);
TCCR1A |= _BV(WGM11) | _BV(WGM10);
TCCR1B |= _BV(CS11);    // prescale F_CLK_IO by 8

/* Set up timer4 */
TCCR4A |= _BV(COM4A0);// | _BV(WGM21);
TCCR4B |= _BV(CS41);
```

```
	/* This sets the input pins for Pin 49. Pin 49 is our Accelerometer PWM input. */
	DDRL&= ~_BV(PL0);
	PORTL&= ~_BV(PL0);

	/* Set up pin 12 for motor controller direction output. */
	DDRB |= _BV(PB6);			//Set PB6 to output
	PORTB |= _BV(PB6);			//Set PB6 to Output high

	/* Enable Timer4 interrupts. Rising edge triggered initially */
	TIMSK4 |= _BV(ICIE4);
	TCCR4B |= _BV(ICES4);
```

Accelerometer Triggered Interrupt

This is the routine that is executed on each edge of the PWM signal from the accelerometer:

```
SIGNAL(SIG_INPUT_CAPTURE4){

	if ((TCCR4B & _BV(ICES4)) == _BV(ICES4)){// if currently rising edge triggered
		/* read the period of the accelerometer pwm signal (low byte first) */
		AccPeriod = ICR4L;
		AccPeriod |= (ICR4H<<8);
		/* reset timer count to avoid dealing with rollovers */
		TCNT4=0;
		/* switch to falling edge triggered interrupts */
		TCCR4B &= ~_BV(ICES4);
	}
	else{
		/* read the pulse width (time high) of the accelerometer pwm signal (low byte first) */
		AccPulseWidth = ICR4L;
		AccPulseWidth |= (ICR4H<<8);
		/* switch to rising edge triggered interrupts */
		TCCR4B |= _BV(ICES4);
	}
}
```

Main Program Loop

The main program loop is the first code to execute on system power-on. This loop calls the hardware initialization routine, enables interrupts, and then enters the infinite control loop:

```
int main(){
```

```
	hardwareInit();				// initialize hardware
	sei();					// enable interrupts

	for(;;){// infinite program loop
		accelY = accelerometerIn();	// calculate new accelerometer data
		controlsys(accelY, &MotorDutyCycle, &MotorDirection);	// process control system
		OCR1AH = ((unsigned int)MotorDutyCycle>>8);	// set new duty cycle (high byte first)
		OCR1AL = (unsigned int)MotorDutyCycle & 0xFF;

		if (MotorDirection == 1)
			PORTB |= _BV(PB6);	// direction is clockwise looking from rear ?
		else
			PORTB &= ~_BV(PB6);	// direction is counter-clockwise looking from rear ?
	}
	return 0;
}
```

Motor Control

In order to control the speed of our motor, we are generating a PWM signal using the 10-bit Fast PWM mode of timer1. To adjust the duty cycle, we write a number between 0 and 0x3FF to OCR1A. Writing a value of 0 produces a duty cycle of 0%. Writing a value of 0x3FF to OCR1A generates a duty cycle of 100%.

VII. Conclusion

To summarize, we propose to create a balance-assist for a bicycle that can be used on any standard bike. The applications are in learning to ride a bike, aiding the disabled, and aiding the elderly. Using control systems theory, we will mount a flywheel to a reversible motor, feedback accelerometer angle data into our control system, and output compensated motor commands to correct for the lean associated with a falling bike. Our design encompasses many aspects of engineering, primarily those listed in the senior design requirement as defined by Accreditation Board for Engineering and Technology (ABET).