SMART LADDER

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Abstract

Our Device calculates and displays a percent margin of safety for a user to determine how close the ladder is to falling so that they can proceed with caution. There are both visual and audio cues for the user, and the ladder is meant to be used on two legs. The results of our project were a PCB that was able to send and receive signals based on theoretical safety conditions and the location of the user on the ladder.

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1. Introduction

Ladder falls from improper use are a chief safety hazard in both the workplace and around the home. Falls are one of the leading causes of injury mortality, and according to the CDC 43% of all fatal falls involve a ladder; there are around 30,000 injuries per year from falling ladders based on numbers from previous years. Our ladder solves this problem by analyzing all the forces applied on the ladder, the angle the ladder makes with the wall, and the user's location on the ladder, and then displaying how close the ladder is to sliding or rotating by using digital display. In case the user's attention is off of the display, they are also warned audibly if the safety is below the threshold so that they have time to correct their position before falling. Currently there is no way for someone to know how stable the ladder they are using is or if they are pushing the ladder too far. The ladder is useful for work efficiency due to stability assurances, and it also prevents users from attempting to climb the ladder if the conditions are unsafe before use, preventing incorrect ladder setups.

1.1 Block Diagram

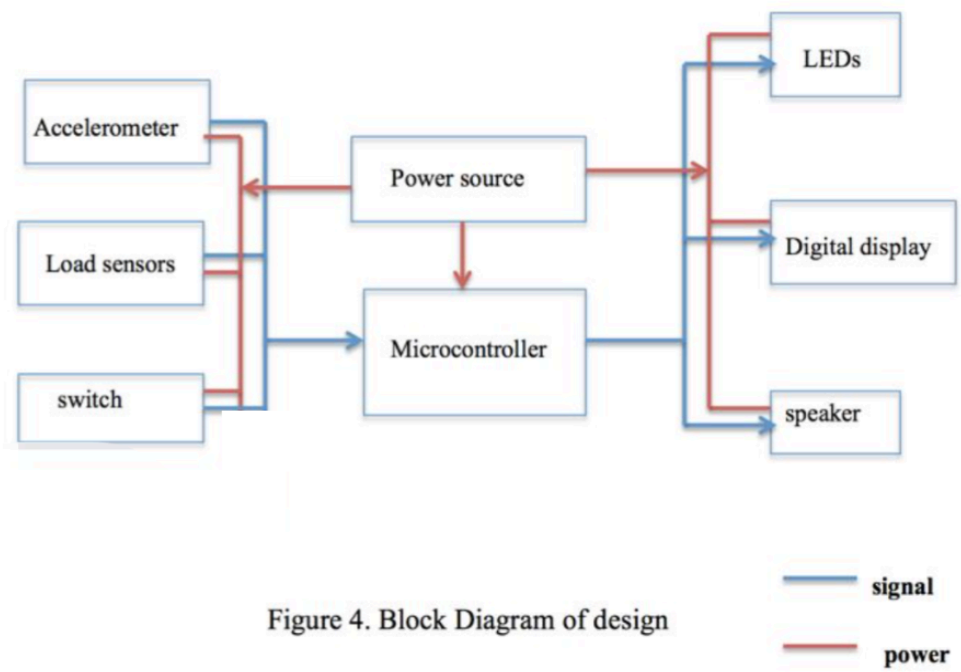

Figure 4. Block Diagram of design

2 Design

2.1 Design Procedure

Our design uses switches, load cells and accelerometer to send signals to microcontroller as showed in the block diagram. We process and analyze the data collected from those parts via the program we upload into atmega328P chip and then the chip will send the signals to LED, digital display and speakers. Each part below will show how they work individually. Here is the schematic(Figure 2.1.0):

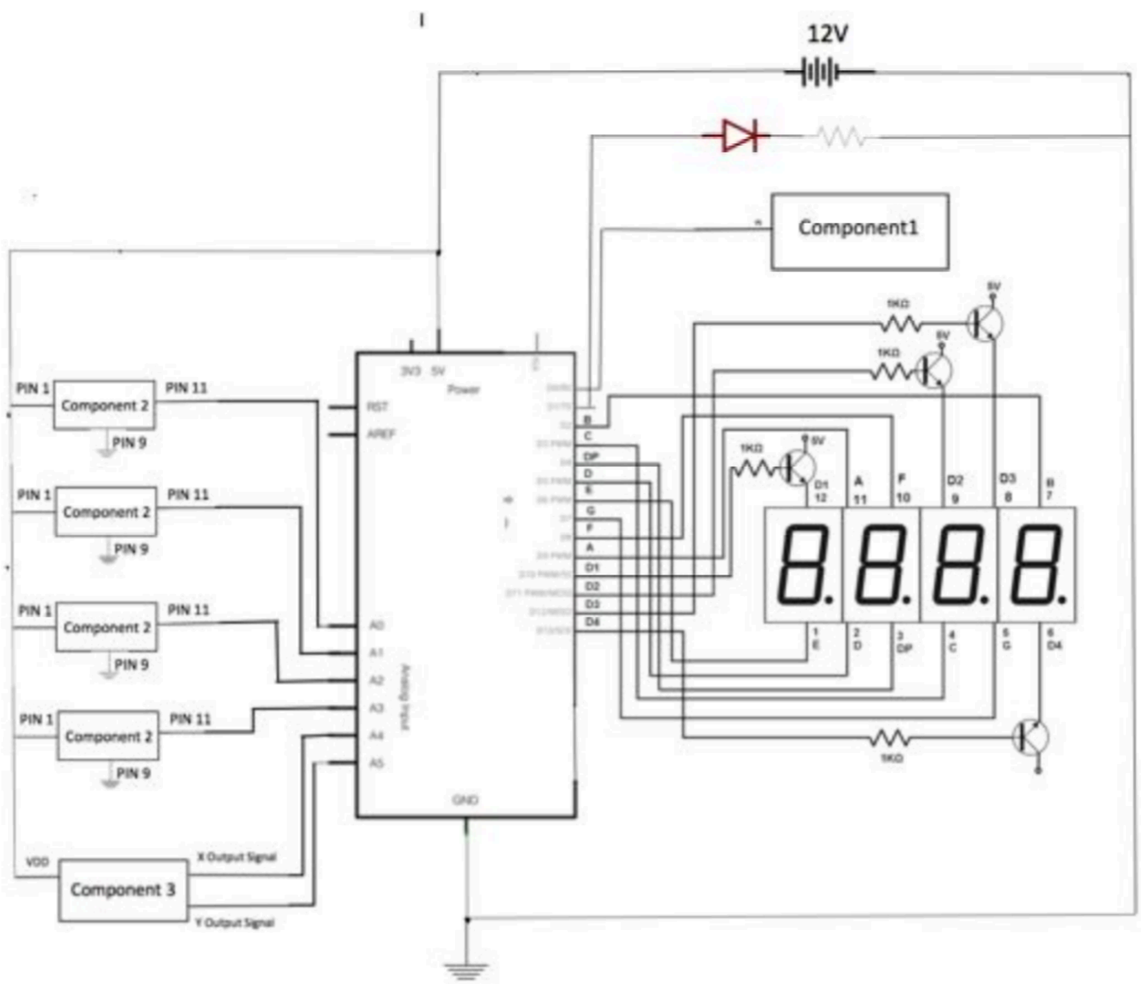

Figure 2.1.0

Component1: speaker – figure 2.1.1[12] show the schematics of the speaker

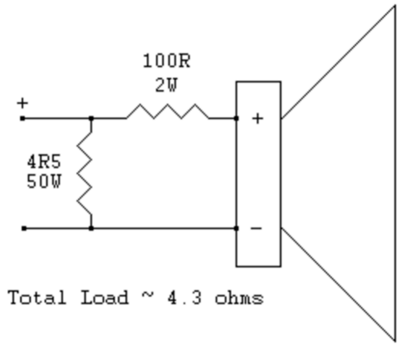

Figure 2.1.1

Component2: amplifier + load sensor – figure 2.1.2[6] show the schematics of the amplifier and load sensor

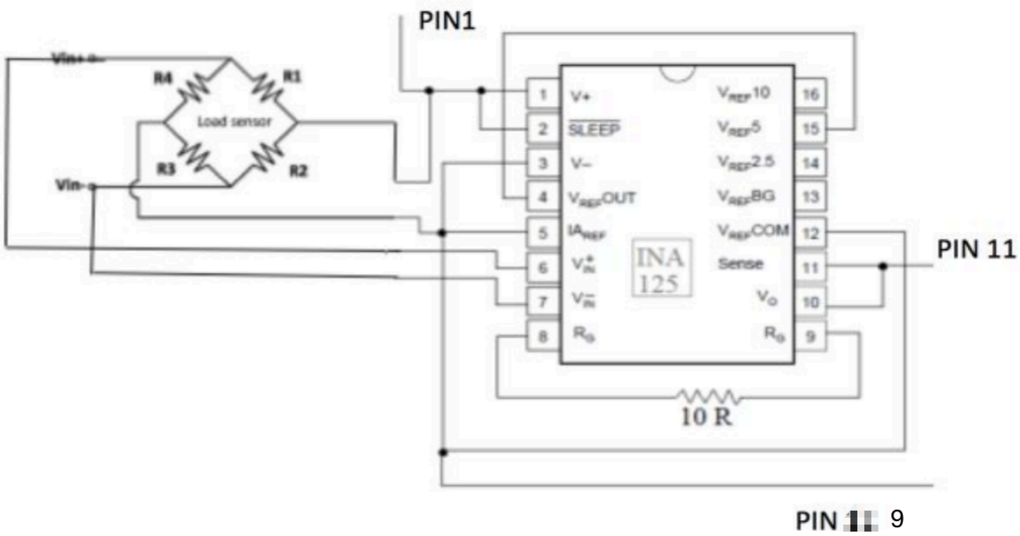

Figure 2.1.2

Component3: accelerometer: – figure 2.1.3[9] show the schematics of the accelerometer

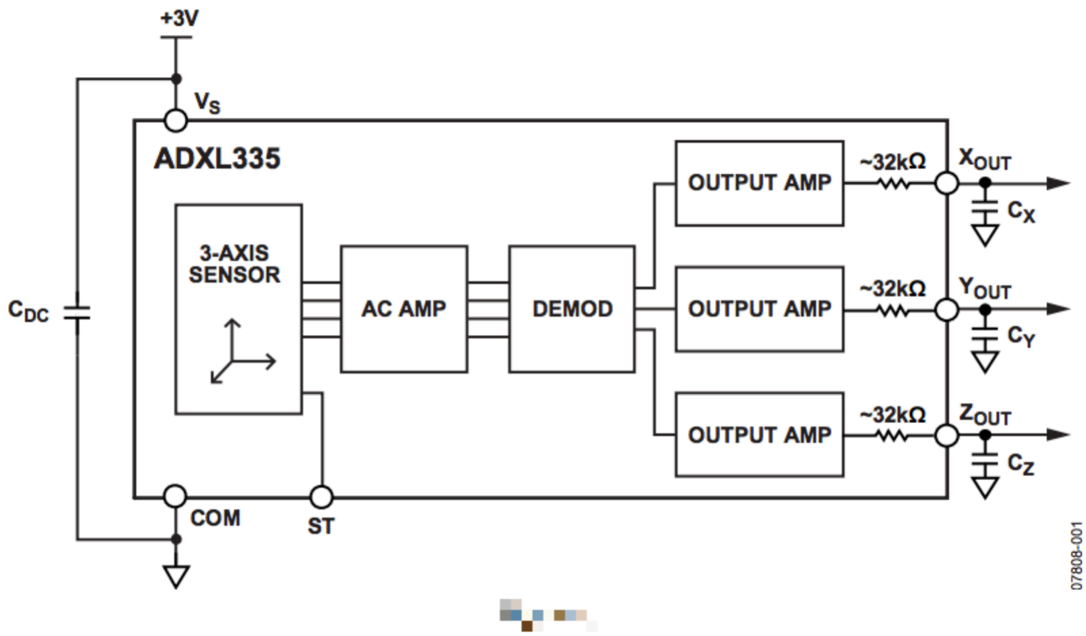

Figure 2.1.3

2.1.1 Power Source

A 9V battery powers our PCB board or circuit through a power jack. We use two more resistors to divide the voltage across the switches, load cells to 5V and divide the voltage across the accelerometer to 3.3V. We expect the power source will work for at least 8 hours.

For the general alternatives, we can always change to different battery if current battery does not work or out of charge.

2.1.2 Microcontroller - atmega328P [4] use Arduino board [5] to program

The microcontroller is responsible for collecting data from the sensors and controlling all the feedback devices in the system. The accelerometer and load sensors will be connected to microcontroller; then it will analyze the data, determining whether the ladder is safe or not, and send a signal to LED, Digital Display and speaker. This part is important because it will analyze the data collected by all of the sensors and determine the degree of safety of the ladder.

The data will be analyzed and the information will be used in computing the center of gravity of the ladder relative to the base stability by comparing all the forces acting on the base of the ladder; the safety margin of the ladder is computed based on how close the ladder is to slipping by first finding the forced applied from the user on the ladder and comparing that value to the friction force the ladder makes with the ground. If the force applied is greater than friction then it is not safe. If the user reaches out in any direction, the amount of force this creates will be compared to the forces acting on the ladder to determine if the ladder will fall to the right or left as well. This module analyzes the accelerometer and switch data in order to know the user's position and the angle that the ladder is set at. It must also reduce the safety margin by 8% to account for the tolerance error of the load sensors. i.e. The ladder will never read 100% safe; 92% would be the maximum value displayed.

For the general alternatives, we can use 1528-1021-ND Microcontroller as well.

All equations without citations are derived by the group members.

Scenario1:

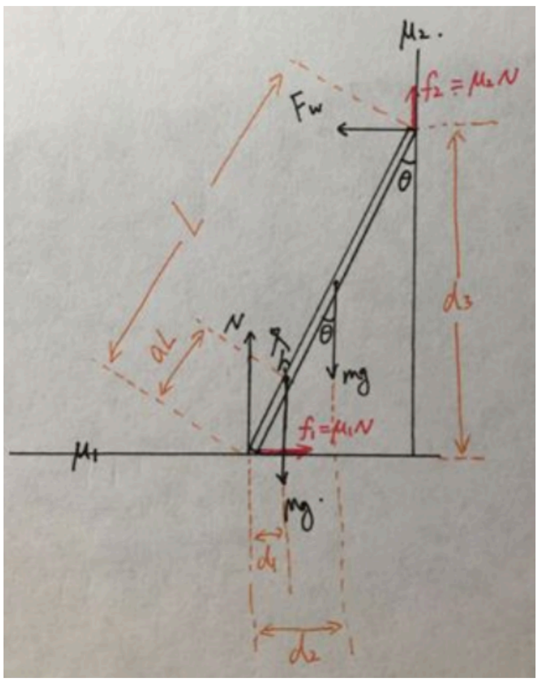

Figure 2.1.2.1: slipping analysis of the ladder

Formula:

$$\sum \tau = 0 = \sum r \times \vec{F} = M * g * d_1 + m * g * d_2 - F_w * d_3 - f_2 * d_4$$

Therefore,

$$F_w = \frac{M * g * d_1 + m * g * d_2 - f_2 * d_4}{d_3}$$

$$= \frac{M * g * a * L * \sin(\theta) + m * g * \frac{L}{2} * \sin(\theta) - (M * g + m * g - N) * L * \sin(\theta)}{L * \cos(\theta)}$$

$$= \frac{M * g * a * \sin(\theta) + m * g * \frac{1}{2} * \sin(\theta) + N * \sin(\theta) - M * g * \sin(\theta) - m * g * \sin(\theta)}{\cos(\theta)}$$

$$= (M * g * (a - 1) + 0.5 * m * g + N) * \tan(\theta) \quad \textbf{(1.1)}$$

if $F_w \leq F_{friction,max}$, the ladder is consider safe, otherwise, not safe.

The smaller F_w is, the safer the ladder is.

Safety Analysis:

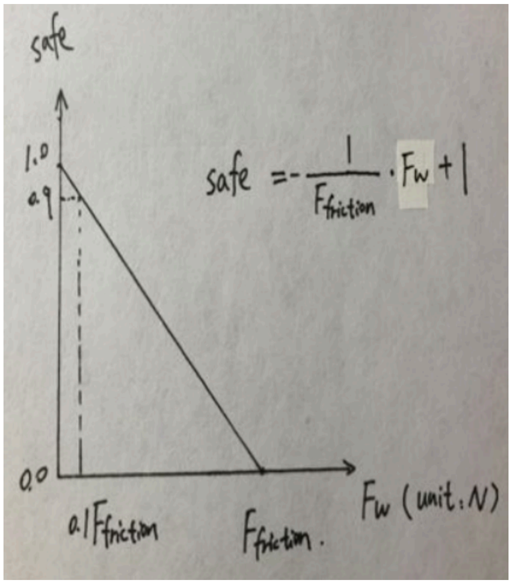

Figure 2.1.2.2: Setup for safety margin plot

Plot:

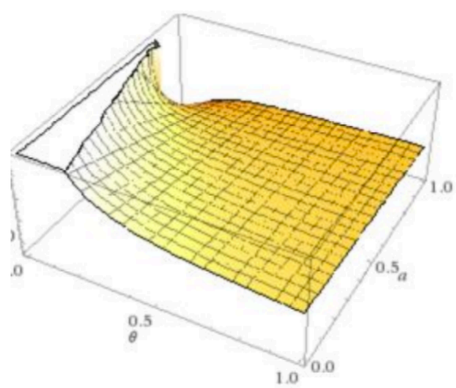

Figure 2.1.2.3: 3D plot of safety margin

Formula:

$$\text{safe} = -\frac{1}{F_{friction,max}} * F_w + 1$$

$$\text{safe}(a,\ \theta) = -\frac{1}{F_{friction,max}} * (M * g * (a-1) + 0.5 * m * g + N) * tan(\theta) + 1 \qquad \textbf{(1.2)}$$

suppose M = 60kg, m = 10kg, g=9.8m/s^2, $F_{friction,max}$ is constant

For the variables that appear in formula(1.2), we will use switches to get the value of the variable a, we will use load cell to get the N and m which is the body weight of the user and we will use accelerometer to measure the angle θ between the ladder and the wall. The remaining variables are constant. For instance, M is the weight of the ladder which is 9.8 kg for our project and g is gravity 9.8 m/(s*s).

Scenario2:

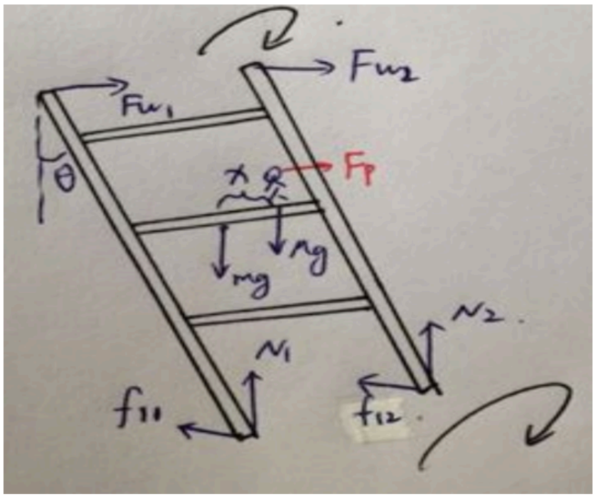

Figure 2.1.2.4 analysis of how the ladder will rotate

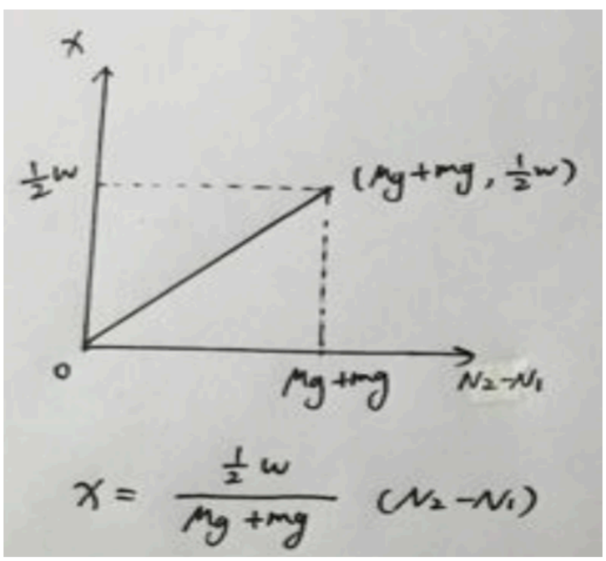

Figure 2.1.2.5 Plot of relationship between user's position and the data that load cells receive

x is the distance between the position of user and the center of the ladder
treat N1 - N2 as a variable
x=0, N1 = N2 = 0.5*(M*g+m*g), N2-N1=0
x=0.5w, N1=0, N2=M*g+m*g, N2-N1=M*g+m*g

$\sum\tau = 0 = \sum r\times\vec{F} = -M*g*(0.5*w-x)*sin(\theta) - m*g*(0.5*w)*sin(\theta) - f_{11}*w*cos(\theta) + F_{w1}*w*cos(\theta) + N1*w*sin(\theta) + F_p*(0.5*w-x)$

$$F_p = -\frac{-M*g*(0.5*w-x)*sin(\theta) - m*g*(0.5*w)*sin(\theta) - f_{11}*w*cos(\theta) + F_{w1}*w*cos(\theta) + N1*w*sin(\theta)}{0.5*w-x} \quad \textbf{(2.1)}$$

If $F_p \le f_{11,max} + f_{12,max} - F_{w1} - F_{w2}$, the ladder is consider safe, otherwise, not safe.
The smaller F_p is, the safer the ladder is.

Safety analysis:

$$\text{safe} = -\frac{1}{f_{11,max} + f_{12,max} - F_{w1} - F_{w2}} * F_p + 1$$

$$\text{safe}(a, \theta) = -\frac{1}{f_{11,max} + f_{12,max} - F_{w1} - F_{w2}} * -\frac{-M*g*(0.5*w-x)*sin(\theta) - m*g*(0.5*w)*sin(\theta) - f_{11}*w*cos(\theta) + F_{w1}*w*cos(\theta) + N1*w*sin(\theta)}{0.5*w-x} + 1 \quad \textbf{(2.2)}$$

Scenario 3:

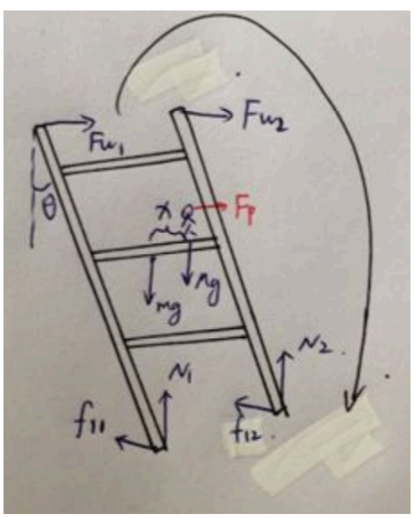

Figure 2.1.2.6 rotation analysis of the ladder

$$\sum\tau = 0 = \sum r \times \vec{F} = -M*g*a*L*sin(\theta) - m*g*(0.5*L)*sin(\theta) + (F_{w1}+F_{w2})*L*cos(\theta) + F_p*a*L*sin(\theta)$$

$$F_p = \frac{M*g*a*L*sin(\theta) + m*g*(0.5*L)*sin(\theta) - (F_{w1}+F_{w2})*L*cos(\theta)}{a*L*sin(\theta)} \qquad \textbf{(3.1)}$$

If $F_p \leq f_{11,max} + f_{12,max}$, the ladder is consider safe, otherwise, not safe.
The smaller F_p is, the safer the ladder is.

Safety analysis:

$$\text{safe} = -\frac{1}{f_{11,max}+f_{12,max}} * F_p + 1$$

$$\text{safe}(a, \theta) = -\frac{1}{f_{11,max}+f_{12,max}} * \frac{M*g*a*L*sin(\theta) + m*g*(0.5*L)*sin(\theta) - (F_{w1}+F_{w2})*L*cos(\theta)}{a*L*sin(\theta)} + 1 \qquad \textbf{(3.2)}$$

Since we have 3 scenarios, we combine 3 safety percentage into one and each weight 1/3:

$$\text{total\_safety} \leftarrow \frac{safe\_scenario1 + safe\_scenario2 + safe\_scenario3}{3} \qquad (4.1)$$

We set the threshold safety to 50 percentage, if the safe(a, theta) we get via above formula is below 50%, we will warn the user by turning on the LED and speaker.

2.1.3 Load Sensors [2] + amplifier [6]

We will place load sensors at the base of the ladder in order to detect the directions of the all the forces being applied, including gravity. The load sensors will also determine if the ladder can handle the weight of the person and whatever they might be carrying. These sensors are connected to the voltage amplifier.

The microcontroller will get different values from load cells when we put things with different weight. However, these values is meaningless so we need to calibrate:

Table 1 shows some data we collected:

Table 1: data collected from load cells

Weight of the stuff (kg)	Values
0.0	28
2.5	118

Weight of the stuff = $\frac{Values - 28}{\frac{(118-28)}{2.5}}$; **(5.1)**

After getting the actual weight, we can plug into the safety formula (4.1).

For the general alternatives, we can use a round one(i.e. Load Cell - 50kg, Disc TAS606 (Sparkfun SEN-13331)) instead of a block shape, they just use different techniques to measure the weight.

2.1.4 Accelerometer [9]

For the accelerometer, we use ADXL335 as an inclinometer to measure angle between the ladder and the wall. Figure 2.1.3 shows the schematics of the accelerometer we use.

Again, the value they give is not meaning full so we need to calibrate it as well just as what we do to the load cells:

1. find the offset:

   put the accelerometer on a flat table and the value for X, Y and Z is 563, 542, 578
2. use the formula to computer the angle θ in radians

   $$\theta = tan^{-1}(\frac{A_{X,OUT}}{A_{Y,OUT}}) \quad [1] \qquad \textbf{(6.1)}$$
3. change θ from radians to degrees:

   $$\theta = \frac{\theta}{\pi} * 360° \qquad \textbf{(6.2)}$$

For the general alternatives, we can use ADXL 345 instead of ADXL 335 because they are quite similar.

2.1.5 Switches

Hardware:

We put four switches on the side of the ladder in order to detect which rung the user is currently standing on. Every time a user moves upward, he or she will push the switch right in front of him or her. We will receive the signal from this switch and send the information to microcontroller. The figures below show how the switch look like(Figure 2.1.5.1) and the schematics of the switch(Figure 2.1.5.2). We will connect pin 4 to Vcc which is 5V, connect pin 2 to GND with a 2.2KΩ resistor between them and connect pin 1 to the microcontroller.

Figure 2.1.5.1 [10] shows what the switches look like and figure 2.1.5.2 [11] shows what schematics look like

Figure 2.1.5.1 [10]

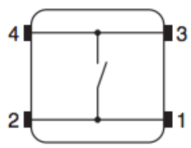

Figure 2.1.5.2 [11]

Software:

If the button is pushed, we will receive the high signal from the switch, else we will receive the low signal. Figure 2.1.5.3 shows how the program works and if the button is not pushed, we will believe the user is on the rung that corresponding to last switch that was pushed.

```
int buttonPin = 10;
int temp = 0.001;
float a = 0;

if(digitalRead(2) == HIGH){
    buttonPin = 1;
}
else if(digitalRead(3) == HIGH){
    buttonPin = 2;
}
else if(digitalRead(4) == HIGH){
    buttonPin = 3;
}
else if(digitalRead(5) == HIGH){
    buttonPin = 4;
}
else{//no switch is pushed
    buttonPin = 10;
}
if(buttonPin == 10){
    a =  temp;
}
else{
    a  = (0.2 + StepLength * (buttonPin - 1)) / L;
    temp = a;
}
```

Figure 2.1.5.3

For the general alternatives, there are lots of push type switches and we can simply choose one.

2.1.6 LED

The LED is meant to turn on when the ladder safety is below the safety threshold. It is used to indicate to the user to proceed with caution and that the displayed percentage puts the user at risk. It is in series with a 100 ohm resistor and the voltage supply is regulated to five volts. The input comes from the microcontroller and the output is externally emitting light.

For the general alternatives, there are lots of types and colors of LED and we can simply choose one.

2.1.7 Digital Display [3]

This module receives a signal from the microcontroller to display to the user how safe and stable the ladder currently is based on sensor data. If the center of mass of the ladder is completely stable, a 92% reading would be displayed; if the ladder is falling 0% to 8% would be displayed. Since the tolerance and noise of the load cells and accelerometer will affect the accuracy of the safety margin, a percentage of 8% is being reduced and added to the total above. The supply voltage of the digital display is regulated to five volts and the inputs come from the output of the microcontroller.

For the general alternatives, there are lots of types and we can choose Adafruit 878 LED 7-Segment Digital Display.

2.1.8 Speaker [8]

The speaker is also meant to turn in with the LED when the ladder safety is below the safety threshold. It indicated that the ladder will soon be at risk of falling if the user does not process with caution. This module is necessary to add another cue for the user in case their attention is focused elsewhere and not on the digital display. The supply voltage is regulated to five volts and the input comes from the microcontroller.

For the general alternatives, there are lots of types and we can simply choose one. (i.e. 665-AS05008PR2R Speaker)

3. Design Verification

3.1 Microcontroller and Data Analyzer

The requirement of testing of the microcontroller was to ensure that the appropriate signals were sent to the digital display, speaker, and LED and that the data analyzer was able to interpret the signals from the different sensors in order to provide a reasonable percentage of safety. To verify that the calculations worked, the display values were to change as pressure is applied to the ladder, the ladder rotates, or when a switch is pressed on the ladder. Since the accelerometer burned out, we had to used values that correspond to the desired accelerometer output to calculate an angle to be used in our calculations. The correct signals were all sent when a switch indicating an unsafe height was pressed, indicating that the microcontroller and equations were working as intended.

3.2 Power Source

The power source was intended to last an entire eight hour workday with all external devices turned on, but we were unable to verify this due to timing limitations once the entire circuit was assembled to draw power. We also were required to regulate the voltage to five volts from nine volts to insure that all of the chips and devices were powered properly. To test that the voltage regulator was working as intended, the voltage was swept from six volts to ten volts across the input, and we observed that the output was a constant five volts on the multi-meter.

3.3 Switches

The switches were required to determine where on the ladder the user was currently located. Since we had a limited number of switches, we placed them were the user would press with their finger, and proceeded to calculate their position on the ladder based on average height and switch position. When the switches were pressed, the microcontroller was able to interpret the data and when the switches were released their value was maintained, as expected.

3.4 Load Sensors + amplifier

For the load sensors, we wanted to verify that they were accurate with +/- 1 kg for objects weighing from 1 kg to 200 kg. The testing of the load sensors was done by securing one end of the load cell to a table while the other end was suspended in air. First, the object we wanted to weigh was placed onto a scale to determine its actual weight. We then moved the object from the scale onto the load cells to see how they compared; after calibration, the load cells were able to accurately measure three objects and the results are shown in table. When the load cell was detecting nothing, a value of 28 was given through the amplifier, but when 2.7 kg was placed on the load cell, a value of 118 was given. We used these values to determine the relationship between the actual measurements and the measurements from the amplifier and load cell combination. The formula for the calibration is in Design part formula(5.1).

The left below figure show the actual weight of the stuff and right below figure show the weight after calibration.

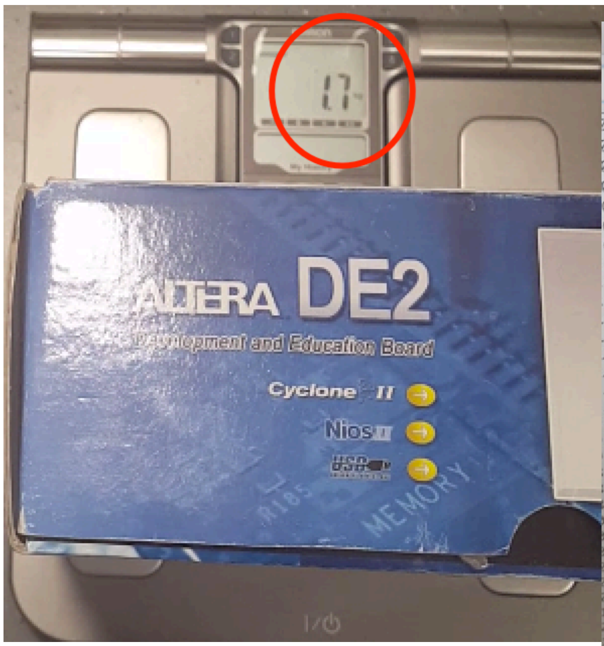

Figure 3.4.1

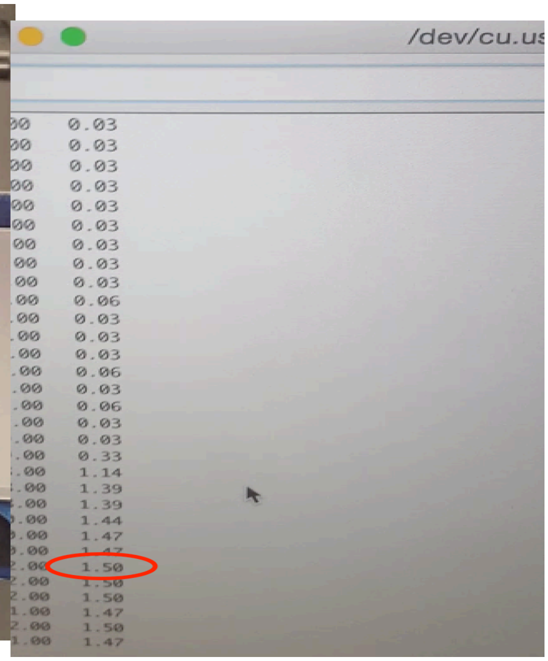

Figure 3.4.2

Table 2 shows some comparison between actual weight and the weight we measured.

Table 2: Comparison

Object	Actual Weight	Load Cell Measurement
Two Altera Boxes	1.7 kg	1.5 kg
A Stack of Paper	2.7 kg	2.5 kg
Another Load Cell	0.3 kg	0.2 kg

3.5 Accelerometer

The accelerometer was intended to be able to sense 1g of acceleration on a single axis in order to calculate the tilt angle. This component was unable to be verified, and we instead had to use the intended acceleration values that corresponded to a safe and unsafe angle in the tilt angle calculation measurement based on three dimensional acceleration. It would be tested by observing the sensor output values when on a flat surface; the microcontroller should indicate high values on one axis and values close to zero for the other axis's. As the sensor is rotated about a single axis, the values of one axis should increase and another axis should decrease, which was not verified.

3.6 Speaker, Digital Display, and LED

The requirements and verification for the external devices were tested the same way as the microcontroller. We compared the threshold to the computed safeness and observed whether or not the devices received the appropriate signals as before, which occurred.

4. Costs

4.1 Parts

Table 3 shows the total parts costs along with the manufacture of the part.

Table 3 Parts Costs

Part	Manufacturer	Singular Retail Cost ($)	Quantity Bought	Total Actual Cost ($)
Aluminum Extension Ladder	Yaheetech	$55.99	1	$55.99
1PCX 200kg Load Cells	Yixing Fenghua Electronic Apparatus MFG Co.	$15.21	4	$60.85
Atemga 328PU Microcontroller	Atmel	$2.56	1	$2.56
22pf Ceramic Capacitors	N/A	free	4	free
16-MHz Crystal Oscillators	N/A	$3.17	2	$6.34
INA-125 Amplifiers	Texas Instruments	$6.12	4	$24.48
ADXL335 Accelerometer	Adafruit	$6.99	1	$6.99
665-AS05008PR2R Speaker	Mouser Electronics	$3.69	1	$3.69
LED 7-Segment Digital Display	Lumex	$5.45	1	$5.45
HLMP1340 Red LED	N/A	free	1	free
CoCOM-08720 ROHS Switches	On Shine Enterprise Co.	$3.00	4	$12.00
9V Battery	Energizer	$3.63	1	$3.63
DC Power Jack	N/A	$1.50	1	$1.50
NTE961 Voltage Regulator	NTE Elelctronics	$2.50	1	$2.50
Total				**$173.98**

4.2 Labor

The total labor costs from table 4 are from the following equation: ideal salary (hourly rate) × actual hours spent × 2.5.

Table 4 Labor

Name	Hourly Rate	Total Hours Invested	Total Labor Costs
Brad	30.00 $/hour	200	$15,000
Lingying	30.00 $/hour	200	$15,000
Total		400	$30,000

4.3 Overall Costs

The table 5 shows the grand total costs of the parts and labor combined.

Table 5: Overall Costs

Section	Total
Labor	$30,000
Parts	$173.98
Grand Total	$30,173.98

5. Conclusion

5.1 Accomplishments

The PCB design was implemented as intended without some desired external inputs. The signals from the load cells were able to be amplified before being processed by the microcontroller and the safety of the ladder was able to be determined based on the location of a user on the ladder.

5.2 Uncertainties

The accelerometer values were behaving erratically after running too much voltage through the breakout board, and therefore we used the intended acceleration values that correspond to both unsafe and safe angles in order to test that the angle would be implemented correctly, had we obtained the desired output from the sensor. To account for unforeseeable outcomes resulting from assuming the ladder is at a safe angle, the user is warned that the ladder must be placed a distance from the wall that makes an angle less than 75.5° with the horizontal. The load sensors were also implemented in a way that the change in signal from increased resistance due to bending was not properly converted into kilograms. We attempted to compare a ratio between the data received from the two respective load cells, but this was unable to be applied in time. It would be more suitable and reliable to use a disk load cell, although the cost is about ten times as much.

5.3 Ethical considerations

[1] To accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;

> There are warnings placed on the ladder to tell the user how the ladder is meant to be properly operated in order to avoid injury.

[3] To be honest and realistic in stating claims or estimates based on available data;

> There are no false claims on how well the ladder can evaluate a user's safety on the ladder that could lead to improper usage and incorrect feedback to the user. We have thoroughly tested our ladder and ensured that the safety claims that we made are backed by data.

[5] to improve the understanding of technology; its appropriate application, and potential consequences;

> Our ladder is used to create a safe ladder for users at home and at work and to help them understand how technology can help to solve common issues.

[9] to avoid injuring others, their property, reputation, or employment by false or malicious action;

The ladder gives no false data from the sensors that were implemented properly. The purpose of the ladder is to help others avoid injury, and therefore we made no false claims.

5.4 Future work

The ladder applications could be extended for use on four legs instead of just two by implementing more equations into the data analyzer. Further work must be done on the accelerometer in order to determine that the ladder was placed on a safe angle, based acceleration in three axis's. The ladder will not always be placed safely no matter how many warnings the user has access to beforehand, and therefore it would be important receive actual data instead of simulating expected data. For the power source, a better way to hold the battery and a usable DC power jack would reduce the amount of space and clutter around the PCB board. Changes were also made to the PCB board which may affect performance; we would reduce the size of the PCB based on what pins from the microcontroller didn't work as expected and how many outputs we would be required to use. We also used two microcontrollers communicating together; one as a master and one as a slave, but this ended up being unnecessary because a mux would better control the number of inputs to the microcontroller and take up significantly less space on the PCB board.

References

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Appendix A Requirement and Verification Table

Table 6 System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
Load Sensors 1. Requirement Must be able to determine the value of the forces acting on the base of the ladder with weights from 1 kg to 200 kg within a tolerance of 1 kg.	1. Verification Use a scale to measure the weight of multiple objects and compare the values given by the scale with the values given by the load cells after calibration is complete.	Y
Data Analyzer 2. Requirement Must analyze the data collected from the load cells, switches, and accelerometer and compute how close the ladder is to sliding or rotating: An appropriate percentage no greater than 92% safe due to tolerance must be displayed on the digital display.	2. Verification The value on the digital display should change when pressure is applied to the load cells, the ladder rotates, and when switches are toggled; the data should match up with the theoretical calculations to ensure the sensor data is read correctly. (No values over 92% should be displayed as well)	N
Microcontroller 3. Requirement Must send appropriate threshold voltages to activate the loads such as the LED, digital display, and speaker.	3. Verification Toggle a lower switch that corresponds to a safe value, and if the display shows the correct value, ensure that no warning signals are sent. Toggle a higher switch that corresponds to an unsafe value and ensure that the correct display value and warnings turn on.	Y
Power Source 4. Requirements a. Must be able to provide a 9 VDC +/- 0.9 VDC output	4. Verifications a. Measure the voltage across the battery using a multimeter and verify that it	a. Y b. Y c. N

b. Must regulate voltage to 5 VDC +/- 0.5 VDC for the LED, accelerometer, load cells, microcontroller, speaker, and digital display. c. Must be able to last an eight hour workday before needing to be recharged.	is within the correct tolerance. b. Connect the voltage regulator input voltage to the power supply and sweep the input voltage from 6 VDC to 10 VDC. Use a multimeter to verify that the voltage stays within 5 VDC +/- 0.5 VDC. c. Turn on all the devices at once and insure that the battery lasts at least eight hours	
5. Accelerometer Requirements a. The accelerometer must sense an acceleration of 1 g +/- 1% on a single axis when placed completely flat. b. The acceleration must be used to determine tilt angle with the horizontal within +/- 7% error.	5. Verifications c. When the sensor is flat, the microcontroller should indicate high values on one side (+1g +/- 1%) and values close to zero for the other sides (1g +/- 0.01g). As the sensor is rotated about a single axis, the values of one axis should increase and another axis should decrease. d. Measure the output voltage due to acceleration and insure that the angle measured from the data is within the theoretical value from the tilt angle calculation.	N
6. Speaker, Digital Display, and LED Requirement Must all turn on at the appropriate time. (turn on below safety threshold and show percentage of safety)	6. Verification Measure the theoretical values and compare them to the value displayed; compare the threshold and computed safeness to see if the signals should be sent or	Y

	not, and then verify if they actually were.	
Switches on Rungs 7. Requirement Must be able to determine the location of the user currently on the ladder.	7. Verification If a person toggles a switch, a high signal should be sent to the microcontroller to determine the user's position on the ladder. If no switch is on, the previous value should be kept.	Y