Automatic Wireless Moisture Sensing System for Hay Bales

December, 2018

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Abstract

This report discusses the design process of an automatic moisture content sensor specifically created for small hay bales. An adaptive process was followed, in which several design alternatives were theoretically analysed and evaluated. The resulting design is one which most closely adheres to the initial design criteria; flexible, easy to use and install, accurate and efficient, inexpensive, ergonomic and durable. Durability in particular was considered to be very important, and therefore the resulting design consists of an innovative and simplistic mechanism which protects the sensor, and allows for an extended lifespan of the system. Automatic data transmission exists in the form of a microcontroller which receives voltage input from a moisture transmitter, and then communicates the analogous moisture content values via Wi-Fi to an online server. Finally, the overall system was tested for feasibility and measurement accuracy.

List of Acronyms and Abbreviations

CSV - comma separated value
DM – Dry Matter
EMC – Equilibrium Moisture Curve
GND - Ground Pin
GPIO - General Purpose Input Output pin
MC - Moisture Content
RX - Data Receival pin
TX - Data Transmitting pin
VCC - Power supply pin
MC – Moisture Content

List of Figures

Figure 1 - DM loss vs MC at time of storage for alfalfa hay. Source: (Coblentz W., 2000) 8
Figure 2 - Equilibrium Moisture Curves of Alfalfa at Two Temperatures (70F and 95F, or 21C and 35C) Source: (Shewmaker, 2004) 9
Figure 3 - Schematic of a voltage divider, drawn by Hubert and Yuan 17
Figure 4 - Hay Bale Corer for Sampling (RDS Coleman Consulting, 2011) 19
Figure 5 - Relationship between moisture transmitter MTX voltage output and hay moisture content 23
Figure 6 Comparison between two methods of measuring MC. The values obtained using oven-dried method is taken as the reference Delmhorst reading do not exactly match the reference. 24
Figure 7 - Delmhorst sensor reading after calibration 25
Figure 8 - Statistical Analysis demonstrating how significantly values vary from the sample mean 26
Figure 9 - Spear's Von Mises Stress under load 28
Figure 10 - Square Hay Bale Temperature Distribution, measured on October 25, 2018 28
Figure 11 - Moisture content versus Temperature at a certain RH 29
Figure 12 - Statistical Analysis demonstrating how significantly temperature values vary from the sample mean 30
Figure 13 - Overall Assembled Design 31
Figure 14 - Life Cycle Assessment Results for Automatic Hay Bale MC Sensing System (eTool Global, 2018) 34

List of Figures

Figure 1: Delmhorst FX-2000 meter with component names. The “Read Key” must be pressed in order for measurement to be taken
Figure 2: Arduino Uno, microcontroller. Price $22.00 on Official Arduino website
Figure 3: Bluetooth Module HC-05 for Arduino
Figure 4: The bale spear used by the client.
Figure 5: Configuration of Sensor and Arduino Uno required for arduino to receive data from the sensor
Figure 6: Configuration of HC-05 Bluetooth Module and Arduino Uno required for arduino to be Bluetooth enabled

Table of Contents

1.0 Introduction ... 6
1.1 Background ... 6
1.2 Vision Statement ... 6
2.0 Literature Review and Theoretical Background ... 7
2.1 Recommended Hay Bale Moisture Content ... 7
2.2 Measuring Moisture in Alfalfa Hay ... 8
2.3 Moisture Content Sensing Mechanism ... 10
2.4 Hay Bale Temperature ... 11
3.0 Modified Design ... 12
3.1 Design Criteria ... 12
3.2 Alternative Designs ... 13
3.3 Data Collection and Transmission ... 14
4.0 Design Comparison and Selection ... 15
4.1 Physical Design Selection ... 15
4.2 Data Transmission Design Selection ... 16
5.0 Testing and Verification ... 18
5.1 Moisture Content Sensing and Oven Drying ... 18
5.2 Stress Analysis ... 20
5.3 Temperature Profile Simulation ... 21
5.4 Automatic Data Transmission Testing ... 23
6.0 Discussion and Analysis of Results ... 24
6.1 MC sensing and Drying ... 24
6.2 Stress and Strain Analysis ... 27
6.3 Temperature ... 28
6.4 Overall System ... 31
6.5 Modifications on Physical Design ... 32
7.0 Design Considerations ... 33
7.1 Environmental Aspects ... 33
7.2 Social and Ergonomic Aspects ... 34
7.3 Economic Considerations ... 34
8.0 Challenges and Recommendations ... 35
8.1 Challenges ... 35

8.2 Recommendations 36
9.0 Conclusion..36
References 38
Appendices 40
Appendix A – Bale Moisture Content Recommendations 40
Appendix B – Hay Bale Temperature Recommendations...................................41
Appendix C – Technical Drawings 42
Appendix D – Moisture Content Oven Drying Data 46
Appendix E – Moisture Content Calculations 48
Appendix F - Stress Analysis MATLAB Codes and Results 50
Appendix G: Temperature Analysis MATLAB Code 55
Appendix H – Data Transmission Information and Arduino Code 57

1.0 Introduction

1.1 Background

Hay fodder must be stored in appropriate conditions in order for it to be of nutritional value to animals. In Quebec, alfalfa and timothy hay are the two main sources of animal feed (Anon., 2016). Square bales are the most common way to package hay in North America (Shinners, 2009). One of the primary parameters that must be controlled in hay bale storage is moisture content (MC). Bales of unsuitable MC lose nutritional value, reduce farmer yield via hay leaf loss, and may result in environmental hazards (i.e. spontaneous combustion, growth of dangerous microorganisms, et cetera) (Coblentz W., 2000).

Although there currently exist some farming machinery that is able to collect MC data while baling (i.e. MC sensing hay balers), farmers with older equipment are required to manually obtain MC data. Manual MC data collection is performed by using a handheld meter with a long sensing prod attached to one end. This prod is inserted into each bale, a button on the MC meter is pressed, and measurements are recorded manually; using pencil and paper or handheld electronic devices. In this method, farmers are required to drive their tractors throughout the field, and to dismount at every hay bale. Once this process is completed, the farmer then manually enters the data onto a computer in order to upload the information to one of the various hay sensing software.

This process is tedious, and purchasing automatic systems to avoid this process is expensive. Therefore, an ergonomic and economic alternative is presented in this report. The design constitutes a low cost MC sensing system which can be affixed to the farmers' pre-existing tractor via the universal bale spear. This systems is able to collect MC data during regular bale transport, and sequentially transmit the MC data to an online database. The systems allows farmers to save money and time by taking measurements on the go, without having to dismount the vehicle or manually transmit the collected data to a computer for further observance.

The report is a continuation of the BREE 490 Design 2 report (Hubert & Yuan, 2018). This report includes alterations based on the suggestions and recommendations of the previous report.

1.2 Vision Statement

To develop an interconnected sensing system to efficiently help farmers collect and process moisture content data for hay bales, and that such a system is ergonomic, automatic, non-labor-intensive, time-saving and economical.

2.0 Literature Review and Theoretical Background

Prior to the finalization and physical assemblage of the system discussed in this report, it is essential that the theoretical background of all relevant design components are established. Verifying the adequacy of these components ensures that the system is properly able to perform the desired task: accurately and automatically measuring hay bale MC during bale transportation. Therefore, theoretical hay bale MC measurement is considered, along with how these measurements may vary with temperature and season.

2.1 Recommended Hay Bale Moisture Content

Hay must be stored within a specific MC range in order to avoid losses, spontaneous combustion, mold growth, and reduced forage quality. It is important that hay bale MC is known prior to storage, so that MC during storage can be properly calculated. Recommended MC is normally based on bale size (Henning J. C., n.d.). In this report, only small bales are considered, as this report and design system are generally targeted towards small-scale farms owned by individual farmers. A 'small bale' is defined as follows: A bale held together by two or three strings, with approximate dimensions of 14″ x 18″ x 35″ (0.3556 m * 0.4572 m * 0.8890 m) to 16" x 22" x 44" (0.4064 m * 0.5588 m * 1.1176 m), and weighing between 50 lbs (22.68 kg) to 150 lbs (68.04 kg) (Griffiths, 2011).

While there are no set federal or provincial regulations for hay bale storage MC, several recommendations exist, including recommendations from the Beef and Cattle Research Council of Canada (BCRC), Delmhorst Instrument Co., and various Canadian provincial guidelines. These recommendations are similar throughout North America, and examples of specific values is shown in Appendix A – Bale Moisture Content. Generally, a MC range of 15 - 20% is recommended for small hay bales, where the low end of the MC range is preferred in low humidity climates, and the high end is preferred in high humidity climates (OMAFRA, 2004). Round hay bales require a slightly lower MC than rectangular (Laurenzi, 2018).

Several factors are responsible for the loss of dry matter (DM) in hay, including improper mowing, conditioning, raking, tedding and baling. Despite this, the primary contributing factor to DM loss is inadequate MC immediately before storage (Coblentz W., 2000). Figure 1 below demonstrates the effects of excessive MC (above 20%) on hay bales, and the relation to dry matter loss.

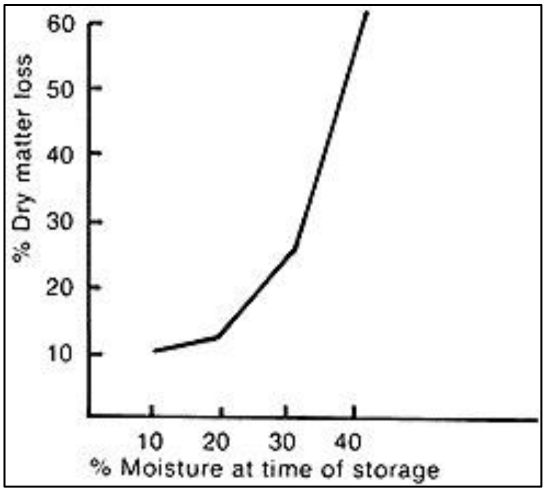


Figure 1 - DM loss vs MC at time of storage for alfalfa hay. Source: (Coblentz W., 2000)

These losses are mainly due to excessive heating and molding, but in severe cases, DM losses can be the result of spontaneous combustion (Coblentz W., 2000). To avoid losses, accurate MC sensing prior to storage is essential. According to the various sources mentioned above, hay bales must be at a MC of between 15% and 20%, depending on climate. In Quebec specifically, alfalfa hay is the most commonly used type of hay, and has an ideal wet basis MC value of 19% or less (Shinners, 2009).

2.2 Measuring Moisture in Alfalfa Hay

In order to ensure that the system discussed in this report is able to accurately measure hay bale MC, hay samples were taken, and MC values measured by the systems' MC sensor were compared to alternative MC measuring methods. Several alternative methods exist which do not include the use of a MC sensor. These include both physical and chemical methods. Multiple samples should be taken from a single bale to ensure measurement accuracy throughout. All methods depend on proper hay sampling. Only a small amount of hay should be sampled to minimize the energy required to perform MC measurements (i.e. drying energy), and also to reduce waste. Therefore, it is important for the samples to be evenly distributed throughout the hay bale so that they are representative of the entire bale (Shewmaker, 2004).

Below are several methods which can be used to determine alfalfa hay sample MC, according to Shewmaker, (2004), along with their respective accuracy rates:

1) **Laboratory Drying:** This method uses gravimetric or near infrared reflectance spectroscopy (NIRS). Accuracy of this method is +/- 3% (MC calculated compared to true MC).
2) **Microwave Oven Drying:** This method is more time efficient than several of the other methods, as it only takes several minutes. It involves the comparison of pre and post-drying sample weights. There is a possibility of over-drying, which may

result in calculation errors. Close monitoring is required. Accuracy of this method is -2% to +1%.

3) **Koster Field Drier:** This method uses the same concept as both microwave oven drying, and convection oven drying, but it is able to perform the task in a single device. A flow of warm air is directed at the sample, and pre and post-drying weights are compared in order to calculate MC. This process can be completed within 30 minutes to an hour. Accuracy of this method is +/- 3%.
4) **Convection Oven Drying:** This method is the most commonly used, and allows for multiple samples measured simultaneously. Samples should weigh between 100 and 300 grams, and should be dried for at least 24 hours. Accuracy of this method is +/- 1%.

(Shewmaker, 2004)

Generally, these MC measurement tests require between 12 and 20 samples of a uniform hay bale to ensure measurement precision; i.e. to ensure that repeated measurement of the same hay bale results in similar values. Additionally, several rounds of sampling should be taken over the period of several weeks. This will allow for the MC measurement to be validated for different MC ranges, which vary with temperature, time of year, weather conditions, et cetera (Shewmaker, 2004).

Relative humidity of the atmosphere has an impact on the MC of alfalfa hay bales. This relationship can be demonstrated using an equilibrium moisture curve (EMC). Therefore, it is important to perform MC measurement during various weather and humidity conditions, ideally the conditions which the system will be most subjected to. The EMC for alfalfa hay is shown in Figure 2 below.

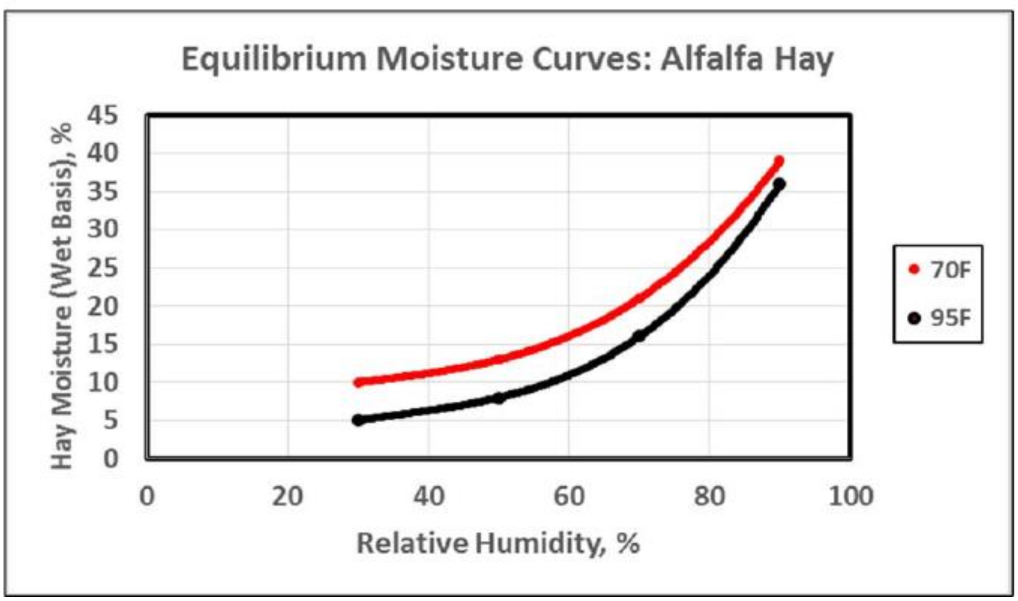


Figure 2 - Equilibrium Moisture Curves of Alfalfa at Two Temperatures (70F and 95F, or 21C and 35C) Source: (Shewmaker, 2004)

Figure 2 above also demonstrates the relationship between hay bale MC and temperature. Although there is a relationship between these two parameters, impact of temperature on hay bale MC is considerably less than the impact of relative humidity on bale MC, which can vary by a factor of three (i.e. 90% in the morning and 30% in the afternoon) (Collins, 2007). At a given equilibrium level of relative humidity, hay moisture will decrease with increasing temperature (Shewmaker, 2004).

2.3 Moisture Content Sensing Mechanism

2.3.1 Measurement Using Electrical Resistance Sensor

To validate the accuracy of the system discussed in this report, MC measurements mentioned above in section 2.2 should be compared to values measured using the systems' MC sensor. As previously discussed in the report preceding this one (Hubert & Yuan, 2018) this design system utilizes the handheld FX-2000 Delmhorst Moisture Content sensor. This sensor measures MC on the principle of detecting the electrical resistance by measuring voltage given by Ohm's Law:

$$V = IR \qquad \text{Equation (1)}$$

Electrical resistance is measured between two electrodes on the sensor. An increased resistance between these electrodes implies decreased conductivity in the medium (i.e. hay). Because moisture - namely water - is an electrical conductor, decreased conductivity in the meter implies lower MC. Therefore, electrical resistance in a medium can be used to estimate MC (Gawande, 2003). After a short period of time of the sensor's electrodes being surrounded by the medium, matric potential equilibrium is reached between the sensor and medium, and MC is estimated based on the sensor's calibration curve (Gawande, 2003).

The Delmhorst MC sensor uses a two-pole cell, contact resistance measuring technique between two metal electrodes. In a standard two electrode cell, an alternating current (AC) is applied between the two poles using a current source, while the resulting voltage is recorded. After obtaining the voltage and current values, the resistance across the electrodes can be calculated (equation 1). At low frequencies, capacitance between the electrodes has no effect on the measurement.

This method of determining MC results in an approximate hay bale MC value, which is acceptable for the purposes of this report. Hay bale MC will vary within the bale itself due to the non-uniformity and variability of the hay's electrical properties (Laurenzi, 2018). In order to acquire an accurate and representative MC reading, farmers must ensure that their handheld sensor is able to measure the electrical resistance near the geometric center of each hay bale, where MC values will be the greatest. To do this, a prod is required with a length that is appropriate to the size of the bale (Laurenzi, 2018).

Although it is preferable to take MC measurements at various locations in the hay bale to account for the hay's non-uniformity, the design system discussed in this report will likely only take readings at the center of the bale. Due to the fact that the MC readings occurs during bale transportation, the sensing system will likely be inserted near the center of the bale at a single location, remain there during bale transport, and then be removed. Therefore, it is important to note that this system will be able to provide a general knowledge of the maximum MC of multiple bales, but will not be effective for bales of extreme variability (i.e. for hay bales where a portion of the bale has a drastically different MC value than the center).

2.3.2 Sensor Calibration

The FX 2000 Delmhorst MC sensor has a measurable range of between 6% and 40% MC. This is considered an acceptable range for the purposes of this report as it includes the target MC range for alfalfa hay bales (between 15% and 20% MC). The accuracy of this sensor is partially dependent on its calibration process.

Accuracy and calibration information was provided directly by Delmhorst Instrument Co. The primary calibration follows National Institute of Standards and Technology (NIST) standards, and has an electrical accuracy of +/- 0.3. The FX 2000 meter has a built-in calibration check. This form of calibration requires the sensor to be surrounded by clean, dry air for a specified amount of time. Then, a physical button on the meter is pressed, and a value of 12 +/- 2 should appear on the screen if the meter is properly calibrated. If not, the meter is out of calibration or the battery is low and should be changed.

A manual calibration check can be performed for all sensors that have a voltage output. This process can be done by reading the voltages from the sensor of known MC values and then plotting the calibration curve (i.e. voltage versus reference MC) to find the intercept and slope of the curve. Once the equation of the calibration curve is obtained, it can be validated using a different set of data.

2.4 Hay Bale Temperature

As previously mentioned in section 2.2, relative humidity and hay bale MC are correlated. Temperature will have an effect on relative humidity, and therefore, comparing sensor MC values to calculated MC values (i.e. via oven drying) should be carried out in several batches, over a period of time with multiple ambient temperatures. This will allow for the MC measurement to be validated for different MC ranges, which vary with temperature, time of year, weather conditions, et cetera (Shewmaker, 2004).

Because of the relationship between hay bale temperature and MC, temperature should be maintained within acceptable ranges (Shewmaker, 2004). Hay should remain below 130 ºF (or 54.4 ºC) to avoid risk of fire (Overhults, 2015). Appendix B – Hay Bale Temperature Recommendations displays certain critical hay bale temperatures and their associated risks from various sources.

Measuring hay bale temperature can be achieved using a long thermometer that does not use mercury. The thermometer used should be durable enough to penetrate through highly dense bales, therefore mercury thermometers should be avoided as they present various hazards should they break. Generally, the part of the bale with the most elevated temperatures is from 6'' to 12'' from the center (15 to 30 cm), so thermometer length should be chosen accordingly. The thermometer should be able to measure up to 200º F (94º C), with an accuracy of +/- 5º F (or +/- 15º C) (Alberta Agriculture and Forestry, 2005).

3.0 Modified Design

The design system has been modified to ensure all the design criteria are met. The previous design from Hubert & Yuan (2018) was discussed with various parties, including several farmers, and Delmhorst Instrument Co. president, Thomas Laurenzi. Using this consultative process, the design was modified as discussed in this section.

3.1 Design Criteria

The criteria required for this design system to achieve its primary objectives are as follows:

- **Flexible / Versatile:** As per the client's request, the design system must be able to be installed on a wide variety of tractors.
- **Easy to install:** The design system must be able to be installed by farmers, and with minimal effort.
- **Easy to use:** The system must be able to measure MC of hay bales with minimal involvement of the farmer. It should measure and transmit data during the transportation of bales, without the farmer having to do anything that he wouldn't normally do in bale transportation.
- **Accurate and Efficient:** Sensor must be able to accurately measure MC of hay bale, and data transmission must accurately transfer data in a timely manner.
- **Inexpensive:** The total initial cost of the system must not exceed $5000. Operating costs must be minimized i.e. the cost to transfer data wirelessly over time, the cost to run the system, et cetera.

- **Durable:** The sensor must be able to withstand high forces of repeated piercing through and carrying of hay bales (see detailed dimensions below *in Physical Configuration of Design*). The system must not break during normal bale transportation, and the system must not detach from the bale spear and/or become lodged inside the bale after measurement. Additionally, data transfer mechanism must be suitable for farm environment (i.e. outdoors, waterproof, et cetera).

Initial research performed and discussed in Hubert & Yuan (2018) demonstrated various potential designs which met all the above design criteria except for durability. High stress due to bale density, and fatigue stress due to repeated bale transportation was shown to cause the FX – 2000 sensor to fail. This section of the report focuses on design modifications to address these issues.

3.2 Alternative Designs

3.2.1 Physical Design

The design process followed was adaptive. In Hubert & Yuan (2018), the physical system design consisted of the sensor prod connected to the bale spear using a spring. The spring was intended to reduce stress. The prod was exposed to the environment at all times, and was required to withstand compressive and bending forces without adequate support. For this reason, stress analysis concluded that the design would fail. Several alternative designs were taken into consideration to prevent failing. All alternative designs include minimizing direct contact between the sensor and the bale, as well as avoiding continuous prod exposure. These alternative designs are listed below.

1) **Inserting the sensor within bale spear:** In this design, the tip of the sensor (i.e. the sensor's electrodes) is permanently exposed. A hole is drilled along the axis of the bale spear, and the prod is inserted and held in place using set screws. This method would reduce the amount of stress on the prod, as the spear would be able to carry the weight of the bale during transportation.
2) **Movable Sensor Cover to expose prod tip:** Loading a hay bale on the spear pushes back a movable cover so that only the tip of the prod is exposed, thus reducing forces on the prod.
3) **Thin cover with blade:** Prod tip is always exposed, unlike alternative design 2, but prod tip is protected with a small blade. This blade reduces amount of pushing (compression) force on the prod tip as the system enters a hay bale. Entire case enters bale to reduce bale mass forces. There is an option with this

design to have case slide forward when needed, to cover prod tip and blade for safety.

Drawings of each of these design alternatives can be seen in Appendix C – Technical Drawings. Disadvantages of option one include the fact that drilling axially on the bale spear will significantly decrease its strength to pick up a hay bale. Disadvantages of option two include the fact that depending on angle of loading and hay bale size, the hay bale might not necessarily be in the proper position to fully push back cover and expose prod tip. Hay bale positioning on bale spear varies and depends on each farmer.

3.3 Data Collection and Transmission

3.3.1 Wi-Fi versus Bluetooth

Analysis and comparison of different methods of automatic data transmission can be found in Hubert & Yuan (2018). As mentioned in said report, Bluetooth data transmission is ideal for all farmers who do not have Wi-Fi access on their farms, as it is less expensive and does not require router installation. In Hubert & Yuan (2018), Bluetooth communication was deemed the superior data transmission method. Upon further investigation and discussion with several farmers at McGill Macdonald Campus and at McGill's *Emile A. Lods Agronomy Research Centre*, it was discovered that farmers preferred Wi-Fi data transmission, despite its disadvantages.

Wi-Fi transmission has several benefits which appeal to farmers; particularly range and speed. Although Wi-Fi transmission does not allow for instantaneous uploading of MC values (due to the lack of network access throughout the entire field), farmers claimed that they were willing to have the design system collect and store MC values, and only upload them when the system (i.e. the tractor) passed by the main farming building. All farmers that were consulted had Wi-Fi in one of the main buildings near the field. Therefore, the system should be designed to pause data transmission when it is not in network access range, and to resume transmission when it is.

This topic is discussed more in depth in Hubert & Yuan (2018), along with several examples of sensing products on the market which currently use Bluetooth and/or Wi-Fi data transmission. There were no alternative design consideration for data transmission hardware in this report, as the Hubert & Yuan (2018) concluded that the use of an Arduino microcontroller met all design requirements. In order to modify the design to incorporate Wi-Fi, an Arduino Wi-Fi module is used instead of an Arduino Bluetooth module.

4.0 Design Comparison and Selection

4.1 Physical Design Selection

Option three is the recommended physical design with drawbacks less significant than the previous two. The design consists of a rail that the removable cover can slide on, a steel cover machined into a shape like an uppercase letter ohm (Ω) which is screwed in place, a blade to cut through hay, two rings to hold sensor in place.

The rail is to be welded on the two sides, blade is to be welded on the spear in front of the sensor tip, and two rings are welded on the spear to hold sensor.

Sensor is fitted through the two rings (one placed in front and one placed at the back) to be held in place and then the sliding cover to place over sensor so protect sensor during penetration into hay to pick up bale (see Appendix B for drawings and dimensions).

The blade welded in front of sensor on the spear is to cut the hay and to reduce the abrasiveness on the sensor tip. Setscrews are used to hold cover on spear.

Materials selections between aluminum and steel (See Appendix C for details). Aluminum is cheaper and easier to machine however is less in strength while steel is more expensive and hard to machine but it is better in strength.

Decision Pugh Chart			Material Types				
	Weight		Steel		Aluminum		
Evaluation Criteria		Baseline Material	Rating	Weighted	Rating	Weighted	
Cost	3	0	-1	-3	1	3	
Material Availability	5	0	1	5	1	5	
Ease to machine	4	0	-1	-4	0	0	
Strength	5	0	1	5	-1	-5	
Maintenance	2	0	0	0	0	0	
				3		3	Total

Steel and Aluminum are equally acceptable for this project. Steel is chosen to be uniform with the material of the spear.

Decision Pugh Chart								
			Alternatives					
	Weight		Tube		Movable Cover		Sliding Cover	
Evaluation Criteria		Baseline Material	Rating	Weighted	Rating	Weighted	Rating	Weighted
Easy of use	3	0	1	3	-1	-3	1	
Ability to withstand weight	5	0	-1	-5	1	5	1	
Cost	3	0	1	3	0	0	1	
Ease to manufacture	4	0	-1	-4	-1	-4	1	
Ease to maintain	2	0	1	2	0	0	0	
				-1		-2		

The final physical design is selected to option 3, 'Thin Cover with Blade. See Appendix C – Technical Drawings. The dimensions in this project is quite small because the available width of spear face is quite small. Material must be chosen so that cover can penetrate into the hay bale.

Note: Design is removable once weld is sawed off spear.

4.2 Data Transmission Design Selection

As mentioned in section 3.3.1, the data transmission method chosen for this design system consist of an Arduino microcontroller. Generally, a sensor is connected directly to the Arduino board via connecting wires, but this is not possible with advanced sensors such as the FX-2000. Due to the proprietary nature of the Delmhorst sensor's circuitry, it is not possible to discuss the connection of the sensor to a microcontroller. Instead, this report will discuss connection to a microcontroller via a Delmhorst Moisture Transmitter. The information discussed in this section, as well as the transmitter itself (model MTX), was directly supplied by Delmhorst Instrument Co.

The MTX transmitter is a device which connects directly to the same prods used with the FX-2000 sensor. When a prod is placed into the hay, the transmitter generates a readable voltage or current output. Using the provided calibration information, this electrical output can be used to determine MC. Calibration information, or a chart relating MTX voltage outputs and hay MC are shown in Appendix ??.

The output voltage range over which the MTX operates is from 0V to 10V Recommended input voltage for Arduino boards is between 7V and 12V (Arduino, n.d.). Because of this, it is important to reduce voltage input to the Arduino board to avoid burning the board. This can be achieved via a voltage divider, as shown in Figure 3 below.

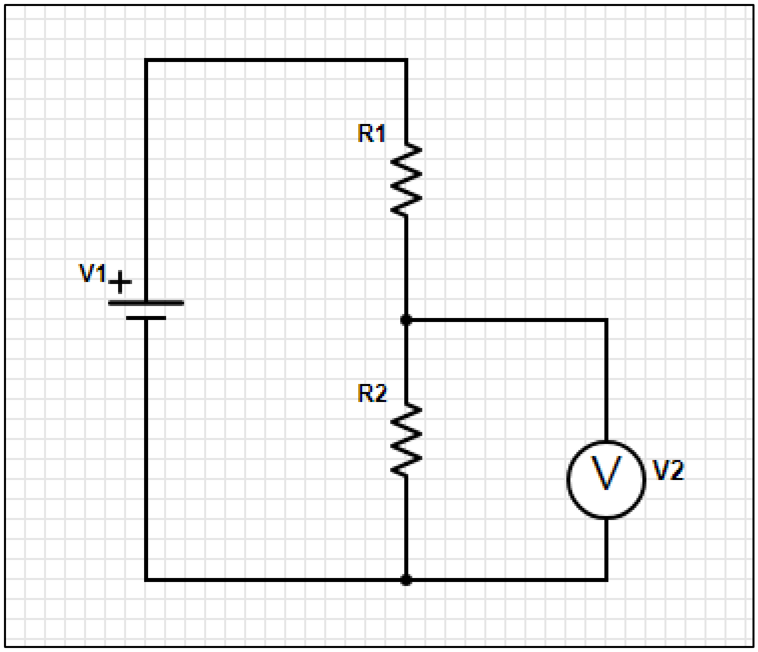


Figure 3 - Schematic of a voltage divider, drawn by Hubert and Yuan

The input voltage for the circuit will have a maximum value of 10V at V1. The voltage value measured using a voltmeter around R2 will show a smaller output voltage, which will then be supplied to the Arduino board. The value of resistors used in this voltage dividing circuit is based on the equations 2, 3, and 4 below.

$$V_{out} = V_{in} \frac{R_2}{R_1+R_2} \qquad \text{Equation (2)}$$

$$Power\ Dissipated = \frac{{V_{in}}^2}{R_1+R_2} \qquad \text{Equation (3)}$$

$$Max\ Power\ Dissipated = \frac{T_{dmax}-T_A}{\theta_{DA}} \qquad \text{Equation (4)}$$

Where: V*out* and V*in* are V2 and V1 respectively, in Figure 3 [V]
R1 and R2 are represented in Figure 3 [Ω]
Power dissipated is the amount of power that is lost as heat [W]
Max power dissipated is the maximum amount of dissipated power that can be safely reached [W]
T*dmax* is the maximum safe operating temperature [K, C, F]
TA is the ambient temperature [K, C, F]
θ_{DA} is the total thermal resistance [K/W, C/W, F/W]

(Electronic Tutorials, n.d.)

The desired voltage output is calculated using equation 2. Because smaller voltage values output from the MTX transmitter correspond to increased hay MC values (45-60% MC), voltage output can be reduced without greatly influencing MC measurement accuracy. As previously mentioned in section 2.2, hay bale MC values are ideally between 15 and 20%. It can be safely assumed that the majority of hay bales being measured with this system will not be within the upper range of 45-60%.

It is essential to ensure that appropriate resistance values are chosen that minimize power dissipated (equation 3). If resistance values are too low (and therefore dissipated power is too high), resistors will dissipate excessive thermal energy, which may result resistor damage, damage to the Arduino board, and in severe cases, in electrical fires (Boyer, 2018).

Power dissipated must not exceed maximum power dissipated (equation 4). The maximum operation temperature for an Arduino board is 257 ºF or 125 ºC, but at this temperature, accuracy of the system will decrease. Recommended maximum operating temperature is 185 ºF or 85 ºC. Recommended maximum operating temperature for carbon composite resistors is 248 ºF or 120 ºC (Coates, 2018). Therefore, the lower value of 185 ºF or 85 ºC is used for the purposes of this design system, in equations 3 and 4 above.

Total thermal resistance of an Arduino board in these conditions will be assumed as 3 ºC/W (Arduino, 2012).

The data transmission portion of the system design, including MTX transmission, voltage divider, and Arduino board are presented in the Figure 4 below.

5.0 Testing and Verification

Once the system was designed and assembled, its accuracy and feasibility were verified using the various testing methods discussed in this section.

5.1 Moisture Content Sensing and Oven Drying

To ensure the accuracy of Delmhorst MC sensor readings, each sensor measurement is compared to values obtained using the oven-drying method. This method was chosen over the alternative methods described in section 2.2 for availability and accuracy reasons. A brief description of the oven-drying MC measurement method used is described below:

- First, 16 sampling locations were marked
- Hay MC values were taken at each of these sampling locations using the FX-2000 sensor. These values were noted and associated with sampling location number. Schematics of marked sampling locations on the hay bales are shown in Appendix D – Moisture Content Oven Drying Data
- Hay samples were taking using a drill and corer, which penetrates the hay bale and removes a small sample of hay from the center. Figure 4 below displays the type of corer used for this step. The specific corer used penetrates 16'' (or approximately 40cm) into the hay bale. A sample was taken at each of the 16 sampling locations
- Each sample was placed into a sealed bag and was labelled with sampling location number. These samples were then brought to the lab for oven-drying. The specific lab where drying was carried out is the *Emile A. Lods Agronomy Research Centre*.
- Samples were weighed, placed in separate paper bags, and placed in a drying oven set at 50C for 72 hours.
- Following the specified time period, dry weight was measured. Using the process described in the Appendix E – Moisture Content Calculations, MC was calculated based on dry and wet weight (post and pre-drying weight).

Figure 4 - Hay Bale Corer for Sampling (RDS Coleman Consulting, 2011)

Following this processes, the MC of two hay bales were calculated, and compared to the FX-2000 readings. The first was on October 25th, 2018, and the other on November 29th, 2018. The time period and seasonal differences between the two hay bale sampling dates provides temperature information (i.e. how seasonal changes and temperature differences relate to MC). This is discussed further in section 6.0.

Hay bale samples were first taken from a farm in southern Vaudreuil-Dorion, Quebec. The second hay samples were taken from a farm near Vaudreuil-sur-le-Lac. Climate data for these two locations was assumed to be identical, as they are within a reasonable proximity of one another.

Finally, a MC test and analysis is carried out to determine how representative one central MC reading is of the entire bale. As previously mentioned, MC measurements which are taken at various locations throughout the entire volume of the bale will likely yield an overall average value different than the MC resulting from a single, central measurement. When farmer lifts and transports a hay bale, the spear will only be inserted once, somewhere near the center. To see if the measurement taken at this central location can be representative of the entire bale, a statistics test using the t-distribution is performed. This allows us to see whether the points vary significantly from the mean at significance level $\alpha = 0.05$. The Statistical software, SAS is used in this application.

Results of the various MC analyses are discussed further in section 6.0.

5.2 Stress Analysis

Compression and bending stresses develop on the bale spear as hay bales are lifted. A mathematical analysis is carried out to ensure that developed stresses are acceptable and will not lead to failure. For simplification, this project assumes the bale spear to be homogeneous and isotropic (i.e. spear material is uniform and forces are the same in all directions). To solve stress in an object in rectangular coordinates, the Navier equation is used (equation 5 below). For an axisymmetric object with external loading, the Navier equation describes the displacement or deformation as a function of body forces and structural properties of the material. By knowing the displacement field, stress and strain field can be calculated:

$$(\lambda + \mu)\nabla(\nabla \cdot \boldsymbol{u}) + \mu\nabla^2\boldsymbol{u} + \boldsymbol{f} = \rho \ \frac{\partial\text{^}2u}{\partial t\text{^}2} \qquad \text{Equation (5)}$$

Where:
u = displacement vector in 3D [m]
λ = Lamé modulus of the material, expressed in terms of Young's modulus, E
μ = shear modulus, expressed as materials' Poisson ratio, v
∇ = Laplace operator; the gradient of a function in Euclidean space
f = the vector of forces in an volume of the object [N]

(Lautrup, 2000)

Using the Navier equation (equation 5), a stress analysis of the bale spear can be carried out via MATLAB. The required steps to perform this analysis using MATLAB are discussed below:

- Create a special structural analysis model for a plane stress solid (3D)
- Import AutoCAD geometry as a .stl file, and mesh the geometry. Default MATLAB mesh can be used for the purposes of this analysis.
- Enter the structural properties of the bale spear material (i.e. Young's modulus, Poisson's ratio, and mass density). The bale spear is made of structural steel. For structural steel, Young's Modulus (E) is 200 GPa, and Poisson ratio (v) is 0.3 (Engineering Toolbox, 2003).
- Specify the gravitational acceleration as a body load.
- Apply a 'fixed end' at the left end face (face 22, see Appendix F - Stress Analysis MATLAB Codes and Results). Face 22 is where the spear will be fixed onto the tractor.
- Apply a uniform distributed load on spear's face 17 in the negative z-direction (down). This represents the forces on the spear due to the hay bale. The load is 500 Pa. Although the weight of the bale varies between bales, and therefore is not known, an average weight is calculated in this stress analysis using the standard bale mass as presented in Appendix A – Bale Moisture Content Recommendations (Alberta Agriculture and Forestry, 2005).
- Solve and plot results, such as displacement, velocity, acceleration, stress, strain, von Mises stress, principal stress, and strain.

The results of this stress analysis are discussed in section 6.0.

5.3 Temperature Profile Simulation

Temperature measurements were taken during hay sampling and MC sensing. These measured temperature results were then used to mathematically produce a temperature profile simulation, using an Autodesk Finite Element Analysis (FEA) software. In doing this, the system design discussed in this report can be validated for MC values over a range of measured temperatures.

Temperature measurements were taken using a thermometer borrowed from McGill professor, Dr. Qi. Temperature was taken at each of the sampling locations mentioned in section 5.1, and displayed in Appendix D – Moisture Content Oven Drying Data. This temperature data was then entered in the FEA software to determine temperature profile under natural convection of surrounding ambient air, and internal convection and conduction heat transfer. However, due to software limitations, a 3D thermal analysis was conducted in MATLAB as opposed to using the FEA software.

The rectangular bale was drawn in AutoCAD and imported into MATLAB.

The governing equation which describes internal conductive temperature flux of the hay bale is called Fourier's law of heat transfer, and is shown below in rectangular coordinates:

$$Q = \rho * c * \partial T/\partial t \quad -\nabla \cdot (k\nabla T) \qquad \text{Equation (6)}$$

Where:
Q = heat flux [W/m]
α = ρ*c thermal diffusivity (need to use thermal diffusivity instead of ρ*c) [m2/s]
∂T/∂ = partial temperature differential with partial time [K]
k = thermal conductivity [W/mK]
∇ = Laplace operator; gradient of a function in Euclidean space.

(Opoku, 2004)

This heat transfer equation is a parabolic partial differential equation that describes the distribution of temperature over a given time. MATLAB has a built-in thermal model to solve heat transfer problems. The required steps to perform this temperature analysis using MATLAB are discussed below:

- Start a thermal model script for a steady-state thermal model
- Import the AutoCAD geometry as a .stl file into the thermal model
- Assign thermal properties of the material (i.e. thermal conductivity k, specific heat c, and mass density ρ).
- Specify temperatures or heat fluxes on or through the boundaries. For convective heat flux, specify the ambient temperature T∞ and the convective heat transfer coefficient *htc*.
- Set an initial temperature of the object (which was measured on site).
- Solve and plot results, such as the resulting temperatures and temperature gradients.

Although the thermal conductivity of alfalfa hay was not found, it is assumed to be comparable to that of timothy hay. The average thermal conductivity of timothy hay is 0.6 W/mC. Thermal diffusivity, α= 1.675 $*10^{-7} m^2/s$ (Opoku, 2004). Note: Unit changes should be performed in MATLAB if necessary to ensure uniformity (all units are SI except for temperature). Thermal conductivity temperature unit needs not be converted to Kelvin, because all temperature measurements were taken in Celsius degree.

The results of this temperature analysis are discussed in section 6.0. Detailed process information and MATLAB code can be found in Appendix G: Temperature Analysis MATLAB Code.

5.4 Automatic Data Transmission Testing

The capability of the design system to automatically transmit measured MC values was tested. The system was assembled as shown in Figure 13. The Arduino code used to control the Arduino board is shown in Appendix H – Data Transmission Information and Arduino Code More discussion on the process used to write this code is written in Hubert & Yuan (2018).

First, various MC measurements were taken using only the FX-2000 sensor. The first measurement was taken of ambient air, i.e. the sensor's 'read' button was pressed without first inserting the prod into hay. Then, a bale of hay was measured at several locations. Following this, this same process was repeated, but instead using the entire system design as displayed in Figure 13. MC values measured by the FX-2000 meter and the system design were compared. Due to the previous accuracy verification of the FX-2000 meter, the system design is assumed to be accurate if measurements are near FX-2000 measurements.

Because the system contains a moisture transmitter, it no longer directly outputs MC values, but instead outputs voltage values which much be changed into MC (done by Arduino code). The relationship between voltage output and MC values was provided by Delmhorst Instrument Co., and is displayed in Figure 5 below.

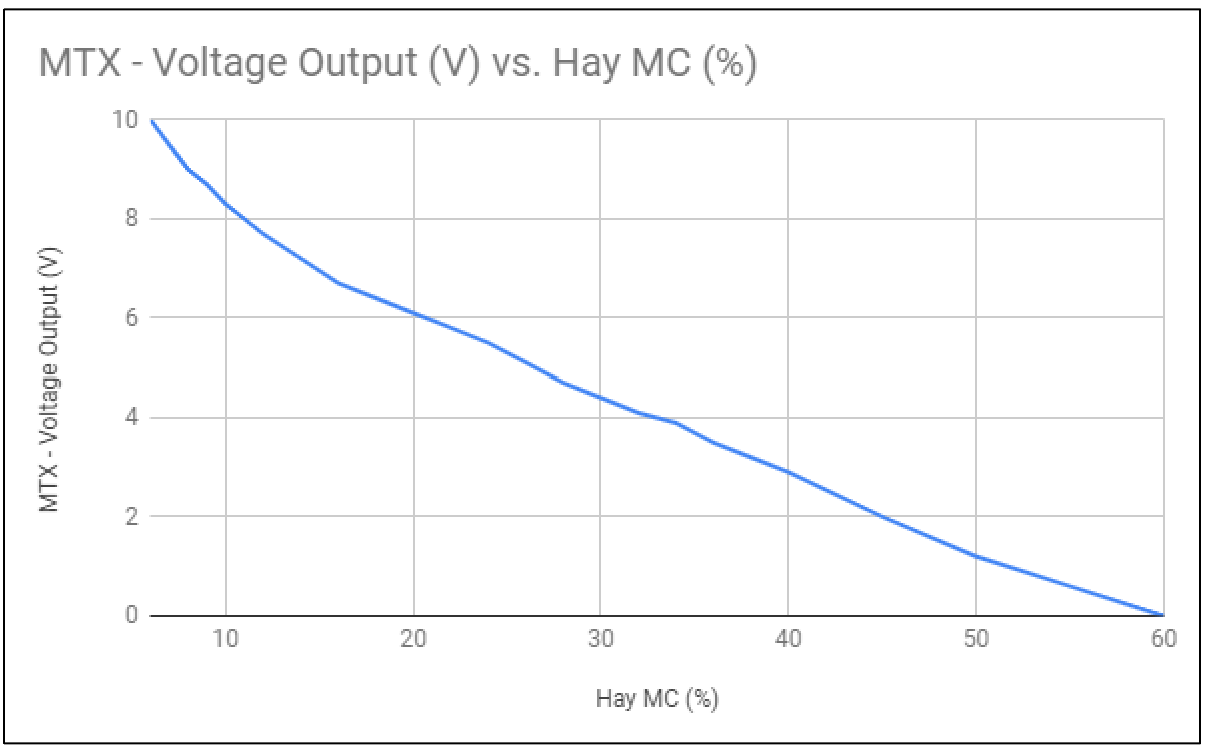


Figure 5 - Relationship between moisture transmitter MTX voltage output and hay moisture content

This relationship allows the system to estimate MC values via the Arduino code, and therefore allows MC values to be determined automatically. Sample calculations used to modify this relationship when using a voltage divider are shown in Appendix H – Data Transmission Information and Arduino Code.

The results of this data transmission testing are discussed in section 6.0.

6.0 Discussion and Analysis of Results

6.1 MC sensing and Drying

Result of the oven-drying hay sample testing is displayed in Figure 6 below:

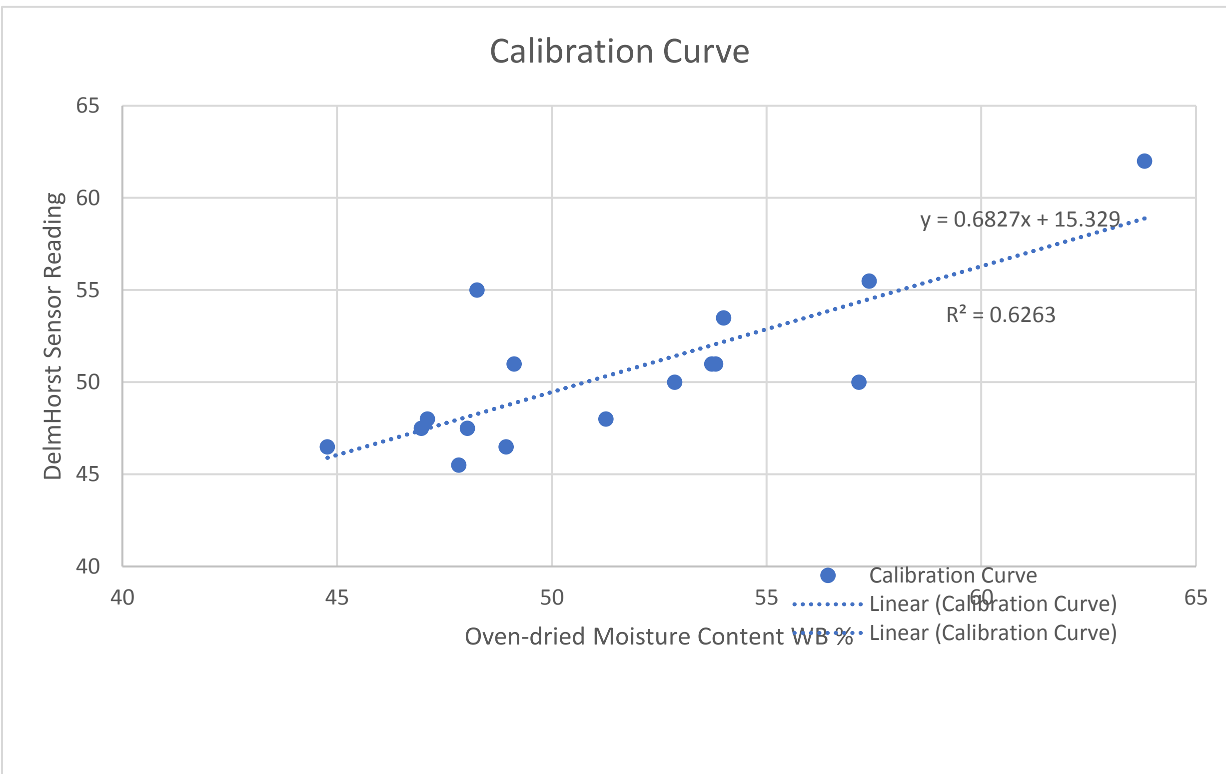


Figure 6 Comparison between two methods of measuring MC. The values obtained using oven-dried method is taken as the reference Delmhorst reading do not exactly match the reference.

The MC values obtained using oven-dried method is used as the reference to calibrate Delmhorst MC sensor. Sensor reading is plotted with reference MC values. These measurements are taken on the first bale (on Oct.25, 2018) to use for sensor calibration with an R value of 0.62 and percent error 3.9% (consistent with company reported error at 3-4%). Delmhorst sensor should be calibrated further to produce measurements closer to oven-dried measurements. Calibration is done following the handbook given by the company.

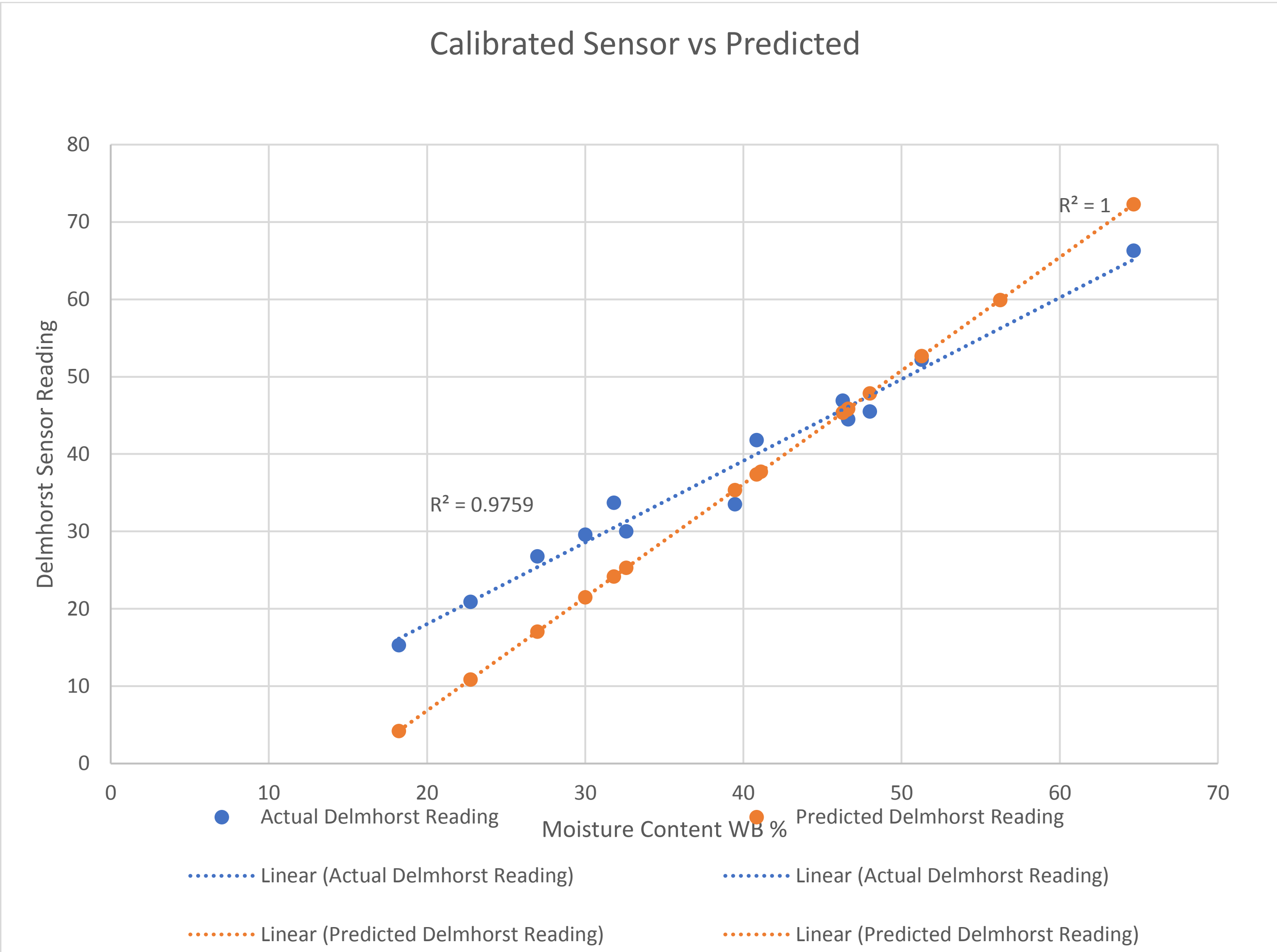


Figure 7 - Delmhorst sensor reading after calibration

After the instrument was calibrated another bale is measured to verify. Delmhorst is more accurate and produced an R value of 0.98 and a percent error of 2.4%. Both hay bales are below fire hazardous MC range and temperature range.

Analysis of SAS results, which allows us to determine whether a central MC reading is representative of the entire hay bale, are discussed below, and displayed in Figure 8.

The SAS System

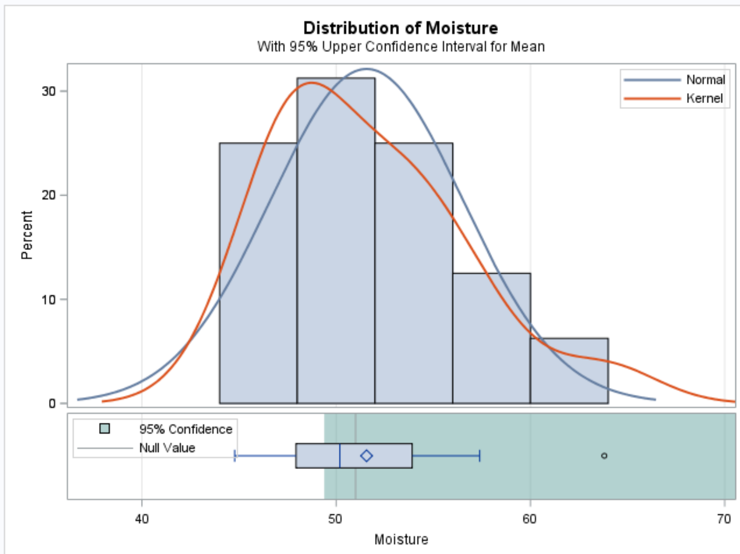
The TTEST Procedure

Variable: Moisture

N	Mean	Std Dev	Std Err	Minimum	Maximum
16	51.5652	4.9658	1.2414	44.7755	63.8063

Mean	95% CL Mean		Std Dev	95% CL Std Dev	
51.5652	49.3889	Infty	4.9658	3.6682	7.6855

DF	t Value	Pr > t
15	0.46	0.3277



Output - (Untitled) | Log - (Untitled) | Moisture Content Anal... | Results Viewer - SAS ...

Figure 8 - Statistical Analysis demonstrating how significantly values vary from the sample mean

SAS uses a probability approach to evaluate population parameters (MC content in this case). At the significance level of 0.05, it is safe to assume that the bale has a uniform MC at its mean value – the probability area (0.3277) is much greater than the significance level (0.05). Important points to note are as follows:

- Both bales are not in the ideal range of MC for hay (15 – 20 %MC)
- Both hay bales are below fire hazardous MC range and temperature range (i.e. not under 5% nor above 54.4 C).
- Both bales are above 20% MC which means they are at risk of biological activities that degrade the quality of hay.

These hay samples were only taken for testing, so specific values are not important. The primary result of this analysis is positive; that the sensor is accurate and that for the purposes of this design, it is feasible to take a central MC reading for hay bales of moderate uniformity, and have these values be representative of the entire bale. It is still important to note that this would not be the case for a hay bale of extreme non-uniformity. Detailed results of this section are shown in Appendix D – Moisture Content Oven Drying Data.

6.2 Stress and Strain Analysis

The spear is under load from the hay bale. With the left end fixed at the tractor, this problem can be viewed as a cantilever beam problem with uniform distributed load. The greatest stress will be at the fixed end (Figure 7). The maximum stress is no more than 2.5 MPa which is well below the minimum yield strength of structural steel at 250MPa. This model is set up such that the load is applied over the entire face 17 when in reality the load is only like to be distributed near the front tip that picks up the bale. In reality, the Von Mises Stress should be lower that presented in the model. It would be ideal to perform a stress test on the design with cover but in the MATLAB model, it does not accept geometry with shared edges therefore a geometry with design mounted on the spear could not be produced. Using a FEA software would be much a better option for this application.

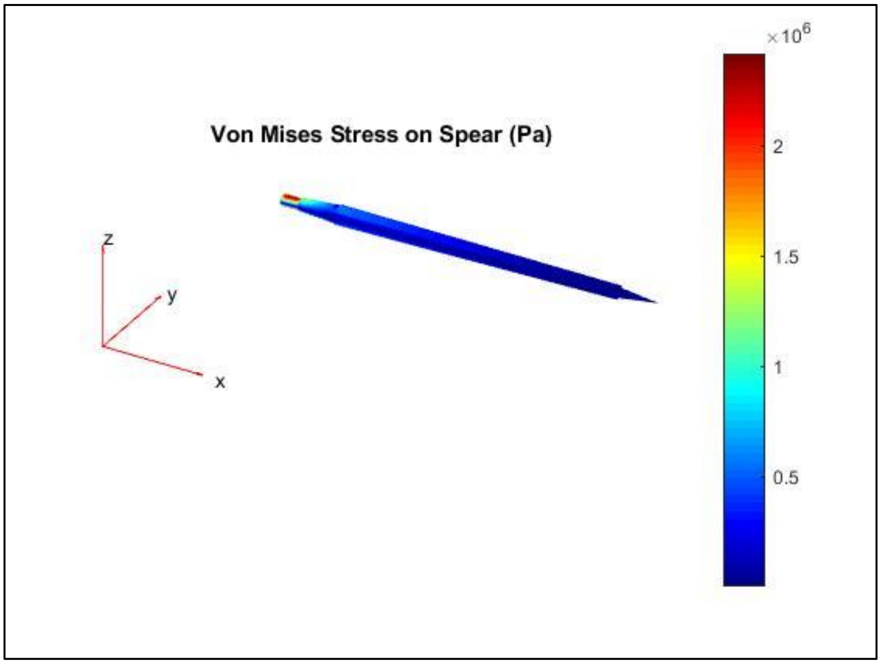


Figure 9 - Spear's Von Mises Stress under load

6.3 Temperature

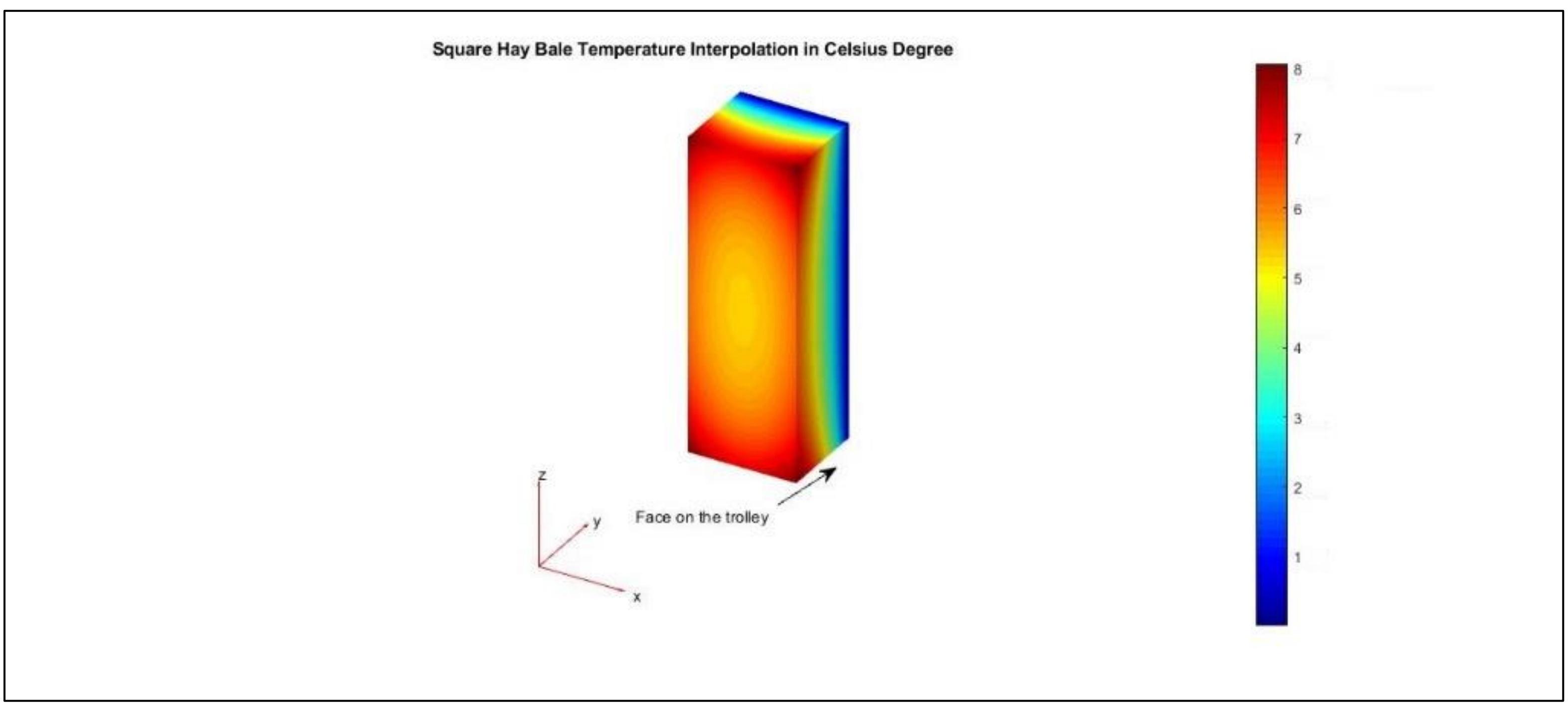


Figure 10 - Square Hay Bale Temperature Distribution, measured on October 25, 2018

The temperature distribution under nature convection at ambient temperature 6.1 C and conduction between particles (i.e. represented as meshing size) of the bale measured on October 25, 2018. The rear face is placed on the trolley is assumed to be having a heat flux of temperature lower than the rest of the faces under temperature of ambient air. The heat transfer and temperature distribution in this model seems too dramatic which might be due to the large size of mesh and cold surface on the rear face (where that is blue). A more uniform temperature distribution with mean value between 6C to 10C should be more appropriate. A FEA software would have a better approximation.

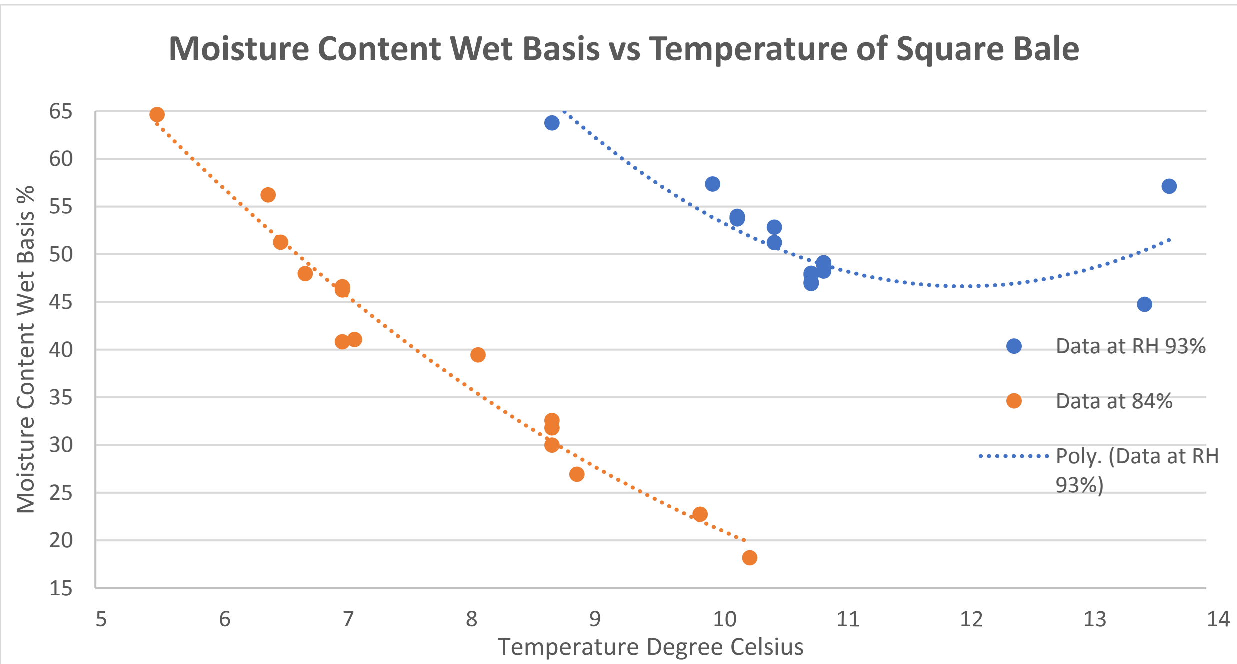


Figure 11 - Moisture content versus Temperature at a certain RH

Both bale measured are considerably wet (mean MC around 50% for the first bale and 40% for the second bale). The first bale is measured during the fall when the air is at 93% RH which might be the reason that the hay is very wet at that time and the temperature is higher in the fall compared to the second bale. The second bale is measured later (given more days to dry) and air becomes drier and colder; so second bale has less MC than the first bale and the temperature of the second bale is also lower which might be because it was measured in the winter time with lower air temperature. As MC increases, temperature decreases for both bales.

Both bale's MC values are within the operating range of the sensor – but the highest MC for both (over 60%) is near the upper limit of sensor operation range at 75%.

Both bales are not at risk of fire nor in the optimum MC range. Further drying is needed for both bales.

The SAS System

The TTEST Procedure

Variable: Temperature

N	Mean	Std Dev	Std Err	Minimum	Maximum
16	10.8375	1.2115	0.3029	8.7000	13.7000

Mean	95% CL Mean		Std Dev	95% CL Std Dev	
10.8375	10.3065	Infty	1.2115	0.8950	1.8751

DF	t Value	Pr > t
15	0.12	0.4516

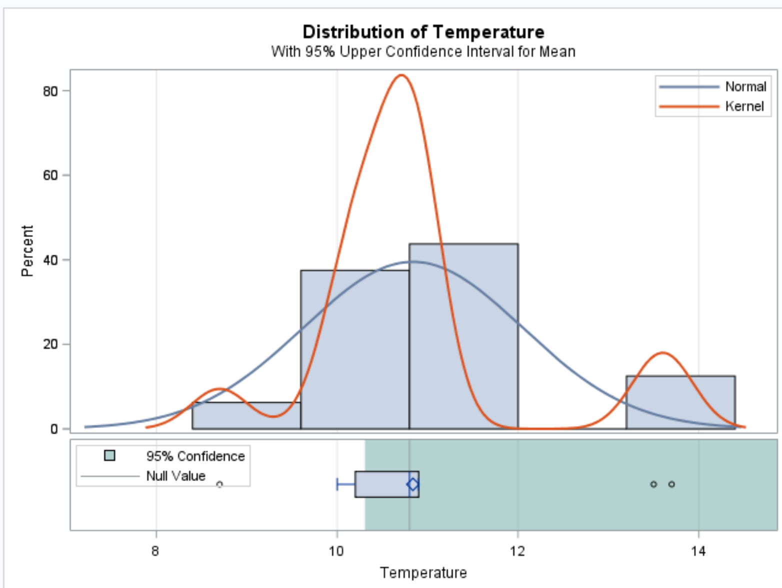


Figure 12 - Statistical Analysis demonstrating how significantly temperature values vary from the sample mean

Similar to the statistical analysis performed on MC, statistical analysis on temperature yield similar results. That the mean temperature can be used as the uniform temperature for the entire bale because probability area of variance for temperature (0.4516) is much higher than the significance level at 0.05.

6.4 Overall System

The overall system is displayed in Figure 13 below.

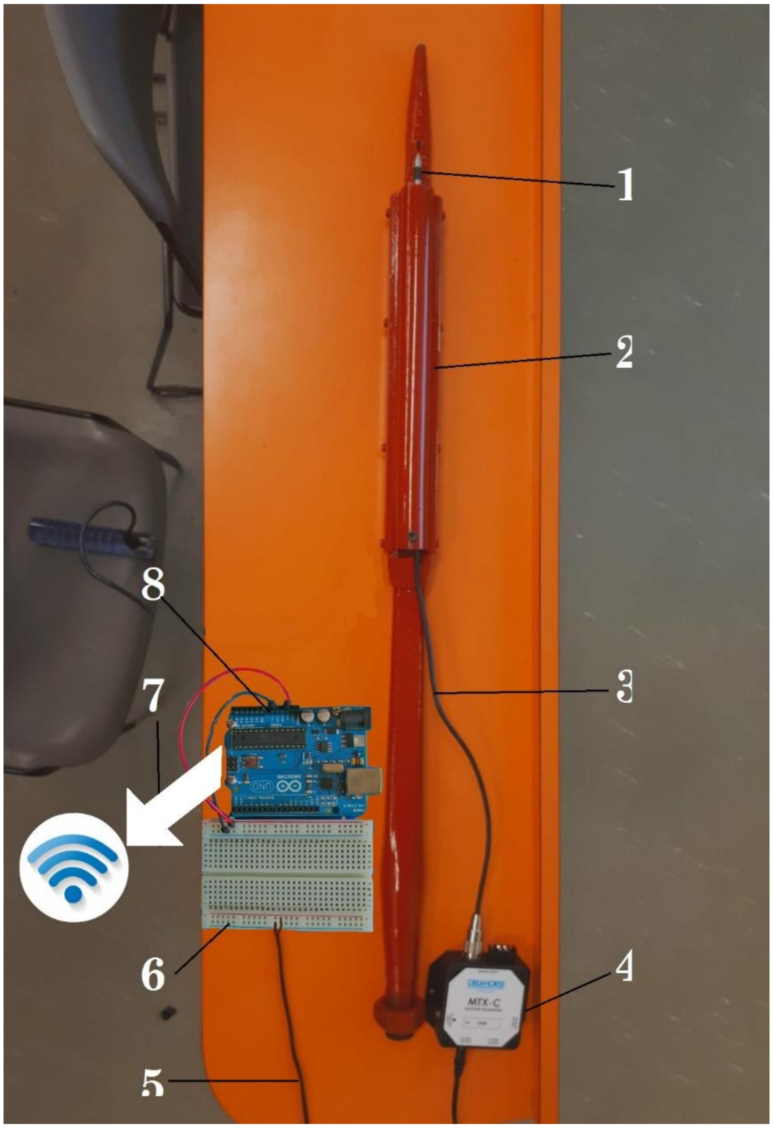


Figure 13 - Overall Assembled Design

Legend

1	Tip of prod (electrodes) exposed
2	Cover on rails to protect prod body during bale loading
3	Wire connecting MTX transmitter to end of prod

4	MTX transmitter supplied by Delmhorst Instrument Co.
5	Wire connecting MTX transmitter to breadboard
6	Breadboard containing two resistors in series to reduce MTX voltage output
7	Wi-Fi automatic uploading using Arduino Wi-Fi module *
8	Arduino Uno Microcontroller

* Wi-Fi access can be achieved with the use of an Arduino Wi-Fi shield as well.

Once assembled, this system was able to measure MC and automatically upload the values in the form of a CSV file. Software which is able to process this information was not considered in the scope of this project, but many farmers stated that they already possess software which is able to perform this task.

6.5 Modifications on Physical Design

The design initially drawn was not feasible to manufacture as consulted with the technicians the Belmac Atelier. The drawings were done with very limited welding and technical experience. For example, the choice of spacing and thickness of material are not possible to make as the material at that thickness (0.1 mm) melt under welding. And that the machining aluminum (ne of the material chosen) sheet into the design shape at the thickness of 0.063 inches (1.5 mm) is very hard to do (and possible not able to do) at small machine shop such as Belmac. Although previously, steel and aluminum scores equally. Steel is chosen over aluminum. However, the dimensions of steel plate still need to increase.

The dimensions on the drawings are to fit the design exactly on the spear. Once the thickness of steel plate is increased, all dimensions of design need to adjust. Which means, the design cannot fit exactly on the spear face. Instead, as the technician suggested, the design to be added with appendages on the sides in order to increase the width of spear face to fit design with new dimensions (which is not drawn in the drawing).

In addition, the technician also suggested to change the set screw to a stopper instead as the set screw at even an increased steel plate thickness will not be able to hold the design when picking up a bale.

Therefore, the system design created is considered a prototype. Conceptually, this design works, but the material used for the cover must be changed in order for the dimensions to be small enough for the casing to penetrate into the hay bale. The design process discussed in this report is able to produce an acceptable result if the correct material is used.

7.0 Design Considerations

7.1 Environmental Aspects

The primary environmental concern of this design is to be able to accurately measure MC of hay bales, to ensure storage of hay bales that maximize nutritional value and minimize hazards (i.e microbial growth and fire)

The MC of the hay bale is ideally ~20% (McCartney, n.d.), but this value depends on the size of the hay bale in question. Hay MCs both above and below this value can cause undesirable effects.

- **Low MC:** Moisture content less than 20% cannot support the growth of these microorganisms, but this hay has little to no nutritional value and therefore is not efficient for use as feed (Smith, 2018).
- **High MC:** When the MC of a hay bale is between 20%-30%, the environment within the bale encourages microbial growth in. This can lead to heating of the hay bale, and the production of bacteria and fungi/mold. Unwanted microorganisms will increase in population as they feed off of the hay’s nutrients, such as organic acids and sugars (Smith, 2018). This causes the nutrient value of the hay to diminish. Additionally, being exposed to these microorganisms can cause respiratory issues in farmers, health issues in the animals eating the hay. This can also cause the animals to become “turned off” of the feed, because of either lack of nutrient or unpleasant taste (Smith, 2018).
- **Very high MC**: Moisture content between 30-40% leads to advanced internal heating of the bale, which is caused by thermal expansion. This can lead to spontaneous combustion of the bale, with the probability of this occurring proportional to the size of the bale (LAURENZI, 2018).

A secondary environmental concern consists of the life cycle of the product. A life cycle analysis was performed using an online software called eTool LCD. This analysis showed that the main component of the system which contributes to adverse environmental effects is the disposal of the batteries. This can be avoided by connecting the system to the tractor power supply. The client preferred to use batteries so that the system would be wireless, but through testing, it was shown that the battery of both the Arduino and of the MTX transmitter would need to be replaced multiple times per season. Batteries used for both components are 9V, which are not expensive, but will produce a large volume of waste over time. Results from the life cycle analysis are displayed in Figure 14 below.

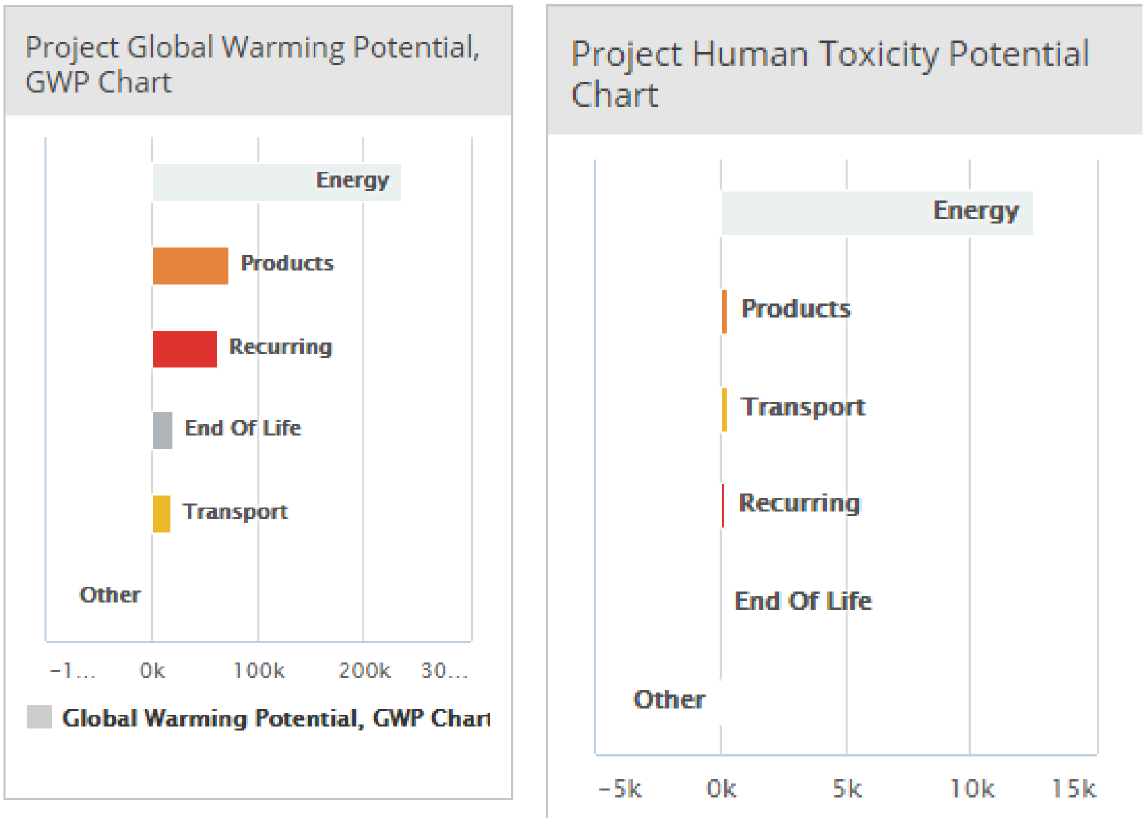


Figure 14 - Life Cycle Assessment Results for Automatic Hay Bale MC Sensing System (eTool Global, 2018)

7.2 Social and Ergonomic Aspects

The social and ergonomic aspects of this design are to facilitate MC measurement of hay bales for farmers. This sensor system is design is to allow farmers to measure, record, and monitor the MC of their hay bales during transportation of the bales without too much manual labor. Farmers save time and energy in this way.

7.3 Economic Considerations

Total estimated initial costs of the sensing system are shown in the table below.

Total Estimated Initial Cost for Wireless Hay Bale MC Sensing System

Component	Description	Price (CAD)
Moisture Sensor (FX-2000) Set	To measure MC	$1283.44
Paulin Steel Sheet	To machine into cover and rail	$17.44
Arduino Uno	To control the sensors and supply power	$22.99
Wi-Fi Module	To enable Wi-Fi on the Arduino board	$10.99
Arduino Breadboard and connecting wires	To assemble circuit	$11.90
Bosch Saw Blade	To cut through hay	$17.35
Labour	To machine the parts and assemble them on spear.	$350
	Total Cost =	$ 1714.11

Sources: (Amazon, 2018) (Arduino, 2018) (Home Depot, 2018)

Ongoing operational costs are negligible as the Wi-Fi system does not cost anything to run, and the system runs off of tractor power supply. Because the system uses digital measurement, the power will not be continuously on. This will result in lower corrosion of the sensor's electrodes, and an increased lifespan. This product is

8.0 Challenges and Recommendations

8.1 Challenges

There are two major challenges during this project. Firstly, the most challenging aspect is the effective and timely *communication* between five parties – company, client, supervisor, team members and technicians. Late communications and misunderstandings result in delays, redundant, incorrect or unnecessary works and mistakes (to fix these issues wasted much time). Many assumptions are made due to client's lack of response to many important questions – such as the density of bale, days since baled, and what type of hay. Additionally, communication with Delmhorst Instrument Co. resulted in the discussion of various proprietary information. The report and the design process had to be adjusted to account for this and to ensure all privacy was respected.

Secondly, the challenge being *realizing a design on drawing*; there are many unexpected issues in this process and much time is spent on consultation with technician to resolve the issues.

Hay bale shortage is also one challenge for this project. Client was unable to provide hay bales for measurement due to the shortage this year.

Difficulty in finding an appropriate instruments (the thermometer to measure temperature) and software (FEA software) is also a challenge.

8.2 Recommendations

One very important recommendation is to speak with a technician early in the project and have good communications with the technician throughout the project.

For this project, sample size of data is too small – only two bales of hay are measured. It is recommended to take more measurements on hay to improve analysis. Use a more accurate method of temperature measurement such as a thermal couple instead of a simple thermometer. Use a FEA software to do better analysis because MATLAB model does not allow too much user defined conditions as in software like COMSOL (i.e. prebuilt solver model based on standard conditions instead of user defined.) And MATLAB does not accept unioned geometry which made it impossible to do a stress analysis with design mounted on the spear. This is a major drawback in this project.

9.0 Conclusion

As quality hay is essential as winter feed, knowing the hay's MC is equally important for farmers to prepare its storage. The hay assumed to be alfalfa because it is a common hay type in Quebec. Ideal MC range for keeping alfalfa is between 15 – 20 % MC and under 54.4 C. To avoid fire hazard, alfalfa hay should be kept above 5% MC and under 54.4 C. To avoid biological activities, alfalfa hay should be kept below 20% MC. Both hay bales are not in the idea range nor in in the fire hazardous range. However, both hay bales are at risk of biological degradation due to excessive MC (mean of both bales' MC well above 20%).Delmhorst sensor has a measurement error of 3.9% - just like how the company reported in their document – before calibration and an error of 2.4 % after calibration. The temperature model gives a bale temperature distribution with in the bale with maximum temperature at 8 C. Most stress is found to be toward the fixed end of spear using Von Mises Stress Analysis. Temperature decreases as MC increases.

This project aims at developing an automated system that measure the MC to help farmer properly manage hay bales. The physical design involves a steel cover that slides along a rail on one face of the spear to cover the sensor. The sensor is held on the sensor by a pair of rings underneath the steel cover. A stopper is placed behind the cover to prevent it to move while picking up the bale. A blade is placed in front of sensor to cut hay to reduce large front contact and abrasiveness of hay on sensor tip. All mechanical parts are removable. Automatic data transmission was possible with the use of an Arduino microcontroller and an MTX moisture transmitter built into a circuit with a voltage divider.

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Appendices

Appendix A – Bale Moisture Content Recommendations

Bale Moisture Content Guidelines according to the Albertan Agriculture and Forestry Department for Canada (Alberta Agriculture and Forestry, 2005)

Bale Shape	Height, ft	Width, ft	Length, ft	Volume, ft3	Typical weight, lb	Safe baling moisture, %
Rectangular	1.2	1.5	3.2	5.5	60	18-20*
Rectangular	2.7	3	7	56	900	12-16*
Rectangular	4	4	8	112	1800	12-16*
Round	4	--	4	50	500	15-18*
Round	4	--	5	63	850	15-18*
Round	5	--	4	79	1000	15-18*
Round	5	--	5	98	1300	15
Round	6	--	5	141	1900	15

*The lower moisture range is preferred in areas of low humidity; the higher moisture % for other areas

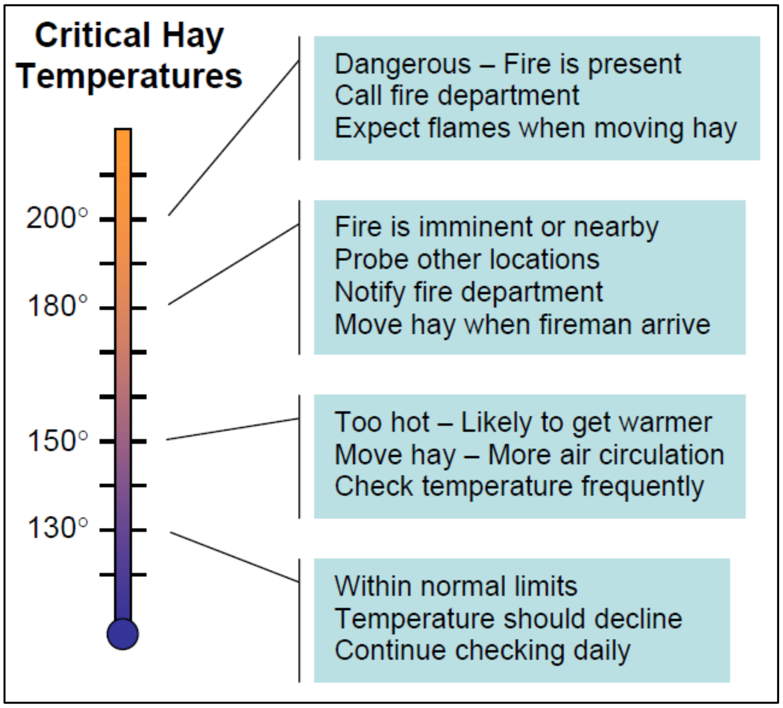
Source: Adapted from an article presented at the Alfalfa Intensive Training Seminar, National Alfalfa Alliance, Salt Lake City, Utah, March 2-4, 2004, Dr. Mike Collins, University of Kentucky

Recommended Moisture Content Levels according to OMAFRA – Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA, 2004)

Small square	15 - 18%
Large round (soft core)	13 - 16%
Large square & large round (hard core)	12 - 15%

Appendix B – Hay Bale Temperature Recommendations

Critical Hay Bale Temperatures with associated risks according to Overhults (2015)



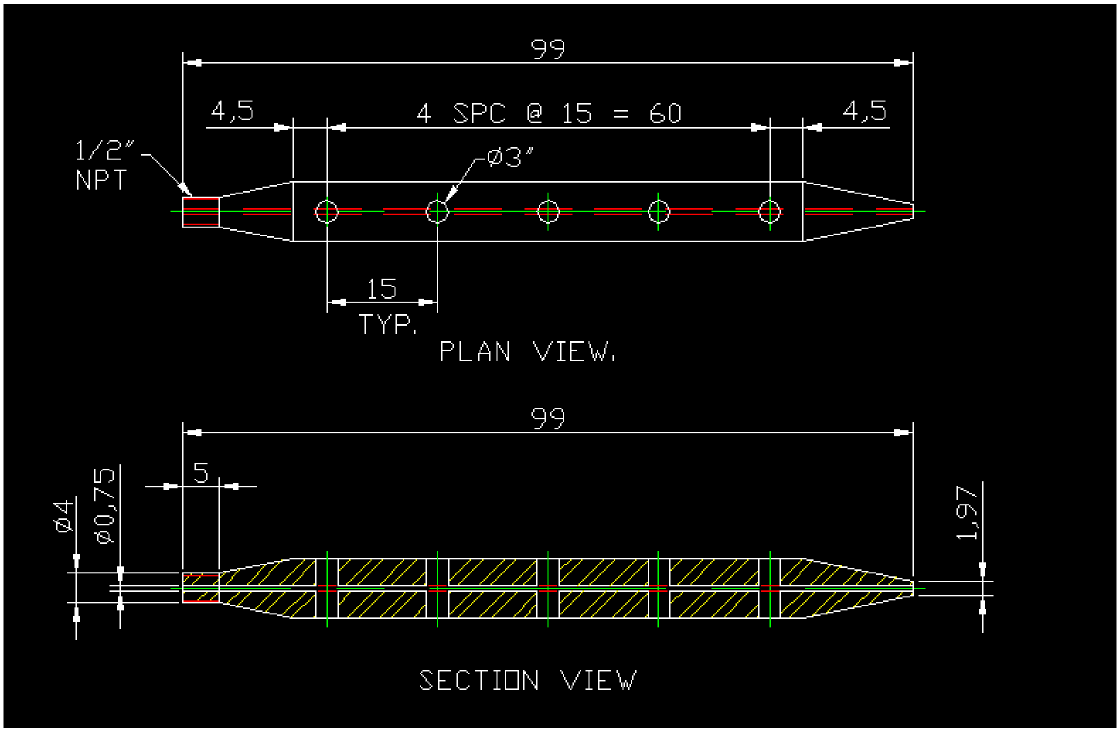
Critical Hay Bale Temperatures with associated risks according to Alberta Agriculture and Forestry (Alberta Agriculture and Forestry, 2005)

Temperature	Characteristics of heating
Up to 120° F (49° C)	Not considered to cause serious forage quality loss.Mold or mustiness may develop at this temperature range. No problem.
121 to 140° F (50 to 60° C)	Heating can cause some of the protein and fibre to become less digestible. Hay will caramelize, smell like tobacco and have a brown colour. Loss in digestibility is greater at these temperatures than at lower temperatures. The level of heat damaged proteins increase. If excess heat can be released from the stack or bale, temperatures do not generally rise above 130 to 140° F (54 to 60° C). Temperature may go up and down, recheck in a few hours. Caution zone.
141 to 160° F (61 to 71° C)	Heating dominated by the respiration of fungi. At 150° F (65.5° C), check the temperature everyday! At temperatures above 160° F chemical reactions dominate the heating process these can escalate very rapidly. If temperatures continue to rise and heat cannot be released from the storage site a dangerous condition can occur. At 160° F check the temperature every four hours.
175° F (80° C)	Check temperature every few hours. Notify the fire department that you have a potential problem and ask them for their recommendations. Danger of fire.
195° F or hotter(90.5° C)	Spontaneous combustion is possible. Do not attempt to move hay without fire department assistance. Moisture loss escalates until the forage is dry enough to burn, material will ignite at 450 to 525° F (232 to 274° C).

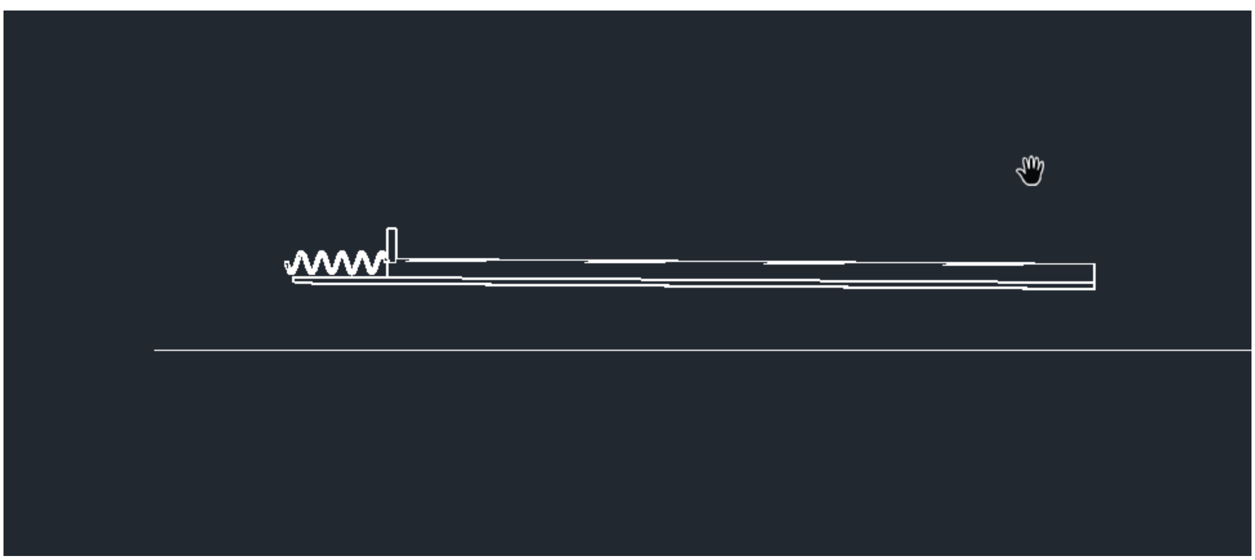
Adapted from "Hot hay! How hot is too hot?" by Dr. Steve Barnhart Iowa State University Department of Agronomy, 1998. "Guarding Against Hay Fires" by Dr. Charles B. Ogburn, Alabama Cooperative Extension System, Auburn University, Department of Agricultural Engineering. 1995.

Appendix C – Technical Drawings

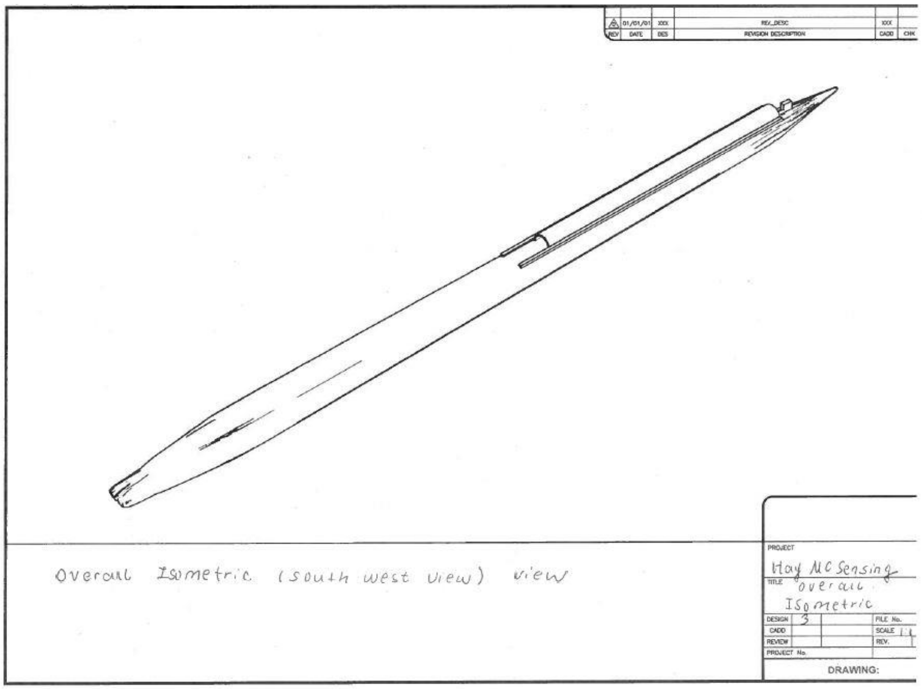
Alternative Design 1 – Inserting the Sensor within the Bale Spear. Drawn by Hubert and Yuan

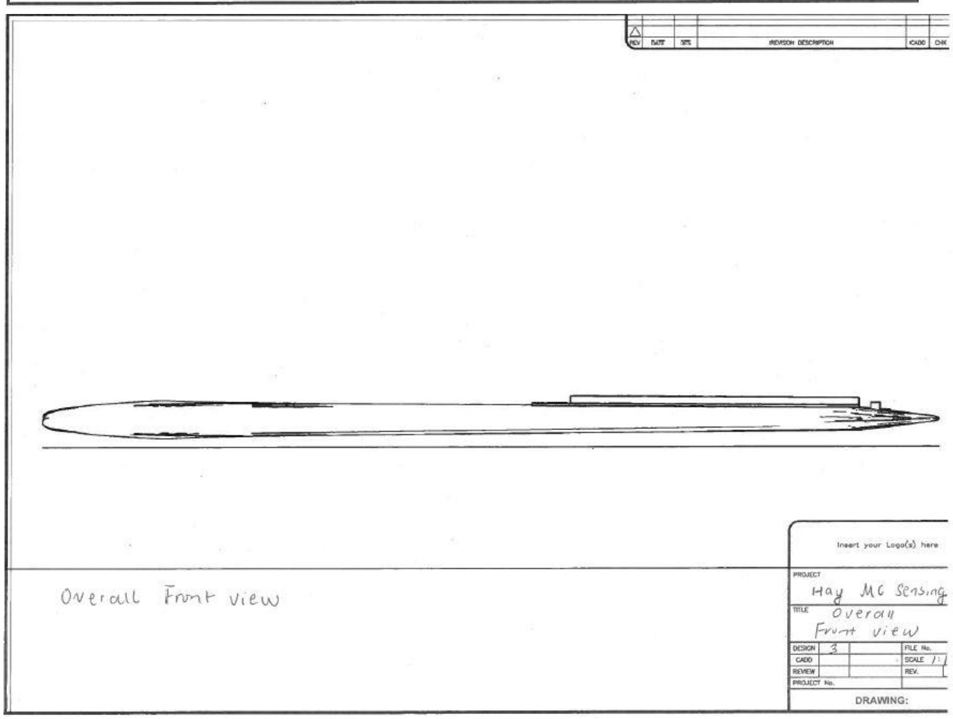


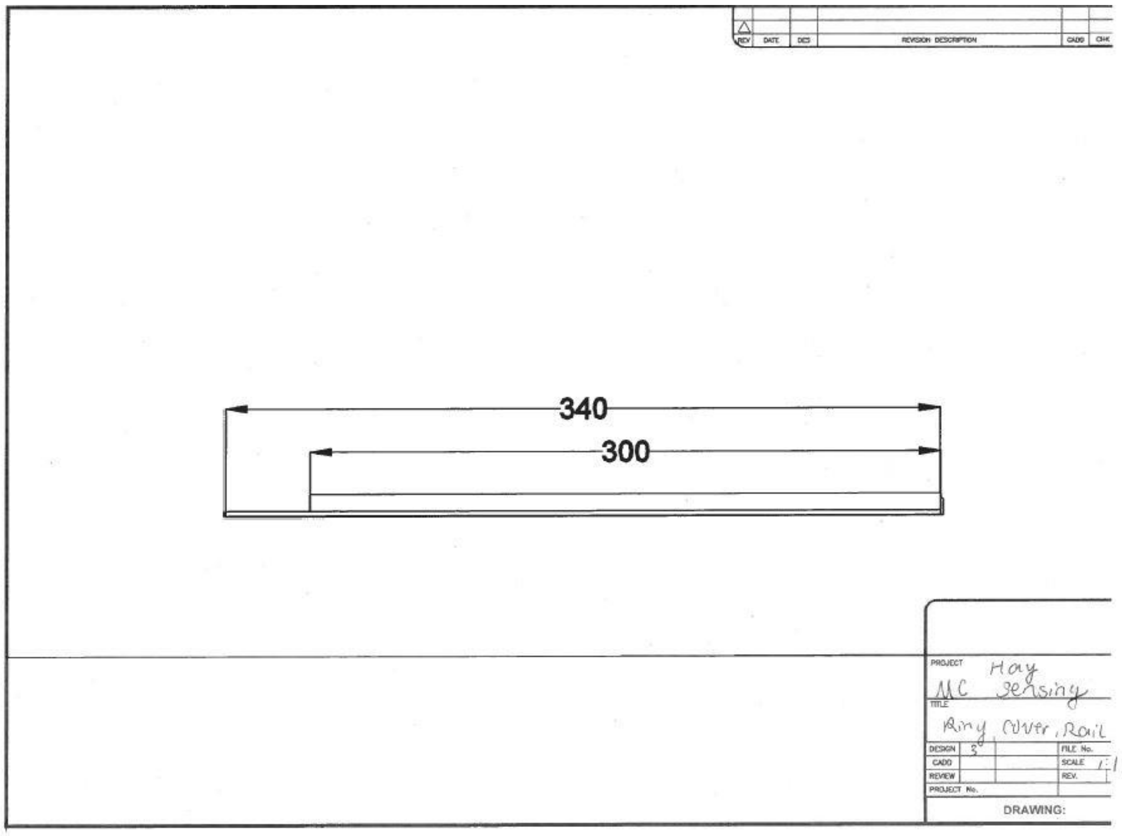
Alternative Design 2 – Moveable Case. Drawn by Hubert and Yuan

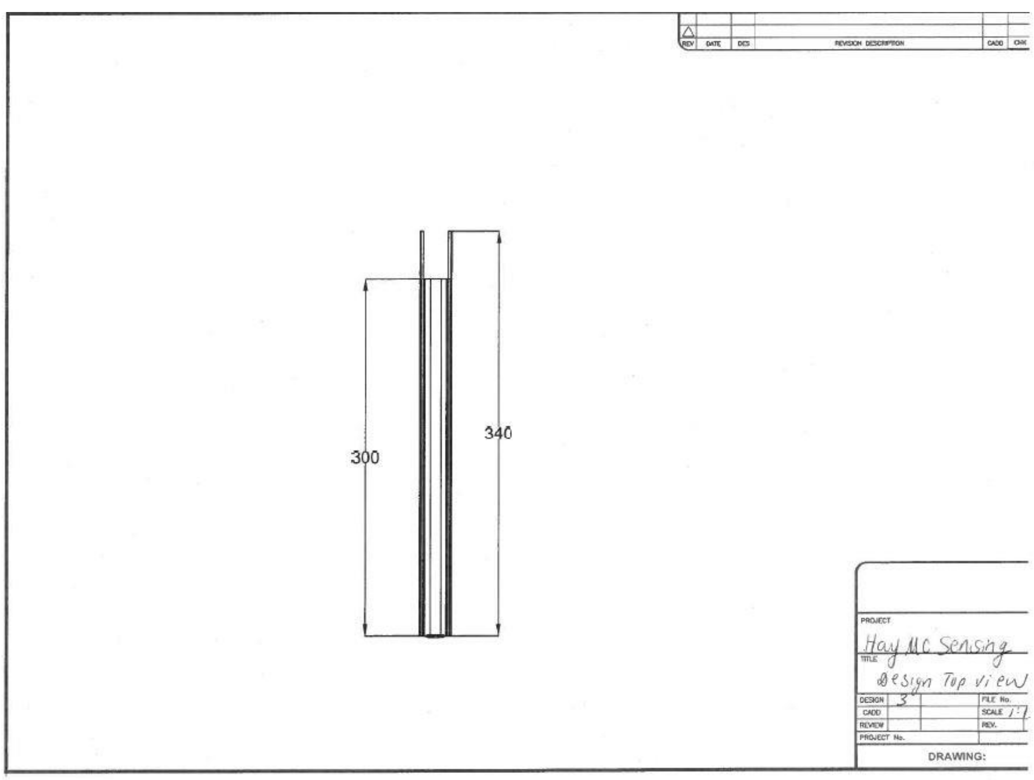


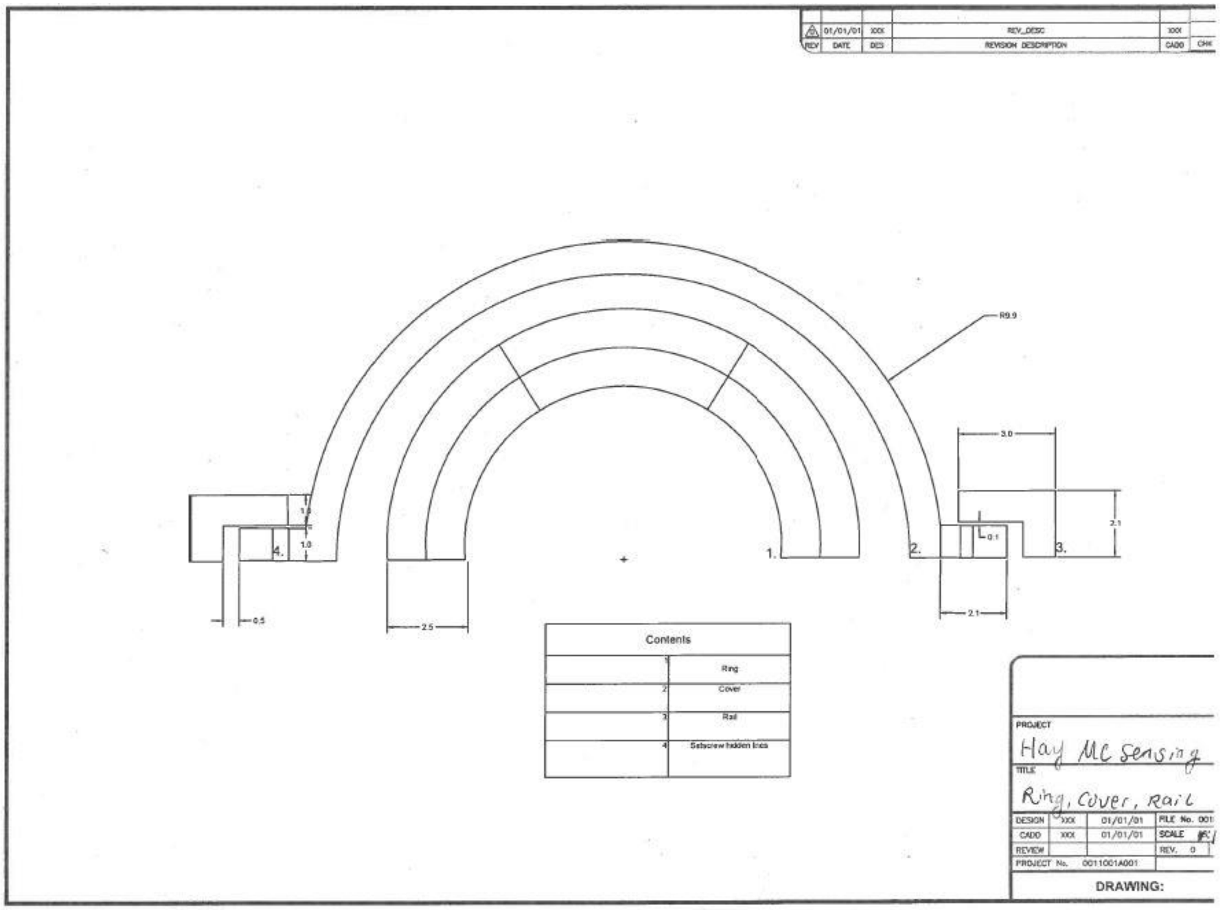
Design 3 – Thin Case with Blade to protect Prod (Multiple Drawings) Drawn by Hubert and Yuan:






REV
DATE
DES
REVISION DESCRIPTION
CADD
CHK
340
300
PROJECT
Hay MC Sensing
TITLE
Ring, Cover, Rail
DESIGN
CADD
REVIEW
PROJECT No.
FILE No.
SCALE 1:1
REV.
DRAWING:


REV
DATE
DES
REVISION DESCRIPTION
CADD
CHK
300
340
PROJECT
Hay MC Sensing
TITLE
Design Top view
DESIGN
CADD
REVIEW
PROJECT No.
FILE No.
SCALE 1:1
REV.
DRAWING:



Details of Alternative Design 2 components

Steel Plate			
Assembled Depth (in inches)	0.063	Assembled Height (in inches)	12
Assembled Weight (in lbs)	1.25	Assembled Width (in inches)	24
Item Depth	0.063	Item Height	12.0
Item Weight	1.25	Item Width	24.0

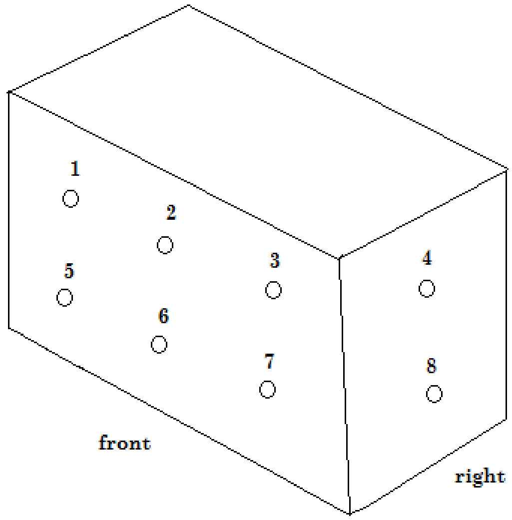
Appendix D – Moisture Content Oven Drying Data

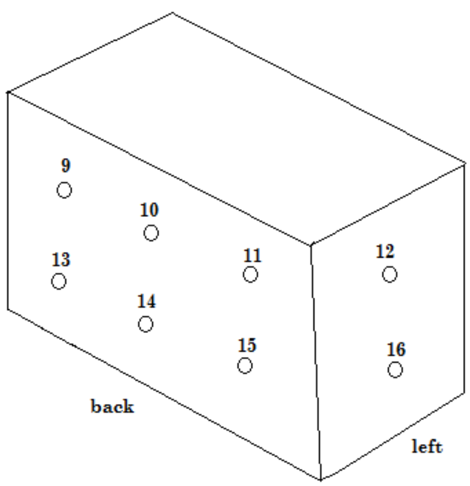
Hay Bale sample locations for MC measurement

1-3 on top, 5-7 on the bottom (where numbers continue horizontally to right side of the bale). This image was taken on October 25, 2018, but the same configuration of sample locations was used for subsequent sampling and MC measurement.

Side view of marked hay bale sample locations

Schematic of marked hay bale





Appendix E – Moisture Content Calculations

Wet basis moisture content was measured using the following formula:

$$MC\%\ (wb) = \frac{wet\ weight - dry\ weight}{wet\ weight} * 100$$

Wet and dry weight measurements with associated moisture content readings and calculations for October 25, 2018 hay sampling

Measuren	25-Oct								
	Day average temperature ©	6.1							
	Dew Point Temperature ©	5.2							
	Relative Humidity (%)	93							
	Sea Level Pressure (Kpa)	100.5							
Bale A	Location	wet weight	dry weight	MC wet basis (%	MC dry basis (%)	Delmhorst Reading	Temperature Measured		
	1	12.22	6.35	48.03600655	0.924409449	47.5	10.8		
	2	16.66	8.12	51.2605042	1.051724138	48	10.5		
	3	12.42	6.57	47.10144928	0.890410959	48	10.8		
	4	24.5	13.53	44.7755102	0.810790835	46.5	13.5	12.2	4AND 8
	5	20.3	8.65	57.38916256	1.346820809	55.5	10	10.26667	1,2,3,5,6,7
	6	20.86	7.55	63.8063279	1.762913907	62	8.7	11.11667	9to14
	7	14.09	7.35	47.83534422	0.917006803	45.5	10.8	10.35	
	8	18.82	9.61	48.93730074	0.958376691	46.5	10.9		
	9	18.65	9.65	48.25737265	0.932642487	55	10.9		
	10	24.04	10.3	57.1547421	1.333980583	50	13.7		
	11	25.57	13.01	49.12006257	0.965411222	51	10.9		
	12	26.33	12.16	53.81693885	1.165296053	51	10.2		
	13	24.29	11.24	53.72581309	1.161032028	51	10.2		
	14	20.57	10.91	46.96159456	0.885426214	47.5	10.8		
	15	31.46	14.47	54.00508582	1.174153421	53.5	10.2		
	16	20.45	9.64	52.8606357	1.121369295	50	10.5		
			Mean 1	51.56524069		49.53125	10.8	Error %	0.039445
			Variance	24.65871939		Variance	1.467833333		
			Standard I	4.965754665		Standard Deviation	1.211541718		
					Slope	0.682672554			
Date:	29-Nov				Intercept	15.32907543			

Wet and dry weight measurements with associated moisture content readings and calculations for November 29, 2018 hay sampling

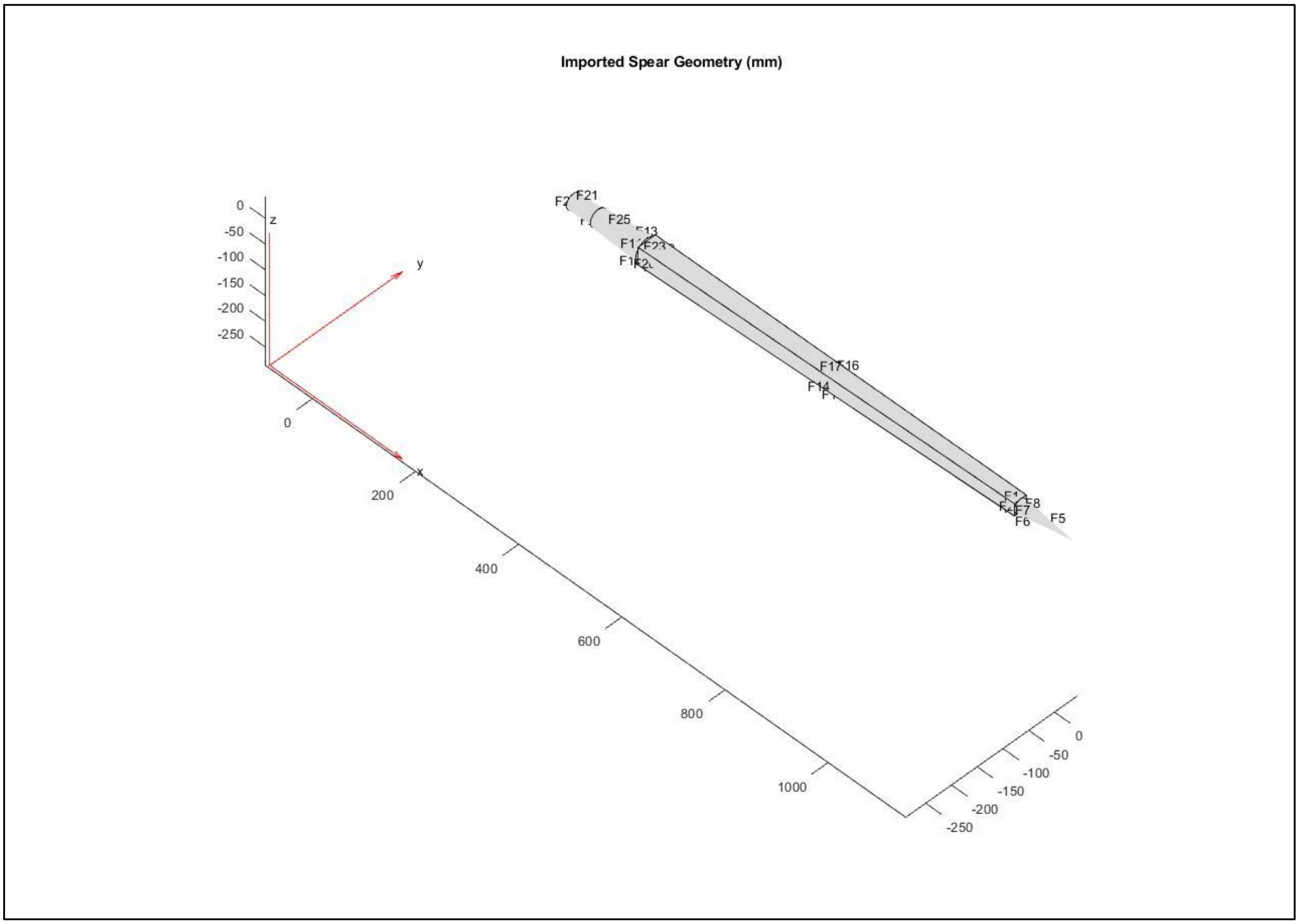
Date:	29-Nov				Intercept	15.32907543			
	Day average temperature ©			1.4					
	Dew Point Temperature ©			-1.0					
	Relative Humidity (%)			84					
	Sea Level Pressure (Kpa)			101.2					
Bale 2	Location	wet weight	dry weight	MC wet basis (%	MC dry basis (%)	Delmhorst Reading	Temperature Measured	Predicted Delmhorst F	
	1	13.67	4.83	64.66715435	1.830227743	66.3	5.5	72.3	
	2	15.43	10.52	31.82112767	0.466730038	33.7	8.7	24.2	
	3	10.9	7.63	30	0.428571429	29.6	8.7	21.5	
	4	17.5	12.78	26.97142857	0.369327074	26.8	8.9	17.1	
	5	19.22	11.37	40.84287201	0.690413369	41.8	7	37.4	
	6	20.13	10.47	47.9880775	0.922636103	45.5	6.7	47.8	
	7	11.39	5.55	51.27304653	1.052252252	52.2	6.5	52.7	
	8	20.49	13.81	32.60126891	0.483707458	30	8.7	25.3	
	9	20.18	10.77	46.63032706	0.873723305	44.5	7	45.9	
	10	13.07	10.69	18.2096404	0.222637979	15.3	10.3	4.2	
	11	28.95	15.55	46.28670121	0.861736334	46.9	7	45.3	
	12	19.56	15.11	22.75051125	0.294506949	20.9	9.9	10.9	
	13	17.33	10.49	39.46912868	0.652049571	33.5	8.1	35.4	
	14	28.65	15.31	46.56195462	0.871325931	45.9	7	45.8	
	15	30.54	17.99	41.09364768	0.697609783	40.3	7.1	37.7	
	16	23.47	10.27	56.24201108	1.285296981	54.4	6.4	59.9	
			Mean	40.21305609		39.225	7.7		
			Variance	156.9940669		Variance	1.832291667	Error %	0.024571
			Standard D	12.52972733		Standard Deviation	1.353621685		

Appendix F - Stress Analysis MATLAB Codes and Results

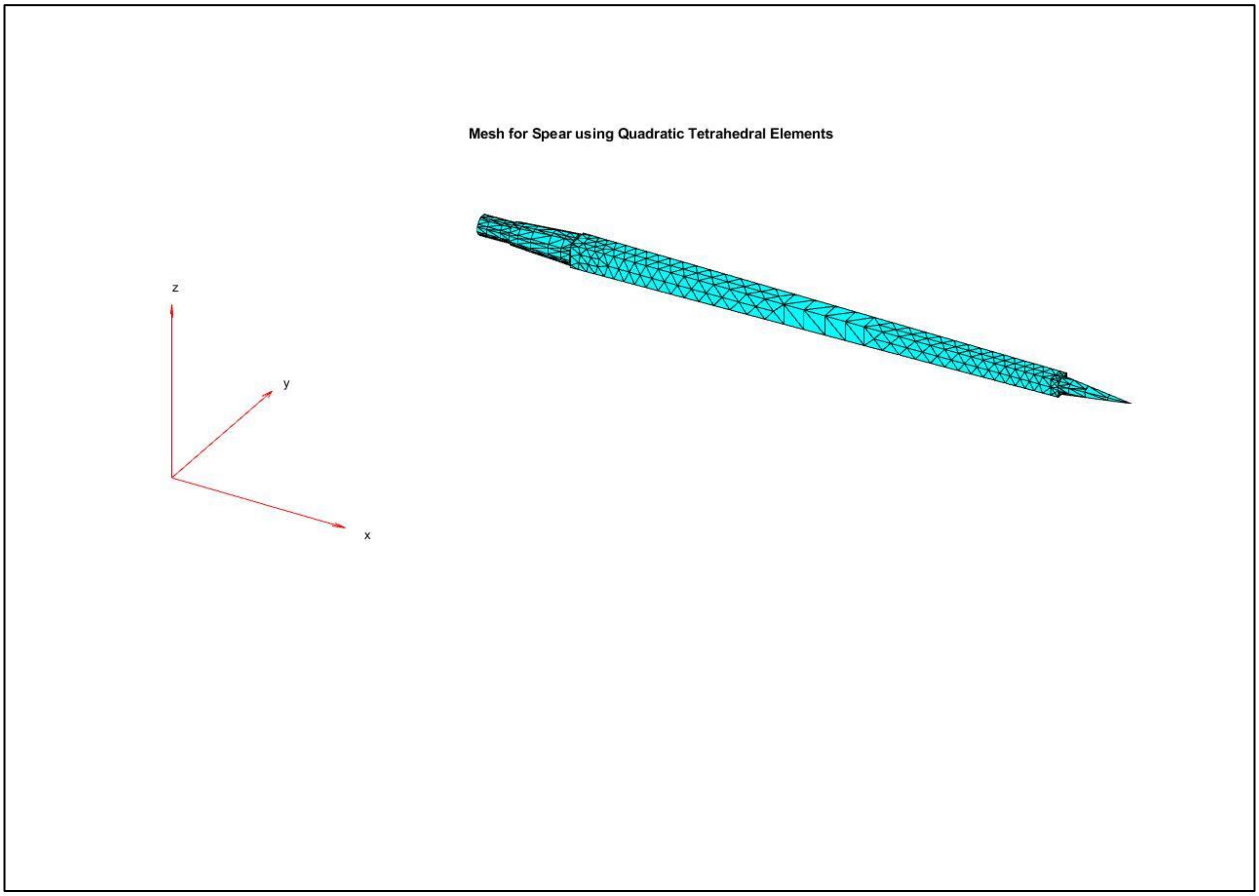
```
%% The program performs a simplified Version of Stress and Strength Analysis
on Spear
% The first step in solving a linear elasticity problem is to create a
% Matlab has pde models that can solve the Navier's deflection equation.
% A predrawn geometry (in stl) is required
% However, this model cannot load files with geometry with more than two
% facets that share edges. Due to this limitation, the model is only done on
% the spear alone.
model = createpde('structural','static-solid');
%% Import the Geometry
% Import the stl file of spear drawn in AutoCad suing function
% "importGeometry"
importGeometry(model,'Final_Design1.stl');
%%
% Plot the geometry and label faces.Faces need to be numbered in order to
choose to apply boundary conditions.
figure
pdegplot(model,'FaceLabels','on')
view(45,45);
%% Enter material properties.The material of spear is assumed to be steel.
Young's modulus and Poisson's ratio for this steel. E= 200GPa
% Poissoon ratio = 0.3
structuralProperties(model,'Cell',1,'YoungsModulus',200e9, ...
                                    'PoissonsRatio',0.3);
%% Define the Boundary Conditions
% The problem has two boundary conditions:
% 1) Face 22 is fixed at the (i.e. fixed on the tractor )
% 2) Face 17 where will take the load of the bale.
structuralBC(model,'Face',22,'Constraint','fixed');
%% Apply a distributed load in the negative $z$-direction to the top face of
% spear ( Face 17)
distributedLoad = 500; % Applied load in Pascals, this is estimated based on
the guideline of bale weights in
%Appendix A
structuralBoundaryLoad (model,'Face',17,'SurfaceTraction',[0,0,-
distributedLoad]);% This step applied the load in the negative z-direction

%% Create a Mesh
% Create a mesh that uses 10-node tetrahedral elements with quadratic
% interpolation functions. This element type is significantly more accurate
% than the linear interpolation (four-node) elements, particularly in
% elasticity analyses that involve bending.
generateMesh(model)% Ideally, mesh size should be user defined but it takes
too many trial an errors.
%So in this project, the meshsize is generated using default
figure
pdeplot3D(model)% Plot meshed model.
title('Mesh for Spear using Quadratic Tetrahedral Elements');%Model default
analysis elements is the quadratic tetrahedral elements
%% Calculate the Solution
result = solve(model);% Navier partial differential equations
% for the displacement field as a function of body forces and structural
properties of the material.
```

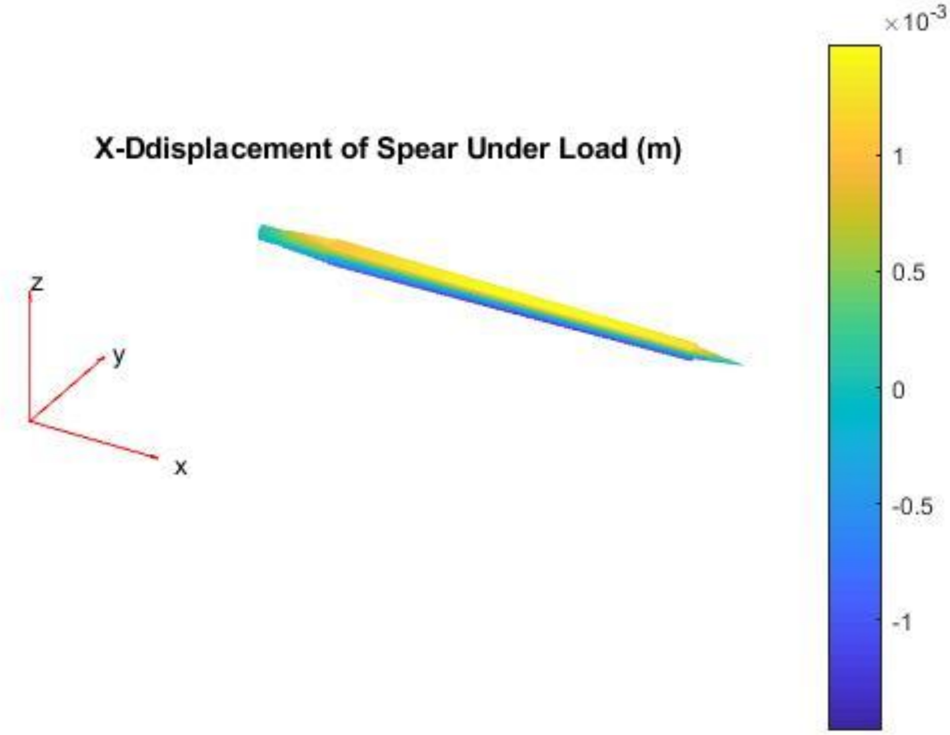
```
minUz = min(result.Displacement.uz);
fprintf('Maximal deflection in the z-direction is %g meters.', minUz)%This
step finds and
%displays the max deflection of spear under load
%% Plot Displacement in 3 directions
figure
pdeplot3D(model,'ColorMapData',result.Displacement.ux)% Plot deflection of
spear in x direction.
title('X-Ddisplacement of Spear Under Load (m)')
colormap('parula')

figure
pdeplot3D(model,'ColorMapData',result.Displacement.uy)% Plot deflection of
spear in y direction
title('Y-Displacement Spear Under Load (m)')
colormap('parula')
%There should not be much deflection in both x and y directions as load is
%applied mostly in the negative z direction.

figure
pdeplot3D(model,'ColorMapData',result.Displacement.uz) % Plot deflection of
spear in z direction
title('Z-Displacement Spear Under Load (m)')
colormap('parula')
%% Plot von Mises Stress
% Plot values of the von Mises Stress at nodal locations.
figure
pdeplot3D(model,'ColorMapData',result.VonMisesStress)
title('Von Mises Stress on Spear (Pa)')
colormap('jet')
% End of Matlab Program
```

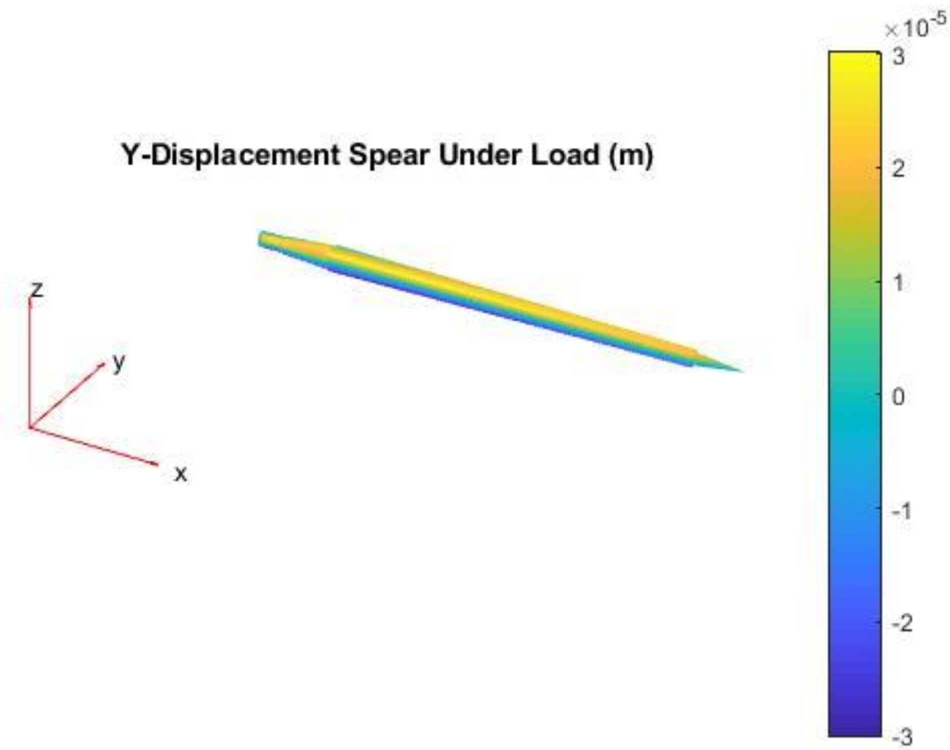
MATLAB Schematic of imported AutoCAD spear geometry with face numbers



MATLAB Schematic of spear with quadratic tetrahedral elements




×10^-3
X-Ddisplacement of Spear Under Load (m)
1
0.5
0
-0.5
-1
z
y
x


×10^-5
3
Y-Displacement Spear Under Load (m)
2
1
0
-1
-2
-3
z
y
x

Appendix G: Temperature Analysis MATLAB Code

```
% This Programs simulate a simplified version of solving for Bale's
temperature profile under natural convection
% and conduction between particles in the bale. Essentially solving for the
heat transfer pde:
% ?c?T?t?????(k?T)=Q
% Matlab has built-in simple models to solve simple heat transfer problems.
% A predrawn geometry of the bale (in stl ) is required
% The measurements on the bale are taken on Oct.25,2018
%% Creates a thermal model in Matlab
thermalmodel = createpde('thermal');
importGeometry(thermalmodel,'Square_Bale_Model.stl'); %Import bale stl
pdegplot(thermalmodel,'FaceLabels','on','FaceAlpha',0.5)% Plot thermal model
with face labels on because
% faces need to be numbered when applying for boundary conditions
title('Square Hay Bale, mm')
axis equal
%% Specify thermal properties
%such as the thermal conductivity of hay and initial face boundary
%conditions.
thermalProperties(thermalmodel,'ThermalConductivity',0.6);%Thermal
conductivity of alfalfa hay is found
% ( in literature ) to be around 0.6 W
% And the initial boundary temperature of each face is the average of the
% points measured on the face.
thermalBC(thermalmodel,'Face',1,'Temperature',10.4);
thermalBC(thermalmodel,'Face',3,'Temperature',10.4);
thermalBC(thermalmodel,'Face',2,'Temperature',10.3);
thermalBC(thermalmodel,'Face',4,'Temperature',10.4);% Face 4 was not measured
because it is placed on the
%ground it is given an arbitary temperature lower than the rest assumming the
ground is at lower
%temperature
thermalBC(thermalmodel,'Face',5,'Temperature',11.1);
thermalBC(thermalmodel,'Face',6,'Temperature',12.2);

%% Specify ambient air temperature on all faces
% The temperature of ambient air on Oct.25,2018 is 6 degree C.
% Assume all faces except face 4 is exposed in ambient air.
thermalBC(thermalmodel,'Face',1,'AmbientTemperature',6);
thermalBC(thermalmodel,'Face',2,'AmbientTemperature',6);
thermalBC(thermalmodel,'Face',3,'AmbientTemperature',6);

thermalBC(thermalmodel,'Face',5,'AmbientTemperature',6);
thermalBC(thermalmodel,'Face',6,'AmbientTemperature',6);
%% Create a mesh of bale using default size
generateMesh(thermalmodel);
thermalresults = solve(thermalmodel);
%% Plot the result of solved temperature distribution within the bale
figure;
pdeplot3D(thermalmodel,'ColorMapData',thermalresults.Temperature)
%End of Temperature Distribution Analysis in MatLab.
```

Appendix G SAS Codes for Statistical Analysis on Hay Bale Moisture Content and Temperature

For Moisture

```
data Moisture ;
      input Moisture  @@;
      datalines;
48.03600655
51.2605042
47.10144928
44.7755102
57.38916256
63.8063279
47.83534422
48.93730074
48.25737265
57.1547421
49.12006257
53.81693885
53.72581309
46.96159456
54.00508582
52.8606357

  ;
   run
    ods graphics on;

   proc ttest h0=51 plots(showh0) sides=u alpha=0.05;
      var Moisture;
   run;

   ods graphics off;
```

For Temperature

```
data Temperature ;
      input Temperature  @@;
      datalines;
10.8
10.5
10.8
13.5
10
8.7
10.8
10.9
10.9
13.7
10.9
10.2
10.2
10.8
10.2
10.5
```

```
;
 run
  ods graphics on;

 proc ttest h0=10.8 plots(showh0) sides=u alpha=0.05;
    var Temperature;
 run;

 ods graphics off;
```

Appendix H – Data Transmission Information and Arduino Code

MC and MTX Voltage Output Chart Provided by Delmhorst Instrument Co.

Hay MC (%)	MTX - Voltage Output (V)
6	10
7	9.5
8	9
9	8.7
10	8.3
12	7.7
14	7.2
16	6.7
18	6.4
20	6.1
22	5.8
24	5.5
26	5.1
28	4.7
30	4.4
32	4.1
34	3.9
36	3.5
38	3.2
40	2.9

45	2
50	1.2
55	0.6
60	0

Note: This chart was modified with the use of a voltage divider. The trend remains the same between the two parameters, but voltage is reduced depending on the orientation and value of the resistors in the Arduino breadboard. For example, using two resistors of 2 Ω in series:

$$V_{out} = V_{in}\,\frac{R_2}{R_1+R_2} \qquad \text{Equation (2)}$$

$$V_{out} = (10V)(0.5) = 5\,V$$

$$Power\ Dissipated = \frac{{V_{in}}^2}{R_1+R_2} \qquad \text{Equation (3)}$$

$$Power\ dissipated = \frac{100}{4} = 25\,W$$

$$Max\ Power\ Dissipated = \frac{T_{dmax}-T_A}{\theta_{DA}} \qquad \text{Equation (4)}$$

$$Max\ Power\ Dissipated = \frac{85-7}{3}$$

Max Power Dissipated = 26 W, so this circuit is feasible

<u>Adjusted MC and MTX Voltage Output Chart</u>

Hay MC (%)	Adjusted MTX Voltage Output (V)
6	5
7	4.75
8	4.5
9	4.35
10	4.15
12	3.85
14	3.6
16	3.35
18	3.2

20	3.05
22	2.9
24	2.75
26	2.55
28	2.35
30	2.2
32	2.05
34	1.95
36	1.75
38	1.6
40	1.45
45	1
50	0.6
55	0.3
60	0

Wifi and Bluetooth Arduino Code Used made with Arduino Editor (Hubert & Yuan, 2018)

Arduino Automated Soil Moisture Code Sample (SparkFun, 2015)

```
/*  Soil Mositure Basic Example
    This sketch was written by SparkFun Electronics
    Joel Bartlett
    August 31, 2015

    Basic skecth to print out soil moisture values to the Serial Monitor

    Released under the MIT License(http://opensource.org/licenses/MIT)
*/

int val = 0; //value for storing moisture value
int soilPin = A0;//Declare a variable for the soil moisture sensor
int soilPower = 7;//Variable for Soil moisture Power

//Rather than powering the sensor through the 3.3V or 5V pins,
//we'll use a digital pin to power the sensor. This will
//prevent corrosion of the sensor as it sits in the soil.

void setup()
{
  Serial.begin(9600);   // open serial over USB

  pinMode(soilPower, OUTPUT);//Set D7 as an OUTPUT
```

```
  digitalWrite(soilPower, LOW);//Set to LOW so no power is flowing through the
sensor
}

void loop()
{
Serial.print("Soil Moisture = ");
//get soil moisture value from the function below and print it
Serial.println(readSoil());

//This 1 second timefrme is used so you can test the sensor and see it change in
real-time.
//For in-plant applications, you will want to take readings much less frequently.
delay(1000);//take a reading every second
}
//This is a function used to get the soil moisture content
int readSoil()
{

    digitalWrite(soilPower, HIGH);//turn D7 "On"
    delay(10);//wait 10 milliseconds
    val = analogRead(soilPin);//Read the SIG value form sensor
    digitalWrite(soilPower, LOW);//turn D7 "Off"
    return val;//send current moisture value
}
```

<u>Bluetooth coding for arduino, (Rawashdeh, 2013)</u>

```
/ This program shown how to control arduino from PC Via Bluetooth
// Connect ...
// arduino>>bluetooth
// D11   >>>  Rx
// D10   >>>  Tx
//Written By Mohannad Rawashdeh
//for http://www.genotronex.com/

// you will need arduino 1.0.1 or higher to run this sketch

#include <SoftwareSerial.h>// import the serial library

SoftwareSerial Genotronex(10, 11); // RX, TX
int ledpin=13; // led on D13 will show blink on / off
int BluetoothData; // the data given from Computer

void setup() {
  // put your setup code here, to run once:
  Genotronex.begin(9600);
  Genotronex.println("Bluetooth On please press 1 or 0 blink LED ..");
  pinMode(ledpin,OUTPUT);
}
```

```
void loop() {
  // put your main code here, to run repeatedly:
   if (Genotronex.available()){
BluetoothData=Genotronex.read();
   if(BluetoothData=='1'){   // if number 1 pressed ....
   digitalWrite(ledpin,1);
   Genotronex.println("LED  On D13 ON ! ");
   }
  if (BluetoothData=='0'){// if number 0 pressed ....
  digitalWrite(ledpin,0);
   Genotronex.println("LED  On D13 Off ! ");
  }
}
delay(100);// prepare for next data ...
}
```

Bluetooth coding for arduino. (Mathavan, 2015)

```
#include "DHT.h"
#define DHTPIN 2
#define DHTTYPE DHT11
DHT dht(DHTPIN, DHTTYPE);
void setup() {
  Serial.begin(9600);
  dht.begin();}

void loop()
{  char c;
if(Serial.available())
  {
   c = Serial.read();
   if(c=='t')
   readSensor();
  }}
void readSensor() {
  float h = dht.readHumidity();
  float t = dht.readTemperature();
  if (isnan(h) || isnan(t)) {
    Serial.println("Failed to read from DHT sensor!");
    return;
  }
  float hic = dht.computeHeatIndex(t, h, false);
  Serial.print("Humidity: ");
  Serial.print(h);
  Serial.print(" %\t");
  Serial.print("Temperature: ");
  Serial.print(t);
  Serial.print(" *C ");
  Serial.print("Heat index: ");
  Serial.print(hic);
  Serial.print(" *C ");
}
```

```
BluetoothAdapter bluetoothAdapter=BluetoothAdapter.getDefaultAdapter();

      if (bluetoothAdapter == null) {

            Toast.makeText(getApplicationContext(),"Device doesnt Support
Bluetooth",Toast.LENGTH_SHORT).show();

      }
```