Design of a Low Cost End Implement Position Sensing System

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Abstract— **Caterpillar Inc. approached Bradley University seeking a cost effective, robust, and reliable solution to replace their current linkage sensors on D8 tractors, which are failing at an unacceptably high rate. These sensors determine the position of the D8 tractor's end implement. The end implement position provides operators with automated controls and increases the efficiency of the D8. A team, consisting of Business, Electrical Engineering, and Mechanical Engineering students, was constructed to meet Caterpillar's request. The team needed to develop a new design that maintains the accuracy and robustness of Caterpillar's current system while decreasing cost and repair downtime. After preliminary research and brainstorming, there were two designs that best fit Caterpillar's requirements: a laser distance sensing system (LDS) and a wheel and encoder system. The LDS uses a rotating laser to determine direct blade location via tracking algorithms. The second system uses three wheel and encoder systems to determine the location of the lift cylinder that controls the blade, which is related to the end implement position. Methods of data collection and algorithms for analysis for both systems were implemented using Texas Instrument's Tiva-C microcontroller. Preliminary housing designs for the wheel and encoder system were produced and prototyped. In order to quantify profitability of the new designs, the team performed a comprehensive return on investment analysis, a net present value analysis, and an internal rate of return sensitivity analysis. In addition, the team created a marketing plan geared toward Caterpillar.**

I. INTRODUCTION

AUTONOMY is the new trend for companies worldwide. Autonomous systems are made up of several sensors that relay information back to a central hub for processing. Autonomous systems are implemented in a variety of areas; which includes manufacturing, shipping, and drive systems. Caterpillar Inc. (CAT) has long been the economic leader in the heavy machinery industry. To maintain this edge, Caterpillar tries to stay ahead of technological advancements in this industry. Autonomy is one of those technologies. Although a future where Caterpillar tractors are driving themselves may be far off, there are features that Caterpillar can add to keep its tractors ahead of the competition. One of these features is knowing the precise position of the end implement on a machine. The end implement is the part of the tractor that is performing the work. Knowing the end implement position is beneficial because it can lead to increased accuracy and a better customer experience.

Caterpillar approached Bradley University to form a team to design a system that can address this problem. The team for this project included two electrical engineering students, three mechanical engineering students, and three business students. The project was focused on developing a new end implement position sensing system for Caterpillar's D8 tractor. The team also analyzed the designs using business criterion. The new system must maintain the same accuracy of the current system while decreasing cost and repair downtimes.

The team worked together to quantify the following information. First was a design process in which possible system solutions were generated and analyzed. Second was for the testing of the design concepts. And lastly was the business analysis. All of this information was combined together to generate a final recommendation for Caterpillar.

II. DESIGN PROCESS

The design process included steps and decisions that would set up the rest of the project. To ensure that any decisions made during the design process were well-educated, the process was subdivided into a research stage and a brainstorming stage.

A. Research Stage

During the research stage, the entire team worked together to build a strong base knowledge of applicable material. The information from the research in this stage would dictate the brainstorming stage.

1) Existing CAT Sensor

The first part of the research stage required the team to understand the specifications and problems with the existing CAT sensor. The sensor that CAT is using currently is a magnetostrictive position sensor, seen in Figure 1, which outputs a PWM signal with a varying duty cycle. This sensor consists of a metal rod and a magnet, which slides up and down the metal rod. As the magnet moves up and down the rod of the sensor the duty cycle of the PWM changes.

Fig. 1: Caterpillar's existing sensor

The team was able to obtain a sensor and tested the system to have a better understanding of how it functions. Figure 2 demonstrates the output, highlighting the simplicity of the PWM output.

Fig. 2: Output of Caterpillar’s current system

Although this sensor maintains a high accuracy, it also has a higher than acceptable failure rate. This high failure rate leads to frequent repairs that are long and expensive. Currently, there is no known reason for failure. However, based on recommendations from Caterpillar, the team did not focus on this area.

2) *New Sensor Technologies*

This part of the research phase consisted of a formidable amount of research into sensor technology. All kinds of technology were investigated. These technologies would then be adapted in the brainstorming stage into application specific designs. The team identified several sensor technologies. Each technology was defined at a high level and the pros and cons of each design were also identified. This large amount of research can be found in Appendix A.

3) *Patents*

Since the end goal of the project is to have the designed system operating on a Caterpillar tractor, it is crucial that any design that the team develops does not conflict with pre-existing designs, especially those with viable US Patents. There were two discovered patents dealing with linkage position sensing systems. The first patent was filed by Caterpillar for a radio frequency based system inside the cavity of the hydraulic system. This system was accurate for the application but was never fully implemented because of constant short circuiting and oil cavitation. The second patent is a design protected by Caterpillar’s competitor Komatsu. The patent is for another linkage position sensing system: a wheel and encoder system.

4) *Consultation Conference*

In 1997 Caterpillar held a large consultation conference to develop an end implement location system design. The team was able to access transcripts from this conference. These transcripts gave the team insight on previous designs as well as gave the team detailed information to help the team generate ranking criteria for developed designs.

B. *Selection Stage*

The selection stage occurred concurrently with the research stage. During the selection stage the team used the research to develop specific application designs and tests. This stage was completed in three steps, an initial brainstorming session, a general elimination stage, and selection stage.

1) *Initial Brainstorming Session*

The initial brainstorming session dealt directly with the sensor technologies researched during the research stage. The team identified which technologies could be used and how these technologies could be used. The initial brainstorming session yielded 35 possible designs. These designs fit under one of three categories: blade to vehicle, blade to external reference, and linkage positioning. The full list of designs are in Appendix B.

2) *General Idea Elimination*

The next step was to eliminate some of the ideas. The team eliminated ideas based on application criteria that was made by combining the elimination criteria used in the consultation conference with specific criteria given to the team by Caterpillar. If a design did not meet one of those criteria it was removed as a possibility. This design elimination and the elimination criteria are in Appendix C. After passing the 35 designs through these criteria six designs remained.

Design Concepts	Designs
Laser Distance Sensor (LDS)	Sleeve
Push Arm	Wheel and Encoder
Triangulation	Magnetometer

3) *Final Selection*

During the selection stage the team took the remaining six designs and analyzed these designs in more detail. The more detailed analysis included cost analysis, identifying specific sensor models and parts, mathematical computations, and anything else the team deemed necessary. After the end of this stage there were two designs that best fit Caterpillar’s requirements: laser distance sensing (LDS) and wheel and encoder.

III. DESIGN CONCEPTS

Using the results from the selection stage, the team decided to move forward with two designs. For each of the two designs, the LDS and wheel and encoder systems, the team developed specific application designs, developed and refined the designs, and performed more intensive testing.

A. *Laser Distance Sensing (LDS)*

In this design, a direct blade measurement system consisting of two LDS units is mounted onto the side of the tractor. The LDS unit contains a rotational laser that takes distance measurement over 360º. For this application the readings are limited to a span of ±45º.

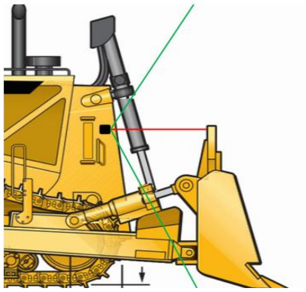


Fig. 3: LDS set up on the tractor

The LDS units measure distances in the vertical plane. These measurements are then analyzed using several algorithms to determine the exact location of the blade relative to the ground. In this project, a NEATO Robotics LDS system from their XV-11 design unit was used for testing.

1) *LDS Specs*

The LDS operates under the following conditions:

- Operating voltage: 5 V
- Output voltage: 3.3 V

During one full revolution the LDS system outputs 90 serial packets. Each packet is 22 bytes. The subdivision of these packets is as follows. The packet starts with 0xFA to indicate the beginning of the packet. The second byte indicates the packet number. The next two bytes are the speed of the motor driving the LDS. The next 16 bytes are made up of four distance and surface quality readings. The last two bytes of the packet make up a check sum. This check sum can be used to determine the validity of a packet.

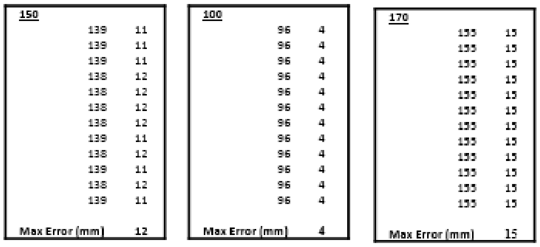
2) *Initial LDS Tests*

Before the team performed advanced analysis, the team performed initial tests with the LDS. These tests were performed to determine the validity of the LDS design and to provide a benchmark for future improvements to the system. These tests were performed using the Neato LDS unit that was programmed to compete for Bradley University in a Robo-Boat competition. These tests were designed to confirm the validity of the design, to see if it was even a reasonable design to move forward with.

The first test was to determine the accuracy of the measurements. In this test, distance measurements were taken from the LDS at the 1º mark every 5 cm and compared to the expected distance which were measured using an ordinary tape measure. This test found that this LDS unit had an acceptable error at a range from 45 to 75 cm. The collected data can be found in Appendix D.

Fig. 4: Results from initial LDS distance tests

Outside of that range the error was much higher than the team would want. The second test determined if the readings were precise. The LDS was outputting inaccurate readings but this test was to determine if the readings were consistently inaccurate. If the readings were consistent then it was possible to compensate for that error. For this test the team took a dozen measurements at three distances 150 centimeters, 100 centimeter, and 170 centimeters.



150		
	139	11
	139	11
	139	11
	138	12
	138	12
	138	12
	138	12
	139	11
	138	12
	139	11
	138	12
	139	11
Max Error (mm)		12

100		
	96	4
	96	4
	96	4
	96	4
	96	4
	96	4
	96	4
	96	4
	96	4
	96	4
	96	4
	96	4
Max Error (mm)		4

170		
	155	15
	155	15
	155	15
	155	15
	155	15
	155	15
	155	15
	155	15
	155	15
	155	15
	155	15
	155	15
Max Error (mm)		15

Fig. 5: Results from initial LDS precession tests

The test demonstrated that, in fact, the readings were uniform. Therefore, although there is error in the readings they are uniform and therefore the error can be compensated. Also this older unit has an algorithm that converted the raw LDS data from millimeters to centimeters. This algorithm truncated many of the distance values from the LDS and therefore is most likely where the error is coming from. Therefore, the team extrapolated that with improved algorithms and data acquisition the error can be mitigated.

The final test was designed to grant the team a better understanding of how the LDS data can be used. In this test the LDS data was used to map the room. The system mapped the following set up as seen below. The goal was to use the data to determine the precise location of the box.

Fig. 6: Room mapping set up

This test indicated that by using data from the LDS there is a clear enough distinction between points in the plane which means that an algorithm can be generated to locate specific points in a given plane, as seen in figure 7.

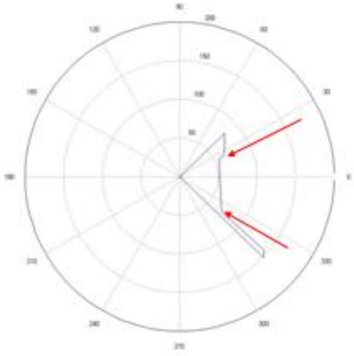


Fig. 7: Results of room mapping

3) *Microcontroller Selection*

Once the team decided that algorithms were needed to determine those distinct points on the blade, the team selected a microcontroller that could allow for that processing. The microcontroller selection was a crucial part of the design implementation process. Based on the specifications required to process the LDS data, the microcontroller had to fulfill the following requirements.

- 2 PWM outputs
- Serial Input/Output
- Memory for Calibration
- 2 16-bit Timers
- Operating Voltage 5V
- High Computational ability

Considering these requirements, the team selected the Tiva-C LaunchPad (Texas Insturments, Dallas, TX). The Tiva-C either met or exceeded all of the requirements.

4) *LDS Interfacing*

To interface with the Tiva-C the team needed to implement several pieces of hardware. First was a 5-volt voltage regulator to power the LDS unit.

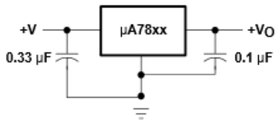


Fig. 8: Implemented power regulator

The regulator was implemented to make sure that the LDS unit would always have a constant 5 V even if there were changes in the original source voltage from Caterpillar’s control unit. The second was a transistor circuit.

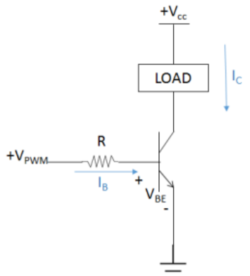


Fig. 9: Transistor surge protection circuit

This transistor circuit was implemented to protect the motor from any possible power surges from passing through to the LDS.

5) *UART Interfacing*

In order to export data from the LDS to the Tiva-C, a serial Universal asynchronous receiver/transmitter (UART) port was used on the Tiva-C. The data form the LDS is stored and sent through various algorithms. The data from the algorithms was then sent to the computer over a UART pin connected to the Universal Serial Bus (USB) port on the Tiva-C. Data could be read over a COM port at a baud rate of 115,200 using any serial connection software.

6) *Motor Control*

If the motor on the LDS ever began to run below the desired speed, then any data would be inaccurate. Therefore, a function is used to check the status of the motor. This function checks to see if the speed of the LDS, which comes from the data packets, with the desired speed. If the two values are the same, then the PWM signal that is driving the motor is maintained. However, if the values are not equal, then the duty cycle of the PWM is changed until the values are equal. If necessary, an acceptable range of motor speeds could be generated instead of an exact value. In addition, a flag is set to indicate that the packet is not good.

7) *Tracking Algorithm*

The tracking algorithm is designed to determine two key unique points on the blade. However, the two unique points will vary based on blade type and because the team does not have access to these blades, it was difficult to design for these cavities . Generally, the points are areas on the blade with large cavities or extensions, some form of physical identifier that is distinct enough to be identified by the LDS unit. The team did visit a D8 tractor at the Caterpillar proving grounds. During this time, the team checked to see that there were points distinct enough to track. Two such points were found, as seen in figure 10.

Fig. 10: Sample tracking points on actual blade

8) *Distance Algorithm*

The distance algorithm uses the two points from the tracking algorithm from the two LDS units to construct a four point plane for analysis. Each point gives a distance *d* and an angle θ. The algorithm uses geometry and known distances (LDS unit to ground, LDS unit to blade, and blade height) to find the distance of the blade tip to the ground. Below is a two-dimensional representation of the distance calculations.

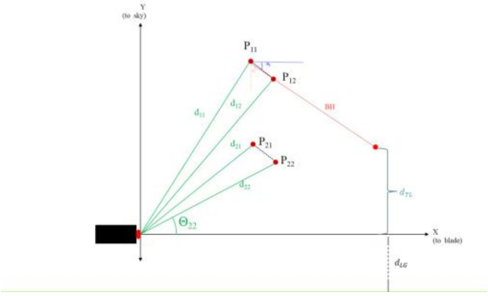


Fig. 11: Two dimensional representation of distance algorithm

The distance will then be output as a PWM signal to the motor control unit on the Caterpillar tractor. The duty cycle of the PWM will vary as the distance varies. The duty cycle is based upon the blade height and max extension outlined in Appendix E. Also, because the algorithms actually analyze information in three dimensions, the algorithm also has the potential to determine the tilt angle and the rotational angle of the blade. The ability to determine the tilt angle is outlined Fig. 11 and the rotational angle is outlined in Fig. 12.

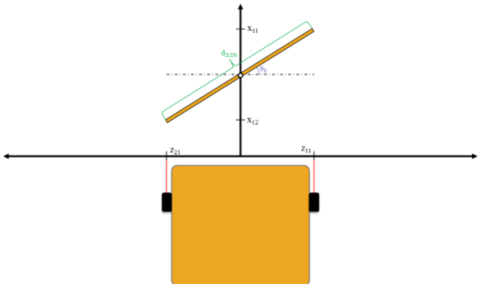


Fig. 12: Two dimensional representation of rotational angle

9) *Testing Results*

After implementing the new Neato LDS system with the Tiva-C, the team tested the system once again to see if the new algorithms and data processing had improved the accuracy of the system. The team also tested the theory behind the distance algorithms and tested various environmental effects on the system.

The first test was a repeat of the accuracy test as performed with the older unit. The measurements had 21 mm of relative error. However, this constant error came from a misidentification of the location that the LDS takes measurements from. Accounting for that, the 21 mm constant error was removed and determined that the error was much less than the original tests in the initial test section outlined earlier.

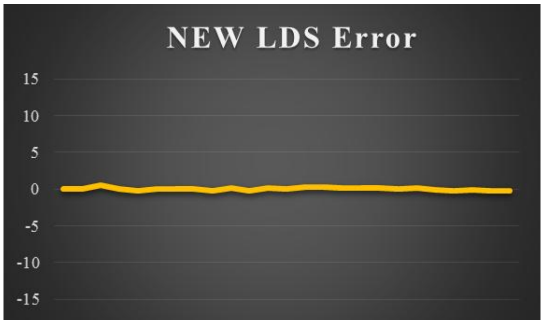


Fig. 13: Results from final LDS distance tests

In the original test the max error was approximately 10%. Now the max error is 0.5%. The accuracy was tested up to 1.5 meters, the approximate distance of the LDS mounting location to the blade.

The second test was a repeat of the precision test performed with the older unit. Once again, the team obtained a dozen measurements at a specific distance to establish the true error. Once again the readings were precise with ± 1 mm fluctuations, which is well within the acceptable limits.

The third test was a blade modeling test. This is similar to the room mapping test performed with the older unit. However, this time the team focused on identifying a specific blade mock up. The goal was to use the blade mockup to evaluate whether the LDS can clearly locate two unique points on the blade. The results of this test are as follows.

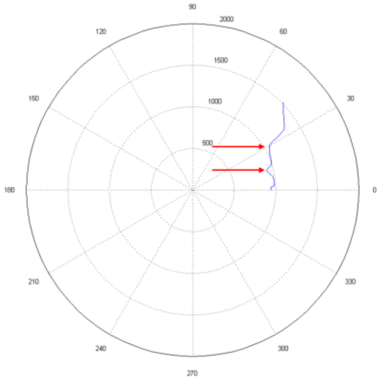


Fig. 14: Results from blade modeling

As seen in figure 14, the data from the LDS can easily identify those two points. Therefore, the points on the blade are distinct enough to be identified.

The fourth test was a coding test of the distance and PWM algorithms. The variables that would have come from the LDS were hard coded to distinct values that would provide a particular distance. The resulting variables and PWM outputs were as expected for the case of full extension of the blade with no tilt or rotation.

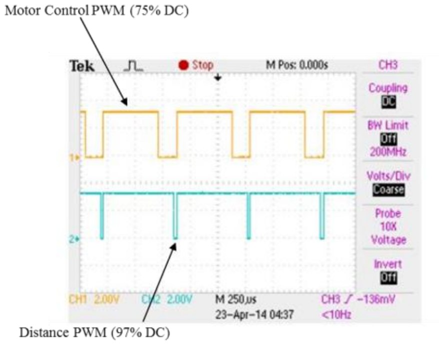


Fig. 15: Results from algorithm test

These results suggest that although the values did not come directly from the LDS, once a tracking algorithm is developed the four data points can be used for analysis as expected.

The final tests performed with this unit were environmental tests. The first test was a vibrational test. Because the LDS units will be mounted on each side of the cab, it is going to experience considerable vibration from the running engine. To test the effects of vibration on the unit a team member vibrated the unit by hand at approximately 60 Hz at approximately ± 10º off the vertical axis. The test was run and had the following results.

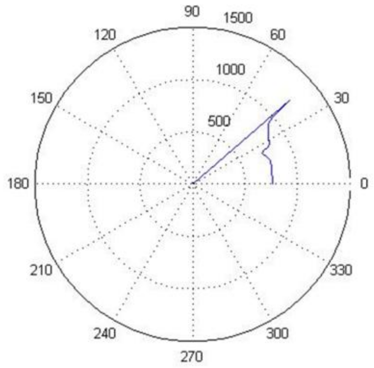


Fig. 16: Results from Vibration Tests

When comparing these results to the initial blade modeling results, the team found that even with the vibrational interference the LDS data still highlights those two distinct points.

The team continued to test some of the more common environmental issues that the LDS would face if mounted onto a Caterpillar tractor. Some of those environmental issues were dirt and debris like rocks or other large objects. For both of these tests, the material in question was dropped from a height off of the LDS units limited (± 45º) field of vision through the LDS's field of vision. The LDS was pointed at a flat wall ~1.5 meters away. An initial picture of the wall was taken and then used for comparison.

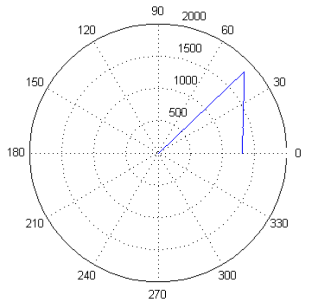


Fig. 17: Initial wall scan

The results of these tests will be seen in the two figures, 18 and 19, below.

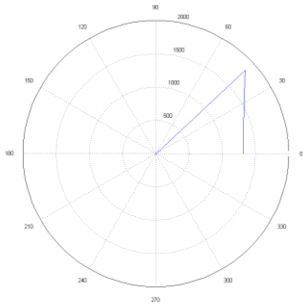


Fig. 18: Wall scan with dirt

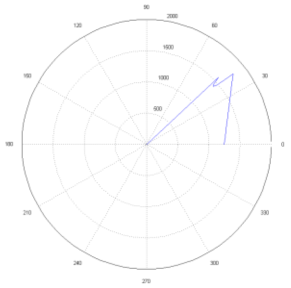


Fig. 19: Wall scan with debris

As indicated in this figure the addition of the two materials did not change the original image greatly. Therefore, although these tests are preliminary, they indicate that even with environmental interference the LDS can identify the target. However, even though these results indicate that environmental factors have a minimal effect on the system, the team still recommends the development of an averaging system which will average several readings to eliminate uncertainty.

B. Wheel and Encoder

In this design, three wheels measure the linear displacement of a cylinder that controls the lift of the tractor's end implement. These three wheels are protected by a collar. Encoders attached to the wheel's axle measure the rotation of the wheels. The wheels are slightly compressed against the cylinder rod to increase the friction between the wheels and the cylinder. The design has two halves, which can be separated from one another to allow for easier maintenance and repair.

1) Theoretical Design

The wheel and encoder design takes linear motion and turns it into rotational motion. This is performed by determining the portion of the circumference the wheel has rotated. The following equations represent this relationship.

$$d = r * \varphi$$

$$F_c \geq \left| \frac{m * r * a_c + T_f}{\mu * r} \right|$$

An important consideration in this design is that the distance is not directly measured but integrated over time. This measurement technique means there could be travel errors due to wheel slip. This wheel slip can potentially cause inaccuracies in the measurement. To limit this risk, slip analysis was performed on the system.

2) Physical Design

The wheel and encoder design consists of three wheels protected by a collar as stated earlier.

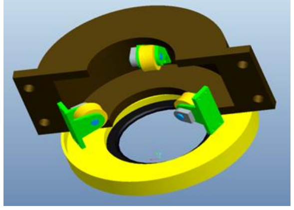


Fig. 17: Design of wheel and encoder

However, there are three physical designs that are the most important physical attributes of the system. The first is its modular design. This design allows for easier maintenance and repair. The second major design characteristic is that the multiple sensors also allow for built in redundancy, which increases life of the unit. The multiple encoder design also improves the accuracy. The third physical design characteristic is the addition of wipers on the outside of the collar to prevent debris from entering the collar system.

For the particular application of the unit on the D8 Tractor, the collar would be attached to the cylinder housing as indicated in figure 18.

Fig. 18: Mounting location of wheel and encoder

This location gives the best option for measuring the cylinder displacement while reducing the loss of cylinder stroke.

3) Testing Results

The first test of the wheel and encoder system was a very basic feasibility test. For this test the team used a temporary two wheeled structure to test the feasibility of the wheel and encoders to measure displacement.

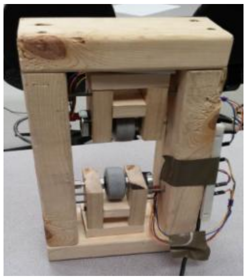


Fig. 19: Initial wheel and encoder set up

This test indicated that the error in the system was approximately ± 10 mm. However, the team deduced that the error was caused by tolerance stack ups, missed pulses, and a general problem with the physical design of the testing rig.

The second test was actually with a wheel and encoder system prototype. To counter the problems from the previous test this model follows the design exactly, using three wheel and encoders.

Fig. 20: Final wheel and encoder Prototype

Also the encoders were updated to absolute encoders. These absolute encoders grant higher tolerances. This proved to be a correct assumption. The average error over 200 mm was 0.4 mm. However, this is still not within the range outlined by Caterpillar for a system of this design which was 0.01 mm for this type of system.

IV. BUSINESS ANALYSIS

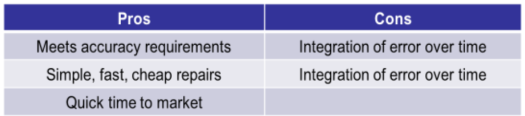
Because this is a convergence project there is a business aspect of the project. This business aspect focused mostly on a return on investment analysis that was used to justify the work of the project. Through the analysis, the team determined that by improving this particular system Caterpillar can receive a 7+ million dollar return of investment over 10 years with a 52% internal rate of return.

Also, the team performed a marketing analysis on each of the designs. This analysis prepared the team to understand how each design would affect Caterpillar as a business. It also gives business support on why each design should or should not be implemented.

V. RESULTS AND RECOMMENDATION

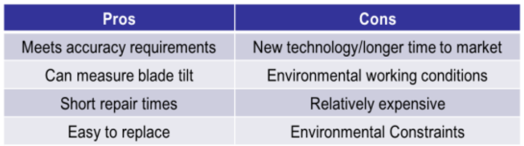
Using the results of the two tests and the business analysis, the team was able to develop some pros and cons for each of the designs.

Wheel and Encoder



Pros	Cons
Meets accuracy requirements	Integration of error over time
Simple, fast, cheap repairs	Integration of error over time
Quick time to market	

LDS



Pros	Cons
Meets accuracy requirements	New technology/longer time to market
Can measure blade tilt	Environmental working conditions
Short repair times	Relatively expensive
Easy to replace	Environmental Constraints

After counseling all of the information from the tests performed by the engineering group and the analysis the business team preformed, the team came to the following conclusion. It is evident by the staggering numbers on the ROI that proves that addressing this issue is vitally important to Caterpillar. Therefore it is evident that a new design is paramount for Caterpillar to implement. Out of the two designs the LDS system is the most promising. From the results of the testing completed in this project it satisfies Caterpillar requirements. Also the environmental effects commonly seen on Caterpillar tractors had minimal effect on the system. Most importantly, the LDS adds the features of determining the rotational and tilt angle of the blade. This additional functionality can provide considerable financial benefit to Caterpillar. However, due to the complex nature of the system, the LDS requires a considerable amount of development time. The wheel and encoder system however, has a much shorter development time. Therefore, the team is recommending that Caterpillar implement the wheel and encoder system as a temporary solution. Then Caterpillar should develop the LDS system as a long term solution. The team decided on this recommendation because, based on the data provided by Caterpillar, the sooner a solution can be implemented the more money that could be saved. However, the LDS is still the more productive solution. The team therefore recommends this dual solution as it would allow for a quicker cash flow while removing the issues of the current system and offers a long term solution that meets Caterpillar's needs as well as offers a wider expansion into the functionality of the feature.

VI. CONCLUSION

Working in a convergence project is a unique atmosphere for undergraduate students. However, it allowed the design team to tackle a real-world business problem in a real-world environment. Through collaborative work, engineering testing, and business analysis the team was able to develop several possible designs, eliminate several designs based on known criteria, and then develop two designs in detail. Based on all of the information gathered in the process, the team recommends a dual structure implementation of the two designs to help Caterpillar save money, maintain the accuracy, and move forward to a future of autonomy.

Leann M. Vernon was born in Peoria, IL in July 1992. She is currently a senior at Bradley University, Peoria, IL, pursuing a degree in electrical engineering with a marketing minor. Expected graduation date is May 2014.

She has worked in a variety of positions including as a server at Flat Top grill. Last summer, she completed and internship with Robert Bosch GmbH. She is currently an undergraduate tutor at Bradley University.

Ms. Vernon is currently a member of the Society of Women Engineers.

Phillip Latka Phillip M. Latka was born in Homer Glen, Illinois in February 1992. He is currently enrolled at Bradley University in Peoria, IL and is seeking a B.S. in Electrical Engineering with a minor in Business Administration.

During the summer of 2013, he was an intern at ComEd, the power utility provider of Chicago, Illinois. He worked in the Distribution Operations department and developed applications designed to improve productivity within the department. Phillip has accepted full time employment with ComEd following graduation in May 2014.

Appendix A

- Option List
    - Hall Effect
        - Description:varies output voltage in response to strength of a given magnetic field, requires hall plate installation
        - Pros: Modeled in a similar way to how a piston or linkage is modeled
        - Cons: would probably require external sensor addition, could be bad due to magnetic field
    - Oxygen and Other Gas Sensor
        - Description: used with mathematical calculations to determine the amount of oxygen or other gas
        - Pros: Only requires the one sensor, little intrusion on the existing machine
        - Cons: lots of mathematical calculations and not very accurate
    - Magnetometer
        - Description: measure the strength of magnetic fields, between two locations
        - Pros: relatively accurate, low intrusion
        - Cons: again the issue with the magnetic field
    - Laser Rangefinder
        - Description: illuminating a target with a laser and analyzing the reflected light
        - Pros:
        - Cons: could be bad due to all the metal, interruption, and accuracy issue
    - Capacitive Proximity Sensor
        - Description: capacitive coupling between a capacitive stylus and a capacitive surface
        - Pros: good accuracy
        - Cons: requires considerably manipulation
    - Capacitive Displacement Proximity Sensor
        - Description: non contact devices that have high resolution position
        - Pros: very high accuracy and limited manipulation to existing system
        - Cons: may require and external addition
    - Eddy Current Proximity Sensor
        - Description: consists of driver and probe that repel each other
        - Pros: very durable
        - Cons: takes up considerable space
    - Radar Proximity Sensors
        - Description: uses radio waves to determine range altitude or direction of objects
        - Pros: good accuracy
        - Cons: reflective quality of the air with considerable noise and interference
    - Sonar or Ultrasonic Proximity Sensor
        - Description: sound propagation
        - Pros: accurate
        - Cons: requires considerable technology (may be excessive)

Appendix B

VEHICLE STRAIGHT TO BLADE:

1. Vision Tracking (Camera-PS2 MOVE)

- A camera mounted on the engine housing would track different locations on the blade. These points could be high contrast locations (similar to PlayStation move technology) or just physical features on the blade. From the points the blade could be located in all three dimensions.

2. Vision Tracking (LiDAR)

- A LiDAR system would be mounted to the top of the cab or engine housing and could determine the blades location in three dimensions. The LiDAR system could also possibly be used for other environmental mapping at the same time as well. (more information at http://velodynelidar.com/lidar/lidar.aspx)

3. Vision Tracking (IR)

- An IR camera mounted on top of the engine housing could locate the blade in three dimensions.

4. Vision Tracking (Laser Ranging)

- Described in more detail in the full report under the name LDS (laser distance sensor).

5. RF Strobes

- This design would place strobes that send out a known time pulse on the blade. By calculating time of flight to a receiver mounted on the cab, the blade position can be determined.

6. Triangulation

- This system would mimic how GPS works. Radio signals would be sent from multiple locations on the blade to a receiver on the cab. Because these signals originate on known locations of the blade, the receiver can then determine the distance to each signal source as well as orientation of the blade.

MEASURING LINKAGES

1. Removable Sensor Package

- More a design aspect than a sensor technology, a sensor system that can easily be removed

2. Wheel on rod and encoder

- Described in more detail in the full report under the name Wheel and Encoder (Collar).

3. Linear potentiometer

- A linear potentiometer would be mounted externally parallel to the current cylinder. The mount locations of the linear potentiometer would be the same as the hydraulic cylinder.

4. Hall Sensor array and magnet

- A hall sensor array lines the outside of the hydraulic cylinder in the direction of the stroke length. A magnet is attached to the cylinder head and has the stroke length changes the magnetic field at each sensor changes and can be related to the distance moved.

5. Hall Sensor Top and Bottom

-Same as above except an array of hall sensors will be placed at the top and bottom of the cylinder instead of along the entire length.

6. Barcode

-A barcode is etched into the cylinder rod. An optical device then could be used to read the barcode and determine the cylinder displacement.

7. Ultrasonic Sensor (internal)

- An ultrasonic sensor is placed inside at the base of the cylinder and the signal bounces off the cylinder head and back to the sensor to determine the cylinder displacement

8. IR Distance (internal)

-Same as #7 except using an IR sensor instead of the an ultrasonic one

9. Ultrasonic Sensor (internal)

- An ultrasonic sensor is placed outside at the exit of the cylinder and the signal bounces off the connection point between the cylinder and the blade and the cylinder displacement can be found

10. IR Distance (external)

- Same as #9 except using an IR sensors instead of the an ultrasonic one

11. Laser Distance

- Same as #9 except using a point laser sensor instead of the an ultrasonic one (similar to Keyence LK-G3000 series)

12. Linear variable differential transformer

- A linear variable differential transformer (LVDT) utilizes three magnetic coils and a ferromagnetic core to measure position. Alternating current is applied to three transformer coils external to the cylinder, and the ferromagnetic core is attached to the piston. As the ferromagnetic core moves between the transformer coils, magnetic inductance is varied between the three and the difference between the two secondary coils yields a linear distance.

13. INS on push arm

-An inertial navigation system would be attached to the push arm so that orientation of the push arm is known and then the location of the blade through linkage analysis

14. Accelerometer

-An accelerometer mounted to the cylinder head is used to determine the cylinder displacement by integrating the accelerations back to position

15. Yo-Yo Measurement

-A yo-yo sensor is fixed to the exit of the cylinder and the other end is attached to the end of the cylinder rod. As the cylinder rod retracts and extends the “string” of the yo-yo the yo-yo moves and the displacement of the cylinder rod can be determined.

16. Capacitive Displacement Proximity Sensor

-Plates would be placed in both ends of the cylinder, including the piston head. As the cylinder extends, the distance between the capacitor plates would change, causing a change in the capacitance. This capacitive difference would then be measured.

17. Inductance

-By wrapping the outer cylinder in a coil of wire, and placing a magnet on the piston head, the induced current can be measured and integrated to determine the position of the magnet within the coil and therefore the piston head location

18. Flow Meter

-Flow meters would be placed at the inlet ports of the hydraulic lines measuring the hydraulic fluid in the cylinder and from there the cylinder displacement could be determined.

19. Pressure Sensor

-The pressure in the cylinder would be determined using a pressure sensor placed in the cylinder and that pressure would be related back to a cylinder displacement.

20. Eddy Current Proximity Sensor

- An alternating current source drives a magnetic field in a sensing coil. This creates an alternating magnetic field inducing small magnetic currents in a target material (hydraulic fluid). These currents create and opposing magnetic field to the driving magnetic field. Measuring the strength and direction of these currents allows for determination of the distance of the target material.

21. Gear tooth sensor

-A rack and pinion system would be attached to the side of the cylinder and be used to determine the cylinder displacement. As the piston moves the rack moves spinning the gear and generating rotation. (Could be used with the Wheel and Encoder)

22. Current Case

-Maintain the current system

EXTERNAL POINT TO BLADE:

1. Magic Drive

-This system requires a very precise map of the ground of the area. The system would use GPS to determine where the tractor is on the ground map and then laser systems mounted on the blade would scan the ground in front of the blade. The image from the scanning and from the ground map would be compared to determine where the blade is relative to the ground. Idea came from Mercedes-Benz magic body control

2. External LiDAR

-LiDAR unit mount in an eagle eye position overlooking the ground. It can see the vehicle and the ground in its view. Then through scanning the area it can determine blade height.

3. External IR

-Same as External LiDAR but using IR.

4. External Laser Ranging

- Same as External LiDAR but using Laser Ranging.

5. GPS

-Similar to the current Accugrade system with the poles but would try to remove the poles. Try to shrink the pole size and make them more robust.

7. Triangulation

-Same as for vehicle Triangulation expect receiver is not mounted on the vehicle

Appendix C

<u>KEY:</u>

The following are the screening conditions used.

S1 - Working conditions
  a.) Vibrations
  b.) Debris
  c.) Fluid
  d.) Magnetic field interference
S2 - Accuracy (0.1 mm for linkage – 1/2inch for blade direct)
S3 - Time to market (>5 years)
S4 - Development cost (> $2 million)
S5 - Cost of sensing system (> $2,000)
S6 - Reliability (>10,000 hours)
S7 - Fundamentally flawed

VEHICLE STRAIGHT TO BLADE:

1.	Vision tracking (Camera-PS2 MOVE)	**[S1b]**
2.	Vision tracking (LIDAR)	**[]**
3.	Vision tracking (IR)	**[S1b, S2]**
4.	Vision tracking (Laser Ranging)	**[S1a]**
5.	RF strobes	**[S2]**
6.	Triangulation	**[S2, S5]**

EXTERNAL POINT TO BLADE:

1.	Magic drive	**[S2,S4,S5]**
2.	LIDAR	**[S5]**
3.	IR	**[S2]**
4.	Laser ranging	**[S2]**
5.	Ultrasound	**[S2]**
6.	GPS	**[S2]**
7.	Triangulation	**[S2]**

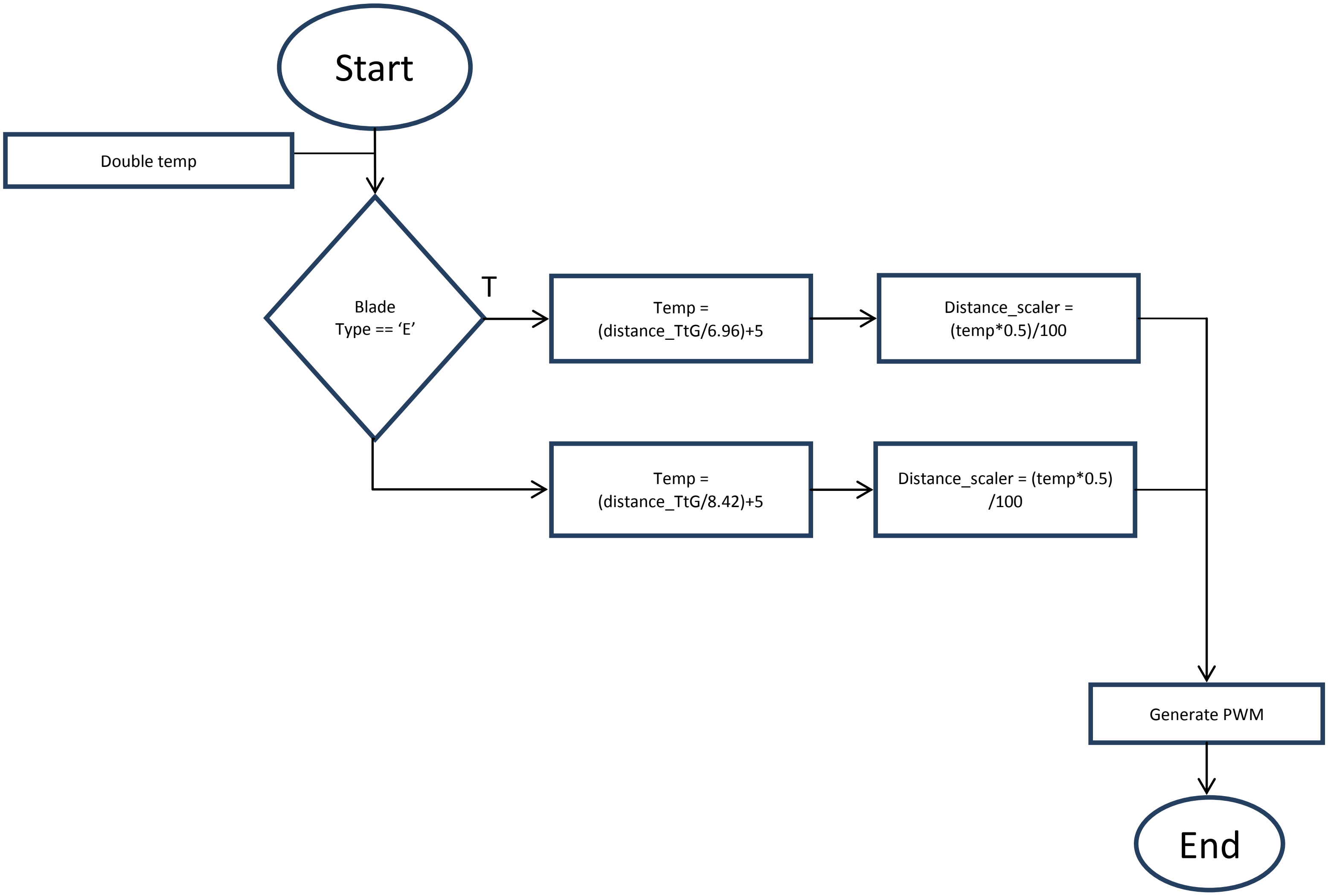
LINKAGE POSITIONING:

1.	Removable sensor package	**[]**
2.	Wheel on rod and encoder	**[]**
3.	Linear potentiometer	**[S2, S5, S6]**
4.	Hall sensor array and magnet	**[S2]**
5.	Hall sensor top and bottom	**[S2]**
6.	Barcode	**[S6]**
7.	Ultrasonic sensor	**[S1c]**
8.	IR distance (internal)	**[S1c, S2]**
9.	IR distance (external)	**[S2]**
10.	Laser distance	**[S1a]**
11.	Linear variable differential transformer	**[S3,S4,S5]**
12.	INS sensor on push arm	**[S2,S5]**
13.	Accelerometer	**[S1c, S2]**
14.	Differential GPS/GPS	**[S5]**
15.	Sonar in cylinder	**[S1c, S2]**
16.	String measurement	**[S1b, S2, S6]**
17.	Capacitive displacement proximity sensor	**[S1c, S2]**
18.	Inductance (magnet moving in a coil)	**[S1c, S6]**
19.	Flow meter	**[S1c, S2]**
20.	Pressure sensor	**[S7]**
21.	Magnetometer	**[S1d,S7]**
22.	Eddy current proximity sensor	**[S7]**
23.	Wi-Fi	**[S2]**
24.	Gear tooth sensor	**[S1b, S7]**
25.	Linear transducer (hall effect)	**[S5]**

Appendix D

Actual (mm)	**LDS**		**Percent Error**
300	330		-10
350	370		-5.714285714
400	420		-5
450	460		-2.222222222
500	510		-2
550	560		-1.818181818
600	600		0
650	650		0
700	690		1.428571429
750	740		1.333333333
800	780		2.5
850	830		2.352941176
900	870		3.333333333
950	910		4.210526316
1000	960		4
1050	1010		3.80952381
1100	1050		4.545454545
1150	1090		5.217391304
1200	1130		5.833333333
1250	1180		5.6
1300	1220		6.153846154
1350	1260		6.666666667
1400	1300		7.142857143
1450	1340		7.586206897
1500	1390		7.333333333

Appendix E



Function Declaration:

PWM_Distance(int distance_BTtG, volatile uint32_t PWM_Period_Signal, char blade_type)