The Design of a Low-Cost and Robust Linkage Position Sensor

Project Proposal

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Introduction

Caterpillar Inc. is a recognized leader in a variety of fields, including mining equipment, engines, turbines, and locomotives. Throughout the years, its bright yellow fleet has come to encompass an enormous array of machines that range from the 3,200 horsepower Caterpillar 797 haul truck to the Caterpillar 216 skid steer. The senior electrical engineering design project program at Bradley University prepares students for real world projects after graduation. This project is designed to combine these two worlds into a project that satisfies the needs of Caterpillar and helps prepare the students for post-graduation projects. The objective of this project is to develop a sensor system that determines the location of the tractor's end implement. This project brings together students from various disciplines but will still fulfill the requirements set by the client, Caterpillar, and the requirements of the electrical engineering senior project program. This report subdivides the project into four components that best describe the project: the **project description**, an overview of **preliminary work** completed up to this point, the **proposed schedule** of the project, and the **required equipment**.

Project Description

Caterpillar approached Bradley University to see if the university could find a solution to their end implement position problem. This request was turned into a convergence project consisting of students from the Business, Electrical Engineering, and Mechanical Engineering departments with Caterpillar serving as the client. Caterpillar's requirements for the alternative system, which dictate the structure of the project, are that it must be precise, robust, maintain a low cost, and have an ease of implementation. The new sensing system can either determine the end implement position directly or determine the position of the linkage which can be combined with other signals to find the end implement position. The most important aspects of the project are how the system will be setup as outlined in the **block diagrams**, the **design requirements** set by Caterpillar, and the **system specifications** required so the system can be implemented on Caterpillar's existing machines.

Block Diagram

This project is designed as a research and development project. Therefore, there will be many different designs each with their own unique block diagram. However, there are several general system block diagrams that are pertinent in developing the design.

Overall System Diagram

The high level system diagram describes the basic input and output characteristics of the end implement position system. This overall system diagram will be used to design a compatible sensor design. The overall system is in Fig. 1.

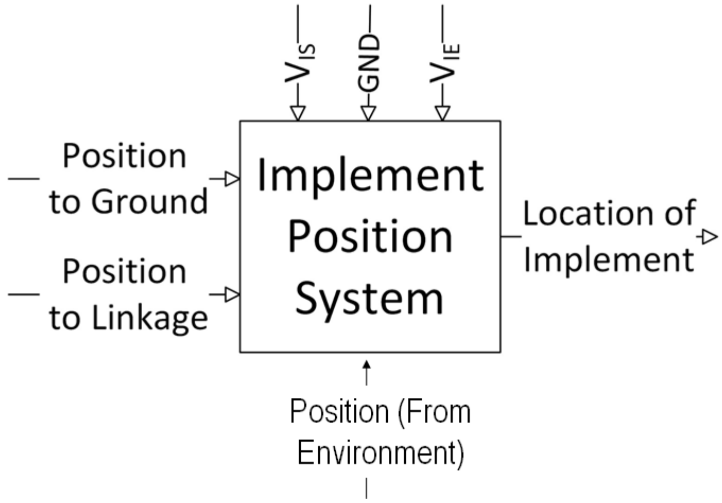

Fig. 1: Top Level Description

The inputs into the system are the input voltages V_{IS} (the voltage to drive the sensor) and V_{IE} (the voltage that will drive the electronic controller module (ECM)). The position to ground and position to linkage inputs come from sensors already implemented on Caterpillar machines [1]. These signals may or may not be used with the final sensor design. The system output indicates the location of the implement.

Secondary Subsystem Diagram

The implement position system as outlined in Fig. 1 may contain many elements, depending on the sensor design. There are two types of sensing system categories. These categories include a linkage sensing system seen in Fig. 2 similar to Caterpillar's existing system and a direct implement position sensing system as seen in Fig. 3.

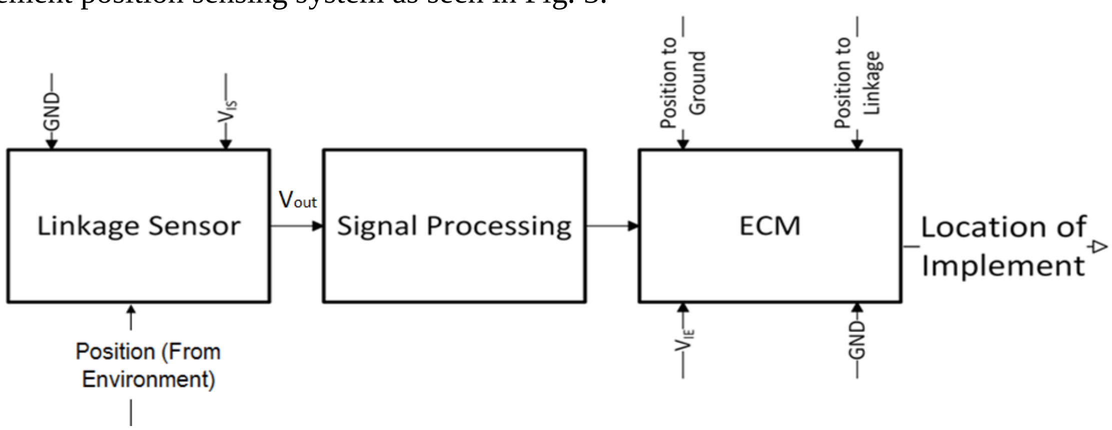

Fig. 2: General Block Diagram of Linkage Sensing System

The linkage sensors will output the voltage signal V_{out} which is based on the position from the environment. If V_{out} is not a PWM signal, then a signal processing component will be added to adapt the signal to a PWM signal. The final output of the system, the location of the implement, is determined within the ECM by relating the position of the sensor output V_{out} to the location of the implement using the position to ground and position to linkage signals. The relationship between these signals will be determined by the team but programmed into the actual ECM by Caterpillar employees.

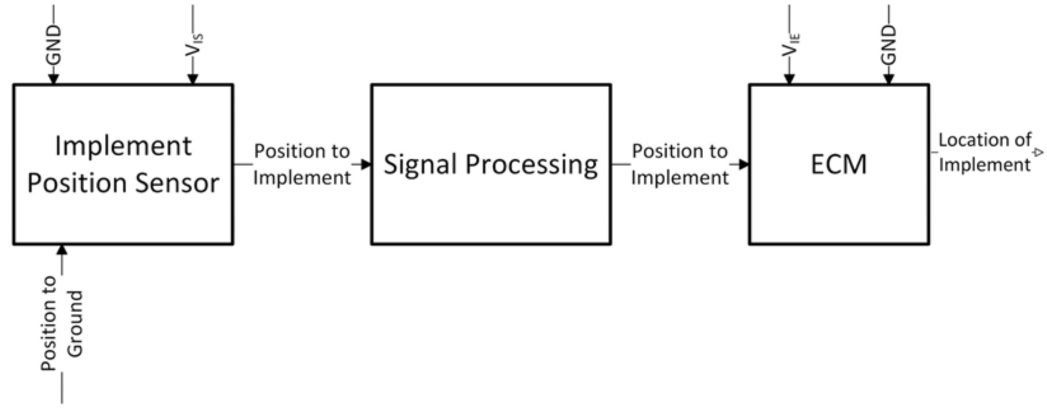

Fig. 3: General Block Diagram of Implement Position Sensor

Not many of the specifications for the direct implement sensing system change from the linkage sensing system. There are only two changes. The first change removes the position to linkage measurement because that step has been bypassed. The second change is in the internal calculations of the implement location using the ECM.

Design Requirements

The first set of requirements of the design are the design requirements. These design requirements are characteristics outlined by Caterpillar that will guide the design process. These requirements focus more on the physical aspects of the design and may be adapted by the client if the change in requirements yield a positive trade off to the overall system.

- Cost
  - Cost, including the cost of the sensor, manufacturing, and installation costs, must be reasonable
    - Benchmark cost based on the cost, manufacturing, and installation of current sensing system
      - Less than $1,000-1,500
- Robustness
  - The sensor system must withstand vibration of 8 g minimum when on the tractor
  - The sensor system must operate in an environment with high levels of dirt, smoke, and dust
  - Must be able to handle extreme weather conditions
- Reliability
  - The sensor system must have the potential for 10,000 operating hours.
    - Tested by Caterpillar
- Accuracy
  - The sensor system must determine the location of the linkage with an accuracy of 0.1 mm with only 3% uncertainty

    - The sensor system must determine the location of the implement with an accuracy of 0.5 inches

System Specifications

The sensor system specifications are the technical aspects of the design. These specifications will also guide the design process by ensuring that the final design will be successfully integrated into Caterpillar's existing system.

- Output of Sensor Design
    - PWM signal
    - Low current ~3.8 mA
    - ECM has pull up resistors to handle up to 5 V
    - Frequency range: 0.1 Hz to 12.8 Hz
    - Duty Cycle Range: 3-97 %
- Output of ECM to Sensor
    - Output Current Capacity (Engine): min: 300mA
    - Output Current Capacity (OEM): min: 80mA
    - Output Voltage: min: 4.90 VDC, nom: 5 VDC, max 5.10 VDC
- ECM pins
    - ECM active analog sensor input: Pin 2
    - ECM passive analog sensor input: Pin 4
    - PWM/Freq input: Pin 16
    - PWM/Freq input (precision): Pin 4
    - 300mA sinking/PWM driver output: Pin 3
    - 5 V sensor supply: Pin 200
    - 8 V sensor supply: Pin 400
- A/D in ECM
    - Sampling rate is 50 Hz, 16-bit resolution

Preliminary Work

Because of this project's strong design aspect the preliminary work is very important. The preliminary work dictates the design work, the testing procedures, and in general the workflow of the coming months. There have been two primary stages of preliminary work completed up to this point. These two stages are a **research stage** and a **brainstorming stage**.

Researching Stage

The researching stage was the very first stage in the preliminary work. The research stage required a lot of work by all team members to generate a strong base knowledge to be used as the project moved forward. The researching stage had several components. These components were an initial **team management study** to outline teamwork moving forward, research on the

existing CAT sensor to determine a benchmark for new designs, and research on **patents/existing designs** which could limit our designs.

Team Management Study

This project's team includes two electrical engineering students, three mechanical engineering students, four business students, and four advisors. Therefore, we needed to spend time to set up a communication system and management structure that would yield the most productive environment for the project. Although this was a small portion of the research stage and consisted mainly of surveying people to find the most opportune meeting times, it was one of the most crucial steps to move forward.

Existing CAT Sensor

Research was performed on the existing CAT sensor in order to establish how the current sensor works. The preliminary findings revealed several flaws in the current system that contributed to high cost and unreliability. Currently, the internally placed sensor requires gun boring to be performed within the cylinder. This placement leads to high installation costs, lengthy replacement time, and exposes the sensor to a highly pressurized conditions. These factors helped to construct the benchmark points used when searching for replacement systems.

New Sensor Research

As soon as the benchmarks were created based on CAT's existing system the team could begin to look at alternative options. This stage, the general research phase, focused on a broad range of new and different sensor technologies that could be used in a new design. This research would be used extensively in the next stage, the brainstorming stage, in which applications for the sensors would be generated.

Patents/Existing Designs

Although we wanted to maintain an unbiased brainstorming process, the team could not ignore the fact that other existing designs or information could limit the feasibility of our designs. In researching existing designs there were two key pieces of information that would be used as we moved forward. The first was a U.S. patent, number 7757547, filed by Komatsu. This patent is for a wheel and encoder linkage position sensor. Using wheel and encoder technology was one of the new sensor options we had found in our sensor research. This patent will dictate how, if at all, a wheel and encoder can be used within a design. The other pertinent piece of information was information from a Caterpillar conference from 1997 that focused on the same end implement position problem. From the information generated within this conference, we were able to determine more benchmark and evaluation criteria based on why certain designs were eliminated.

Brainstorming Stage

After the research was completed, giving the team a better understanding of the field in which the project resides, the team could move onto the brainstorming stage. This stage is currently still being finalized. However, several key components have been completed: the **initial brainstorming stage** gave a large pool of designs, the **general idea elimination** used basic feasibility to eliminate ideas, and the **specific idea elimination** brought the list down to six designs. The final part of the brainstorming stage is the **top three selection** process and is currently being completed.

Initial Brainstorming Session
The initial brainstorming session was a combined effort by the engineering group members. This session included several ideas and designs that were very basic in nature or even strange in application. However, the goal was not to remove any ideas for any reason so the team could get an overall idea of where the team was in the design process. At the end of this initial brainstorming session the team had generated a list of more than thirty design ideas.

General Idea Elimination
In the general idea elimination portion of the brainstorming stage, the larger list of more than thirty ideas was re-evaluated to determine the feasibility of each design. During this process pros and cons were generated for each design. Based on those pros and cons each design was classified as feasible, possibly feasible, or not feasible for Caterpillar's application. The original list of over thirty ideas was limited down to thirteen ideas that were deemed feasible or possibly feasible.

Specific Idea Elimination
The list generated in the general idea elimination process was once again re-evaluated in the specific idea elimination portion of the brainstorming stage. The purpose of this portion of the brainstorming stage was to solidify each design in a top level sense. First, several of the ideas were eliminated after secondary evaluation, resulting in a list of six remaining designs. Then characteristics were determined for each of the six designs. These characteristics include the mounting location, installation requirements, communication protocols or sensor technology if necessary, and any other characteristics that seemed appropriate to solidify the designs.

Top Design Selection
The six designs were then limited to four designs. The four designs were a magnetometer, INS system placed within the push arm, laser distance sensing system, and a wheel and encoder design. These designs were presented to Caterpillar using a team constructed design report. Some information from that design report is below.

Wheel and Encoder

- Collar placed on the end of a cylinder consists of three wheel and encoder systems
- Translates linear motion into rotational motion
- Spring holds wheels tight against cylinder
- The cylinder rod rotates the wheels, which in turn spins the encoders
- Rotational distance is converted to linear distance

- Wiper keeps out dirt and debris

INS (Push Arm)

- INS placed into the push arm of the tractor
- Location and orientation (relative to the body) of the blade given based on the INS
- Movement constrained to only the Z direction

Magnetometer

- Array of magnetometers combined on the outside of the lift cylinder
- Permanent magnet placed in the center of the piston head
- Changes in magnetic field measured by the magnetometers is related to linear distance

Laser Distance Sensing

- Lasers to measure distance between the transmitter and an object
  - Time of flight
  - Triangulation
- Transmitter can be rotated to generate a “picture” of the object

After the ideas were presented to Caterpillar, they recommended that different testing protocols should be made for each of the designs. It is with these testing protocols and their subsequent implementation that will lay the groundwork for next semester.

Proposed Schedule

As mentioned earlier, a schedule is what helps to keep a project productive and eliminates many opportunities for a team to fall behind. The Caterpillar convergence team has generated a four phase schedule that is designed to be most conducive to each group’s class requirements while maintaining the most productive atmosphere.

- Phase One: Project Definition
  - August - Mid October
- Phase Two: Design Phase/Research Application
  - Mid October - January
  - Milestones:
    - Top Idea Presentation to CAT
    - Client and Team agree on top solution
- Phase Three: Advanced Analysis/Prototyping
  - January-April
  - Milestones:
    - Top Four Design Testing
    - Prototyping (Client approved)
- Phase Four: Project Delivery
  - April- May

- Milestones:
    - Final Report
    - Final Presentation

Phase one and most of phase two were described in the preliminary work. Phase one was the researching stage. Phase two is the selection and analysis phase. This is the brainstorming stage as outlined in the preliminary work section of this proposal. There are some steps still required within this phase. These steps are the analysis on the top designs by both the business and engineering groups. At the end of this phase the team will combine their information to present the top designs to the client, have a recommendation for a top design and, by working with the client, select a top design. At this time Caterpillar recommended moving forward with the top four designs into phase three.

Phase three is the physical testing phase. Initially the team will build simple proof of concept models that will be tested to prove the validity of the top four designs. From these tests a final design will be selected. Then the team will construct a final prototype that represents the exact design as it would be implemented on the tractor. This prototype will undergo simulations and testing. After testing the team will have quantifiable data that will indicate the performance of the system in different environmental conditions as well as accuracy data. This data will then be presented to Caterpillar as support for the design moving forward. If no final prototyping is approved, the team will re-evaluate the design, complete more advanced testing, perform more simulation, and construct a variety of drawings.

Phase four is the final phase, the project delivery phase. This stage will require all of the information of the project to be collected together and analyzed. This stage will also include several presentations including presenting the deliverables to Caterpillar.

A more detailed schedule can be seen in the appendix.

Required Equipment

The required materials of this project are dependent upon the decision of the client on the structure of phase four. However, there are several pieces of equipment required to complete any kind of prototyping and testing no matter what sensor design is chosen by the client.

- Oscilloscope (to measure PWM output)
- DC voltage source (to drive prototype)
- Cylinder or Tractor Model (for mounting)
- Fabrication metals (for mounting)
- Sensors (dependent on chosen design)
- Microcontroller (dependent on chosen design)
- Vibration Testing Setup
    - Table
    - Vibration driver
        - By man or machine

- Environmental Testing
    - Location: Somewhere where dirt and water can be used without it being an issue
    - Water hose
    - Bucket of dirt
    - Means to distribute dirt (i.e. a fan)

Conclusion

At the end of the project, the team will have a potential solution to Caterpillar’s end implement position problem. The team has setup a productive team schedule and used their time so far to develop a strong background in possible applicable technology. The team has also outlined several specifications required to adapt their designs to fit best under Caterpillar’s requirements. Moving forward, the team has determined a schedule that even improves on the productivity of the previous schedule and determined required equipment and testing materials. In general, the team has laid the groundwork for a project and a result that is both beneficial for the students, Bradley University, and Caterpillar.

References

[1] R. Carpenter, Private Communication, September 2013.

APPENDIX A

ID	Task Name	Start	Finish	Duration
1	<u>Phase One</u>	9/4/2013	10/4/2013	23d
2	Project Definition	9/4/2013	9/16/2013	9d
3	Project Confirmation Memo	9/10/2013	9/10/2013	0d
4	Old Sensor Research	9/10/2013	9/30/2013	15d
5	<u>Phase Two</u>	10/4/2013	12/20/2013	56d
6	Functional Description	10/14/2013	10/17/2013	4d
7	MS: Functional Description	10/17/2013	10/17/2013	0d
8	Brainstorming	10/4/2013	10/24/2013	15d
9	Functional Requirements	11/11/2013	11/15/2013	5d
10	MS: Function Requirements	11/15/2013	11/15/2013	0d
11	Feasibility Study	10/25/2013	11/28/2013	25d
12	Bill of Materials	11/4/2013	12/3/2013	22d
13	Project Proposal To CAT	11/4/2013	11/15/2013	10d
14	MS: Project Proposal to CAT	11/15/2013	11/15/2013	0d
15	Presentation	11/12/2013	11/21/2013	8d
16	MS: Presentation	11/21/2013	11/21/2013	0d
17	MS: Proposal Draft	11/26/2013	11/26/2013	0d
18	Top Three Selection	11/15/2013	12/3/2013	13d
19	MS: Top Three Presentation	12/4/2013	12/4/2013	0d
20	EE Proposal	11/11/2013	12/16/2013	26d
21	MS: Proposal Final	12/16/2013	12/16/2013	0d
22	MS: Top Design Agreement	12/18/2013	12/18/2013	0d
23	Order Parts	12/18/2013	12/18/2013	1d
24	<u>Phase Three</u>	1/22/2014	4/14/2014	59d
25	Advanced Design	1/22/2014	2/7/2014	13d
26	Drawings	1/22/2014	1/31/2014	8d
27	Simulation	2/3/2014	4/14/2014	51d
28	Prototyping	2/17/2014	4/14/2014	41d
29	Building	2/12/2014	3/12/2014	21d
30	Testing	3/19/2014	4/7/2014	14d
31	<u>Phase Four</u>	4/14/2014	5/14/2014	23d
32	Testing Results Analysis	4/14/2014	4/21/2014	6d
33	MS: Demonstration	4/14/2014	4/14/2014	0d
34	Final Presentation	4/21/2014	5/9/2014	15d
35	MS: Final Presentation	4/29/2014	4/29/2014	0d
36	Final Report	4/21/2014	5/9/2014	15d
37	MS: Final Report	4/29/2014	4/29/2014	0d
38	MS: Advisory Board Presentation	4/29/2014	4/29/2014	0d