IDEA

Innovations Deserving
Exploratory Analysis Programs

Safety IDEA Program

On-Board Railroad Wheel Monitoring System

Final Report for
Safety IDEA Project 14

Prepared by:
David Jacobs, Stan Haynes, and Michael McCurdy
L-3 Communications Coleman Aerospace
Orlando, FL

February 2010

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD

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Expert Review Panel

Coleman Aerospace appreciates the input from the following expert review panel members:

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Supporters

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Patent Status

Patent application was filed.

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EXECUTIVE SUMMARY

The purpose of the Safety IDEA Project was to develop an economical on-board wheel monitoring system for railroad applications that will improve railroad safety by reducing complete component failure. The Autonomous Rolling Stock System (ARMS) will provide warnings to train operators as well as railroad car owners before the component failure occurs such that preventive maintenance can be performed on a scheduled basis. There is currently a patent pending on this system.

The ARMS unit is a small electronics package which attaches directly on the outer hub of a train car wheel (Figure 1). It forms its own network and communicates important data and trends to a central data collection unit on the train for transmission to a central database external to the train.

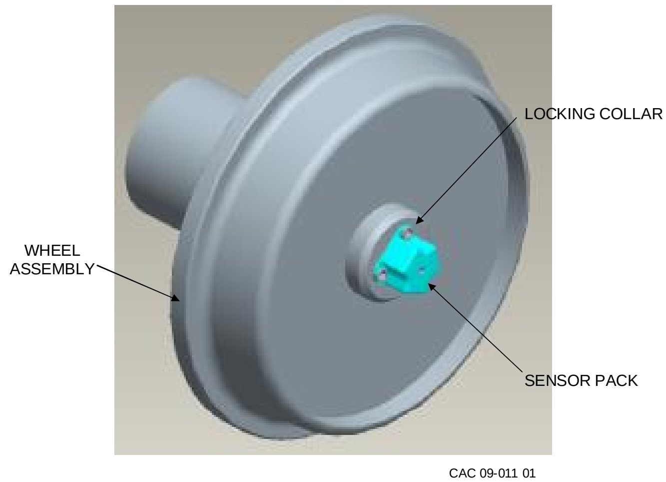

FIGURE 1. Rendering of Installed ARMS Unit

ARMS uses sophisticated processing of signals derived from a three-axis accelerometer, a high-frequency microphone, and a temperature sensor to detect a variety of problems with the wheel bearing components. The signal processing algorithms focus on three wheel elements to determine wheel bearing condition and longevity—the rollers, the bearing cups, and the bearing cones, (Figure 2). L-3 Communications Coleman Aerospace (Coleman Aerospace) expects that even on well maintained trains there will be indications of bearing defect signals present with much lower amplitude than on damaged units. Trending analysis will provide statistical data to track bearing condition and provide early indication of developing degradation. Using this model, the ARMS will be able to predict life expectancy, efficiency and failure.

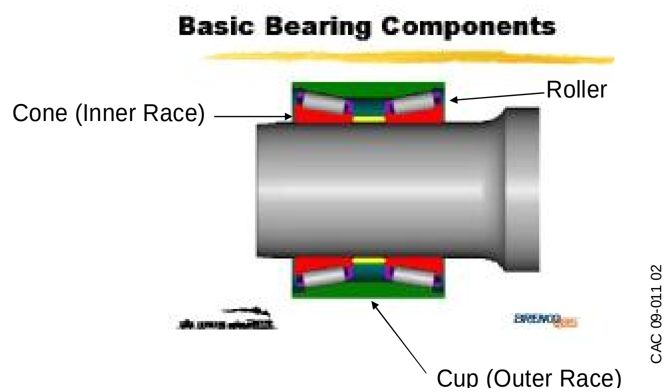

FIGURE 2. Cup Roller and Cone Configuration

Other uses in the future could focus on other railroad truck component wear that causes the oscillatory yawing of the vehicle trucks between the rails, known as truck hunting. This could be accomplished by entering data from the third axis, horizontal or perpendicular component to the direction the car is traveling, of the accelerometer in to the algorithms.

To conserve battery life the system lies dormant until the train exceeds 10 mph. When activated, the ARMS units automatically form a mesh network by comparing current velocity, direction, and signal strength. Once the network is formed, each unit begins collecting data at a preset interval. The interval can be increased or decreased to improve battery life or improve trending analysis. The current expected battery life is approximately 10 years.

Statistical parameters are calculated for the various signals recorded from each wheel being monitored, and information is passed through the wireless link from unit to unit until it reaches the central data hub. The central data hub collects information on all units attached to its train and uploads the information to a central recording and analysis facility (back office) via a high-speed link where it is processed and monitored. Global positioning system (GPS) location data can be added to the uploaded wheel data to allow tracking of the train and individual car locations at the time of the reading. The back office network will be used to proactively inform car owners that maintenance is due on their car or locomotive operators of an impending failure.

An exploded view of the ARMS unit is shown in Figure 3. The current prototype unit attaches to the cap screws of the bearing cap via three locking rings. The unit extends from the bearing cap about two inches and is currently built mostly from aluminum. Future prototypes and the production units are expected to use high-impact plastic or other materials to reduce production costs.

Coleman Aerospace has successfully demonstrated the capability of the ARMS unit and identified the major hurdles and their solutions to commercialize the product. The field testing successfully demonstrated the extension of the concept to a new wireless, on-wheel hub-mounted ARMS unit that produced the expected data sets and transmitted them to the data collection unit.

The ARMS product could revolutionize monitoring the condition of equipment on the tracks as well as the track itself. The challenge to commercializing the system will be to keep the cost low.

Low cost is important because commercializing ARMS could shift direct responsibility for the cost to monitor the condition of railroad cars, from the railroad companies, who currently bear the cost of the wayside detectors (built into the rates charged to their clients), to the car owners. Further market research is necessary to assess the pricing for successful commercialization. However, to a point, these costs could be passed on to the railcar owners' clients.

Over time, ARMS will potentially provide significant savings from the reduced number of derailments, lives not lost to derailments, and reduced emergency repair costs that would justify this system.

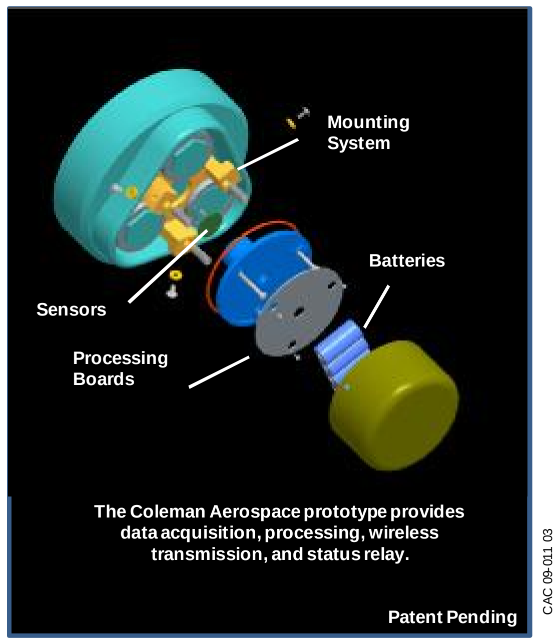

FIGURE 3. Exploded View of ARMS Unit

IDEA PRODUCT

The ARMS product is a system that monitors the condition and location of railcars in real time. The system communicates the condition to the train operators, either those on the locomotive or those monitoring the trains through the Positive Train Control (PTC) systems, and the train car owners or other authorized parties.

With the current level of development, the software is able to predict the need and many of the types of maintenance needed on the car's wheel bearings long before the critical point of failure. Other component wear the Coleman Aerospace ARMS unit will predict and detect include the following:

1) Thin flanges
2) Flat, cracked or otherwise excessively worn wheels
3) Wheel lift,
4) Truck derailment
5) Stuck, unreleased or dragging brakes
6) Insufficient lubrication
7) Worn shims and rings
8) Bowl rim damage
9) Bent or missing center pins
10) Wear on truck bolster gibs
11) Other problems that cause excessive lateral thrust or play in the truck or bolster bowl.

With further development, the ARMS product can detect certain abnormal railroad track wear if correlated with GPS location and multiple sets of data from different axles. The data sets from multiple units are expected to show the periodic shocks that some track defects will generate as each unit encounters the track defect. The harmonics will be from unit to unit instead of within one unit as with the defects confined to a single axle or wheel system. ARMS may even be used on cars in switching yards to detect abnormal shocks that are potentially damaging to the freight being transported.

With a small amount of further development, the system can be integrated with PTC systems, security systems, car refrigeration, temperature monitoring systems and related systems to give a complete picture of the condition and location of a railroad car and its contents.

CONCEPT AND INNOVATION

The innovative design of the ARMS provides features that other monitoring system concepts lack—simple installation, low cost per unit, self-forming network, and adaptability to integration with other systems.

Other systems have involved invasive installation methods, expensive replacement of components with upgraded parts, introduction of other potential failure points, expensive maintenance, and/or operating environment restrictions.

If there is widespread adoption, the ARMS product will eliminate the imprecise snapshot approach of the fixed trackside monitoring systems in use today such as the Hot Box Detector (HBD), Trackside Acoustic Detection System (TADS) and the Wheel Impact Load Detector (WILD). These systems are effective at providing warnings of problems that exist when a train passes the detectors, but fail to provide warnings between the trackside systems.

The ARMS product will provide continuous monitoring while the train is in motion to avoid the potential for certain catastrophic events caused by some component failures that currently can go undetected until a catastrophic failure occurs.

INVESTIGATION

STAGE 0 - INITIAL DESIGN

Stage 0 consisted of the physical design of all the printed circuit boards (PCBs), initial software development, and all simulation and test equipment required to support the ARMS units.

Stage 0 accomplishments were broken up into five tasks,

1) A Detailed Design & Fabrication
2) Inspection & Test of the Components
3) Porting of System Software to the Development Test Board
4) Porting of System Software to the Target Board
5) Integration of the Wireless Communications

Task 1 - Hardware Design

Single Board Computer

The first circuit board designed was the single board computer (Figure 4). This circuit board houses all of the analog circuitry and three digital processors. Because this was a first run design, all of the analog circuitry was designed in triplicate to test different methods of data collection. The single board computer contained over 730 components, is 12 layers thick, and is populated on both sides.

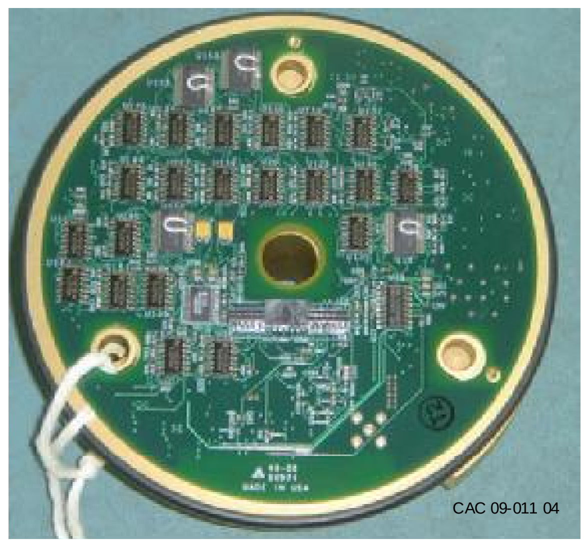

FIGURE 4. Single Board Computer

We evaluated three different methods for measuring the wheel rotational speed. The first was a rotation sensor, the second was a sine wave generator, and the third was a square wave generator. The rotation sensor was abandoned because it only worked in one direction and the ARMS unit would be required to measure rotation in both directions.

The sine wave generator and the square wave generator rotation speed measurement methods use signals obtained from the X and Y axes of the accelerometer. Using the relative phasing of the signals from these two axes, the ARMS determines the rotation direction and measures the frequency of either signal axis to determine the rotational speed.

Defects are detected by analyzing the accelerometer and microphone signals. Though both sensors have very different analog filters that detect specific signals, the digital signal processing for both sensors is the same. Dynamically adjustable gain allows the algorithm to increase or decrease the signal amplitude based on ambient conditions. Analog filters remove all unwanted regions of the frequency spectrum.

Processing is performed by one of three Texas Instruments MSP430 micro controllers. The MSP is the leading processor for battery conservation. In sleep mode, it consumes less than 4 uA.

The main processor provides the structure for the main operating system. The operating system is interrupt driven with priority to messaging. Temperature compensation of the main clock is performed routinely, but only affects external communication. This allows the system to continue functioning even in environments where clock skew prohibits communication.

All external messages are passed to a secondary processor that provides wireless connectivity via a 2.4 GHz 802.15.4 link. The 2.4 GHz band is an open band and does not require Federal Communications Commission (FCC) licensing for use as long as the transmitter is below 10 mW. Using the 802.15.4 format allows the ARMS unit to communicate with any device that complies with the format. The ARMS unit also has the ability to use 128 bit AES encryption but currently is disabled for testing.

The third processor is dedicated to data collection and the math associated with signal processing.

Daughter Card

The second circuit board is the daughter card (Figure 5). The daughter card houses all of the ARMS sensors. By building the daughter card module separately, sensors can be upgraded without re-spinning the more costly processor board. The daughter card comprises a three-axis accelerometer, a high-frequency microphone, a rotation sensor (to be eliminated on future cards), and a temperature sensor. All output signals are buffered with op-amps to ensure signal integrity.

CAC 09-011 05

FIGURE 5. Daughter Card

JTAG Board

The third PCB built is the Joint Test Action Group Integrated Circuit Interface (JTAG board) (Figure 6). The JTAG board is a diagnostic tool used only for programming the processors and communicating with the unit via a serial link instead of a wireless link. The JTAG board has no electronics, only connectors that are too large to be packaged on the processor board.

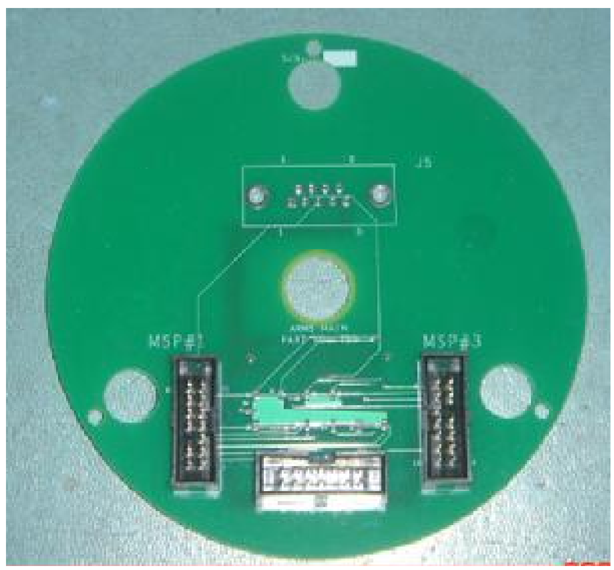

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FIGURE 6. JTAG Board

Task 2 - Inspection and Test

All boards and their components were inspected after production and tested for proper function. Several minor issues were discovered and improvements, changes, re-spinning of boards or part swaps were implemented to gain full functionality of the boards and their components.

Task 3 - System Software

Bearing Defect Simulation

The first task was to build a sample filter circuit to test and prove the concept of bearing monitoring. This circuit consisted of several op-amps in a band pass filter configuration with a frequency roll off of about 19 db. The purpose of the band pass filter is to isolate the specific portion of the spectrum for the bearing frequencies. The steep frequency roll off helps eliminate unwanted portions of the spectrum.

A simulated wave form generator was then designed using National Instruments LabVIEW^{TM} software. LabVIEW^{TM} provides a simple environment for integrating hardware to software and software to hardware interfaces. Using LabVIEW^{TM} , Coleman Aerospace was able to create a software package capable of producing the desired bearing defects based on the mathematical formulas used to derive our equations in the laboratory.

The bearing defect simulation software has several menus for user specified configuration.

The rotation rate noise versus the amplitude of the defect allows election of up to six different defects. Each defect specified is individually configured by entering the rotation rate and the relative amplitude.

Setting how each defect will react is done by configuring each of the defect frequencies independently. Amplitude and signal decay are set to further simulate how a defect would react since signal decay variances are often seen between different types of material and defect amplitudes versus speed.

Lastly, the rotation speed in mph is set and the defect simulation software is then ready to generate defect signals to test the ARMS unit.

Figure 7 is an oscilloscope screen capture showing two signals. The top signal, in yellow, shows the output of the bearing defect simulation software and the bottom signal, in blue, shows the resulting signal after it is passed though the sample filter circuit. The top signal shows several different characteristics. It shows a low frequency sine wave that represents the rotational speed of the wheel. The second noticeable characteristic in the yellow signal is a slight ringing. The higher frequency ringing is caused by the bearing defect. The blue signal is the result of the band pass filter on the yellow signal. The filter allows better analysis through the separation of the higher frequency ringing signal from the higher amplitude, lower frequency rotational speed signal.

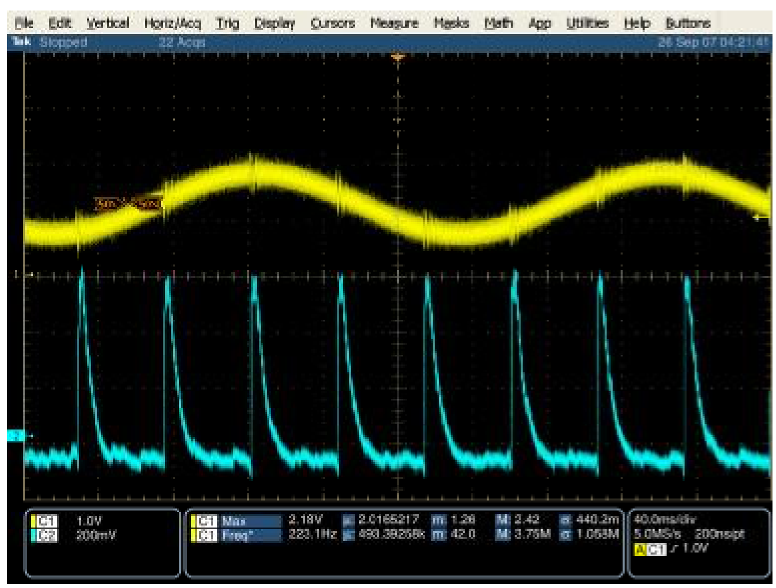

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FIGURE 7. Defect Simulation and Band Pass Filter

Bearing Defect Detection

A Windows-based software version of the detection algorithm was created using Visual Basic to test the algorithms with the simulator, and later ported to Visual C++® for the ARMS hardware. National Instruments LabVIEW™ was used to read in the raw data from the sample filter circuit which integrated into Microsoft Visual Studio®.

The bearing defect detection software program showed high-level statistics about cup, cone and roller defects. These statistics were averaged over multiple samples to achieve a high level of confidence. The software display shows the percentage of samples collected that contained the bearing defects being sought.

The software also displays the bearing defect information on a per reading basis. Each defect category (cup, cone, and roller) have a separate display to show the magnitude of each harmonic found. The algorithm detects the first, second, and third harmonic of each defect type and displays it.

The graphical display of the data for a roller defect produced by the algorithms is shown in Figure 8.

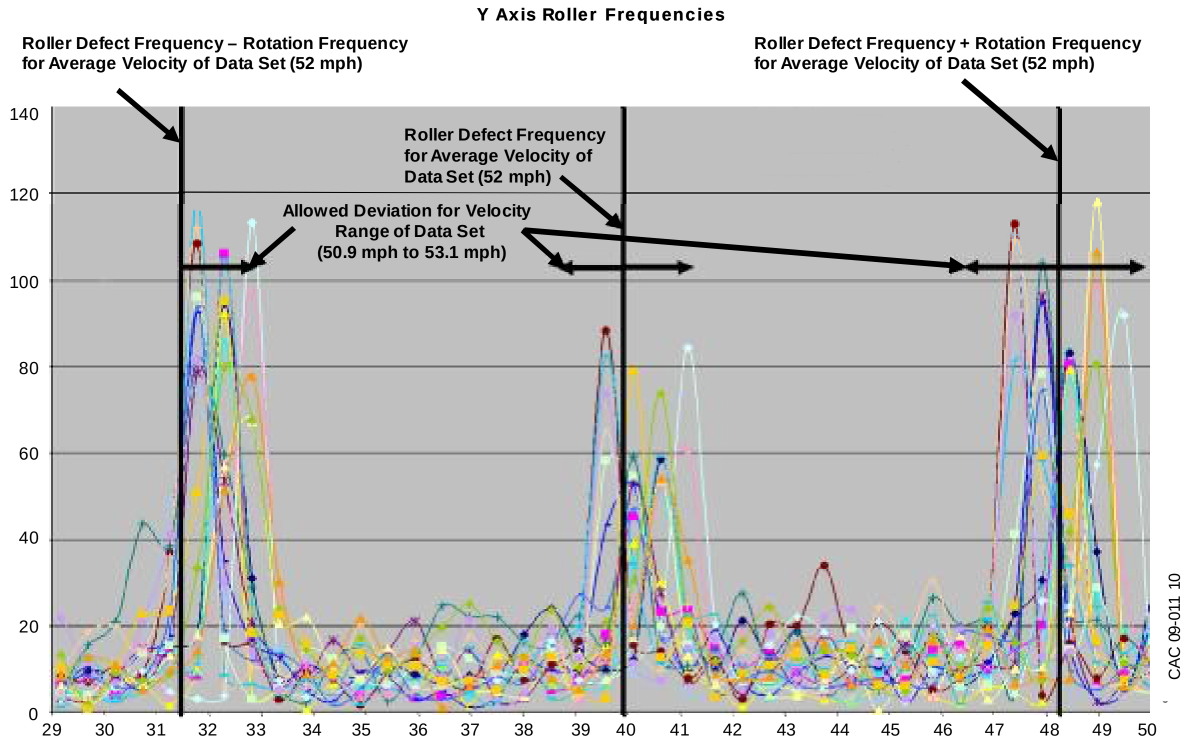

FIGURE 8. Accelerometer Signal for Roller Defect from On-track Testing

Integration

Over 2,000 lines of code were written to support the operating system, user interface, and algorithm processing. The first step during software integration was clock temperature stabilization. Because almost all software functions require accurate timing, clock stabilization was crucial. We found that the base clock had an accuracy of ± 15 percent, which was not accurate enough. We solved the accuracy problem by creating a function to track the ambient chip temperature and recalibrate the system clock any time the temperature changed ±2 degrees.

During testing, a user graphical interface was required to communicate with the ARMS units. Using Microsoft Visual Studio®, we connected the graphical interface to a PC's serial port. Standard RS232 commands were used, but we determined that a complete messaging format was needed. The program currently reads in a Microsoft Excel® spreadsheet which contains a decoding of all the current messages. Any time a message is added or removed, the user only needs to update the excel file to update the graphical user interface. Serial port communications were hard coded at 9600 baud. The user interface also has the ability to record log files and play back macros. Using the messaging system, one user interface can access many ARMS units. We also built in green and yellow indicators on the user interface to indicate which power rails on the ARMS unit were active at a given time.

Messaging

Messaging from processor to processor is based on a master/slave interface. The master processor tells the slave processors when to transmit and when to receive. This method of communication guarantees that there are no dropped messages. A cyclic redundancy check (CRC) could be implemented to further improve upon message integrity, but was not implemented in this phase. Messaging via the wireless link has the highest priority except when signal processing is taking place. Wireless transmit speed is capable of 250 K/s but message throughput is limited to 9600 baud to further improve temperature stability. Message throughput will only be taxed during the testing phase of operations since we will be gathering all data for analysis instead of samples and abnormalities. Normal system usage will not be affected by the limited throughput speed.

Once message processing was in place, command writing commenced. Currently, there are 150 individual user commands to and from the ARMS unit. Each command follows a four byte header which signifies a start of frame, message length, and the category of message being sent. Messages can be sent from the user directly to any of the three processors. A response message is sent if the message category requires it.

The user interface is a Windows® program developed by Coleman Aerospace which is menu driven. Users select specific commands from a drop down menu. Currently there are five unique dropdown categories.

1) The first category is system commands. System commands are the list of options available to an ordinary user. These commands are limited to daily use commands.
2) The second category is debug commands. Debug commands allow access to all functions of the ARMS units.
3) The third category is wireless commands. Wireless commands allow the user to communicate to specific ARMS units or to all ARMS units at once.
4) The fourth category is system alarms. System alarms are mainly informational messages showing the status of specific tasks.
5) The fifth category is system log files. Internal system log files are currently limited due to on chip memory. The log file system will be used to track system performance and system problems over extended periods. Currently all log messages are sent out the wireless link and captured as they happen by the user interface.

The user interface uses a Comma Separated Value (CSV) file at time of load to decode all messages. New messages are easily implemented by simply adding them to the CSV file and restarting the program.

Algorithm Refinement

Significant time was dedicated to algorithm refinement. Specific areas included speed determination, trending analysis, memory management, processing cycle efficiency and an overall stable operating environment.

Coleman Aerospace succeeded in significantly improving the speed determination algorithm throughout the speed range. The initial problem was that below 5 mph the algorithm would only see a 1 Hz signal. To improve upon the resolution we averaged multiple samples to increase the overall accuracy. This required taking samples over several seconds. To shorten the total algorithm time we ran the speed determination in parallel with the defect determination. This cut down the total processing time by three seconds.

Coleman Aerospace also improved the trending analysis algorithm which counts the number of times a defect and its harmonics are present and reports it as a percentage of the total samples taken. Currently, we are processing the last 255 times the algorithm has run. The final algorithm will calculate the percentages over a longer period to further improve the trending analysis.

To improve the software efficiency we focused on memory management and processing cycles. Since each processor only has 10K of RAM, memory management was crucial. Variables were used for multiple purposes and created in a global space to save on stack usage. Processor profiling was used to map the amount of time the processor spent in each function and mathematical operations were reorganized to increase processing speed while still maintaining the same level of performance. Monitoring the program counter and stack usage to ensure program flow culminated to produce a stable operating environment which ran reliably for extended periods of time.

Rotation Determination Circuits

There were three rotation systems implemented in the test hardware to determine the best system for our application.

Rotation Rate Chip

The rotation chip consumed a great deal of power, requiring 5V while the rest of the system consumed 3.3Vs. The rotation chip also only worked in the one direction and its maximum bandwidth was too narrow and by increasing the bandwidth it required a calibration. Coleman Aerospace does not see the rotation chip in this form as a viable option for rotation rate determination.

Sine Wave Rotation Speed Measurement Technique

Sine wave rotation rate determination is based on the raw three axis accelerometer outputs. As the accelerometer rotates it is exposed to a change in gravity. The result is a sine wave signal with a frequency that is proportional to the rotation rate. Using the X and Y axis we determined the rotation direction and achieved excellent accuracy of the rotation rate.

Square Wave Rotation Speed Measurement Technique

The square wave rotation rate determination is based on the three axis accelerometer outputs just like the sine wave rotation rate determination with the addition of analog filtering. The filters limit the instrumented speed from a minimum of 10 mph to a maximum of 55 mph, but processing the square wave requires much less effort then processing a sine wave. Either signal can be fed into a capture compare module (part of the processor) to further simplify processing. Provisions for the capture compare module are accessible on the ARMS main board, but due to time and budget constraints on this project it was not implemented. Currently, the square wave rotation method is the single method being used to determine the rotation rate. Further improvement will be made in the future by also modifying the filters.

Ambient Temperature Sensor

The ambient temperature sensor continuously records the temperature to allow trending. During railcar tests, it was observed that hub temperatures were proportional to rotation speed. Temperatures were fit into a windowed function and anything outside of that window is considered an event. In this version of the ARMS unit, the temperature sensor is not a primary sensor. Data from the temperature sensor is currently monitored, but not integrated into the algorithms. During the testing phase, it will be compared with the main algorithm as supplemental data. Figure 9 depicts a plot of bearing temperature in relation to velocity.

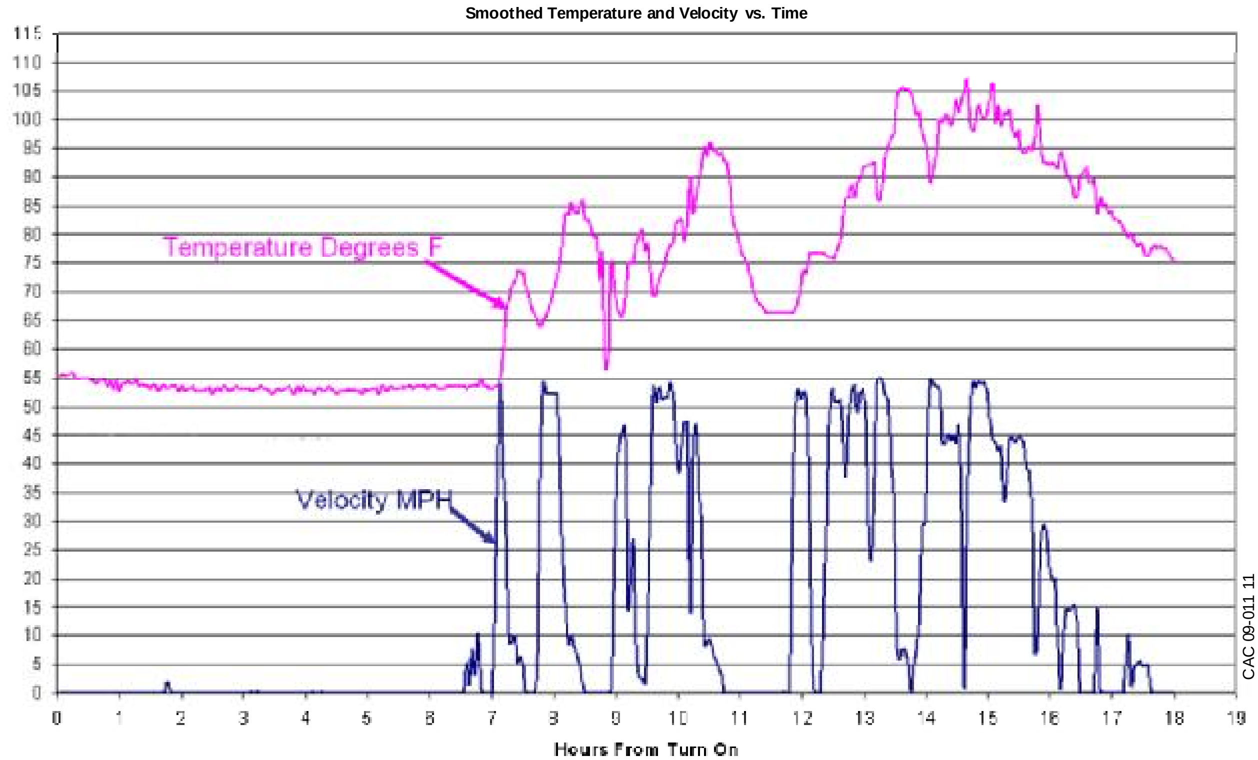

FIGURE 9. Bearing Temperature Related to Velocity

Acoustic Sensor (Microphone)

The ARMS unit has an acoustic sensor with a 20 Hz to 30 kHz frequency response band. The microphone supplements the accelerometers because the accelerometers do not respond to phenomena in the higher frequency ultrasonic range. Analog circuitry for the microphone is similar to that for the accelerometers with band pass filtering and dynamic gain. Because of the low frequencies expected from a bearing defect, the microphone will be a supplemental sensor. During the testing phase, data will be collected from the microphone and stored for post-processing and analysis.

Three Axis Accelerometers

The three-axis accelerometer is the primary sensor used for rotation rate and bearing signal data collection. Analog circuitry for the accelerometers is extensive with multiple taps for various functions. The three-axis accelerometer was selected for its sensitivity in the range necessary to detect bearing defects and its low power consumption. It is capable of seeing ±3g. The X and Y axis of the accelerometer moves forward/backward to the train's travel motion and up and down, while the Z axis moves from side to side. The Z axis will be used primarily to monitor hunting.

STAGE 1 – FIELD TEST PLAN & INTEGRATION

Task 6/7 – Comprehensive Test & Laboratory Integration

Data Collection Hardware

Due to the limited amount of memory on the ARMS boards, a data collection unit was necessary. During the initial on-wheel testing, the data collection unit was a truck tool box with a laptop computer and several car batteries (Figure 10). Coleman Aerospace found that this setup was not optimal for the next on-wheel testing and therefore, scaled everything down. For data collection, we used one of the ARMS prototype boards that contained 64 megabytes of flash memory. The prototype also contained a wireless transmitter for communicating with the wheel-mounted ARMS unit and a serial interface for communicating with the user interface. Because the unit is currently powered from a 3V source, lithium batteries were used. The unit draws less than one amp which allows an estimated 20 hours of data collection. Extra batteries were added to increase the unit's life and the available power. The housing was fabricated from extruded aluminum to make it lightweight and strong. Two, 300-pound magnets were built into the unit to assist with installation.

FIGURE 10. Original Data Collection Unit

Log Files

The prototype data collection unit has a 64 megabyte flash module that has 63 megabytes dedicated to the log files. All communication to and from the ARMS unit is recorded in the log files. Once the log files are extracted from the data collection unit, the data is decoded by the ARMS graphical user interface. Currently, all messages are shown in raw form and with their clear text decodes. This causes the log file seen by the user to quadruple in size. A current limitation of the log file system is the data rate. The data rate is currently set at 9600 baud for temperature stabilization. Increased speeds could be achieved with a clock stabilization routine, if necessary in the future. At this time, all log files are parsed by hand and imported into Microsoft Excel® as a space delimited file. Due to the volume of information, Microsoft Excel® is only able to process the first 32,000 lines. A separate program is being written to parse out each piece of the log file for quicker analysis in future testing.

Antennas

The original ARMS design had a PCB antenna built into the main board (Figure 11). An SMA connector was also designed into the main board to allow the use of an external whip antenna. It was determined that the ARMS PCB antenna was not functioning properly because it is located on the board and caused an attenuated signal from the prototype's aluminum cover. The production version will have a high-impact formed plastic housing instead of the aluminum one, thus eliminating this attenuated signal problem. Another issue discovered with the PCB antenna is that the trace thickness from an unplanned production substitution caused an imbalance with the antenna. With these problems, the PCB antenna still functioned, but with diminished range. A decision was made to use a ¼ wave whip antenna (Figure 12) for data collection and the PCB antenna will be used on future prototypes and in production.

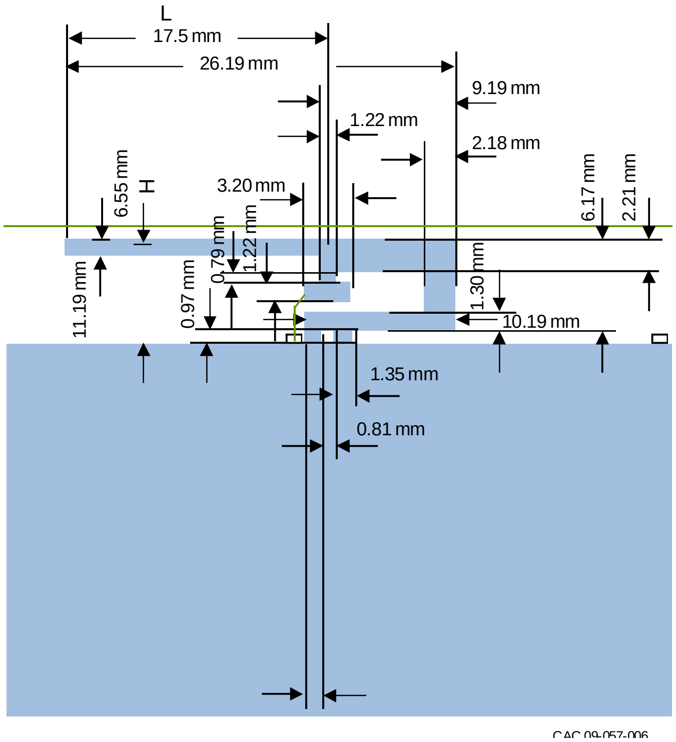

FIGURE 11. PCB Antenna Dimensions

Data Collection

The final ARMS product will need to output a minimal amount of information about its defect determination results. However, for debug purposes, the current unit outputs all of its raw data at each step of the algorithm process. The user interface offers a flag to enable and disable verbose data collection. When verbose data collection is enabled, the ARMS unit will output 1,024 readings for raw data collection, 512 readings for raw FFT results, 512 readings for normalized FFT results, 512 readings for linear least square fit results, average and standard deviation readings for all data. Each time the defect detection algorithm runs these data points and more are generated. The final result is a set of percentages showing the number of times the algorithm has run versus the number of times an anomaly like a defect was detected.

FIGURE 12. Wave Whip Antenna

During the first few train trips. data was collected in verbose mode. This was done to verify the accuracy of each portion of the algorithm. In verbose mode, each time the algorithm runs it is expected to consume 71 kilobytes of log file space. With the algorithm running every 30 minutes, it is estimated that there will be 450 hours of log file space.

Once the unit exceeds its log file space, it will continue to run and transmit data. However, the logging function will be disabled to protect the integrity of the recorded data. There will be a user command in the production version to erase the old log file as necessary.

The ARMS Units

Five PCBs were spun and populated. Of the five, two units were fully built for on-wheel testing and a third unit was held as a bench-top test unit. The two full units are mounted to the aluminum housings and a ribbon cable is mounted between the single board computer and daughter card. The next spin of the ARMS units will incorporate a socketed ribbon cable for quick disconnection.

Test points on the PCBs are limited due to their size, and during the board checkouts, it was determined that the 5V rotation sensor and the 5V regulator were not necessary. Future boards will not include these two items to conserve space.

The prototype ARMS unit external housing is a formed aluminum housing which Coleman Aerospace expects to replace with a high-impact formed plastic housing or other materials when put into production to reduce cost. When fully assembled the ARMS unit had diminished wireless range due to the current aluminum enclosure. For the two fully-built units, the external enclosure was modified with fiberglass windows to regain the range necessary for on-wheel testing.

STAGE 2 – ON-TRACK INVESTIGATION

Task 8 – System Integration and Test

Lab integration began with the software simulator. First, we determined the minimum and maximum speeds at which our ARMS unit would work. We then preset the minimum speed at 10 mph, but did not set a max speed limit. Next, we determined the maximum and minimum battery operating voltages. The maximum battery voltage was set to 3.7V while the minimum operating voltage was set at 2V. The system was set to return to low power mode until commanded by the user once it read three consecutive low-voltage measurements. System stability was evaluated by performing several overnight runs. All data was recorded on a real-time, PC-based log file system and reviewed. The system was then evaluated for any overflow conditions or bugs that would either cause the system to crash or result in erroneous data measurements.

Task 9 – System Test

System testing comprised two components. The first was the ARMS unit and the second was the data collection unit. The data collection unit is a wireless receiver capable of storing all data transmitted by the ARMS unit. Each ARMS message was estimated to be about 13 bytes long, and the average ARMS signal processing size will be 4,000 bytes. The ARMS unit has two transmit modes, normal and verbose. All testing was performed in verbose mode. Verbose mode transmits all the data points of every operation of the signal processing algorithm. Each time the bearing detection algorithm runs, it produces roughly 4,000 bytes of data. The data collection unit is estimated to be capable of recording 16,000 complete algorithm data sets. The ARMS algorithm was set to only turn on when the train exceeds 10 mph and collected data continuously at 10 minute intervals. Current battery power on the test data collection unit was estimated to be capable of producing the power necessary for a one week trip. Battery power was the first entry in the log file and was recorded every hour as part of the system check up routine. This aided in tracking power consumption and system performance.

Data collection consisted of the following components:

1)	Speed	the average of two readings
2)	Z acceleration	1024 Values
3)	X acceleration	1024 Values
4)	FFT result	512 Values
5)	Normalize Data	512 Values
6)	Linear Fit	512 Values
7)	Average and STD	20 Values
8)	Defect determination	9 Values
9)	Number of times run	1 Values

Data review was planned to plot as many runs as possible, given the prototype's limitations on memory and power, to compare the values and trends. The defect determination portion of the code showed the percentage of readings in which a bearing defect was determined for the roll, cup, and cone algorithm.

Task 10 – On-Wheel Test

The on-wheel test results for the new wireless, hub-mounted system produced the expected data sets as predicted from the work in the laboratory. Data analysis also showed the expected variances in the signals from the accelerometer and temperature sensors. Coleman Aerospace considered the on-wheel testing to be a successful extension and demonstration of the new on-wheel data collection system (Figure 13) using the algorithms previously tested in the laboratory.

The new mounting system was designed to be fast and easy to attach while surviving the expected vertical and lateral g forces. Though the specific g forces encountered were not recorded in these tests, the mount, the systems electronics, and its batteries survived the on-wheel testing without signs of eminent failure.

In future work, Coleman Aerospace will continue to refine the algorithms and document the output from various bearings in various stages of known wear or deterioration. It is a continued expectation that even on well-maintained trains; some bearing defects will be present with their amplitude being lower than on more severely damaged units. Coleman Aerospace will also reevaluate the mounting system on future prototypes and complete specific shock testing in the lab and on-track to test the survivability of the mounting system and all other components. In addition, the on-track testing of future prototypes will test the survivability of the unit in various weather conditions.

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Truck-mounted Prototype Hub-mounted Prototype

FIGURE 13. Prototype Testing

PLANS FOR IMPLEMENTATION

Coleman Aerospace plans to team with a commercial partner that has the marketing network and appropriate industry experience. It is our expectation that future work will incorporate further data analysis and a full test of the system including following:

1) The on-wheel unit
2) The full network and its limitations within a working environment where all train cars are not carrying the ARMS unit
3) The data collection unit and the transmission of data to the train operators and a central location off the train.

Coleman Aerospace has succeeded in demonstrating the capability of the ARMS unit and identified the major hurdles and their solutions to commercialize the product. Coleman Aerospace plans to initially focus on monitoring the condition of the bearings and as more data is collected and analyzed will also monitor other conditions on the railcar.

In future follow-on work, Coleman Aerospace will also be able to obtain additional real-time feedback from train operators and maintenance personnel to incorporate into further refinement of the product and marketing efforts.

CONCLUSION

Coleman Aerospace built several working ARMS boards for bench-top testing units and fully operational, ready-to-mount, units. Software development gains were significant with the development of a defect generator, a defect detection simulator, and the target code.

PCB manufacturing and engineering design was streamlined to meet the challenging schedule demand of this program and boards were designed, procured, manufactured, and tested within a short period of time with few engineering issues.

Basic wireless communication was implemented with a full 802.15.4 compliant stack. The current version of the wireless code does not have all of the mesh networking implemented. Full testing of the limits of the currently conceived wireless network is a future goal when more ARMS units are built and mounted on the same train.

Serial communication was not needed as originally planned because wireless communication had progressed further than expected at an earlier stage. Using off the shelf 802.15.4 compliant receivers, Coleman Aerospace was able to quickly connect to the ARMS units using a PC. The user interface on the PC captured all incoming data and stored it to a log file for processing. This real-time interface improved all aspects of system development.

Algorithm testing, porting, and verification went extremely well in the lab. Verification of the algorithms was compared and verified against the simulated data while windowing functions were used to further enhance the algorithm performance before testing in the field.

The field testing successfully demonstrated the extension of the concept to a new wireless, on-wheel hub-mounted ARMS unit that produced the expected data sets and transmitted them to the data collection unit.

Future work planned by Coleman Aerospace will be continuous refinement of the algorithms that collect data from the hub-mounted system. Expected results will be compared with actual results during more on-track testing with/without actual components in known failure situations or various stages of wear or deterioration. It is a continued expectation that even on well-maintained trains; some bearing defects will be present with their amplitude being lower than on more severely damaged units. Over the course of multiple trips, numerous data sets will be collected at different speeds to provide ample insight into the future performance of the ARMS unit and its ability to monitor and predict bearing failure in real time.

In addition, future work will incorporate extensive system shock and weather testing. The harshness of the railroad environment cannot be underestimated; especially in the case of the un-sprung wheel/axle assembly on which the ARMS unit is designed to be mounted. Testing is expected to result in data from shocks up to 100g and analysis to incorporate weather-proof housings and vandal-proof attaching mechanisms.

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