Advanced diagnostics and anomaly detection for railroad safety applications: Using a wireless, IoT-enabled measurement system

Conference Paper · November 2015

DOI: 10.1109/AUTEST.2015.7356502

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ACCURATE VIBRATION AND SPEED MEASUREMENT ON ROTATING SHAFTS USING MEMS AND IoT SINGLE WIRELESS TRIAXLE SENSOR

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Abstract: Industrial equipment, robotics and gear boxes that incorporate rotating shafts often need to monitor rotational vibration and shaft speed, as part of broader condition-based maintenance (CBM) systems. Existing sensor implementations on rotating shafts, including pinion and planetary gears, have been limited by cabling, slip-ring approaches, and multiple sensors to obtain monitoring information. A practical solution is a self-contained, compact, single triaxle sensor design based on micro-electro-mechanical systems (MEMS) technology and an internet of things (IoT) wireless communications.

Ridgetop Group has designed and developed such a triaxle MEMS sensor: RotoSense™. RotoSense is capable of measuring shaft speeds of up to 5500 RPM, while streaming accurate rotational vibration and shaft speed measurement data on a continuous basis. Each sensor possesses its own IP address, which supports remote monitoring over the internet. Applications can range from industrial equipment to transportation systems.

This paper describes the MEMS sensor for monitoring of two example applications: (1) a helicopter gearbox, and (2) conditioning monitoring of a railroad track.

Key words: helicopter; internet of things; MEMS; micro-electro-mechanical systems; wireless communication, railroad track; rotor shaft; triaxle.

Introduction: Industrial equipment, robotics and gear boxes that incorporate rotating shafts often need to monitor rotational vibration and shaft speed, as part of broader condition-based maintenance (CBM) systems. Fault detection equipment on drive systems, such as those use for land, sea, and air vehicles, typically use accelerometers mounted on transmission housing to capture, measure, and process vibration signals. The usefulness and flexibility of such detection equipment for applications involving rotating shafts, including pinion and planetary gears, have been limited by cabling, slip-ring approaches, and multiple sensors to obtain monitoring information. For more complex systems, especially those with poor signal transmission paths, a shaft-mounted, wireless solution based on a micro-electro-mechanical system (MEMS) is needed: a block diagram of prototype MEMS-based solution is shown in Figure 1.

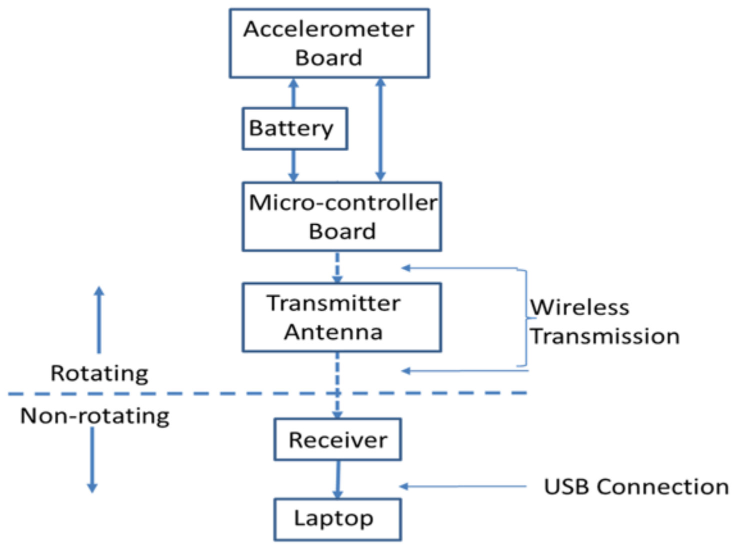


Figure 1: Block Diagram of the RotoSense MEMS.

An example application is the rotating shaft and gears used in helicopter transmissions. The NASA Glenn Research Center awarded Ridgetop Group a Small Business Innovation Research (SBIR) contract to design and develop a prototype MEMS-based solution, such as the one shown in Figure 1, to be embedded on shafts used in helicopters to capture and measure vibration signals. An illustration of a helicopter transmission (OH-58C model) is shown in Figure 2.

Shaft Mounted, Helicopter Pinion Gear: Prototype triaxle-shaft-mounted MEMS sensors, called RotoSense™, were installed on pre-notched OH-58C spiral-bevel pinion gears (see Figure 2), endurance tests were performed, and the tests run to tooth fracture failure: the notch was extended at run time = 51.9 hours and widened at run time = 106 hours. Most of the four stationary accelerometers mounted on the gear box housing and most of the CI's used gave indications of failure at the end of the test.

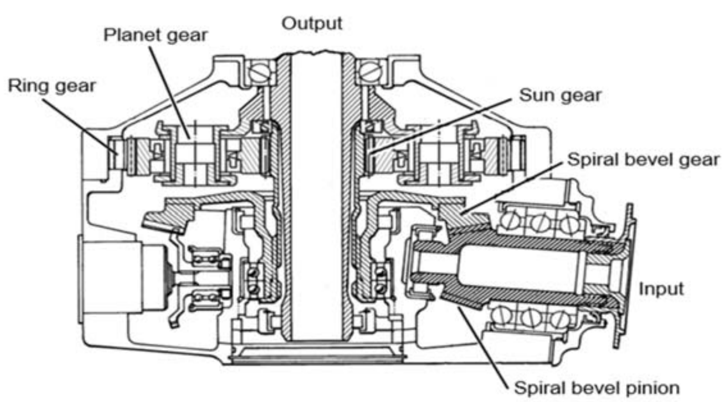


Figure 2: Illustration of an OH-58C Transmission.

The MEMS system (Figure 3) performed well and lasted the entire test. All MEMS accelerometers gave an indication of failure at the end of the test. The MEMS systems performed as well, if not better, than the stationary accelerometers mounted on the gear box housing with regards to gear tooth fault detection (Figure 4). For both the MEMS sensors and stationary sensors, the fault detection time was not much sooner than the actual tooth fracture time. The MEMS sensor spectrum data showed large first order shaft frequency sidebands due to the measurement rotating frame of reference. The method of constructing a pseudo tach signal from periodic characteristics of the vibration data was successful in deriving time-synchronous-average (TSA) signals (Figure 5) without an actual tach, and proved an effective way to improve fault detection for the MEMS [Lewicki, et al 1].

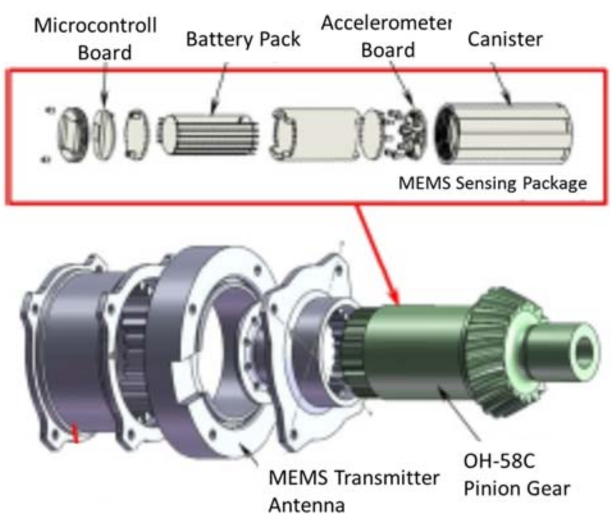


Figure 3: Diagram of MEMS Sensor Mounted on an OH-58C Pinion Gear.

Figure 4: Failed Pinion Gear – Fractured Tooth of a Spiral-Bevel Pinion.

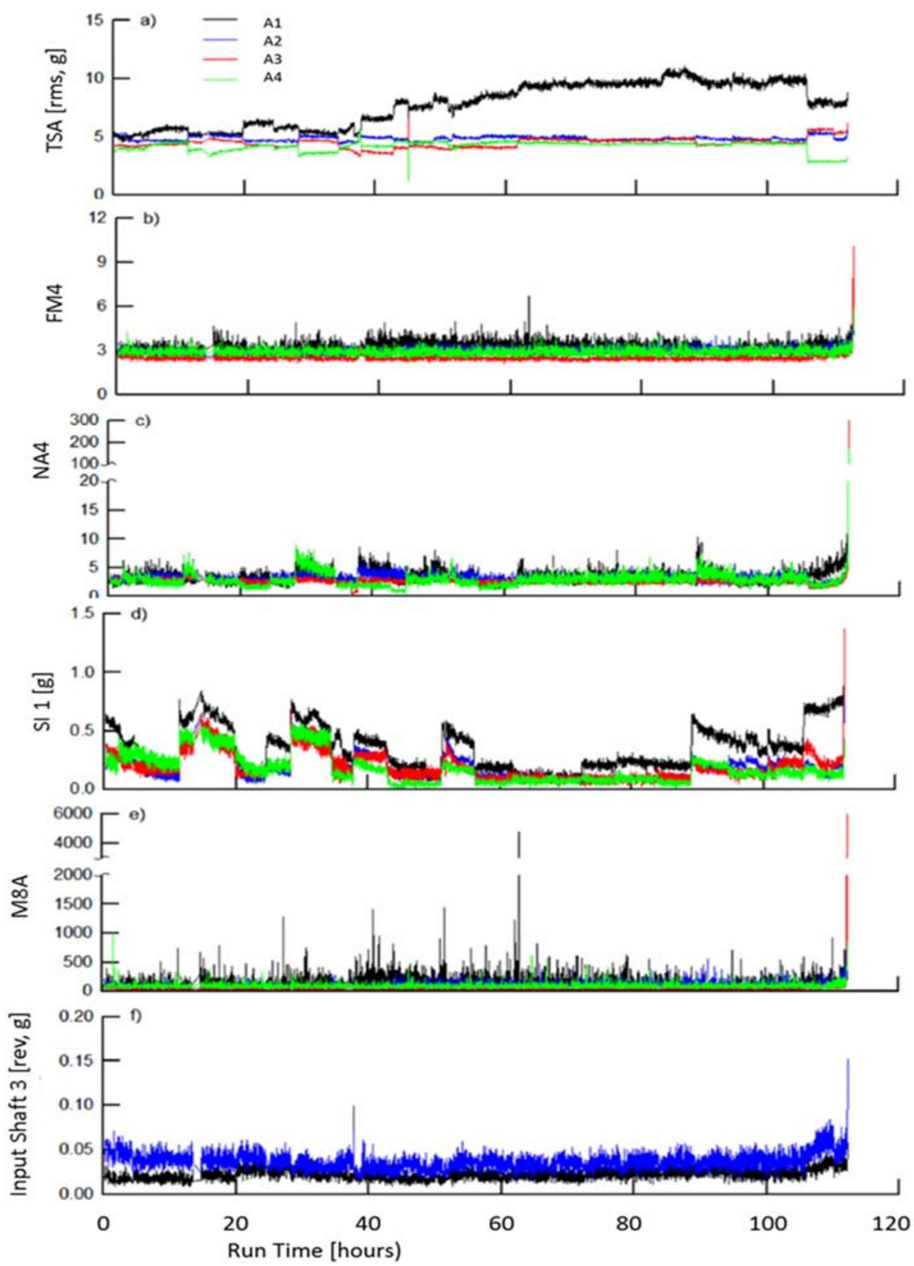


Figure 5: Fault Detection, Condition Indicators, Entire Test.

Wheel-Mounted MEMS Sensor, Railroad Track Monitoring Application: The MEMS sensor was adapted as an experiment for mounting on wheel hubs of the shafts of the trucks of train engines and cars. The experiment was to prove feasibility for using such sensors to locate and identify anomalies related to railroad tracks. Referring to Figure 6, the adapted system comprises a MEMs sensor and a gateway to collect data, collate data with positioning information from Global Positioning Satellite (GPS), and write data to disk storage as files. The MEMS sensors mounted on wheels of a train produced shock data during test runs of a train over a High Tonnage Loop (HTL) test Track (TT) to process the data, identify high-force events (HFEs), and locate the position on the HTL TT where HFEs occurred. A demonstrated ability validates the use of RotoSense and Sentinel Suite to provide a Track Anomaly Detection capability to support focused inspection of tracks to identify and locate anomalies requiring monitoring and service to include replacement.

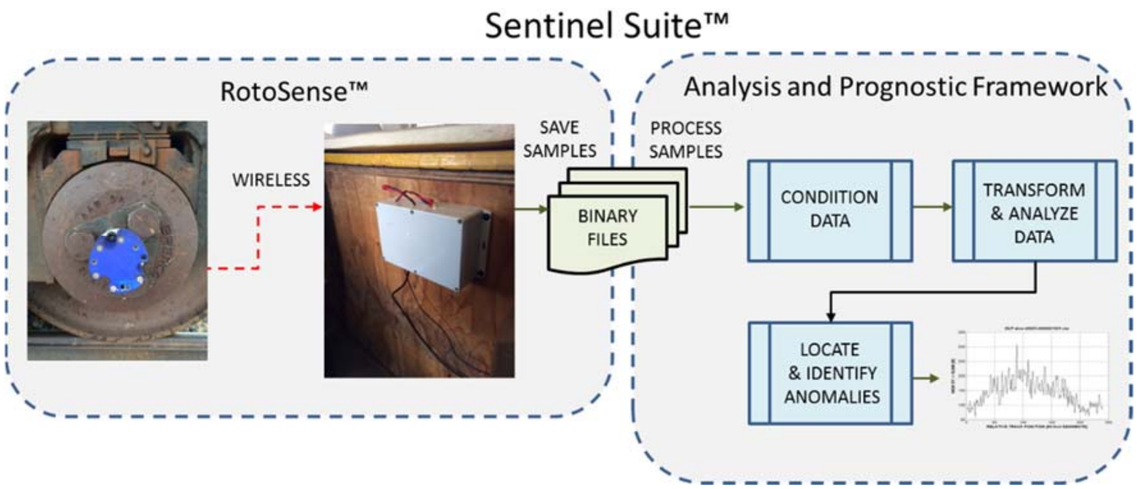


Figure 6: Block Diagram of RotoSense and Sentinel Suite.

After several days of experiment setup, such as mounting the sensors on wheel hubs and building a test train at the National TT Center in Colorado, it was discovered the antenna system for collecting Global Positioning Satellite data had been damaged and been disabled during installation. The challenge then was to prove we could identify and locate anomalies without GPS data.

Experiment Description, National TT Center, Colorado: The test train comprised three (3) locomotives and 110 freight cars and was run on the HTL TT used for research under heavy axle-loads to test track-component reliability, wear, and fatigue. The HTL track length is 2.7 miles divided into test sections that generally correspond to tangents, spirals, curves, and turnouts that are populated with features and test sections, as seen in Figure 7. Table 1 lists the features of the TT, some of which are shown in Figure 8 and Figure 9. Fast-train operation is restricted to a maximum 40 miles per hour.

Table 1: Features of the HTL TT

1. Lubricator	2. Steel Bridge	3. Crib Ties
4. 405 turnout and frog	5. Thermite Welds	6. Rail Temperature
7. Rail Performance Test	8. Concrete Bridge	9. LTM Tests
10. Machine Vision	11. Fiber Optic cable	

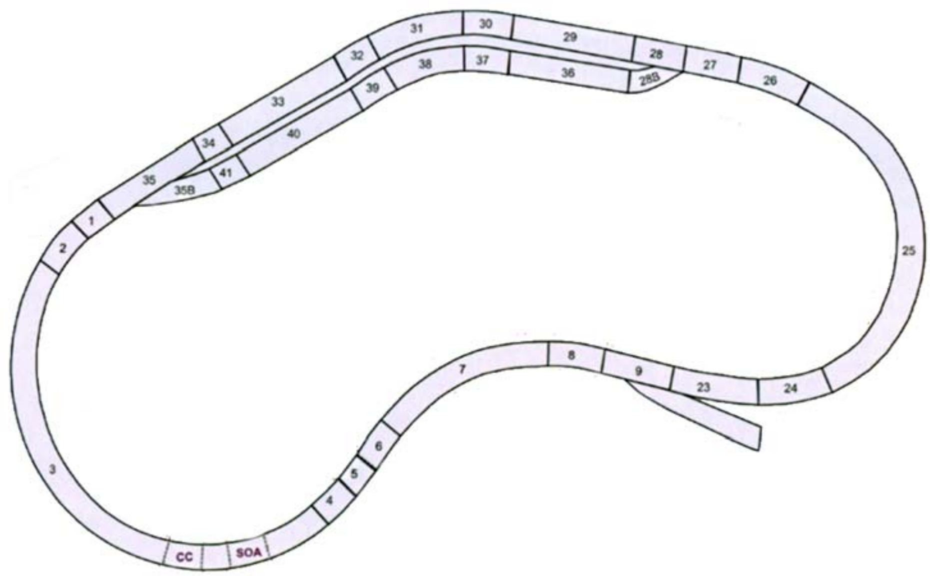


Figure 7: Layout of the Heavy Tonnage Loop Test Track.

[A] [B] [C]

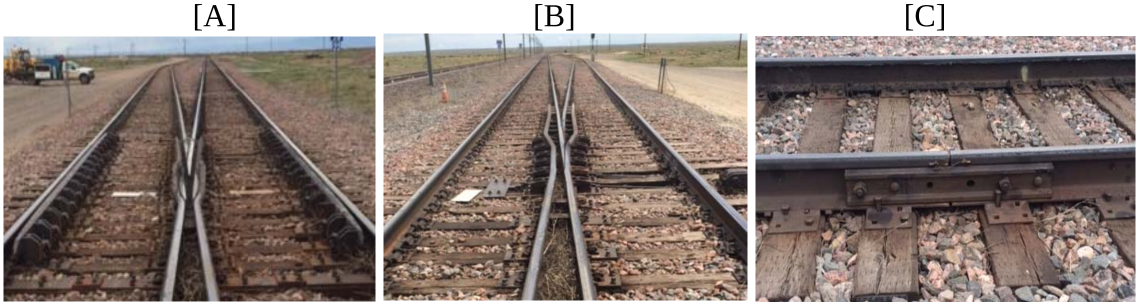


Figure 8: Turnout and Frog, Switch left [A] and Switch Right [B]; Steel Bridge [C].

[A] [B]

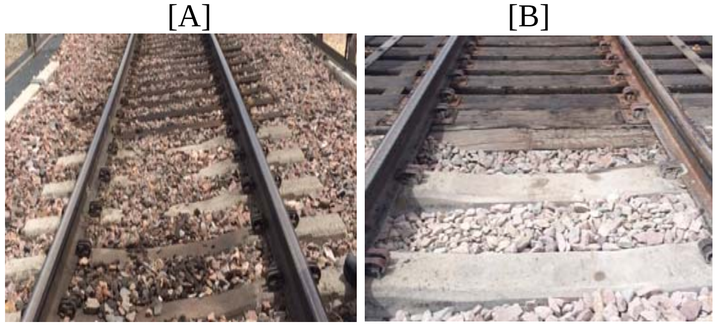


Figure 9: Concrete Bridges [A]; Crib Ties, Top of [B]; Concrete Bridges, Bottom of [B].

MEMS Configuration and Test Setup: The configuration of RotoSense for train applications includes a MEMS sensor and supporting firmware and software to support collecting, wirelessly transmitting data to a gateway, and saving data in binary files. The RotoSense modules are mounted to rotate with the axle so any anomalies in the wheels or track can be detected. The MEMS is configured as a three-axis accelerometer with 57mV/g sensitivity with a 161 Hz sampling rate: sensor was mounted concentrically on each end of a freight car axle and also on a locomotive axle of a train (see Figure 10).

The train was auto-controlled to run 15 laps per hour: 4 minutes per lap and 38,640 samples per lap. Four test runs were started on four days in 2015: May 11 – May 14. The data from the test run started on May 14 from 2000 to 0632 (10 hours, 32 minutes and over 4 million sets of six-byte data.) is analyzed: that test run is summarized in Table 2. Data was collected and buffered for each axis at a sampling rate of 161 Hz and the buffered data was transmitted to a collection hub and saved in output files about once every 1.11 seconds. The data was analyzed, nominal values determined for zero-force conditions, and transformed into +/- values with respect to zero-force.

The train started to move about 30 minutes after the sensors were turned on: the train was moved to the test track and two laps of test conditioning were run. After that, the train was kept at a constant speed of 15 laps per hour (4-minute laps).

Figure 10: MEMS Sensor Mounted on an Axle

Table 2: Summarization of the Test Run Started on May 14, 2015

Description			Comments
Train	3 locomotives 110 cars		6,780’ long (1.3 miles). Hopper car lengths, coupler to coupler, range from ~58.5 to 60.5 feet: used 60-foot length.
Build	92 minutes		2000 start; 2132 completed build
Run	540 minutes	132 laps	2132: started test conditioning run (TCR)
	17 minutes	2 laps	2149: completed TCR
	518 minutes	129 laps	2149 – 0627: testing
	5 minutes	1 lap	0632: end of test
Wheel 1	20645 files		
Wheel 4	20565 files		

Data Analysis: A first step was to synchronize the data (see Figure 11) to the movement of train onto the TT, which was accomplished using the record numbers of data. Sensor data was conditioned by normalizing to the measured steady-state values prior to movement of the train: X0 = 31,488, Y0 = 32,256, and Z0 = 32,768.To emphasize total force, the x-, y-, and z-direction forces were further transformed into XY- and Z-vectors (see Figure 12 and Figure 13) after noise suppression.

The XY-vectors were classified into groups and binned into the defined track sections of 240 bins. Each XY-vector represents the total measured force per sample in a plane vertical to the railroad bed and each Z-vector represents the total measured force per sample in a plane horizontal to the railroad bed.

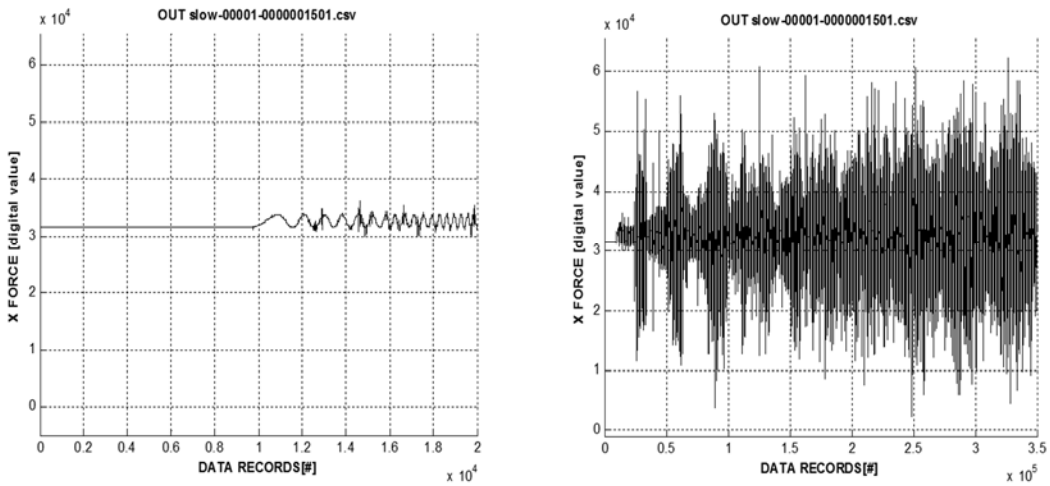


Figure 11: Train Movement [A]; Two CR laps and Three At-speed Laps [B].

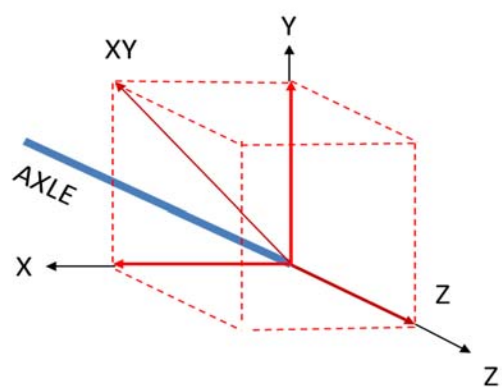


Figure 12: Transformation of X-, Y-, and Z-direction Forces into XY- and Z-vectors.

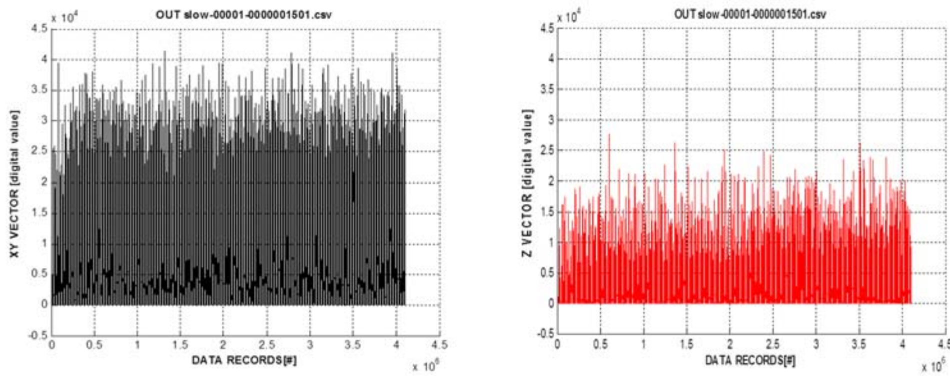


Figure 13: XY- and Z-vector Magnitudes.

RotoSense data is synchronized to the physical track and a starting point selected to correspond to railway identifier S1. The analysis included the following and resulted in the plots shown in Figure 14 and Figure 15 :

1. Start with RotoSense output data file numbered 1501:
2. Start lap processing after sample number 237,120:
   a. 161 samples each second
   b. Each lap = 240 seconds: 38,640 samples
   c. 99 laps of data processed: 3,825,360 samples
   d. Perform analysis using railway lap of 240 sections (1 second of data each)
   e. Selected starting point believed to be the start of S1 shown on the left side of the map shown in Figure 7 on page 6

[A] [B]

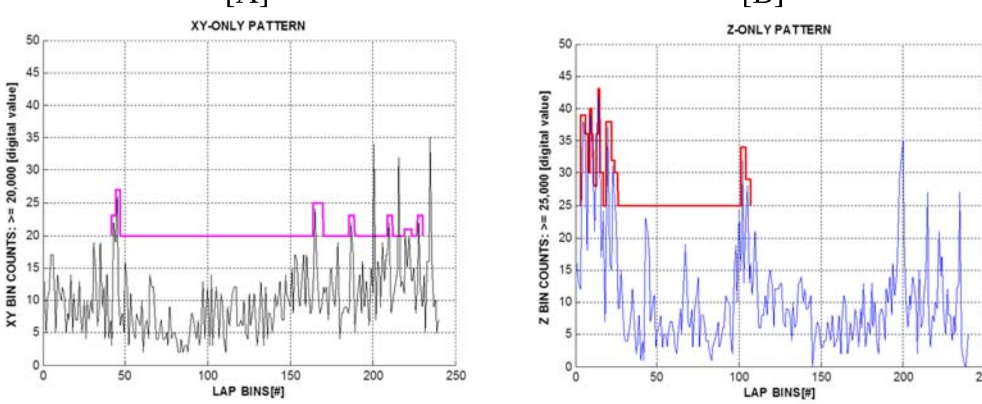


Figure 14: XY-Only Pattern [A] and Z-Only Pattern [B] (No Significant Overlap).

[A] [B]

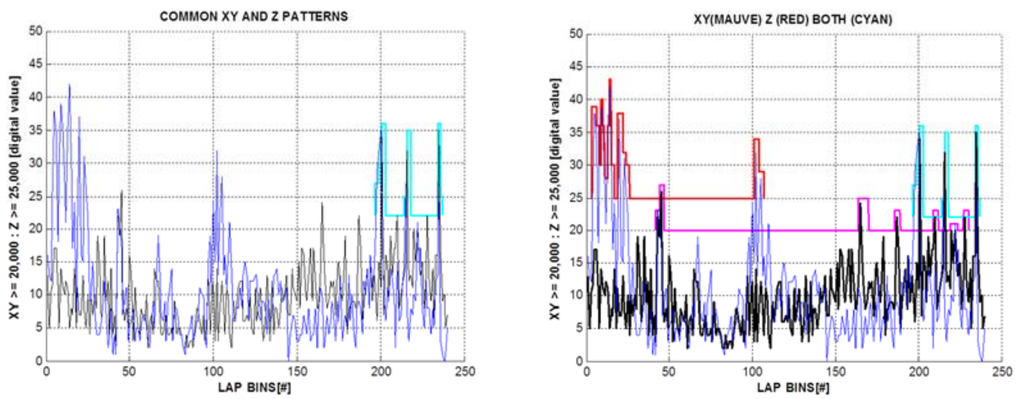


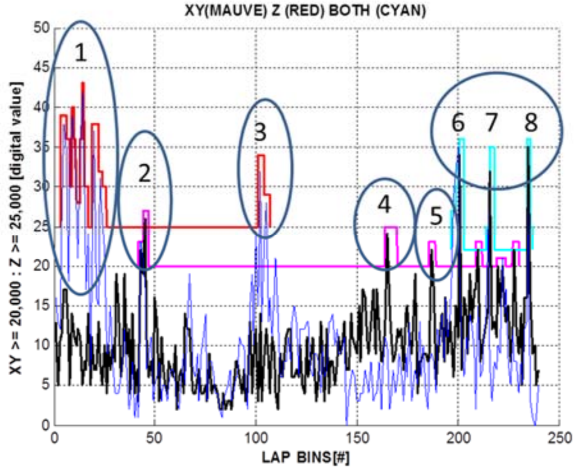
Figure 15: Overlapping XY- and Z-vectors [A]; Composite Patterns [B].

Detected Features: A primary objective of the data analysis was to show that even without GPS, the captured RotoSense data could be used to identify and locate significant railway features such as turnouts. Examination and comparison of Figure 16 and Table 3 on page 11 shows the primary objective is met:

1. All seven of the features evaluated as detectable were detected: feature 1 and 3 through 8.

2. One of the two sets of concrete bridges evaluated as "maybe" was detected (feature 2), the other was not.

3. None of the features evaluated as not detectable were detected.



1. Repair/overlay welds, concrete bridge
2. Concrete bridge
3. 405 turnout and frog
4. TPO, tie and fastener, performance
5. Turn out, steering switch, foundation
6. FRA, rail-set deterioration, welds
7. Crib ties
8. 407 turn out

Figure 16: Correlation Results of Comparing Data to Track Features.

Table 3: Test Track Description and Detection

Track Sections	Feature Sections	TT ID	Track Feature	Detection Evaluation	
				XY-vector	Z-vector
1 – 3		S1	Lubricator	ND	ND
4 – 5		S2			
6 - 62	5-26	S3	Repair/overlay welds		Yes (1)
	30-40	S3	Concrete bridge	maybe	maybe
	42-46	S3	Concrete bridge	maybe	Yes (2)
63 – 66		S4	Steel bridges	ND	ND
67 – 69		S5	Bridge deflection	ND	ND
70 – 73		S6	Steel bridges	ND	ND
74 – 92		S7	Rail performance	ND	ND
93 – 97		S8	Fiber optic cable	ND	ND
98 – 108		S9	405 turnout/frog		Yes (3)
109 - 117		S23	405 turnout/frog		Yes (3)
118 – 125		S24	Lubricator	ND	ND
126 – 163		S25	TPO, Tie and fastener, performance	Yes (4)	
164 – 170		S26			
171 – 175		S27	Lubricator	ND	ND
176 – 180		S28	Turn out, steering switch, foundation	Yes (5)	
181 – 193		S29	LTM Tests	ND	ND
194 – 198		S30			
199 – 208		S31	FRA: Rail-seat deterioration, Thermite welds	Yes (6)	Yes (6)
209 – 212		S32			
213 – 225		S33	Crib ties	Yes (7)	Yes (7)
226 – 229		S34			
230 - 240		S35	407 turnout	Yes (8)	Yes (8)

Note: ND means Not Detectable.

Conclusion: This paper presented the results of applying a tri-axle MEMS sensor for monitoring of two example applications: (1) a helicopter gearbox, and (2) conditioning monitoring of a railroad track. For the helicopter application, the MEMS systems detected a tooth fault on a spiral-bevel pinion gear and it did so better than the stationary accelerometers mounted on the gear box housing. For the railroad track application, despite the loss of GPS for synchronizing MEMS data with locations on the track, the system performed very well: (1) the sensors did not fail physically or electrically (TT center personnel informed us that similar test resulted in physical and/or electrical failure); (2) all seven railroad track features evaluated as being detectable were, in fact, detected; (3) one of the two sets of concrete bridges evaluated as maybe detectable was detected; and (4) all of the features evaluated as not being detectable were not detected.

Reference:

[1] Lewicki, D.G.; Lambert, N.A.; and Wagoner, R.S.; Evaluation of MEMS-Based Wireless Accelerometer Sensors in Detecting Gear Tooth Faults in Helicopter Transmissions, 2015, NASA/TM-2015-218722.