Effective Conveyor Belt Inspection for Improved Mining Productivity

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Abstract

This document details progress on the project “Effective Conveyor Belt Inspection for Improved Mining Productivity” during the period from November 15, 2005 to May 14, 2006. Highlights include significant improvements in the accuracy and reliability of computer-vision based vulcanized splice detection, deployment of the vulcanized splice detection algorithms for daily use in two working mines, and successful demonstration of an early prototype of a Smart-Camera based system for on-site mechanical splice detection in coal mine installations,.

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1 Introduction

This report presents technical progress on the Effective Conveyor Belt Inspection for Improved Mining Productivity project, funded under U.S. Department of Energy award number DE-FC26-04NT42086.

The overall objective of the three-year project is to develop and commercialize a low cost conveyor belt inspection system for use in underground and surface mines, coal-fired power generation plants, and other large scale material handling operations. Mining operations rely on conveyor belts to move mined material from the working face to a processing plant. When a conveyor belt breaks or its operation is halted for unscheduled maintenance, there are often high costs in terms of lost productivity. For example, a mainline belt break in a longwall mining operation generally stops production for at least four hours. Concomitant revenue losses typically exceed \$240,000. CONSOL Energy has identified belt availability as one of the top two productivity bottlenecks in their operations today. Furthermore, belt repair under typical mine conditions is difficult, dangerous work. The system under development will help to reduce the negative impact of belt failure on production while improving worker safety.

During this 6-month period, we have focussed on two primary efforts. First, we are developing computer-vision algorithms to detect splices and defects in material conveying belts, with the goal of mine management of specific belt problems areas prior to failure. This will help eliminate catastrophic belt failures by providing managers with the information necessary to schedule maintenance activities during planned maintenance periods. Second, we are developing low-cost Smart-Camera based conveyor belt inspection hardware which includes cameras, lighting, communications systems, and processing capability. The availability of a low-cost belt inspection system will allow mine operators to monitor all of the production belts in a mine, thus enabling its predictive maintenance capabilities to be applied broadly across a wide range of mine operators and conveyor belt types.

This project leverages a multi-year investment by CONSOL Energy for the National Robotics Engineering Consortium (NREC) at Carnegie Mellon University to successfully develop a belt inspection system for detecting mechanical splices.

The project continuation proposal describes the second-year objective as follows:

Budget Period 2 Objective

Complete tests and refinement of vulcanized splice algorithm on operating belts. Build, test, and demonstrate smart camera, which is the basic component of the low cost Belt Vision system for detecting mechanical splices. Install prototype on operating belt. Integrate vulcanized splice detection in working system and add full resolution recording capability to the Smart Camera. Determine if the engineering challenges associated with rip detection via structured light can be overcome. Continue test and development of RFID tags. Integrate into Smart Camera splice ID capability via RFID tags. Develop splice-numbering capability based on an input to camera that uniquely identifies a particular splice. Evaluate algorithms for detection of edge tears, which frequently are associated with failing vulcanized splices.

The following sections describe progress toward this objective.

2 Executive Summary

This 6-month period includes several noteworthy achievements, which are summarized here. More detailed discussion of these accomplishments is presented in sections 3 and 4.

Vulcanized splice detection algorithm installed on operating belts The prototype vulcanized splice detection algorithm has been significantly refined. An initial executable has been released and installed underground at both the Robinson Run and Blacksville mine sites. These systems are in daily use for testing, belt inspection and data gathering.

Initial packaging of vulcanized splice detector completed A GUI-based application has been written to allow easy control and testing of the vulcanized splice detection code. The application includes graphing capabilities to assist in visualizing program output. A screenshot of this application is shown in figure 1.

Feasibility demonstration of Low-Cost Smart-Camera completed A laboratory prototype of a low-cost smart-camera based belt inspection system was developed and shown to reliably detect mechanical splices in an above-ground demonstration.

16 developmental systems currently deployed A total of 16 pre-production (PC-based) low cost systems have been deployed underground in 7 different mines, including two at commercial customer sites.

Beitzel Corp is continues to produce and sell a very low volume of the pre-production low cost systems The logistics of deploying and supporting a system in mines dictate a cautious approach. Beitzel Corp is also continuing to survey belt managers for input into desired system features and potential new target markets.

More than 2 million cumulative miles of belt inspected by deployed evaluation systems In early 2005, the total inspected belt length passed the 2 million mile mark. In addition to providing unparalleled data on the appearance and evolution of splice images, these installed systems provide important experience with system reliability and usability, as well as having a daily positive benefit on operations in the host mines.

3 Vulcanized Splice Detection Software

When sections of conveyor belt are joined using vulcanized splices, the ends are cut at an angle. For the mines involved in this study, the cut angle is nominally 22° and the junction between the belt sections produces a characteristic diagonal line across the surface of the belt. A vulcanized splice detection algorithm has been developed which operates on 2D visual images of the conveyor belt by searching for these lines. The 2D images are acquired from line-scan cameras mounted above an unloaded section of belt as described in section 3.1. Accurate line detection and classification is challenging because of several factors: the apparent line angle in the belt images depends on the speed of the belt and the line-scan frequency; splice lines are often very faint; and typical belt

Figure 1: A screenshot of the GUI-based vulcanized splice detection application in use. Note that the inclusion of white fiducial markings in the neighborhood of vulcanized splices is very rare: the white cross visible in the screenshot is highly unusual.

images include spurious lines caused by water, pulley lagging, internal belt structure, and other artifacts.

During the reporting period of this document, the vulcanized splice detection algorithm has been significantly refined, initial executables have been released for installation in CONSOL mines, and the algorithm is under daily use and evaluation.

3.1 Experimental Apparatus

Of the 16 PC-based BeltVision systems installed in active mines, several are available for data collection and testing by the research team. Figure 2 shows a schematic of a PC-based BeltVision system, while figure 3 shows one of these systems installed on an above-ground test belt at NREC. Each BeltVision system includes a pair of synchronized high-speed high-resolution line-scan cameras mounted side-by-side so that the output from the two cameras can be concatenated to approximate a single scan-line. The BeltVision system is positioned in such a way that the direction of belt travel is perpendicular to the camera scan-line. As the belt moves under the cameras, successive scan lines are assembled into 2D images as shown in figure 4. These images are saved to hard disk and provide a high-resolution record of the belt surface. The approximate resolution of the surface image is 50 pixels/inch.

The splice detection algorithm is designed to allow incremental processing of image data as illustrated in figure 5. Scan-lines are sent to the detection algorithm one-by-one, and each vulcanized splice is flagged as soon as it is detected. Ultimately, camera output will be sent directly to the splice detection algorithm. At the two currently active installation sites, camera output continues to go to the regular BeltVision processing. Instead, a complete scan of the belt surface is saved to a computer hard drive twice a day, and these saved images are used as input to the vulcanized splice detector. Images of detected splices are sent to the surface via ethernet, where they are reviewed by the belt foreman to monitor splice condition. This process is automated and runs without any user intervention beyond adjustment of detector sensitivity. It is not practical to transmit the complete scan of the belt to the surface, due to the bandwidth limitations of the local network.

Figure 2: A schematic of the PC based BeltVision system. For a photo of the actual system, please refer to figure 3.

Figure 3: The PC-based BeltVision system includes two lightbars which illuminate the belt as it passes underneath the system. A pair of line-scan cameras acquire images of the belt, and processing of the acquired image data is performed in a nearby enclosure containing a commercial PC.

Figure 4: Individual scanlines are assembled into 2D images, which are saved to disk.

Figure 5: The vulcanized splice detector allows incremental processing of image data. In the current installations, direct connection between the cameras and the vulcanized splice detection software is not implemented. Instead, splice detection is automatically performed twice a day using images which have been saved to hard disk. as shown in figure 4.

3.2 Experimental and Operating Data

Full resolution recordings were acquired from installation sites in four different mines, each operated by CONSOL Energy: the Bailey mine and Enlow Fork mine, both located on the Pittsburgh 8 Seam in Southwestern Pennsylvania; and the Robinson Run mine and Blacksville 2 mine, both in Northern West Virginia, and also located on the Pittsburgh 8 Seam. Images from a portion of each belt were transported to the surface for data analysis and testing. The sections of belt analyzed were approximately 1 mile long for each of the Bailey, Enlow Fork, and Robinson Run mines. The section of belt analyzed from the Blacksville mine was shorter, at approximately $\frac{1}{2}$ mile.

Footage from each scan was grouped into a series of 2D images, each representing approximately 82 inches of belt surface. The images from each mine were observed to have different character, depending on both the specific belt and the environmental conditions of the installation site. Reduced resolution images from each of the four installation sites are shown in figure 6. All four of the images in this figure have vertical banding, which is characteristic of all of the belts we have observed to date. Of particular interest are the diagonal lines introduced by pulley lagging in the images from the Bailey mine, since these lines are easily mistaken for vulcanized splices. Also of interest is large amount of noise in the Robinson Run images due to mud and water on the belt. In order to show these phenomena more clearly, sections from both the Bailey image and the Robinson Run image are shown at higher magnification in figure 7. The contrast of each of the images in figure 7 has been increased somewhat to provide a clearer view of the belt detail.

All of the test images were manually inspected to identify vulcanized splices. A total of 37 vulcanized splices were identified: 7 splices were found in the Bailey Mine sample; 15 splices in the Enlow Fork sample; 11 in the Robinson Run Sample, and only 4 in the $\frac{1}{2}$ mile Blacksville sample. The names of the images containing splices were recorded for use as ground truth in analyzing vulcanized splice detector performance. For those splices which overlapped the border between two images, the names of both images were recorded. Figure 8 shows representative splice images from each installation site, and figure 9 shows the same images, this time with enhanced contrast so that the detail is more readily visible. The discontinuity along the vertical centerline of

(a) Bailey Mine

(b) Blacksville Mine

(c) Enlow Fork Mine

(d) Robinson Run Mine

Figure 6: Raw images from each of the four tested installation sites.

Figure 7: Sections of the images from the Bailey Mine and Robinson Run Mine. The contrast of these images has been increased somewhat to permit easy viewing. Pulley lagging in the Bailey mine image leaves an impression on the belt which is easily mistaken for the diagonal line of a vulcanized splice.

the images is due to misalignment of the two cameras in the BeltVision system. This discontinuity is most clearly visible in figure 9(b).

3.3 Data Reduction

The vulcanized splice detection algorithm has one tunable parameter, which adjusts the sensitivity of the detector. Each dataset was processed using several values of this parameter, and the output of the vulcanized splice detector was compared with the human-scored ground truth. A splice was considered to have been correctly detected if the algorithm indicated that a splice was present during processing of the 2D image which contains that splice. Ground truth splices which overlapped the border of two images in the dataset were considered to be correctly detected if the algorithm indicated that a splice was present during processing of either or both of those images. Counts of missed splices and false positives were generated for each combination of mine and tuning parameter value, as shown in tables 1 through 4 beginning on page 16. Figure 10 shows ROC graphs for the Bailey Mine dataset and the Robinson Run dataset. No ROC graphs are presented for the Blacksville and Enlow Fork results because on both of these datasets the algorithm achieved perfect detection for some value of the tunable parameter.

3.4 Hypothesis and Conclusions

Although these results are encouraging, and our experience with the installed system suggests that real-life performance is excellent, the small sample size of the current study prevents us from drawing any strong conclusions. To address this limitation, additional, larger datasets have been collected

(a) Bailey Mine

(b) Blacksville Mine

(c) Enlow Fork Mine

(d) Robinson Run Mine

Figure 8: Representative splice images from each of the four tested installation sites.

(a) Bailey Mine

(b) Blacksville Mine

(c) Enlow Fork Mine

(d) Robinson Run Mine

Figure 9: These are the same images as shown in figure 8, except that the contrast of each image has been adjusted to make the splice more easily visible. The Bailey Mine image is not visibly changed because the original image has very high contrast.

Figure 10: ROC curves for the Bailey and Robinson Run Mine datasets.

from CONSOL mines, and efforts are underway to manually identify and label the splices in these datasets. To date, over 30 miles of belt footage have been manually scored, and several hundreds of splices have been labeled. A more rigorous analysis of vulcanized splice detector performance will be conducted when this new, larger dataset is available.

Continued effort will be put towards minimizing sensitivity to the single tunable parameter of the algorithm, and toward automating the tuning process so that the optimal parameter value can be estimated on the fly during splice detection.

4 Additional Progress

4.1 Smart-Camera Development

The current BeltVision prototypes are built using off-the-shelf cameras, frame-grabber cards, and computers. This approach allowed the system to be developed quickly, and the current design is in daily use at 7 different mines, however it has several drawbacks:

Expense: The frame grabber cards and cameras are expensive, adding thousands of dollars to the price of the system.

Reliability: Packaging a commercial PC for use in a commercial mine is quite difficult. The environment in the mine is harsh, dirty, and dangerous. The computers are installed in totally enclosed cabinets, which makes it a challenge to cool them properly. These factors combine to significantly increase the maintenance requirements of the system.

Size and weight: The installation sites for the BeltVision units are often far underground, and access often requires travel by foot for some portion of the journey. In the current system the enclosure for the PC is large and heavy. This adds significantly to the difficulty of both routine and unscheduled maintenance

Figure 11: A schematic showing the mounting position of the Smart-Camera prototype during the proof of concept demonstration.

In order to address these concerns, a low-cost Smart-Camera based version of the BeltVision system is under development. The initial design includes a Perkin-Elmer line scan sensor element, image capture hardware, a Xilinx FPGA to implement the computer vision algorithms, and a Motorola ColdFire CPU to handle ethernet communication and control the operation of the system. The result of this effort will be a system in which all of the the sensing, processing, and communications are carried out by inexpensive units which are smaller than a loaf of bread, and weigh under 5 pounds. With this small, light, inexpensive unit, system maintenance will consist of simply unplugging any malfunctioning units and replacing them with replacements from a backpack or box.

4.1.1 Completion of Laboratory Prototype

A very early laboratory prototype of the Smart-Camera has been completed at Imaging Systems Group in Hauppauge NY. The unit is about the size and weight of the Dalsa cameras currently used in the PC-based BeltVision system, and can be mounted to the current camera mounts. A simplified version of the mechanical splice detection algorithm has been implemented in RTL for execution on the FPGA, and entire assembly can controlled remotely via ethernet.

4.1.2 Feasibility Demonstration and Proof of Concept

Both a PC-based BeltVision System and the prototype Smart-Camera were attached to the above-ground test rig at Beitzel Corp. The smart camera was mounted mid-way between the positions of the two cameras in the PC-based system, and oriented so that its scan line imaged approximately 26 inches of belt between the two lightbars. In order to visualize this setup more clearly, please refer to figure 11. The test rig was very similar to the one shown in figure 3, and had a short (approximately 20 meter) length of belt containing several mechanical splices. When the motor drive was activated, the belt moved under the mounted BeltVision unit, simulating the motion of the much longer belts at the mine installation sites. The section of belt mounted on the test rig had several mechanical splices, which passed repeatedly underneath the BeltVision unit.

The light bars mounted on the test rig were activated and the belt was run at speeds varying from 1 m/s to 5 m/s over the course of approximately 45 minutes. During this time, the prototype was carefully observed to ensure that there were no failures in mechanical splice detection. The demo

Threshold	True Positives	False Positives	Missed Detects
1.9	7	212	0
2.1	7	39	0
2.3	7	8	0
2.5	7	3	0
2.7	6	0	1
2.9	6	0	1
3.1	5	0	2
3.3	5	0	2
3.5	5	0	2

Table 1: Splice detection results the refined vulcanized splice detection algorithm applied to the Bailey Mine dataset. The column labeled “True Positives” indicates how many splices were correctly identified by the splice detection algorithm. The column labeled “Missed Detects” indicates how many images were manually determined to contain vulcanized splices, but were not identified by the detection algorithm. The column labeled False Positives indicates how many images were manually determined not to contain vulcanized splices, but *were* identified by the detection algorithm.

was deemed to be successful, and work is continuing to develop a more fully featured Smart-Camera based BeltVision system.

5 Closing

During this 6-month period, we have focussed on development of computer-vision algorithms to detect splices and defects in material conveying belts, and on continued development of a Smart-Camera based BeltVision system. This work will continue through the second half of the funding period.

Threshold	True Positives	False Positives	Missed Detects
2.5	4	36	0
2.9	4	8	0
3.3	4	4	0
3.7	4	3	0
4.1	4	0	0
4.5	4	0	0
4.9	4	0	0
5.3	4	0	0
5.7	4	0	0

Table 2: Splice detection results for the Blacksville belt. Column labels are as described in table 1.

Threshold	True Positives	False Positives	Missed Detects
2.1	15	15	0
2.5	15	6	0
2.9	15	2	0
3.3	15	1	0
3.7	15	1	0
4.1	15	0	0
4.5	15	0	0
4.9	14	0	1
5.3	12	0	3
5.7	12	0	3

Table 3: Splice detection results for the Blacksville belt. Column labels are as described in table 1.

Threshold	True Positives	False Positives	Missed Detects
2.1	11	127	0
2.3	11	28	0
2.5	11	4	0
2.7	10	0	1
2.9	10	0	1
3.1	10	0	1
3.3	10	0	1
3.5	10	0	1
3.7	10	0	1
3.9	10	0	1

Table 4: Splice detection results for the Blacksville belt. Column labels are as described in table 1.