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SIMULATING WIRELESS MONITORING IN AUTOMATED MAINTENANCE OF BELT CONVEYOR SYSTEMS

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ABSTRACT

This paper discusses concepts for automated maintenance of belt conveyors by means of wireless temperature monitoring. A powered maintenance trolley that can travel autonomously over the structure of a belt conveyer system is adapted as a platform for the maintenance system. A robot on the trolley performs replacements of the bearings. The wireless concepts are simulated and compared to an earlier maintenance concept, which is based on vibration analyses.
Wireless Sensor Mesh Networks and RFID Systems are two wireless technologies which can potentially be used for condition monitoring of belt conveyors. With a Wireless Sensor Network, condition monitoring can be performed at any time, independent of trolley passage times. In case an RFID system is used, the data reader has to be located on the trolley, which is why condition monitoring is restricted to trolley passage times.
Compared to the Vibration and RFID Strategies, the maintenance strategies, which are based on a Wireless Sensor Mesh Network, have much lower fail rates and higher flexibility.

INTRODUCTION

Belt conveyor systems are generally used for the transportation of commodities over long distances. Some conveyors can reach lengths of more than 10 km. The belt is supported by rollers spread over equal distances. Belt conveyors for the transportation of iron ore contain up to 400 roll bearings per 100 meters. The operational conditions for these bearings are harsh, due to high operational loads and contaminating dust from the transported commodity. Bearing failure can occur frequently and potentially cause damage to the expensive rubber belt. To avoid this, the bearings' condition should be monitored frequently, so that the rolls can be replaced before actual failure occurs. In the current belt conveyor systems, condition monitoring is a manual task, which is generally outsourced to specialists who visually inspect the bearings one-by-one. With 40000 bearings spread over a distance of 10km, this is a time-consuming and expensive task.

Automated maintenance of belt conveyor systems is a promising alternative to outsourcing maintenance, in particular if looking at efficiency, accuracy and costs. A powered maintenance trolley that can travel autonomously over the structure of a belt conveyer system was adapted as a platform for the maintenance system [Lodewijks, 2004] and [Lodewijks, Ottjes,2005]. Data acquisition equipment for vibration analyses was installed on this trolley along with a robot that can replace bearings. The optimum maintenance strategy was determined by means of a logistic simulation model. In this concept, data on a specific bearing can only be collected when the maintenance trolley is present at the location. An alternative to this concept would be the use of a Wireless Monitoring System, where temperature sensors on each bearing actively signal the maintenance system when attention is needed.

This paper discusses concepts for automated maintenance of belt conveyor systems by means of wireless temperature monitoring. Existing Wireless Monitoring Systems that can be used for this will be introduced. Then a concept for the logistic control of an automated maintenance system will be explained and simulated and finally conclusions and future research will be presented.

MAINTENANCE STRATEGIES

Real-world conditions such as improper lubrication, impact loading, vibration, excess

temperature, contamination, excessive loading, and misalignment, will decrease the life expectancy of bearings. If these conditions are severe, they may lead to premature failure of bearings. For belt conveyors, contamination of the lubricant (dust from the commodity transported) and impact loading (too large transported volumes) are the most important reasons for bearing failure. In the final stage of any bearing failure, increased friction between the bearing components causes a steep rise in temperature.
Condition monitoring of bearings, by means of temperature monitoring, is not new to the industry. "Axlebox" bearing units incorporating speed and temperature sensors are already used in high-speed trains, passenger coaches, and locomotives for preventive maintenance [De Man, 2006]. Alternatively, condition monitoring of bearings can be done by vibration monitoring or lubricant analysis, but for this research we restrict ourselves to temperature monitoring.

WIRELESS MONITORING

A typical Wireless Sensor Network is composed of SmartTags (data acquisition points), µNodes (communication waypoints), and Gateways (data collection points). The units are truly "wireless" in the sense that they require neither power nor data wiring. The only wires necessary are between the sensors and the data collecting SmartTags. These autonomous devices self-organize at power-up and quickly re-configure as devices join, leave or move around the network. The system is capable of executing user defined rules, thereby triggering user-defined events such as an increase in the temperature.

The most common layout is the "meshed" network, in which the µNodes form a meshed topology (see figure 1). The SmartTags are the end-points of the network. They can communicate with either one µNode (star topology) or with multiple µNodes (mesh topology). The SmartTags forward their data to the Gateways using redundant paths in the network.
The maintenance trolley would no longer have to be used for condition monitoring of the bearings, as data readings would be sent frequently via the network to the fixed Gateway at either end of the belt conveyor. This would make it possible to create a list of bearings to be replaced (updated frequently), before departure of the trolley. The trolley could be programmed so as to only start a maintenance run, if the repair time of a bearing on the list is due. Suppliers claim that battery life would be 4-8 years at a condition update frequency of twice per day. Although data would have to be collected from a massive 40000 sensors, air bandwidth would not to be a limiting factor.

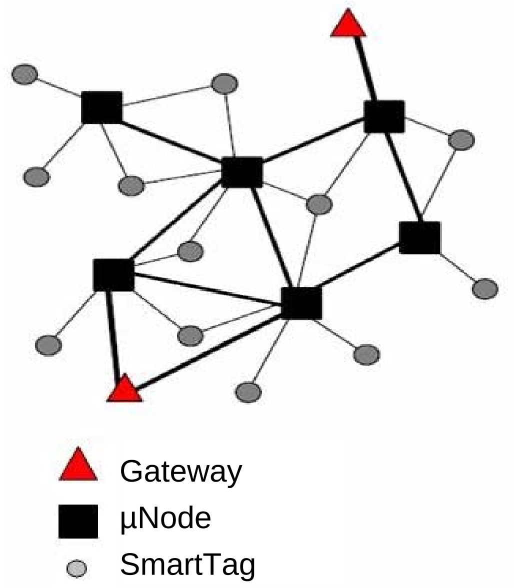

Fig. 1. A Wireless Sensor Mesh Network

A monitoring system for belt conveyors, based on RFID (Radio Frequency Identification), would consist of a Reader/Writer (Data collection Point), which is placed on the maintenance trolley, and of RFID tags (with integrated temperature sensors) placed on each individual bearing. Compared to passive tags, active RFID tags have a longer communication range in harsh environments and are ideal for collecting data from sensors. Therefore the most realistic choice for monitoring belt conveyors would be active RFID tags.
The amount of system components required would be comparable to the Wireless Sensor Mesh Network introduced earlier, except that the µNodes could be left away. Sensor data would be stored in the active RFID-tags and transmitted to the reader on the maintenance trolley when it passes by. The trolley would then have to be detected in time by the Tags, requiring much more listening time (very frequent listening), whether the trolley is coming into the line of sight and therefore requiring much more battery power. The trolley would not have to stop for monitoring of each individual bearing and therefore no time would be lost. However, monitoring would be restricted to trolley passage

times just like in earlier maintenance concepts which work on vibration analyses.

SIMULATION MODEL

A simulation model has been developed in TOMAS [Veeke, Ottjes, 2000], with the intention to compare 3 methods of condition monitoring of the rolls:

1. Vibration analysis as described by Lodewijks [2004].
2. Wireless Sensor Mesh Network (WSMN, Fig. 1)
3. active RFID system.

The model contains the (classes of) elements:

- the belt conveyor
- the rolls
- the automated maintenance robot
- the condition monitoring system
- the estimation of the remaining roll lifetime

The belt conveyor is specified in terms of its length and the number of rolls. Each roll is supported by two bearings. The life length of a specific bearing in a roll is allocated via a tabularized distribution. Under and upper limits can be specified assuming a uniform distribution (minimum and maximum life length as specified by roll and bearing manufacturer). The chance of failure before reaching the minimum life length can be specified, again according to a uniform distribution. All distributions can be changed for the middle and the side rolls of the carrying as well as the return idler sets.

Condition monitoring can be performed either by an active RFID system or by a Wireless Sensor Mesh Network (WSMN). For simplicity, it is assumed in this study that all RFID system- and Wireless Network- components have endless battery life.

The automated maintenance robot consists of a trolley and a replacement robot. It travels back and forth over the structure of the belt conveyor at a constant speed. Replacements are only performed in the forward direction of the robot. It is assumed that the robot is available 24 hours per day. The total replacement time consists of a fixed set-up time (seconds/per frame) for the replacement robot and of a replacement time (seconds/roll), in which the old roll is replaced with a new one.

The total lifetime estimation of an individual roll is based on temperature measurements taken from the sensors on each bearing of the roll. The lifetime of the roll is defined as the minimum of the lifetimes of its two bearings. Each bearing is equipped with a temperature sensor that communicates with the central data collection point, either through an active RFID system or through the WSMN. For the simulation, the temperature-vs.-time curve of a roll is modeled as shown in figure 2 below. The normal operation temperature of a bearing is assumed constant (T_{Normal}) for the major part of its life. A short period before failure of the roll, the temperature will start to rise abruptly. Depending on the failure mode, failure can be due to damage in the bearing structure or due to contamination of the lubricant. In the final stage of either failure mode, increased friction between the bearing components causes this fast rise in temperature.

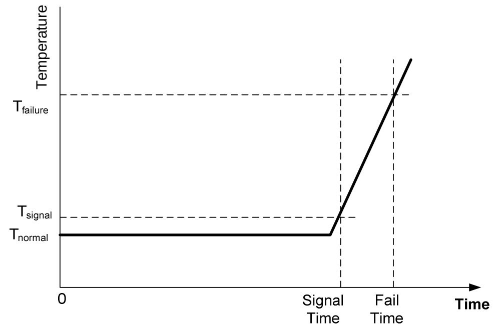

Figure 2. Temperature of the roll

The discrepancy between the roll's actual temperature at a given point in its Signal Interval and the measured temperature is simulated with 2 parameters. The measured temperature is a sample from a normal distribution with as mean the current "actual temperature" of the roll (see Figure 2). The deviation of this distribution determines the accuracy of the measured temperature and is controlled by the first parameter (d). With the second parameter (f), a bias is introduced. The estimator of the measured temperature becomes conservative, biased towards overestimating the temperature.
The measured temperature M is defined by:

M = A + d*(F–A)*X + f (F– A)	
F	Fail Temperature of the Roll
A	Current Actual Temperature of the Roll
X	Random variable, sampled from N(0,1)
d	Deviation, as fraction of the residual temperature
f	Safety factor, as fraction of the residual temperature

SIMULATION SETTINGS

Two options are presented for condition monitoring of the rolls: a Wireless Sensor Mesh Network (WSMN) or an active RFID system.

WSMN: Condition monitoring of all the rolls is performed independent of the robot movement, at fixed *Long* Monitoring Intervals, which must be specified. Once a roll's temperature has reached T_{Signal}, the sensor autonomously sends a warning signal to the network. From that point onwards, the WSMN will start monitoring the temperature of that roll at fixed *Short* Monitoring Intervals.

Active RFID system: Condition monitoring is performed via the central RFID reader located on the robot. This means, monitoring can only be performed during the robot cycles. All temperature measurements are used to estimate the residual lifetime of the roll.

By combining the different options presented above, several maintenance strategies are possible. Four strategies are considered in this paper.

S1	Condition monitoring is performed by a WSMN at fixed Monitoring Intervals (long, then short). The robot performs maintenance cycles at fixed Cycle Intervals.
S2	Condition monitoring is performed by a WSMN at fixed Monitoring Intervals (long, then short). The robot performs maintenance cycles at flexible intervals.
S3	Condition monitoring is performed by a WSMN at fixed Monitoring Intervals (long, then short). The robot performs Ad-Hoc Maintenance Runs.
S4	Condition monitoring is performed by an active RFID system. The robot performs maintenance cycles at fixed intervals.

The Safety Temperature (ST) defines a temperature above which a roll is replaced by the robot. The safety temperatures are explained below for each strategy.

Strategies 1, 4:

ST must be chosen so that the remaining Lifetime of the roll is at least larger than the Robot Cycle Interval.

Strategy 2:

- ST must be chosen so that the remaining Lifetime of the Roll is larger than the short monitoring interval + average Robot travel time per cycle.
- A second Safety Temperature (ST2) is needed which defines a temperature at which replacement may take place. ST2 must be lower than ST, otherwise the robot would replace too few rolls per cycle, dedicating a whole cycle to only one or two roll replacements.

Strategy 3:

ST must be chosen so that the remaining Lifetime of the Roll is larger than the short monitoring interval + average Robot travel time from one roll to another (Ad-Hoc).

Experiments were performed with different conveyor lengths, ranging from 100 to 10000 meters, with a frame distance of 2 meters.
The lifetime of a bearing is distributed uniformly between LMin and LMax. A certain rate of the bearings fails between 0 and LMin. This failure is uniformly distributed between 0 and LMin. From these specifications the average lifetime of each type of bearing can be calculated. The lifetime of a roll is the minimum of the lifetime of two bearings.

Bearing Lifetimes (days)	Lmin	Lmax	Average
Upper side roll	1750	2083	1812.4
Upper middle roll	1667	2000	1733.5
Lower side roll	1875	2208	1931.1

The Signal Interval of a bearing is distributed uniformly between 7 and 10 days.
The bearings' Operation Temperature is taken 30 °C and Fail Temperature 80°C.
The figures for the maintenance trolley are given below.

Speed	0.5 m/sec
Monitoring time	0 sec
Robot setup time	30 sec/frame
Replacement time	60 sec/roll
Cycle interval	6 days

The performance of a maintenance strategy is mainly recorded of:

- the number of rolls that has been replaced (too) late (Failure)
- the average time between replacement and end of lifetime of a roll (Waste)

SIMULATION RESULTS

Because there is no actual system to compare with, it is not possible to validate the simulation model in this stage. Therefore the model has only been verified

There are two different versions of the WSMN Flex strategy:

- WSMN Flex1: ST and ST2 are very close in range (± 2 ºC)
- WSMN Flex2: ST and ST2 are far in range with ST2 equal to ST of the WSMN Fixed Strategy (± 35 ºC).

The five strategies (including Flex2) are simulated several times to find the optimum ST for each individual strategy. This is repeated for 5 different conveyor lengths, ranging from 100 to 10000 m.
WSMN Fixed and RFID Fixed: These two strategies show almost equal results. The travelled distances for these strategies remain within proportion and relatively low for all conveyor lengths. The Average early replace times are the longest at all conveyor lengths, compared to other strategies.

WSMN Flex1: The strategy is outperformed by other strategies for all conveyor lengths. It is only feasible up to a conveyor length of ±150m. For higher conveyor lengths, the travelled distance increases significantly.

WSMN Flex2: This strategy is ideal for conveyor lengths ≥750m. The strategy outperforms all the other strategies in its low travelled distance. However the "price" paid is a higher average early replace-time.

WSMN AD-Hoc: This Strategy proves to have the shortest travelled distance and a low average early replace time until conveyor lengths of ≤ 750m. For short conveyors, this strategy is the ideal solution. Up to ±150m the distance travelled is at least 1:3 compared to other strategies. With higher conveyor lengths, the travelled distance increases significantly.

For the sensitivity of the strategies for the discrepancy between real and measured temperature each strategy is simulated twice: once with a discrepancy of 0% and once 10%. An analysis is done by comparing the difference in the percentage of late replaced rolls between the two simulations. This experiment is repeated for 3 different conveyor lengths. The results are summarized in the table below.

	100m	1000m	10000m
WSMN Fixed	0.8%	0.5%	0.2%
WSMN Flex1	1.1%	0.0%	0.0%
WSMN Flex2	0.0%	0.0%	0.0%
WSMN AdHoc	1.3%	0.1%	0.0%
RFID Fixed	0.8%	0.6%	0.5%

WSMN Fixed: For all conveyor lengths, this strategy is relatively sensitive to changes in the bearings' temperature. The sensitivity decreases with increasing conveyor length.

WSMN Flex 1: For short conveyor lengths, this strategy is sensitive to changes in the bearings' temperature. For long conveyor lengths the sensitivity decreases to 0%.

WSMN Flex 2: For all conveyor lengths, this strategy has 0% sensitivity to changes in the bearings' temperature. It thereby outperforms all other strategies.

WSMN AD-Hoc: This strategy is most sensitive for simulations with short conveyor lengths. However, the sensitivity decreases to 0% with increasing conveyor length.

RFID Fixed: For long conveyor lengths, this strategy has the highest sensitivity to changes in the bearings' temperature. The sensitivity decreases with increasing conveyor length.

Vibration Monitoring vs. Wireless Temperature Monitoring

Earlier, vibration analyses for condition monitoring of bearings was theoretically compared to temperature monitoring of bearings. In theory, damage or wear to a bearing can be detected earlier by listening to the vibrations than by measuring the temperature of the bearing.

The simulation parameters of the vibration analyses strategy are different from the parameters for the wireless strategies. In the simulation program for Vibration analyses, the time to replace a roll is indicated as a certain time interval before the lifetime of the bearing. The user can assign a deviation to this lifetime estimation. In the simulation program for the wireless strategies, the time to replace a roll is when the roll has reached a certain temperature. The user can assign a deviation to the measured temperature. Despite these differences (amongst others) in the two programs, the strategies can be compared to each other:

The RFID fixed strategy is the wireless strategy, which is most similar in working principle to the vibration analyses strategy. In both strategies, condition monitoring is done on the trolley and is therefore dependent on the trolley cycle intervals. These two strategies are simulated several times, to find the respective deviation settings, at which both strategies render the same % of late replaced rolls. For best comparison, the remaining wireless strategies are then simulated using the deviation in measured temperature, which was found for the RFID Strategy.

The next experiments are performed with a conveyor length of 10000m. Wireless strategies are restricted to small monitoring- and cycle intervals, because of the short Signal Interval of 7 days, during which a bearing's temperature rises. Therefore, all strategies (including vibration analyses) are simulated with a Cycle Interval of 6 days. For the vibration Analyses, the Safety Time is set equal to the Cycle Interval, and the Inspection Time was set to twice the Cycle Interval, as was recommended in [Lodewijks, 2004].
Calibration
For this experiment, the deviation in the estimated lifetime of the vibration strategy is set to 1%. A simulation with these settings renders 3.3% of late replaced rolls. By means of repetitive simulations with the RFID strategy, it is found that, when the deviation in measured temperature is set to 29%, this simulation also renders 3.3% of late replaced rolls. The remaining wireless strategies can now be compared to the vibration strategy.

Strategy	Cycles	Travel time	Early (%)	Early/Late Time (days)
WSMN fixed	608	0.5443	99.2	4.59/0.44
WSMN Flex1	3646	0.4766	99.8	1.67//0.07
WSMN Flex2	986	0.5132	100	5.50//0.03
WSMN AdHoc	47435	0.0315	99.0	1.52/0.11
RFID Fixed	608	0.5443	96.7	4.32/0.597
Vibr. Analysis	608	0.87	96.7	3.00/3.71

The results for the different strategies are listed in the table above.

The RFID strategy renders similar early replace-times to the Vibration analyses, which justifies the choice of using the RFID strategy for calibration of the wireless strategies. The only advantage of using the RFID strategy above Vibration analyses is the low average late replace-time (0.59 d). Despite the extreme deviation in measured temperature (29%), the WSMN strategies render very low percentages of late replaced rolls (0-1%), compared to 3.3% for the RFID and Vibration strategies. WSMN Flex2 is the only strategy that renders 0% late replacements. However, the price paid for this good performance is a highest average early replace-time of 5.5 days and a relatively higher travelled distance.

CONCLUSIONS AND FUTURE RESEARCH

Several Wireless Temperature Monitoring strategies for belt conveyors have been introduced and simulated in this paper. The performances of these strategies have been compared to each other and to the Vibration analyses concept, which was introduced by [Lodewijks, 2004].
If a wireless sensor network were to be applied to a 10km belt conveyor, the network would need at least 40000 sensors. This represents a massive investment. However, the current growth of this technology's market promises a significant reduction in costs in the nearby future. Amongst the features of Wireless Temperature Monitoring are:

- Possibility to monitor from a distance, away from location (outsourcing easier)
- Provides an overview of the conditions of all the rolls in the conveyor, at user specified intervals.

- Extremely low fail rate, due to the Signal feature
- Low early replacement times
- Is a basis for automation of the maintenance/replace robot

The features listed above promise low operational costs and easy roll stock management for belt conveyors on which this technology will be applied in future.
Compared to the Vibration Analyses and RFID Strategies, the maintenance strategies, which are based on a Wireless Sensor Mesh Network, have much lower fail rates and higher flexibility. For Vibration Analyses and RFID, the inspection intervals depend fully on the robot's fixed cycle intervals. Therefore, information on the rolls' condition is not available before the robot starts a cycle. This is why these two strategies render the highest fail rate at an elevated deviation.
The Wireless Sensor Mesh Network, in combination with a trolley robot that does maintenance cycles at Flexible Intervals (WMSN Flex 2), has proven to be the most feasible wireless maintenance strategy for long belt conveyors. This strategy has on average, long robot cycle intervals and a low sensitivity for changes in roll temperatures. The result is a very flexible maintenance system with the lowest fail rate.
The Wireless Sensor Mesh Network, in combination with a trolley robot that does Ad-Hoc maintenance runs (WSMN Ad-Hoc), has proven to be the most feasible technology for conveyor lengths ≤ 750m. Below this length, the total distance travelled by the robot is relatively very low and the average early replacement time for the rolls is negligible.
An advantage for Vibration Monitoring is that vibrations, due to damage or wear of a roll, can be detected earlier than an increase in temperature. Because of the relatively short time interval, during which a failing bearing's temperature rises, the wireless strategies, based on temperature monitoring, are restricted to small monitoring- and robot cycle intervals. As a result, the Vibration Monitoring trolley can be set to do maintenance at larger cycle intervals than the Wireless Temperature Monitoring strategies, whilst still maintaining relatively low percentages of late replacements.

Research should be done into the possibilities of combining Wireless Sensor Mesh Networks with Vibration Monitoring. Compact sensors capable of detecting vibrations would be the ideal solution for belt conveyors.
A small scale model of the maintenance system should be built for validation of the simulation model. Tests can then be performed to find the exact values for the temperature characteristics (operation temperature, fail temperature, signal interval, deviation) of conveyor bearings and to further validate the results of the simulation.

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