THE APPLICATION OF RFID TECHNOLOGY IN BELT CONVEYOR SYSTEMS

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SUMMARY

On Beltcon 12 the concept of automated maintenance of belt conveyor systems was firstly introduced. In that paper the concept of using a trolley, to perform inspections and/or carry out maintenance tasks, was described. Also the control of the trolley and the monitoring and maintenance program were described. On Beltcon 13 further belt conveyor monitoring and control tools were presented. This paper continues the discussion of automated monitoring and control of, in particular, large scale belt conveyor systems. Over the last two years, Radio Frequency IDentification (RFID) systems have been studied as a technology to use for the monitoring and control of belt conveyor systems. Extensive field tests have been performed to study the behavior of radio frequency (RF) technology as a communication platform. The implementation of RFID technology in the conveyor belt and rollers has been studied and tested. This paper discusses the technical characteristics of RFID technology and the possibilities to apply this technology in belt conveyor systems. It presents the results of recent field tests and discusses the benefits and drawbacks of the application of RFID technology in belt conveyor systems. Finally, it presents a method to control the monitoring and maintenance program using RFID technology, as an alternative to the method presented at Beltcon 12.

1 INTRODUCTION

On Beltcon 12 in 2003, the concept of automated maintenance of belt conveyor systems was firstly introduced [1]. In that paper the concept of using a trolley to perform inspections and/or carry out maintenance tasks on the rolls of the idlers was described, see Figure 1. The monitoring of the rolls focused on monitoring the condition of the bearings in the rolls since rolls fail primarily due to bearing failure. In addition, the control of the trolley and the monitoring and maintenance program were described in [1].

The concept of using a trolley for both monitoring and carrying out maintenance tasks implies that there is always a time lag between the start of a bearing failure and the time it is detected. This does not have to be a problem if the degradation rate of the rolls is slow enough to allow a timely detection of potential bearing failure. It may in practice however lead to unnecessary movement of the trolley for inspection purposes. This observation led to the idea of reducing the functionality of the trolley to carrying out maintenance tasks only and to use a different means of inspection of the rolls.

Figure 1: Maintenance trolley installed on the RBCT terminal in Richards Bay, Republic of South Africa [courtesy CKIT].

The original trolley [1] was equipped with data processing equipment, which generated straightforward information on the condition of the roll. This information could easily be analyzed and used to base replacement decisions or inspection interval decisions on. If the trolley is not used for inspection any more then the rolls themselves have to provide that information. In theory it is possible to equip each roll with either an acoustic sensor or an accelerometer to pick up vibrations that indicate potential bearing failure. This data however has to be transmitted to the central monitoring unit and processed there. Data conversion in each roll is not viable. This process means that the central monitoring unit has to 'tune in' with a specific roll and take a measurement based on a certain inspection protocol. The measurement has to be long enough to allow detection of the vibrations in the relevant spectrum. Although technically possible equipping each roll with sensors to pick up vibrations was deemed complex and economically not viable.

An alternative way of assessing the technical condition or 'technical health' of bearings is by measuring their temperature. Normal operating temperatures range between 20° C and 50° C depending on the ambient temperature. If the temperature of a bearing increases to higher temperatures, ranging from 80° C to 120° C, then that is a clear sign of potential bearing failure. The time between picking up irregularities in bearing behavior and bearing failure using vibration detection sensors is significant larger then when using temperature sensors [2]. However, if the temperature of the bearings can be measured on-line or if the rolls have the ability to notify the central monitoring unit in time in case of temperatures over a certain threshold value then there is still enough time to replace a roll with potential bearing failure before it actually fails.

Each roll is supported by two bearings. However, if one of those bearings fails then the total roll is considered broken and needs replacement. If a bearing is about to fail and its temperature increases then also the temperature of the shaft that supports the bearing will increase. Since both bearings are supported by the same shaft it is sufficient to measure the shaft temperature instead of the temperature of both bearings to assess the condition of the bearings.

If each roll could measure its own temperature and/or give a temperature overload warning (temperature too high) then that information still needs to be transmitted to the central monitoring unit. Since the trolley is not used anymore to gather inspection data there are in essence two ways: with wires or wireless. If wires are used then each roll has to be hooked up to a common bus since it is not feasible to run cables from each roll to the central monitoring unit. The problem with running cables along conveyors in general is that they may get stolen or damaged. Therefore, in order to have a reliable data transmission wireless technology is preferred. If one of the bearings of a roll is about to fail and its temperature increases then it is not enough to know that a roll is about to fail. It is necessary to know exactly which roll it concerns to allow the trolley to replace it automatically. Therefore, each roll has to be able to provide information on its temperature and it has to identify itself. This combination can be achieved by using Radio Frequency Identification (RFID) technology as a wireless communication and identification platform extended with a thermocouple sensor for temperature measurement.

2 UHF RFID SYSTEMS

RFID is a generic term for systems that read the unique identity of an RF tag [3]. RFID incorporates the use of electromagnetic, or electrostatic coupling in the radio frequency portion of the spectrum to communicate to or from a tag through a variety of modulation and encodation schemes. An RFID system is an automatic identification and data capture system comprising one or more interrogators, also called readers, and one or more transponders in which data transfer is achieved by means of suitably modulated inductive or radiating electromagnetic carriers. An RFID system consists of three components: microchip, antenna, battery in case of active RFID, and an interrogator, see Figure 2.

There are several methods of identifying objects using RFID. The most common is to store a serial number that identifies the object and some additional data on a microchip that is attached to an antenna. The antenna enables the microchip to transmit the information to an interrogator. In passive RFID systems the data transmission is triggered and powered by the interrogator, which implies that the transmission is off-line. Passive tags operate only over short distances since the low power energy from the interrogator supplies the transmission power. Some passive tags, depending on the frequency range, have difficulty performing in environments where a large amount of interference exists, including the presence of metals, liquids, and other RF energy. Passive tags are inexpensive, small in size, light in weight, have long lives, and are subject to little regulation. Without an internal battery for memory, passive tags also have limited memory capability. Passive tags tend to be used in close-range tracking of lower-ends assets, such as in supply chain operations [3]. In active RFID systems the microchip is equipped with a battery or an alternative energy supply that powers it which allows on-line continuous data transmission. The combination of microchip, antenna, and battery placed on a label or sticker is called a tag.

Figure 2: Components of an RFID system.

An RFID system must perform a sequence of communication processes to manage data exchange between tag and interrogator. The exchange process begins with the activation of the tag and its segregation within the total tag population. The process ends with the establishment of a communication link between the RFID interrogator and the tag allowing transaction of data. RFID systems may require extensive communication between the interrogator and the tag to fully complete the desired transaction. It is not uncommon to have dialog errors during wireless communication. The identification, read and write processes are characterized by their range and rate. The range here is the physical distance between interrogator and tag. The rate refers to the quantity of tags per unit time that can be processed. The reliability of an RFID system can be defined as the extent to which the system yields the same result in terms of tag identification and data exchange on successive trials. A reliable transaction specifically refers to the assurance that a tag will be identified accurately based on statistical likelihood and a defined confidence level.

The RFID radio waves are transmitted at a certain frequency. The frequency varies from 2 kHz for very low frequency (VLF) systems to 60 GHz for super high frequency (SHF) systems. Different frequencies have different characteristics that affect the usability of certain frequencies in specific applications. For instance, low frequency (LF, 30-300 kHz) tags are cheaper than ultra high frequency (UHF, 300-3000 MHz) tags, use less power and are better able to penetrate non-metallic substances. UHF tags typically offer better range and can transfer data faster.

Within the UHF range several countries have their own specific bandwidth. In Europe, for example UHF RFID systems operate between 865 MHz and 868 MHz, in the USA they operate between 902 MHz and 928 MHZ. This difference in frequencies is caused by the fact that the UHF band is already in use by many other applications. Therefore, each country needs to find free bandwidth space for RFID applications. However, as long as the frequency is kept within the UHF range, the same tag can be read throughout the world, even if the frequency used by the reader is different. UHF RFID systems are specified in a number of ISO/IEC standards, for example ISO 18000:2004(E) and ISO TR 18046:2005(E), also see [2] and [4]. Other applicable standards include the ETSI/EN standards 300330, 300220, 300440, and 302208 [5].

3 RFID TECHNOLOGY INTEGRATED IN BELT CONVEYORS

In section 2 RFID technology was introduced. As stated in section 1 if the trolley is not used for monitoring any more then the rolls of the idlers have to be able to identify themselves and to measure their temperature. A roll equipped with an extended RFID tag is called a smart roll. The design and functionality of the smart roll will be described in this section.

If an RFID tag is extended with a thermocouple on a combined circuit board then the required functionality is achieved, see Figure 3a and 3b.

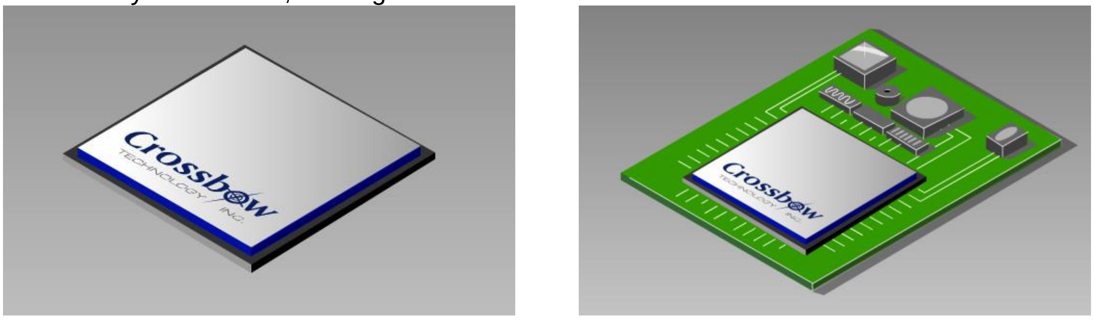

Figure 3a&b: Tag (left) and tag integrated on circuit board with temperature sensor (right) (courtesy Crossbow, Inc.).

Since the tags have to be self supported a battery is required to power the tag, see Figure 4a. It is an option to equip the trolley with an interrogator that powers the tags, but it was decided to use the trolley for maintenance only. Instead of using a battery an energy harvester working on induction is designed that fits inside the roll and that uses the rotation of the roll to generate power. The tag, sensor, circuit board and batteries fit into a casing that fits inside the roll, see Figure 4b. Another word used for the final enclosed tag with options is node.

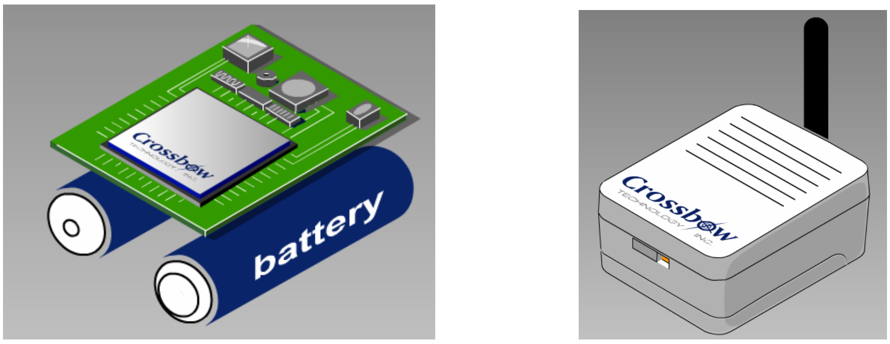

Figure 4a&b: Tag, circuit board with sensor and batteries (left) and final enclosed version (right) (courtesy Crossbow, Inc.).

Each smart roll is equipped with a node that can communicate with the interrogator, see Figure 5. The above described nodes have one drawback and that is that the range over which they can communicate with the interrogator is relatively small caused by the internal power limitations. Typically, this range is smaller than 10 m. Since the envisioned applications are large-scale belt conveyors, see Figure 6, an alternative way of transmission is required.

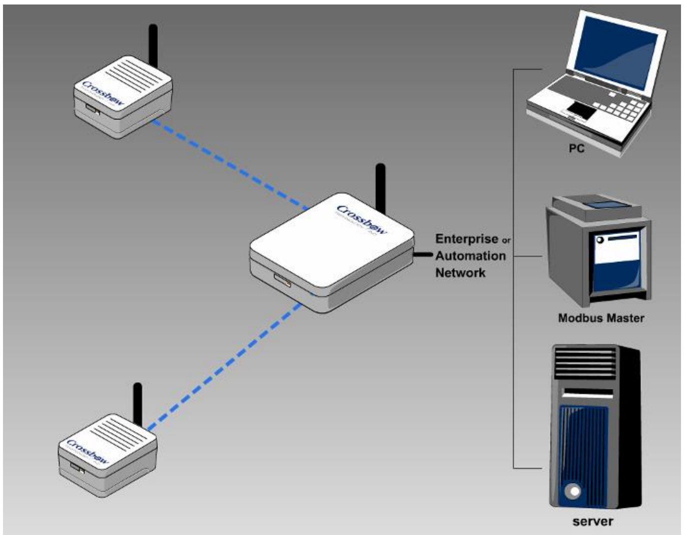

Figure 5: Nodes, interrogator and systems used in the central monitoring unit (courtesy Crossbow, Inc.).

Figure 6: Large scale overland belt conveyor in South Africa (courtesy Conveyor Experts B.V.).

Typically, the idler pitch varies between the 2.5 and 4.5 meters for the carrying belt and between 5 and 10 meters for the return strand. Assume that the temperature of roll A, see Figure 7, exceeds its threshold value. At that time the node is activated and starts to transmit its identity (number) and, if required, its temperature. Since the distance between roll A and the interrogator at the central monitoring unit is far more than about 10 meter, in fact it may be over 10 kilometer; it needs assistance for the data transmission. Two options are available. If all nodes can not only send data but also receive data then direct roll to roll communication is possible. If nodes can only transmit data then extra powered nodes are required that can be installed on the conveyor's frame, see Figure 8. These nodes cannot only transmit data but they can receive data as well. The pitch between these powered nodes does not depend on their range. Typically, the transmission range of these powered nodes varies between 50 m and 150 m. In this case, however the transmission range of the nodes in the rolls determines the pitch between the powered frame nodes to ensure full coverage.

For the development of the smart rolls communication option 1 was chosen. Therefore, direct roll to roll contact ensures that data transmitted by one roll is transmitted from that specific roll to the interrogator via its neighboring rolls.

The path used for data transmission is not fixed. The network is build up every time a roll starts to transmit data. Examples of data transmission routes are given in the Figures 9 and 10. The configurations shown in these figures are so-called Hybrid Star (ZigBee) configurations. In principle each roll can participate in the data transmission route. If the node in one of the rolls fails then the network can reconfigure itself. This feature ensures a self-healing network. This concept is shown in Figure 11.

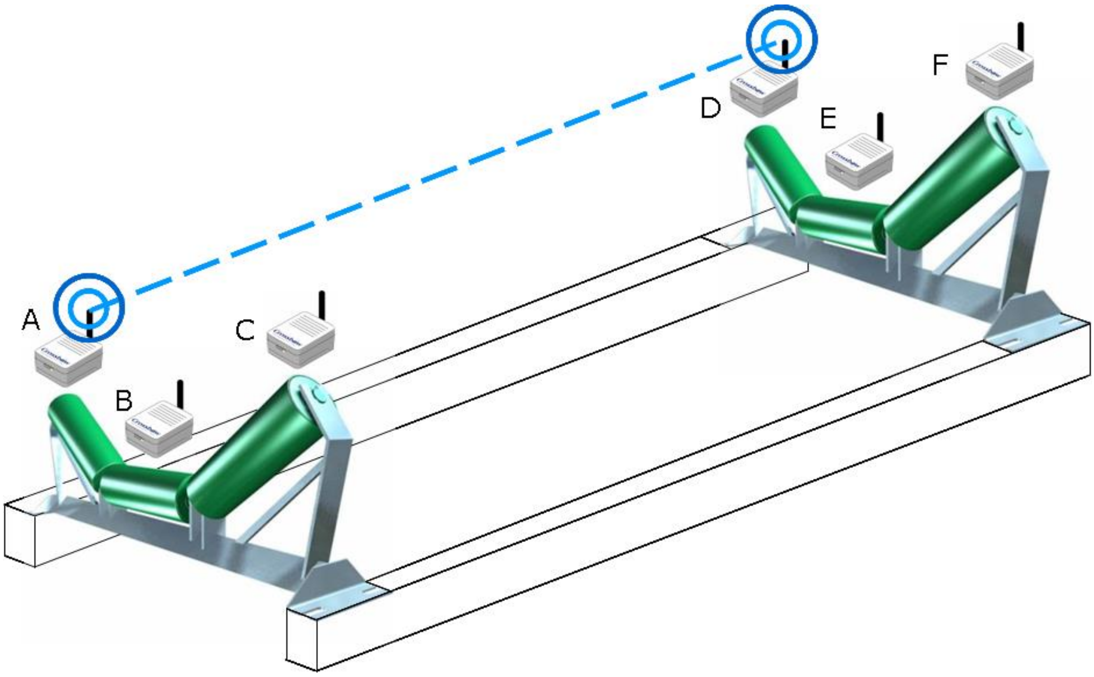

Figure 7: Direct roll to roll communication
(in reality the nodes are placed inside the rolls).

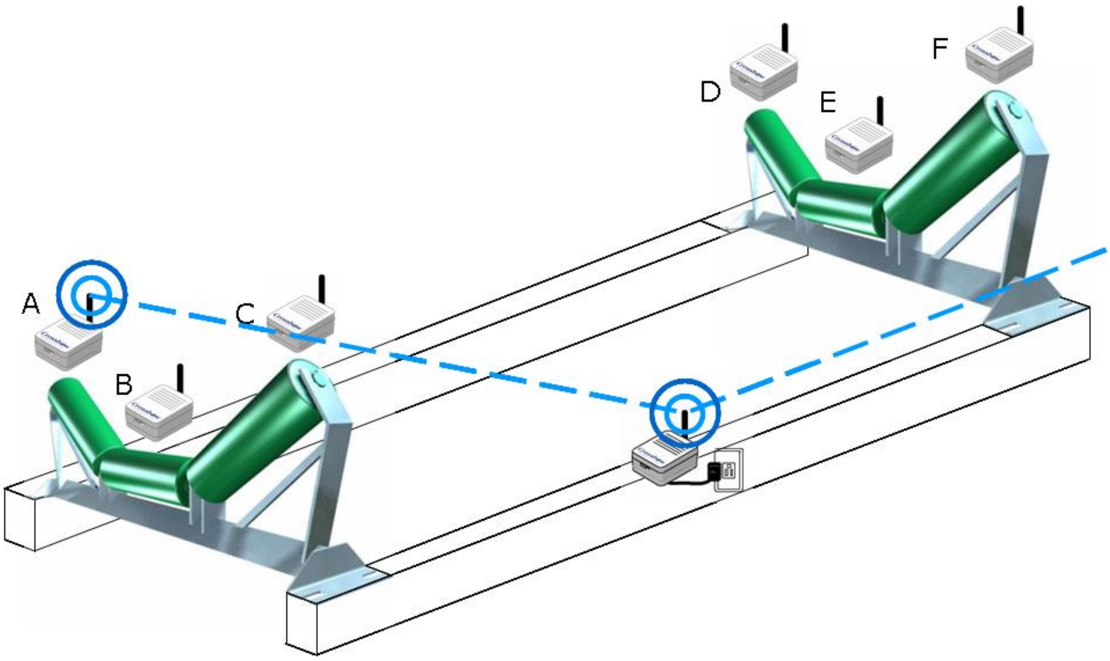

Figure 8: Roll to roll communication via a powered node on the conveyors frame (in reality the nodes are placed inside the rolls and the frame).

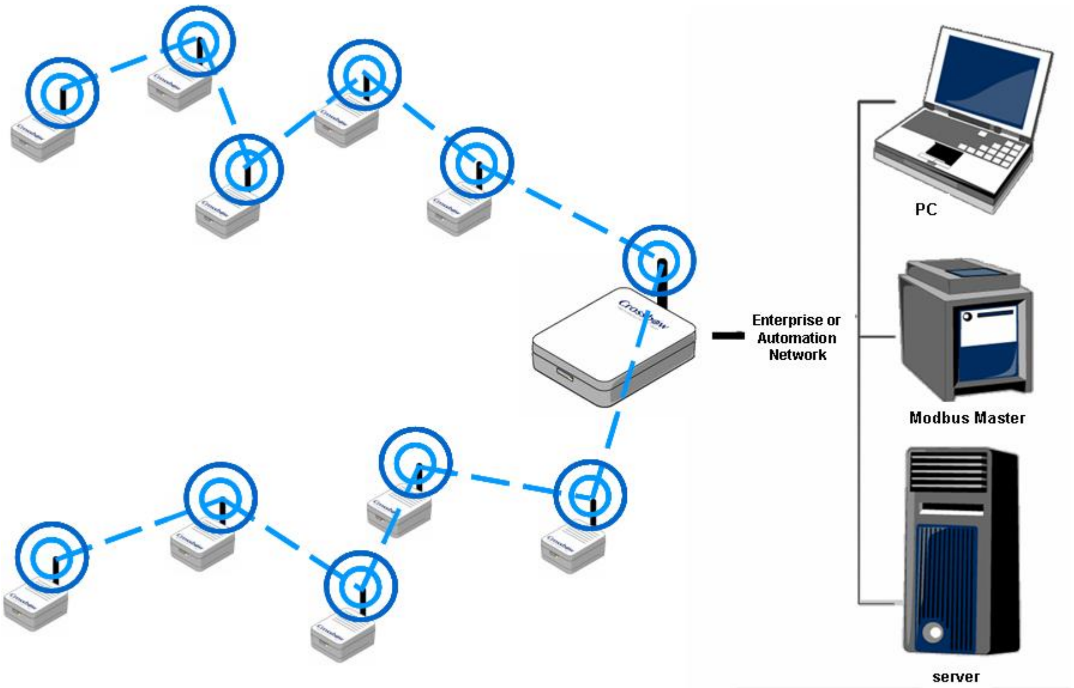

Figure 9: Communication through the network from nodes through interrogator to automation network.

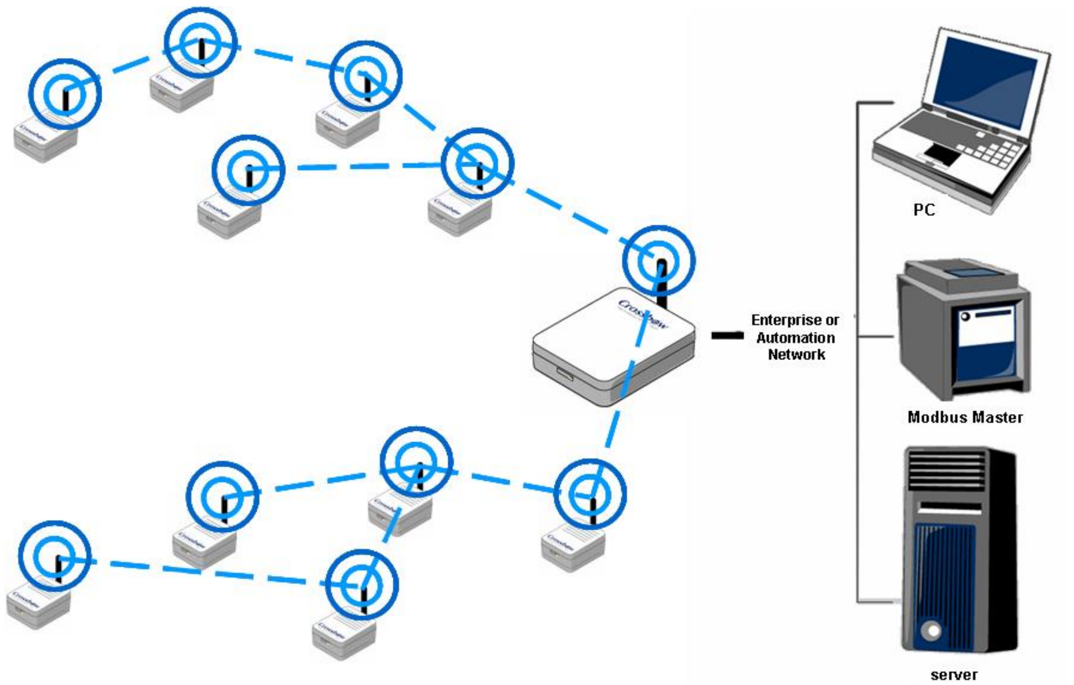

Figure 10: Alternative data transmission route.

The smart tags are developed at Delft University of Technology, faculty of Mechanical, Maritime and Materials Engineering, section Transport Engineering and Logistics together with the faculty of Electrical Engineering, LogicaCMG and CKIT in the framework of the TRANSUMO PILOT research program. The smart tags are implemented using the hardware features of a mote processor radio platforms and programming interface from for example SOWnet or CrossBow. This hardware gives the possibility of designing real sensor networks, smart RFID and ubiquitous computing applications. Currently 10 prototype rolls have been build and successfully tested in the RFID laboratory of the section Transport Engineering and Logistics, see the Figures 12 and 13. Full scale tests in an industrial environment are foreseen later in 2007.

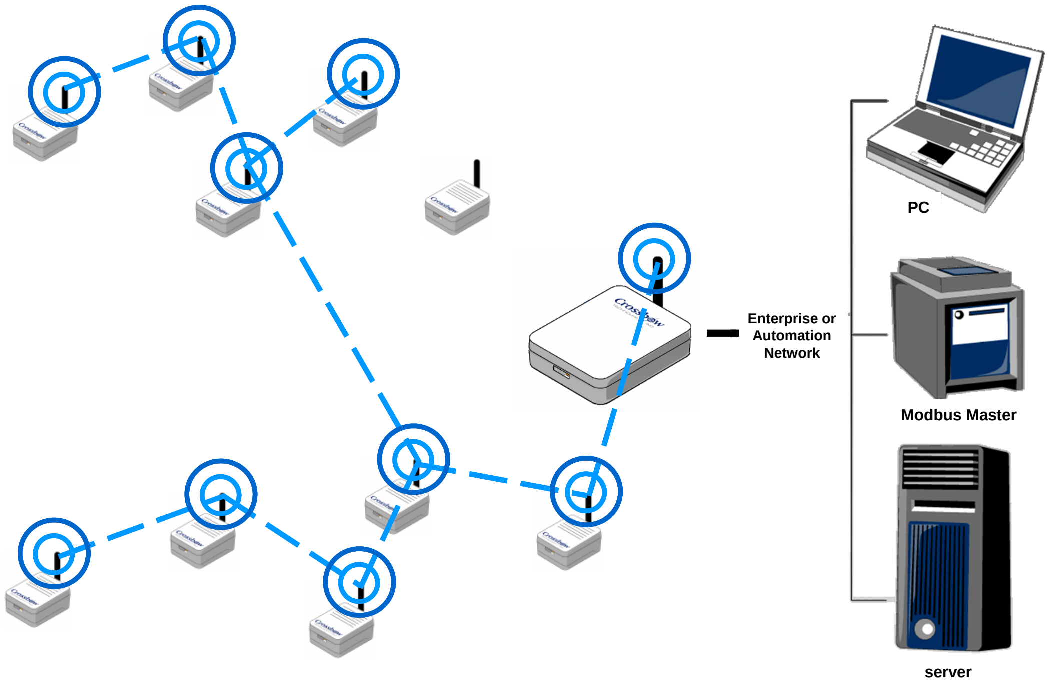

Figure 11: Self healing network after node failure.

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The rolls have three operational modes:

- *Internal activation mode*; when the temperature of the roll exceeds the threshold value then the node is activated and starts to transmit its identity. If required it can also transmit its temperature and battery status. This option will be used initially to determine the correct threshold value for the bearing and roll temperature. The threshold value depends partly on the application and ambient conditions.
- *Central external activation mode;* if a roll does not transmit its identity it can be assumed that the roll temperature is below the threshold value. However, if for whatever reason the node in the roll is malfunctioning or it does not have power then it will not be able to transmit data. Therefore it is possible that the roll temperature is above the threshold value without the node transmitting data. To periodically check whether the nodes are functioning or not the central communication unit can request each node to identify itself and report its temperature and battery status. If a roll does not respond then it can be considered broken and needs replacement.
- *Local external activation mode*; if a neighboring roll is transmitting data then the node in the roll is activated to transmit the same data. This mode is used to either support the central request for identification of specific rolls or for the transmission of the identity and temperature of a roll whose temperature exceeded the threshold value.

Figure 12a&b: TU Delft RFID laboratory (left computer and RFID equipment, right four of the 10 prototype rolls).

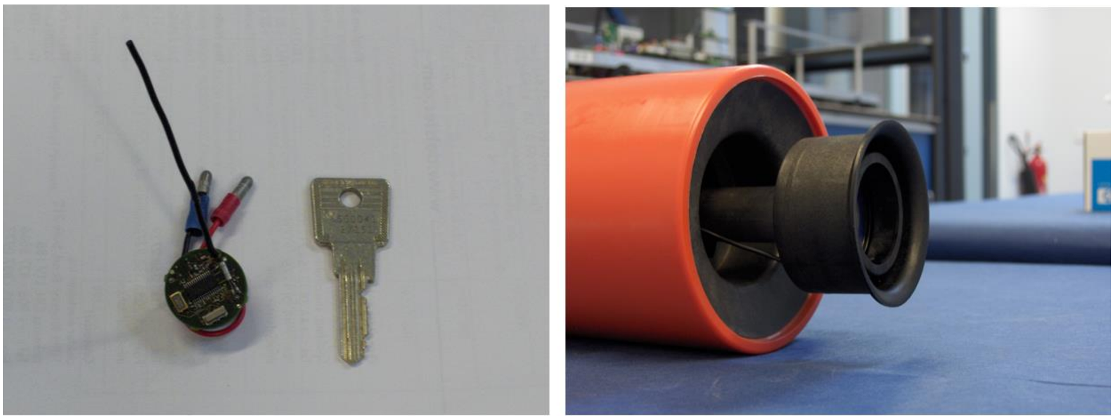

Figure 13a&b: Prototype sensor and roll (left RFID tag with antenna and temperature sensor, right detail of one of the prototype rolls).

In this paper the focus is on the development of smart rolls. However, RFID technology can also be used in other components of belt conveyors. An example is the application of tags in the belt as used by ContiTech. These tags are passive tags and only provide the identity. They can for example be used near a splice. The tag number then is connected with a database with information on that specific splice. This data can include splicing date, splice crew, splice design etc. Although these tags are handy to keep information on a specific spot in the belt they are insufficient for monitoring purposes. If RFID is applied for monitoring purposes then the RFID tag has to be combined with a sensor to acquire specific data. Depending on the application these tags may have to be active. The application of (active) RFID tags with sensors inside the belt has been studied but not applied. Other examples of the application of RFID in belt conveyor systems are RFID tags to monitor the condition of bearings of pulleys or motors. These applications have yet to be developed.

Finally, the successful application of smart rolls depends primarily on the reliability of the technology and its price. The tags currently used in the smart rolls add about 40% to 50% to the price of the rolls. This is not acceptable for widespread application in belt conveyor systems. However, if instead of 10 10,000 tags are manufactured then the price can be reduced considerably. Large scale belt conveyors easily contain 10,000 rolls ore more. In addition, the trend is that RFID technology is becoming less expensive. Therefore, it is believed that smart tags in the near future are feasible, even for small-scale systems.

4 MAINTENANCE CONTROL USING RF BASED SYSTEMS

In [1] the concept of automated maintenance of belt conveyor systems was firstly introduced. In that paper the concept of using a trolley, to perform inspections and/or carry out maintenance tasks on rolls, was described. Also the control of the trolley and the monitoring and maintenance program were described. If the trolley is only used for maintenance tasks and the monitoring task is taken over by the smart rolls then also the maintenance strategy and program are affected. This section described the change in maintenance strategies and compares the effectiveness of using a trolley versus using smart rolls for monitoring purposes.

In this section a concept for the logistic control of an automated wireless maintenance system for belt conveyor systems is presented. The maintenance concept is based on the predictive maintenance concept, using temperature measurements to determine the remaining lifetime of a roll [1]. The technical lay-out of the maintenance system is based on the application of an automated maintenance robot including a roll replacement robot. Condition monitoring of the roll is done via a system of smart rolls and a central monitoring unit. The following paragraph describes the concept model for a computer simulation.

4.1 Simulation model

In the model a number of elements are detailed including:

- the belt conveyor,
- the rolls,
- the automated maintenance robot,
- the condition monitoring systems,
- the estimation of the remaining roll lifetime.

4.1.1 Belt Conveyor

In the simulation model the belt conveyor can be specified in terms of its length and the idler pitches. The number of idlers then is calculated automatically assuming that the pitch is constant. It is assumed that a carrying idler has 3 rolls and a return idler 2.

4.1.2 Rolls

Each roll is supported by two bearings. The lifetime of a bearing in a specific roll is allocated via a tabularized distribution. Under and upper limits can be specified assuming a uniform distribution (minimum and maximum lifetime as specified by bearing manufacturer). All distributions can be changed for bearings in the middle and the side rolls of the carrying as well as the return idler sets. The chance of failure of a bearing before reaching the minimum lifetime can also be specified. As a standard this chance is 10% (L_{10} life is specified by the roll manufacturer). The lifetime of a roll is defined as the minimum of the lifetimes of its two bearings. If at the beginning of a simulation, used rolls, instead of new rolls are installed, the simulation model accounts for this effect by allocating remaining lifetime to individual rolls.

4.1.3 Automated Maintenance Robot

The automated maintenance robot consists of a trolley and of a replacement robot. It travels back and forth over the structure of the belt conveyor at a constant speed. It is assumed that the robot is available 24 hours per day. The replacement robot uses data collected from the condition monitoring system to determine whether a roll needs replacement. An aged roll is always replaced by a new roll of the same type. The total replacement time consists of a fixed setup time (seconds/per frame) to setup the replacement robot on location and of a replacement time (seconds/roll), in which the old roll is replaced with a new one.

4.1.4 Condition Monitoring Systems

Condition monitoring of the rolls can be performed by a system of smart rolls and a central monitoring unit. For simplicity, it is assumed in this study that all smart rolls and other wireless components have endless battery life. The estimation of the remaining lifetime of an individual roll is based on temperature measurements, which are read by the condition monitoring system from the sensors on the shafts of the rolls. The actual time it takes to monitor a sensor is considered negligible, since all data is transmitted via radio waves.

4.1.5 Estimation of the Remaining Roll Lifetime

The remaining lifetime of a roll is estimated, by measuring the temperature of its shaft. The remaining lifetime of the roll is defined as the minimum of the remaining lifetimes of its two bearings. The shaft is equipped with a temperature sensor that communicates with the central monitoring unit. For the simulation, the temperature-vs.-time curve of a bearing is modeled as shown in figure 14 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 a bearing, 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.

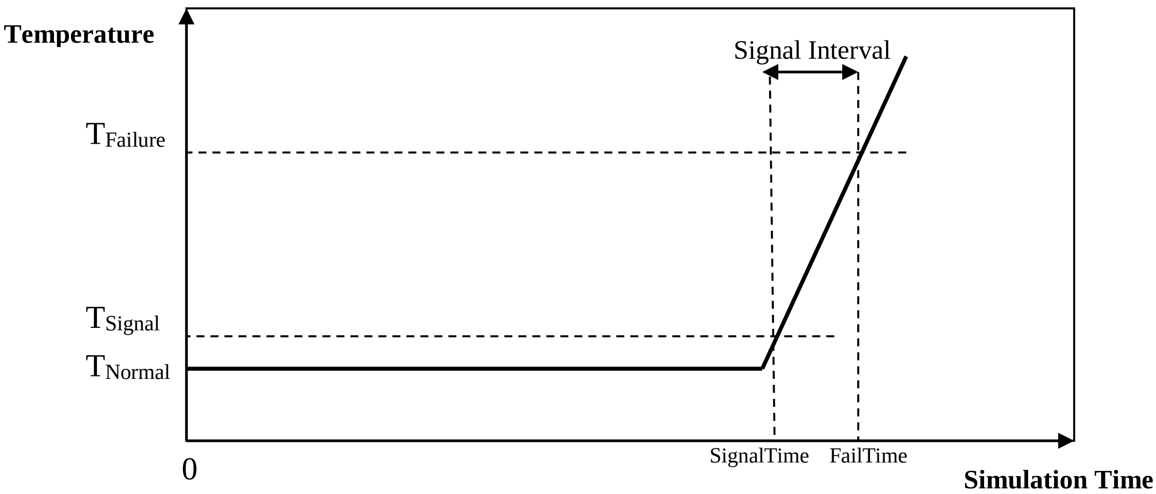

Figure 14: Temperature versus time curve of a roll bearing.

A smart roll is assumed to be programmed to autonomously send a warning signal to the central monitoring unit, when the temperature measured from one of the bearing sensors starts to rise above a specified limit temperature T_{Signal}. From this point onwards, the temperature will continue to rise until actual failure of the roll's bearing (and thereby of the roll) at $T_{Failure}$. The time period, during which the temperature rises, is called "Signal Interval". For the simulation, the specific Signal Interval for each bearing is allocated via a uniform distribution. Minimum and Maximum values for the uniform distribution can be specified.

The discrepancy between a bearing'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 bearing. 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 is defined by:

$$M = A + d*(F–A)*X + f (F– A)$$

Where F, Fail Temperature of the Roll

A, Current Actual Temperature of the Roll.

X, Random variable, sampled from a Normal(0,1)-distribution

d, Deviation, as fraction of the residual temperature (until fail temperature)

f, Safety factor, as fraction of the residual temperature (until fail temperature)

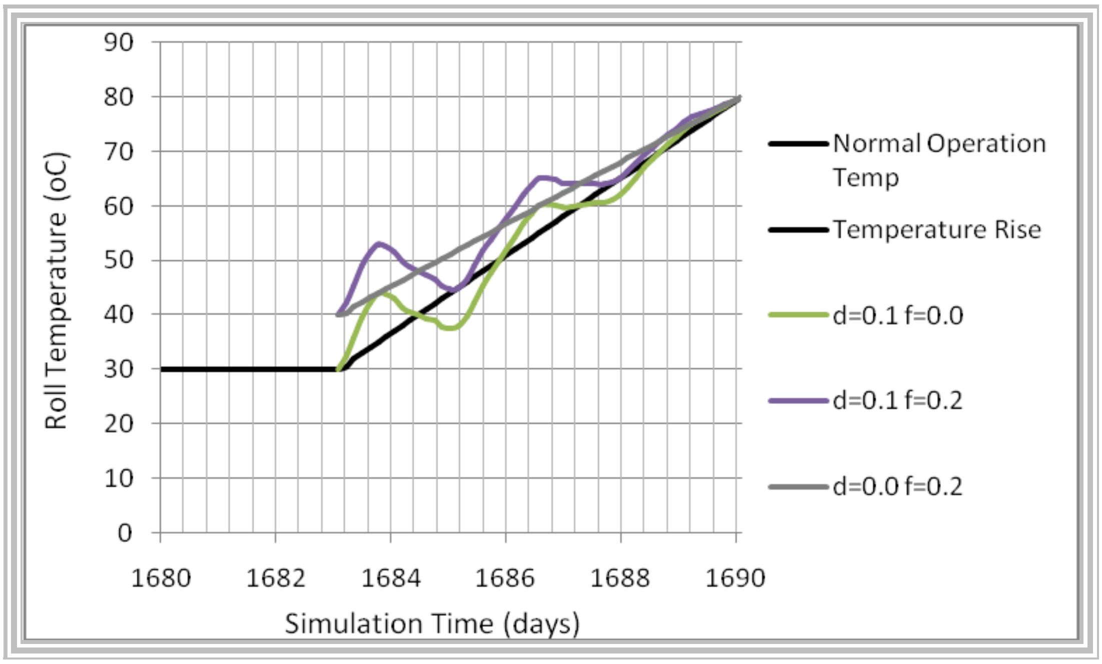

Figure 15: Behavior of the measured temperature for different values of d and f.

A sample of X is drawn for the normal distribution each time a measurement is required. If f equals zero, the temperature measurement is unbiased. The probability that the measurement underestimates the temperature is 50 %. This could result in late replacement of a roll, which is unwanted. With f > 0 the measurement becomes biased towards overestimating the temperature. The deviation and safety factor are a fraction of the residual temperature (F – A). This means that the closer the current Actual Temperature is to the Fail temperature, the closer the value of the deviation and the bias f of the measurement get to zero. When the current actual temperature equals the fail temperature, M is 100 % accurate. The effect of different values for d and f on the behavior of the temperature measurement can be seen in Figure 15. The proper value for d depends on the physical properties of the robot and must be determined experimentally during validation of the model. Then, the simulation model can be used to determine the optimal value for f.

4.2 Simulations

In this paragraph the results of the simulations are discussed and compared with the results discussed in [1] where the robot performed the inspections and monitored the rolls. It should be noted that it is assumed that in both cases, whether smart rolls are used or whether the trolley is used for inspection purposes, the trolley is used for maintenance in this case meaning roll replacement.

4.2.1 Simulation settings

The settings used in the simulations are as follows:

- Normal operating temperature = 30 ^oC
- Failure temperature = 80 ^oC
- Conveyor length = 10,000 meter
- Simulation length = 100 days

It is assumed that the belt conveyor is equipped with smart rolls and that the maintenance trolley with robot travels when required. The maintenance interval is therefore flexible and not fixed [1].

The Safety Criterion defines a temperature above which a roll is replaced by the robot. If the Safety Criterion is too low, the rolls will be replaced too early which is not feasible. If the Safety Criterion is too high, the rolls will be replaced too late, which is even worse. Two safety temperatures can be distinguished: T1 and T2. T1 is the roll temperature that triggers replacement by the maintenance trolley. While the maintenance trolley is performing its duty T2 is the temperature (lower than T1) at which the trolley also replaces a roll. The idea behind this is that while the roll that triggered the trolley to move along the conveyor definitely needs replacement other rolls may trigger the trolley to replace them quite soon afterwards. However, when that happens the trolley may be working on other rolls, which means that rolls having a temperature above T2 may be replaced too late. In order to prevent this situation a second safety temperature is defined.

Three options as far as temperature settings are discussed:

- T1=37°, T2=35°
- T1=71°, T2=69°
- T1=71°, T2=35°

4.2.2 Performance indicators
The performance of the smart roll system combined with the maintenance robot is determined by two factors. Most important is the number of rolls that are replaced too late. Too late replacement means that the roll already failed; this could cause damage to the conveyor belt. The other performance indicator is the average time between replacement and lifetime of the roll. Replacing rolls with a large residual lifetime is a waste. The following results are presented:

- Average cycle time for the robot
- Average number of inspections per cycle
- Percentage of early replaced rolls
- Average time between early replacement and lifetime roll
- Percentage of late replaced rolls
- Average time between lifetime roll and late replacement

The performance is summarized with two performance indicators:

Failure: percentage of rolls replaced (too) late
Waste : average time rolls are replaced before the end of their lifetime

4.2.2 Setting 1: T1=37°, T2=35°
The results of the simulations with T1=37° and T2=35° are presented in Table 1.

Settings					Cycle		Early replaced		Late replaced	
Safety Time 1 (d)	Safety Time 2 (d)	d	f	Monitoring interval (h)	Nr Cycles	Avg. Time	% Early	Avg Early	% Late	Avg Late
37	35	0.00	0.00	24	98	0.52	100.0%	7.0	0.0%	0.0
37	35	0.25	0.00	24	99	0.52	100.0%	7.1	0.0%	0.0
37	35	0.50	0.00	24	99	0.52	100.0%	7.0	0.0%	0.0

Table 1: Results with different values for the deviation.

The results of the simulations can be summarized as follows:

- Safety criterion 2 is close to criterion 1; both are relatively low
- Number of cycles shows that strategy results in daily robot cycles
- No late replacements
- Average waste per replaced roll is 7 days

4.2.3 Setting 2: T1=71°, T2=69°
The results of the simulations with T1=71° and T2=69° are presented in Table 2.

Settings					Cycle		Early replaced		Late replaced	
Safety Time 1 (d)	Safety Time 2 (d)	d	f	Monitoring interval (h)	Nr Cycles	Avg. Time	% Early	Avg Early	% Late	Avg Late
71	69	0.00	0.00	24	94	0.52	100.0%	1.2	0.0%	0.0
71	69	0.25	0.00	24	94	0.52	99.6%	1.5	0.4%	0.1
71	69	0.50	0.00	24	98	0.52	99.5%	3.3	0.5%	0.1

Table 2: Results with different values for the deviation.

The results of the simulations can be summarized as follows:

- Safety criterion 2 is close to criterion 1; both are relatively high
- Number of cycles shows that strategy results in daily robot cycles (except during first 6 days)
- Percentage late replacements is higher if deviation is higher
- Average waste per replaced roll is 1 to 3 days

4.2.4 Setting 3: T1=71°, T2=35°
The results of the simulations with T1=71° and T2=35° are presented in Table 3.

Settings					Cycle		Early replaced		Late replaced	
Safety Time 1 (d)	Safety Time 2 (d)	d	f	Monitoring interval (h)	Nr Cycles	Avg. Time	% Early	Avg Early	% Late	Avg Late
71	35	0.00	0.00	24	16	0.80	99.9%	4.4	0.1%	0.1
71	35	0.25	0.00	24	24	0.69	100.0%	5.3	0.0%	0.0
71	35	0.50	0.00	24	87	0.53	100.0%	6.9	0.0%	0.0

Table 3: Results with different values for the deviation.

The results of the simulations can be summarized as follows:

- Safety criterion 2 is high; safety criterion 1 is low
- Number of cycles low (1 per 6 days) without deviation; towards daily with high deviation
- Percentage late replacements is (almost) zero
- Average waste per replaced roll is 4 to 7 days

4.2.4 Conclusions on simulations
The results of the simulations are summarized in Table 4.

Setting	T1	T2	Failure	Waste
1	37°	35°	0%	7 days
2	71°	69°	0%-0.5%	1 – 3 days
3	71°	35°	0%	4-7 days

Table 4: Results all simulations.

From Table 4 the following conclusions can be drawn:

- T1 should be chosen sufficiently high, for example at 71°.
- T2 should be also be chosen high (for example 69°) since d is low using RFID technology. In theory d=0 with using smart rolls.
- With T1=71° and T2=69° the failure will be 0% and rolls will hardly be replaced early (waste is 1 day).

4.3 Performance comparison

In [1] the performance of the monitoring and maintenance trolley was discussed. It should be realized that there is an important difference between the technology discussed in [1] and the smart rolls introduced in this paper. In [1] the monitoring was frequency based, here it is temperature based. However, a case that is comparable is presented below in Table 5, which is Table 8 in [1].

Settings					Cycle		Early replaced		Late replaced	
d	f	Cycle interval	Safety Time	Inspection Time	Avg. Time	Nr Inspect	% Early	Avg Early	% Late	Avg Late
0.10	0.25	30	30	60	3.02	5876	100%	25.4	0%	0.0
0.10	0.25	20	20	40	2.25	4288	100%	17.0	0%	0.0
0.10	0.25	10	10	20	1.44	2462	100%	8.5	0%	7.5
0.10	0.25	5	5	10	0.98	1380	100%	4.2	0%	8.8

Table 5: Results with different cycle interval setting (Table 8 from [1]).

When Table 5 is compared with the results presented in the previous paragraphs it can be concluded that the results shown in the last row of Table 5 are comparable with the results of setting 2 simulations. The most important difference is that in [1] the cycle time is 0.98 days where in Table 3 it is 0,8 days. This is caused by the fact that in [1] the robot was also used for inspection where that function in this paper is taken over by the smart rolls and the inspection does not take time. The waste is comparable.

In general it can be said that:

- With the smart rolls a failure rate of 0% can be achieved assuming that the safety temperatures are set correctly.
- With the smart roll system the waste, in terms of days of early replacement, can be reduced to a minimum.
- Simulation is an excellent tool to determine the correct settings of the monitoring system.
- The time available between a possible failure warning and the final failure is much shorter when temperature monitoring is used than is the case when using vibration monitoring. This may have an affect in practice on the failure rates. This needs to be investigated in practice.

5. CONCLUSIONS

In this paper smart rolls were introduced as a means of monitoring the performance of idler rolls. The technology has been developed and is working. One important issue is the costs of the technology. Today in its prototyping stage it is too expensive. However it is believed that when it can be produced in large numbers the costs will be small compared to the costs of a single roll. In that case the technology is feasible for both small scale as well as large scale applications. The setting of the trolley, or alternatively the instructions given to maintenance personnel, used for the replacement of rolls that are close to failure can be investigated by using simulation. An important issue for that determination is the accuracy of the model used to predict the raise of the rolls temperature in time. Finally it should be realized that the RFID technology introduced in this paper can also be used for other components than the rolls. The smart rolls introduced here are believed to be the first step to a future where “smart dust” sensors can be used to monitor all relevant components of a belt conveyor.

6. REFERENCES

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