Adaptive Optical Sensors

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Abstract—**The sensors containing microcontrollers, digitizers and some standard communication line(s), offering digital output expressed in corresponding units of measured quantities, are usually called intelligent sensors. This contribution offers another view on the sensor intelligence – on the ability to adapt their measuring range to different tested materials' physical properties to get accurate results. The article describes two methods of measurements and control of band material position by means of optical sensors, which adapt their range to the current optical properties of the material used (steel, web or plastic foil).**

Keywords- optical sensors; band material; optical transmitter and receiver; microcontroller.

I. INTRODUCTION

The task of band material positioning is very frequent in companies manufacturing band shape materials such as tyre makers, sheet rolling mills, conveyor belts, and textile or plastic film rolls producers. In these cases, the central position or constant width of the soft material bands are required during the technological process. The importance of the accurate measurement of the belt position and its dimension (the width) is crucial, if a good quality of the final product is to be achieved. This measurement must be worked out without any mechanical contact with the measured band material. For this purpose, optical sensors are usually used. The sensors create the measurement part of an automation control system, the goal of which is the position or dimension control of a processed band material. The basic tasks of the band material position control can be explained from the schematic diagrams in Figures 1 and 2.

The case of the band material centre is shown in Figure 1. The position is measured by two optical sensors positioned symmetrically with respect to the longitudinal axis of the technological equipment, e.g., a rolling mill, calendar, etc. If the signals from both sensors are identical (their difference is equal to zero), then the band is situated in the centre of the machine. Achieving this position is the goal of the control task.

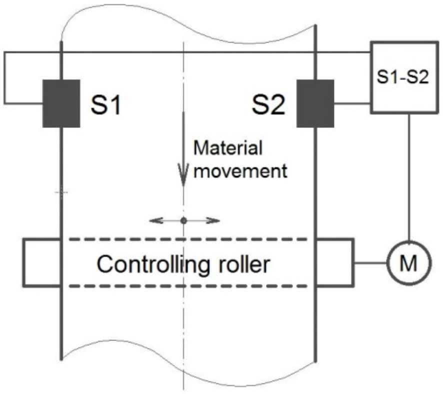

Figure 1. The basic principle of the belt material automatic centering.
S1, S2 – optical sensors, S1-S2 electronic unit, M – actuating mechanism.

The band transversal position can be changed by a roll, which can be moved in the direction orthogonal to the band movement. If the centered material does not transmit any light, then, in many cases, only a single sensor is used to determine the central material position. In such configuration, the optical centre of the sensor determines the required position of the material edge.

Similar to this task is the setting of the processed band width, the principle of which is shown in Figure 2. If a soft material (plastic foil, textile, cord, etc.) is processed, its width is changing with the pulling force causing the band movement.

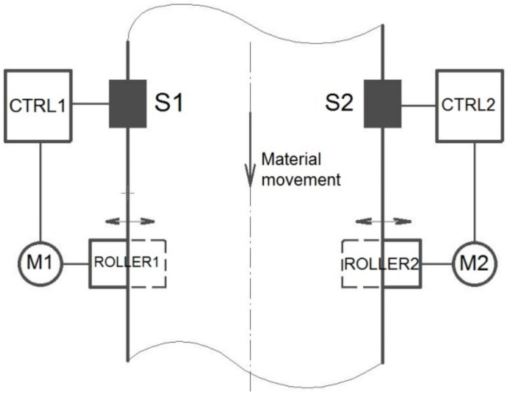

Figure 2. The basic principle of the belt web material width automatic control. S1, S2 – optical sensors, CTRL1, CTRL2, measurement and control units, M1, M2 – actuating mechanisms.

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A pair of optical sensors placed symmetrically with respect to the longitudinal axis of the technological equipment again measures the band edge position. Besides, their centers are fixed in distance which is equal to the required width of the band. If both sensors show a half of their measuring range, then the width is set correctly. If one or both sensors give a false position, the band width is adjusted using two independent rolls, which correct individually the material edge position in the required width.

Both methods have some bottlenecks that should be overcome to achieve satisfying results.

The rest of the paper is divided into the following sections. Section II contains the present state overview. Section III describes the new concept of the system solution. Section IV includes the sensors realization and results of the first test. The acknowledgment and conclusions close the article.

II. STATE-OF-THE-ART

A. Mechanical Arrangement

At present, optical sensors consist of an optical transmitter, which involves the light source, usually Light Emitting Diodes (LED) operating in the InfraRed (IR) region of the light spectrum, and an optical receiver, which uses phototransistors operating also in the IR region. The optical elements of both sensor parts are arranged in the shape of a row array, and both arrays are placed against each other [1]. The optical transmitter and receiver are built in a frame that can have either a narrow rectangle or a horse-shoe shape. Usually, the measuring system contains a pair of the sensors, each equipped with one transmitter and one receiver. The centered material is led in the gap between sensors so that its edges will lie in the active range of sensors, in the gap between the transmitter and receiver inside the frame. The principle arrangements of both shapes of sensor frames are shown in Figures 3 and 4.

Figure 3 shows the position of optical sensors in the rectangular frame. The red fields assign the IR flux emitted by the optical transmitters and accepted by the optical receivers. The range of the material width is given by the difference MAX – MIN. This type of frame is usually used if the centered band width is within the range from 1 to 2 m (cords for tires or conveyor belts). The row array of the sensor parts must be wider than this measuring range. The advantages of this sensor arrangement are its simplicity and no need for manipulation if the material width is changed for another type of final product during the process of production. But this performance requires a very careful match of several tens of applied optoelectronic elements for transmitters and receivers to ensure good linearity and symmetry of both sensors [2].

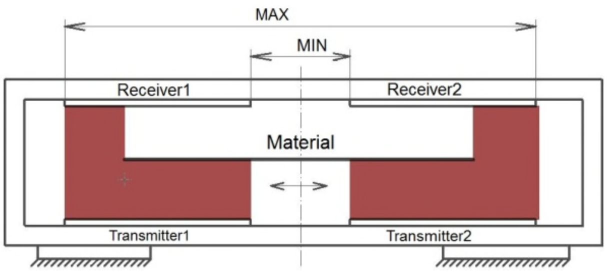

Figure 3. The frame performance of the optical sensor for the automatic centering task.

The sensor shown in Figure 4 takes advantage of two horse-shoe frames placed on carrier 3, equipped with an adjustable mechanism 1,2,5,6, which makes it possible to set the distance of both sensors 5 according to the actual width of the band material 7 [2]. This arrangement requires much fewer matched optoelectronic elements, but its mechanical construction is more complicated (slide way of frames, bidirectional set screw, width scale, etc.). This type of the sensor is often used either if the belt material is extremely wide (more than 2 m) or not flexible (steel plates).

The principal problems of this sensor type are the match of optoelectronic components for the IR radiation generating and sensing, and undulated edges of non-flexible materials. The only solution of these problems is the precise match of components with the same characteristics on one side, and the subjective decision of a rolling-mill worker about which plate edge could be the reference one, if the centering process determines only one edge position.

The sensors for the material width measurement are very similar to the horse-shoe shaped sensors; the only difference is that the frames are fixed so that their centres will be positioned at the measured distance. In this case, only one width can be measured and, thus, these sensors are built in special purpose machines. The problem of the measurement is that the material, a web, is more or less transparent. This material property causes errors in measurement, especially if the transparency (the material optical density) varies from place to place.

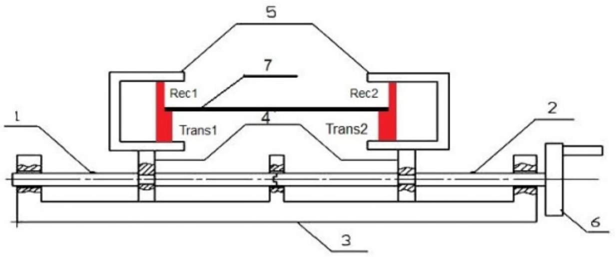

Figure 4. The horse-shoe type of the optical sensor for the automatic centering.

B. Electrical Equipment

The electronic units of the sensors serve to supply the optical receivers and to process the received signal proportional to the luminous flux passing through the material in the operating space of the sensor. To prevent unwanted influence of outer sources of the IR radiation, the LEDs of receivers are supplied with a constant current source which operates in the switching mode so that the luminous flux is modulated. The signals from the receivers are demodulated, amplified and subtracted using a differential amplifier. All present systems we have met in various factories take advantage of the analogue principle. The sensors are calibrated in two points, at the zero luminous flux and the maximum luminous flux, when no object is placed in the working place of the calibrated sensor. In both cases, the LEDs are fully excited from their current source.

In systems with the horse-shoe frame, which use only one sensor selected by the operator, the reference position is determined by the active sensor centre. The electronic equipment must be able to handle both sensors individually, because the reference sensor is selected during the material processing.

The sensors measuring the band material width are used to control the leading rolls position. Each of the sensors controls its own roll so each sensor has its own electronic control unit taking advantage of a similar signal processing as in the previous task.

C. Band Position Control Problems

It is no problem to control the width of band materials that are not transparent, but if the material is more or less transparent (plastic foils) or diaphanous (textile, tyre cord) the measurement becomes very problematic. For instance, if the receiver measures 50% of the full scale luminous flux, the material edge is in the centre of the sensor in case of an opaque material. But this is not true if some light passes through the material. Then, the material must cover more than 50% of the sensor active space to get the same signal. Thus, the sensor offers a false result of the width measurement. The error depends on the material transparency. To avoid this problem, it is necessary to calibrate the sensor whenever the material transparency changes. This is very problematic because it requires a production interruption, but in case of the inhomogeneous material (tyre cord) such calibration does not bring sufficient improvement. Certain suppression of this effect can be achieved, if the sensor frame is turned a bit so that the light beam is not orthogonal to the material surface (Figure 5) and the gaps between material threads are smaller. Again, the problem is reduced, not eliminated. Besides, the sensor can be damaged because of the material longitudinal swing if the angle between the light beam and the material surface is acute.

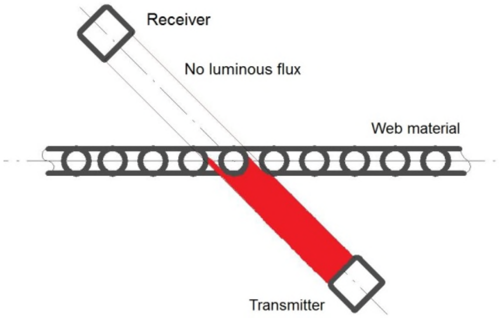

Figure 5. Turning of the sensor drops off the material transparency error.

III. NEW CONCEPTION

Our effort was turned to the width control and automatic reference edge selection tasks as a reaction to the requirements of industrial companies. To address the above mentioned problems requires a new strategy of the sensor and electronic equipment conception. If the system has to change its properties automatically, or has to make any decision, if the process conditions are changing, it is necessary to use the digital principles of the control. The following paragraphs show the solutions of two tasks, measurements of the width of materials the transparency of which varies in time and the automatic reference steel sheet edge selection during its procession in the rolling mill.

A. Band Width Measurement

The basic goal of this task is the measurement of the processed material transparency, its evaluation and the system recalibration based on the measurement results. It was necessary to develop an original type of the optical sensor capable of the continual material transparency measurement and then to calculate the material width.

The sensor mechanical concept comes out of the horse-shoe shape, but it consists of three sections (Figure 6), equipped with three optical transmitters (Tr1 – Tr3) and receivers. These are placed in the working space so that the first section is fully covered by the band material, the second one, the measuring part of the sensor, is partially covered by the tested material, and the third section is clear of the material. All the three transmitters are connected in series and take advantage of the pulse current, the peak value of which is 10 mA. The signals from the first receiver (REC1) and the third one (REC3) provide the zero and full scale points of the material coverage. The central, measuring part of the sensor is provided by the signal of the second section receiver REC2, which lies between the boundaries defined by the signals REC1and REC3. Then, the degree of the measuring sensor coverage D can be calculated:

$$D = (REC2 - REC1) / (REC3 - REC1) \qquad (1)$$

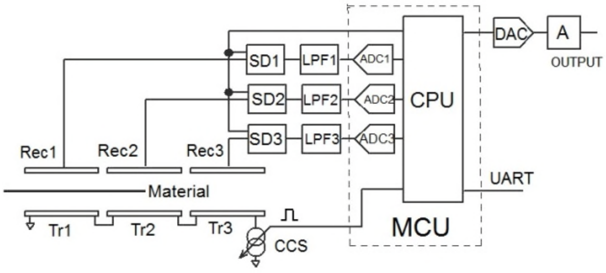

Figure 6. The basic block diagram of the three - section sensor for the width measurement.

If all three sections provide the same signals after the calibration of signal traces, and if the centre of the second section determines the correct material width, then the goal of the control task is to reach the value of 0.5.

According to Figure 2, there are two identical sensors located on both material edges (S1 and S2). The distance between the measuring section centers is equal to the required material width.

The signal trace function is controlled by a built in MicroController Unit, MCU, (Texas Instruments MSP430AFE253) [3], which ensures excitation pulses for optical transmitters (Tr1, Tr2 and Tr3) supplied with the Constant Current Source (CCS), and switching pulses for Synchronous Detectors (SD1, SD2 and SD3) processing the received signals from all three sensor sections. These signals are then led to the Low-Pass Filters (LPF1, LPF2 and LPF3) that reject high frequency modulation products presented in the detected signals. The signals are then digitized in three independent 16-bit Analogue-to-Digital Converters (ADC1, ADC2 and ADC3). The digitized signals are calculated in compliance with (1). If the value of D is different from 0.5, a non-zero error signal is generated. This digital signal is converted to the analogue form using a 12-bit Digital-to-Analogue Converter DAC, Analog Devices AD 5320 [4]. This analogue signal is amplified in amplifier A and used for the control of the position roller that adjusts the material width.

The MCU measures and controls the material optical density in 100 ms intervals, and so continuously adapts the measuring range to the actual optical transparency of the processed band material. This arrangement completely eliminates the material transparency error. For the purposes of the basic signal trace calibration, the MCU serial Universal Asynchronous Receiver Transmitter (UART) is used for communication with the host PC. The block diagram of the sensor and its signal trace are shown in Figure 6. The electronic unit is supplied from the mains electricity, 230 V, 50 Hz.

B. Steel Plate Centering

This task is solved during the roll-milling process, when the processed band is led to the centre of the rolling-mill machine. The plate is then rolled up to a spool, the centre of which is also localized in the centre of the rolling-mill machine and it is necessary to put the turns of the plate onto each other with minimum position fluctuation. The sensing mechanism consists of two horse-shoe optical sensors, the positions of which are controlled by a bidirectional screw (if the screw turns clock-wise, the horse-shoes distance diminishes, if the screw is turned in opposite direction, the distance rises). The active width of each sensor is 60 mm. The sensors are fixed so that the distance of their centres is equal to the input material width. For this purpose, the sensors are equipped with a scale, so that the required width of the material can be adjusted before the controlling process starts. During this process, only one sensor is active to measure the band position. The problem of this position control is in undulated edges of the plate because of unequal material tensions. These undulations cause control errors. Therefore, it is suitable to select the less undulated edge as the reference one to reach better results of the control. As mentioned above, the choice is worked out by the worker who is in the control room several meters from the processed material and, thus, his decision is very subjective. To get a more objective choice, the decision was committed to a MCU controlled sensor unit, which learns the material edges fluctuations during the process and after a time period (30 seconds) is able to evaluate the undulations because of that learning. The less undulated side of the plate is determined as the reference one. During the learning period, the control is running on the default or previously optimized reference edge. The undulation errors are, in most cases, within a range of +/- 10 mm. To get the best results, the maximum gain of the control unit is required round the sensor centre. Therefore, the dynamic range of the controller manipulating variable was divided into two ranges (Figure 7). The highest gain of the control loop was within the range of +/- 6 mm from the zero point of the sensor. In this region, one half of the output 12-bit DAC dynamics was used for the control. The other half of the DAC dynamics is intended for the control within the rest of the sensor range – the sensor adapts its sensitivity to the error magnitude. It should be noticed that the material position data from both sensors must be mirrored to get the proper direction of the position correction (it is necessary to resolve the right and left side sensors).

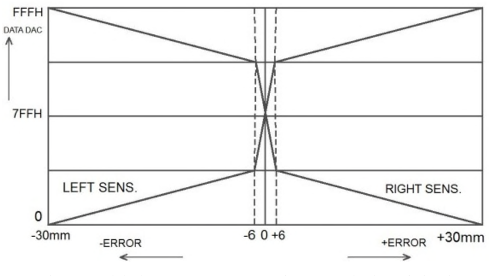

Figure 7. The sensitivity versus error characteristic of the horse-shoe sensors for the steel plate centering during the roll-mill process.

The sensor electronic unit takes advantage of the same electronic circuits and the signal processing as in the case of the width measurement, but only two measuring channels are used. The basic difference is in the firmware of the MCU, because the tasks of the measurement are different.

IV. SENSORS REALIZATION AND RESULTS

Both types of sensors were designed and manufactured as per the mechanical and electrical construction specifications. Figure 8 shows the width sensor arrangement with three measuring sections.

Figure 8. The three sections sensor for the belt width measurement.

The sensor is placed on a welded frame formed by square profiled tubes. To save space, the sensor part which is never covered by the band is placed upright to the remaining two sections. The sensor takes advantage of three sections; the active width of each section is 60 mm. There are glass windows protecting the sensor optoelectronic elements on the active sides of the sensor. They protect the sensor elements against the mechanical stresses and dust.

The Printed Circuit Boards (PCB) of the sensor transmitter and receiver are shown in Figure 9. The PCBs are built in the sensor frame. The figure shows two sections of the sensor. Note the linear arrangement of the optoelectronic elements. The dimensions of the sensor carriers are 200 x 15 mm.

The PCB electronic circuitry is shown in Figure 10. It includes the mains power supply, supply of the optical transmitter and all three signals analogue and digital traces processing the transmitter's signals. This PCB is built in the BOPLA Elegant box, and its dimensions are 130 x 75 mm.

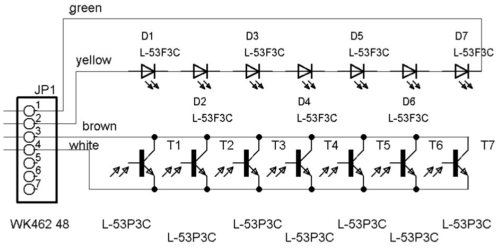

Figure 9. One section schematic diagram of the transmitter (upper) and receiver (lower) optical elements.

Figure 10. The PCB with all controlling and measuring electronics of a three sections sensor.

The sensor for the centering of the steel sheet band is shown in Figure 11. This figure shows its implementation during the tests in the roll-mill. See the adjusting wheel (RK) for setting the sensor centre to the required position.

The firmware for both tasks' solutions was created and the sensor's functionality was tested.

V. CONCLUSIONS

The first function tests in the real industrial environment were successful because the achieved results of the control process were much better compared with previous solutions. The width control error was within the range of +/- 1 mm (at the material width of 2000 mm); the error of the control in the case of centering of the steel plate was +/- 2 mm at the output spool. However, these errors are the errors of the entire control process caused by the propagation delay between the points of measurement and the position actuating, by the hydraulics of the manipulator, etc. These tests showed improved properties of the systems and confirmed expected results. At present, a new test tool has been designed and is being produced. This will let us perform detailed analysis of the system parameters.

Figure 11. The implementation of the horse-shoe sensor in the roll-mil machine.

The sensor parameters (accuracy, resolution, repeatability and stability) will be evaluated in the following weeks because the project dealing with these sensors is not yet finished.

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REFERENCES

[1] Electronic publication: Highly Precise, Non-contact Width Measurement of Webs and Boards. https://www.elovis.com/en/applications/non-contact-widths-heights-diameter-measurement/webs boards-plates/, ELOVIS GmBH, Germany 2019. [retrieved: 9, 2019]

[2] User Manual of the Centering System of bands width 950 - 2200 mm. [In Czech] HAAL, s.r.o., Brno, Czech Republic, 2001.

[3] Electronic publication: 16-bit Ultra-Low-Power Microcontroller, http://www.ti.com/lit/ds/symlink/msp430afe253.pdf, pp. 28, 35, 38, Texas Instruments Incorporated, Dallas, Texas 75265, USA, 2019. [retrieved: 9, 2019].

[4] Electronic publication: 2.7 V to 5.5 V, 140 µA, Rail-to-Rail Output 12-Bit DAC in an SOT-23. https://www.analog.com/media/en/technical-documentation/data-sheets/AD5320.pdf, pp. 1, 11, 12, Analog Devices, USA, 2019 [retrieved: 9, 2019].

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