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Real-Time Flatness Inspection System For Steel Strip Production Lines

This paper describes the development of a flatness inspection system, integrated in the control process of a hot strip mill in the steel industry. The objective of the system is to calculate flatness indexes for every strip, comparing the length of its lateral profiles with the central length. The reconstruction of the profiles is based on a nonlinear triangulation technique. Images of the steel strip, at high temperature and high speed, are sampled every 2 ms at five different points and are processed on-line in order to calculate height displacement values of the strip, which allows the calculation of final flatness indexes for the steel strip. The measurement method developed introduces an innovative geometry in the disposition of the optical elements which increases the measurement range without reducing precision. It also includes a tracking system to compensate for the effects of lateral displacements of the strip. The flatness inspection system has been implemented using a heterogeneous distributed computer system.

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Introduction

Among the most important manufacturing products in the steel industry are those known as *flat products*. These products are long strips of steel which are normally stored as coils after their manufacturing. They are used in other industries to make several products, ranging from cans to automobiles.

During the manufacturing of flat products the two main quality problems which arise are the crown problem (nonuniform thickness of the strip), and the flatness problem for which this system was developed.

Industries continually endeavor to manufacture their products with superior quality; in consequence they demand higher quality, defect-free materials. In order to increase the quality of its flat products, the department of R & D Automation of the *CSI Planos* steel factory, in cooperation with the department of Computer Science and Engineering of the University of Oviedo, carried out preliminary studies concerning the flatness inspection problem [1–3], and initiated the development of an industrial prototype for a real-time flatness measurement system.

The main goal of this system is a real-time inspection of the steel strip during its manufacturing process to detect, measure and help to eliminate flatness defects in order to increase the quality of flat products.

What are flatness defects? Why do they appear? What do they look like? To answer these questions, we will begin by briefly describing the manufacturing process, and detailing the measurement problems.

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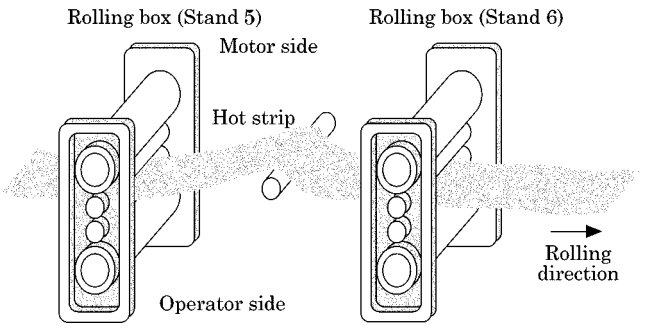

Figure 1. Strip manufacturing process.

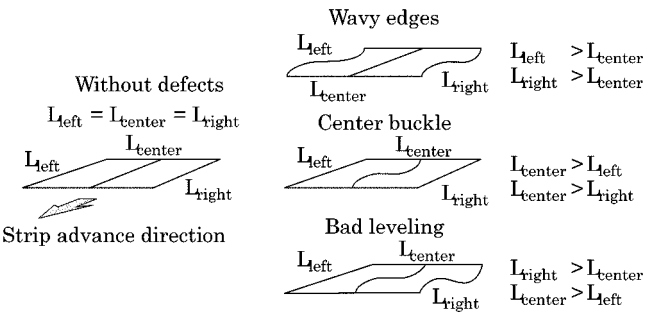

Figure 3. Types of flatness defects.

Flat strips are obtained from large pieces of steel called slabs. These slabs are heated in a furnace. When they reach a temperature above 1200°C, they leave the furnace and are passed through pairs of cylinders, called rolls. These rolls press the hot steel, so that the strip reaches the desired width and thickness, increasing its length. In Figure 1, two sets of rolls and their operation are shown.

The rolls used to press the material are never perfect, so they do not press on the entire transversal section of the strip with the same force. In consequence, the increment of length will not be the same at all points of the section of the strip. Therefore, if the strip is considered as several adjacent fibers [4], the application of different forces to each longitudinal fiber will produce different increments in length, ΔL, for each fiber. However, all the fibers of a strip are enclosed in a surface of a fixed length, L, Figure 2 shows this effect.

These differences in fiber lengths create internal tensions in the strip, which produce strains in the material, called *flatness defects*. These defects may be of several types, depending on the shape of the rolls that produce them. If the rolls produce higher pressure at the edges of the strip than in the center, they produce defects called *wavy edges*. However, if the pressure is higher at the center of the strip than at the edges, they produce defects called *center buckles*. Finally, if the forces are different throughout the strip-roll contact line, they produce *bad levelling*. These three types of defects are represented in Figure 3.

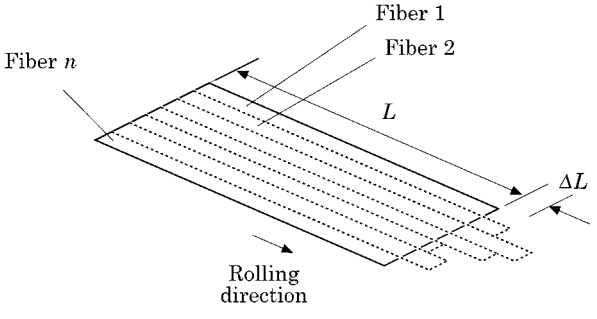

Figure 2. Origin of flatness defects: different fiber lengths enclosed in a fixed-length surface.

Flatness defects are quantified by indexes called *I-units*. These I-units are obtained by comparing the lengths of two fibers during the strip rolling. One fiber acts as a reference, normally the central one, and the other is compared to it.

In steel strip production, the following ranges of flatness indexes (I) expressed in I-units are normally considered [5]:

Low defects	$0 <$	I	≤ 5 I-units
Normal defects	5 I-units $<$	I	≤ 50 I-units
High defects	50 I-units $<$	I	

In the next section, the way in which strips are inspected to find defects and an analysis of previous existing measurement systems are presented. The following sections present our approach, including also a description of the system implementation, the results obtained with this system in the laboratory and in the factory and, finally, the conclusions are presented.

Measuring Flatness

Where to measure

As seen in the previous section, the problem of measuring flatness can be reduced to the measurement of

length of longitudinal fibers the strip while it is being manufactured. However, the measurement of fiber lengths presents some problems due to the environmental conditions in the place where the inspection system must be located.

When the steel strip leaves the last pair of rolling cylinders, at its final width and thickness, it is passed through several showers situated along a 100 m path called the *run out table*. Here the temperature of the strip is reduced. Finally, the strip is caught by a coiler which rolls it into a coil. Flatness defects can be detected while the beginning of the strip, called the *head*, is moving freely along the run out table until it reaches the coiler. When the coiler catches the strip head, the defects seem to disappear due to the tension introduced in the strip by the coiler. Therefore the best place to detect and measure flatness defects, enabling the generation of feedback signals to correct them, is immediately after the last pair of rolling cylinders.

However, the strip temperature at this point is over 700°C, and its speed can reach 15 m/s, making the measurement conditions extremely adverse. Furthermore, there is a great quantity of dust and steam. Thus, any optical measurement equipment installed here must be protected by air-curtains in order to avoid dust and steam.

Obtaining flatness indexes

Flatness is expressed to the mill operators as flatness indexes called *I-units*. These values are obtained by comparing the lengths of different fibers. Normally, three or five fibers are measured, one at the middle of the strip, which acts as a reference, and one at each side of the strip, close to the strip border. If the strip is very wide, two additional fibers are measured between the others.

In Figure 4 the real fiber and a possible reproduction of the fiber are shown. In order to reproduce the strip fiber it is necessary to measure both the horizontal and vertical displacement in each sample period. Applying Eqn (1), an approximation of the fiber length can be obtained; where v_i is the strip speed when it leaves the last pair of rolls (this speed is directly available from a mill sensor); t_i is the time stamp when data is captured; and h_i is the fiber height at each different point. The sum is applied to the whole integration period, n being

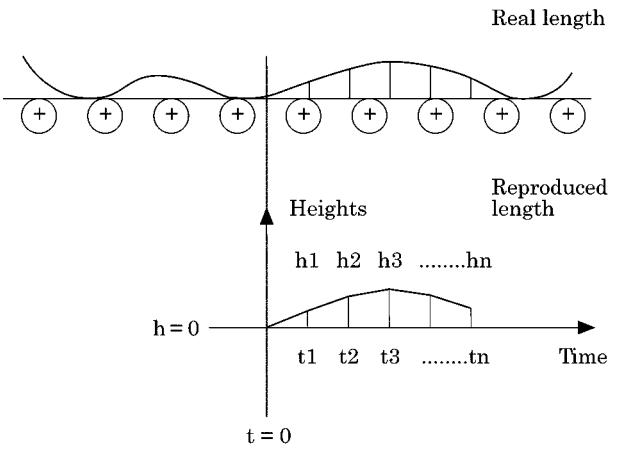

Figure 4. Method for the strip profile reproduction.

the number of samples in the integration period. The shorter the sample period, the closer the reproduced fiber will be to the real length.

$$L = \sum_{i=1}^{n} \sqrt{(h_i - h_{i-1})^2 + v_i^2 \cdot (t_i + t_{i-1})^2} \qquad (1)$$

Two aspects must be considered in measuring fiber lengths:

- The system must always measure the same fiber, which involves a tracking system to compensate for the effects of lateral strip displacements.
- The length of the sample measured. The definition of the integration period depends on whether the complete strip is measured, or a sample length chosen.

Related work

Flatness is a permanent problem and an issue of interest in steel strip production lines, and over the years several kinds of flatness measurement systems have been developed [4].

The first flatness measurement system appeared in the late 1970s. It was based on two rolls, each divided into nine independent pieces equipped with load cells. This system measured flatness using the different tensions in a section of the strip. The main problem of this system was the wear of the system components caused by the direct contact with the strip.

In the early 1980s in Japanese factories, two measurement systems based on other physical principles appeared. One of them measured the fiber length through an indirect measurement of the electrical resistance along a path closed by a water jet column. The other was based on the measurement of eddy currents. These systems were cumbersome and their measurement rates were low.

The development of optical methods began in the mid 1980s. Originally, these methods were based on the analysis of matricial images. An area of the strip surface was lit and an image of this area was captured by a camera to be analysed later. These methods differed in the type of light source: special incandescent light or laser light. The main problem with this kind of system was the low measurement rate due to the complexity of the image analysis.

In the late 1980s, and early 1990s several systems based on laser triangulation were developed [4, 6, 7]. These systems differ mainly in the number of points at which the strip was measured and the number of lasers and cameras used. In general, this kind of system gives accurate flatness measurements, allows high sample rates, and generates relatively small maintenance costs. However, these systems have some limitations due to the disposition of the optical components.

This kind of system can be divided into two main groups: those with and those without mobile parts. The systems with no mobile parts have many triangulation units to allow the measurement of any width of the manufactured strip. Normally, 10 or more lasers are located at equidistant points across the strip width. These lasers are monitored by two cameras, one at each side of the strip. This type of system is more robust because it has no mobile parts. On the other hand, it involves the use of many elements which are not always used. When the strip is wide, all of the lasers are monitored, but only some of them are valid. When the strip is narrow, some lasers do not produce any measurements. In any case, the measurements are not always taken at the appropriate points.

The systems with mobile parts [8] are able to measure the strip in the correct position whatever the strip width may be. The existing systems of this kind are based on a triangulation geometry of 45°, which makes it easy to obtain measurements. However, this geometry limits the measurement range and increases the size of the system.

Motivation

Since 1992, the R & D Automation Department of *CSI Planos S.A.* has been interested in the flatness problem and in the development of their own measurement system, so several studies have been carried out and one experimental prototype [1–3] has been produced.

In 1993, *CSI Planos S.A.* installed a commercial measurement system in one of its two hot strip mills. After the installation, several defects and limitations were detected. The main limitation of this system was its low measurement range, because when the strip moved vertically more than a certain height, the system missed the laser spots and was not able to measure them. This was a frequent problem which limited the usability of the system. Thus, the R & D Automation department, together with the Department of Computer Science and Engineering of the University of Oviedo, became involved in the development of an industrial prototype of an advanced flatness measurement system, to overcome the defects of commercial systems and to improve their performance at a lower cost.

The New Flatness Measurement Approach

Optical triangulation and flatness index

Like most of the existing measurement systems, the industrial prototype developed uses the well-known optical triangulation technique. However, the main innovation of this system is the way in which it is applied.

The flatness inspection problem is largely based on the measurement of the height of the strip in each sample period. The optical triangulation method is applied to measure this height. In this method, a laser sends a monochromatic light beam over the strip surface. This light beam is reflected towards the lens of a linear camera. Thus, a relationship between the position where the laser beam strikes the camera photodiode line and the strip height can be established.

In Figure 5, the geometrical principle of this method is shown. The laser beam reaches the strip surface at an angle α and is reflected at this same angle. If we consider that at point A the field of vision is perpendicular to the camera, it is possible to analyse what happens when the strip height increases by Δh.

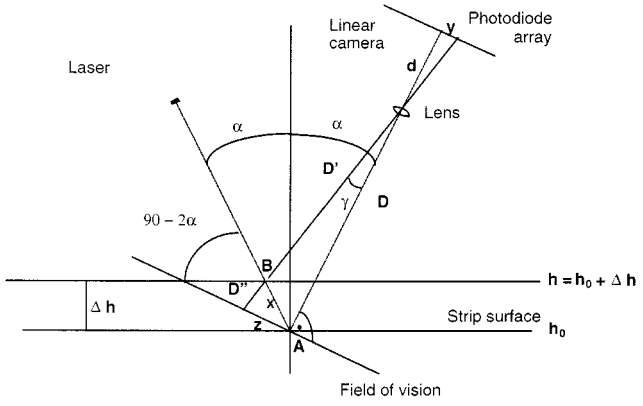

Figure 5. Geometrical principle used for the measurement of height.

When the strip surface increases its height by Δh, the laser beam reaches the strip at point B instead of at point A. This change of position will produce a displacement of y in the photodiode array.

From Figure 5, and using trigonometric expressions, the relationship between the variation of strip height and pixel displacement is given by Eqn (2), where D is the distance from the camera lens to the initial strip position, and α is the angle of reflection. The scale factor K is a constant, which represents the relationship between the size of the real object, and the size of the object in the camera array. This constant depends on the lens, and the distance between the camera and the object.

$$\Delta h = \frac{D \cdot \cos\alpha \cdot K \cdot N_{px} \cdot K_{px}}{D \cdot \sin(2\alpha) + K \cdot N_{px} \cdot K_{px} \cdot \cos(2\alpha)} \quad (2)$$

The product of the factors N_{px} and K_{px} of Eqn (2) gives the distance y, measured on the photodiode array. It is represented in Eqn (3), where N_{px} is the laser-beam image displacement measured in pixels and K_{px} is a constant that represents the distance between two pixels in the photodiode array.

$$y = K_{px} \cdot N_{px} \quad (3)$$

Equation (2) enables the calculation of strip height from pixels. Thus, all the factors in Eqn (1) are known and it can be applied, directly or by its series approximation, to provide the fiber length.

Flatness indexes (I), measured in I-units, are obtained by comparing the length of one fiber with the length of another fiber which is taken as a reference. These lengths are calculated over an integration period. Normally, the integration period is very short and therefore the relative length difference is also small. So the flatness indexes adopt the form expressed in Eqn (4), where L_{edge} is the length of a fiber at the strip edge, while L_{center} is the length of the central fiber of the strip, which acts as a reference.

$$I_{edge} = \frac{L_{edge} - L_{center}}{L_{center}} \cdot 10^5 \quad (4)$$

Advantages of the system

Equation (2) is the general expression for optical triangulation, showing that the relationship between height and pixels is nonlinear, which makes the transformation from pixels to height more difficult. If the angle of reflection, α, were 45°, Eqn (2) would become a linear relationship between pixels and height. All the existing systems based on laser triangulation use this angle [4, 5, 7, 8]. However, this angle also presents an important disadvantage: it limits the measurement range.

The system presented in this paper introduces a new geometry in the disposition of the optic elements, using an angle of reflection, α, close to 30°. With this angle, the relationship between the height of the strip and the pixels is nonlinear, which increases the computation time of the algorithm. However, this increment has been measured and can be considered negligible. On the other hand, the system presents two important advantages.

- *First*, and most importantly, the system almost doubles the measurement range for the same field of vision of the camera. Figures 6 and 7 show this aspect. In Figure 6a the position of the laser spots

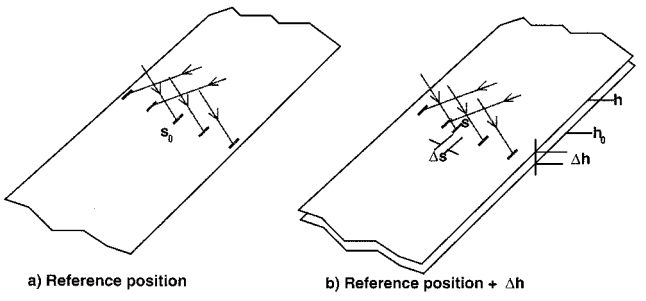

Figure 6. Displacement of measurement lines due to vertical movement of the strip.

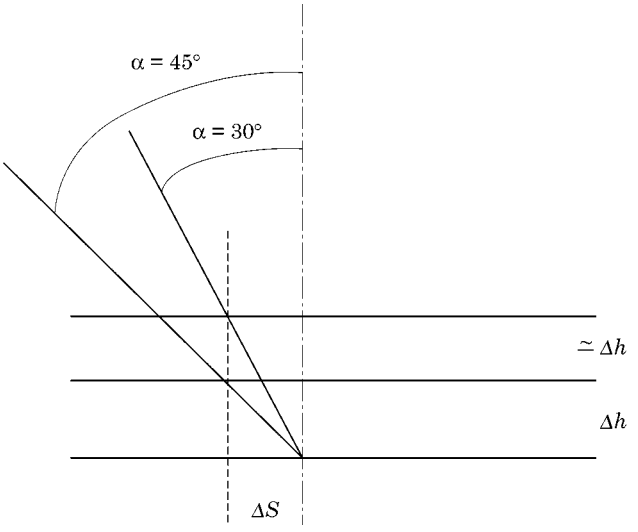

Figure 7. Measurement range increment.

on the strip can be seen; when the strip suffers a vertical displacement, Δh, the points at which the laser beams are reflected over the surface change, as shown in figure 6b.

The lateral movements of laser spots, Δs, are related to strip height, Δh, in Eqn (5), where α is the angle of reflection. The narrower the angle, the shorter the lateral displacement. In Figure 7, it can be seen that for the same lateral displacement, the vertical displacement measured is bigger using the narrower angle.

$$\Delta s = \Delta h \cdot \tan \alpha \tag{5}$$

- *Second*, the distance between the camera and the laser, measured horizontally, is reduced. This is very important because the sensors are enclosed in a gauge room over the strip path in order to protect the equipment from the aggressive environmental conditions in the mill.

The system also presents another important characteristic, which increases the quality of measurement. To obtain accurate measurements, the same longitudinal fiber should always be tracked. Thus, dynamic tracking capabilities have been incorporated to the flatness measurement system. The laser–camera pairs of the system are initially positioned in function of the strip width, but the strip may suffer small lateral displacements while it is being manufactured. These displacements are measured by another factory sensor and are represented by two anologic signals. These signals are fed to the tracking subsystem, enabling the movement of the optical elements, so that they always measure at the same longitudinal fiber of the strip.

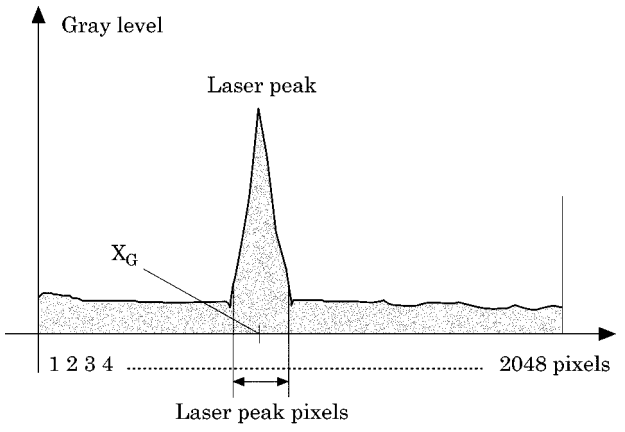

Figure 8. Laser beam as seen by the linear camera.

Image processing

The disposition of the optical elements make the laser beam and the field of vision of the linear camera meet perpendicularly on the strip surface. Thus the linear camera sees the laser beam as a spot. This spot reaches the photodiode array of the camera producing a luminance peak called the *laser peak*. When there is a change of strip height, the position of the laser peak on the array also changes. The relationship between these two displacements makes flatness measurement possible.

The laser peak appears on the photodiode array with the form shown in Figure 8. The whole laser peak does not represent a height over the strip surface, because it contains between 20 and 30 pixels in the linear image. It is necessary to obtain one point of the laser peak, which represents the fiber height. This point will be the center of gravity.

The mathematical formula of the center of gravity is given by Eqn (6), where X_G is the center of gravity, X_i is the position of each pixel in the array and I_i is its gray level.

$$X_G = \frac{\sum_{i=0}^{2047} X_i \cdot I_i}{\sum_{i=1}^{2047} I_i} \tag{6}$$

The question now is the number of pixels necessary to calculate the center of gravity. The use of all the pixels of the linear image is too slow and not very accurate, because the luminance of pixels which do not belong to the laser peak have a negative influence. If only the pixels belonging to the laser peak are considered, the method will be faster and more accurate. Furthermore, previous works [1–3] showed a great symmetry of the laser peak, so even the middle point of the laser peak could be considered as the center of gravity of the laser peak. This method is the fastest and, as the studies carried out have shown, does not sacrifice accuracy.

The flatness measurement system works in real-time, using a short sample period, each linear camera taking an image every 2 ms. The linear cameras are equipped with an interferential optical filter, which enables only laser light to pass. This filter is necessary to avoid the noise introduced by the thermal radiation of the strip. This technique provides a clear laser peak.

The algorithm to calculate flatness indexes from the strip images can be divided into the following stages:

1. When one of the system sensors detects the proximity of the strip, the camera vision boards are activated to continuously acquire images, with a sample period of 2 ms.
   Continuous acquisition is possible because the DT-2856 vision boards used in the system have two channels, so while one linear image is being processed, another is being acquired. The vision boards, in addition to raw linear image acquisition, enable the following processing of the image: *template matching*, *run length encoding* or *binary compression*. Using these capacities of the board, the processing time of the algorithm is considerably reduced.
   The five vision boards work concurrently, acquiring and processing linear images in order to extract their characteristics. The sample period is established by one of the vision boards which acts as a timer. When the end of the sample period is reached, the board emits an interruption request to the processor of the host computer.
2. When the interruption request is received, the processor will attend to it. This form of work assures strict real-time processing; however, this technique may have serious limitations when working simulta-

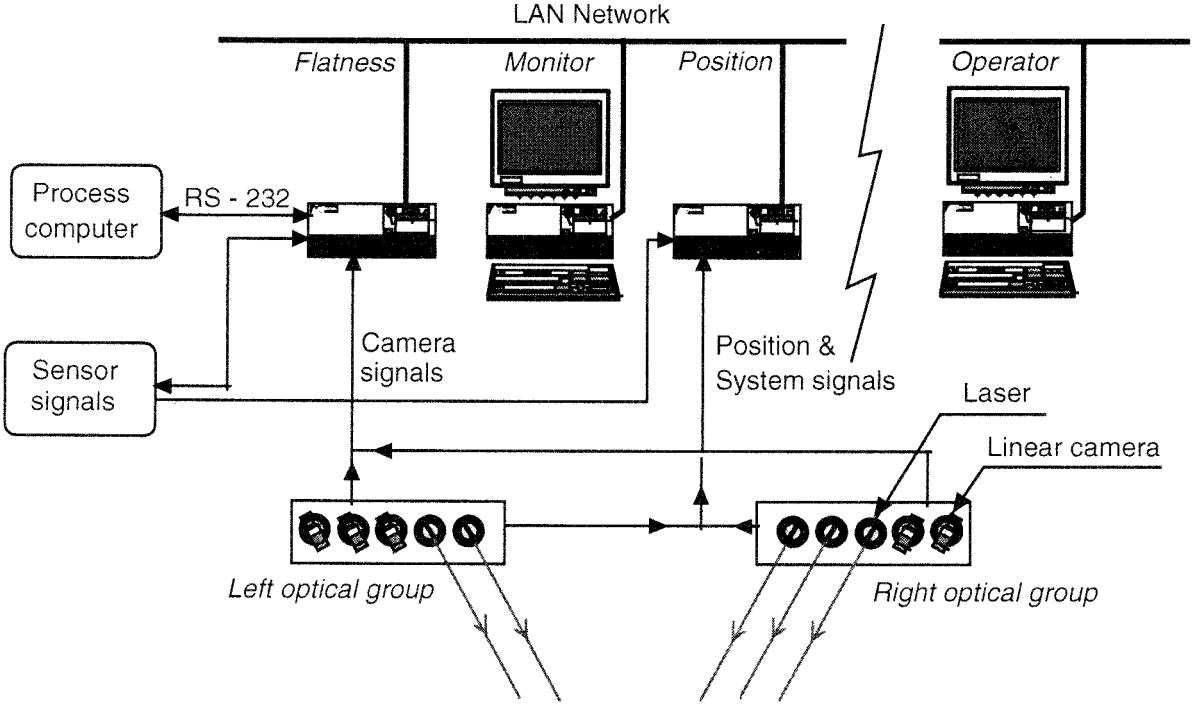

Figure 9. Flatness measurement system representation.

neously with several processes in real-time.

The values which represent the laser peak are transferred from the camera vision board to the CPU computer to obtain the center of gravity of the laser peaks. Several algorithms based on template matching and run length encoding [1–3] have been tested. Both kinds of algorithms give similar precision for flatness measurement, but in general the algorithms based on template matching are faster. These algorithms detect and store the position of pixels which are above a fixed limit; these pixels determine the laser peak.

The transfer of the laser peak information takes approximately 35% of the whole processing time of the interrupt routine execution. It is limited by the bus transfer rate, because although the linear images are processed simultaneously on all the boards, the laser peak values are read sequentially from each board.

3. Heights are calculated by applying the nonlinear Eqn (2). These values are filtered to prevent false readings due to dust or water drops over the strip surface. The filter compares each camera reading with the previous one. If two readings differ by more than a defined value, the old reading replaces the new one. Finally, fiber heights at each point are obtained.
4. After the strip speed is obtained, which takes approximately 8 μs, the fiber lengths are calculated using the speed and the filtered height values. Then, by comparing the lengths, flatness indexes are obtained. The lengths are calculated using an integration window which includes a configurable number of samples. The integration window is updated every 10 ms and flatness indexes are recalculated.

   The calculation processes take 55% of the whole time of the interrupt routine execution, and it is limited by the power of the processor.
5. Finally the calculated indexes can be sent to three different destinations: to the basic control instruments in analogic form for feedback purposes; to the process computer for registration; and to the operator consoles throughout the local area network.

This process takes the remaining of the time of the interrupt routine execution. Speed reading and error checking is also included in this time.

The time of the complete interrupt routine execution has been measured and found to be approximately 0.3 ms, far lower than the sample period limit. The difference in time using the nonlinear method instead of the linear one was found to be 0.03 ms, a negligible value compared with the sample period, but approximately 20% of the time taken by the calculation process.

When the system does not execute the interrupt routine, it sends information about the measurement process to the monitor computer and checks for errors.

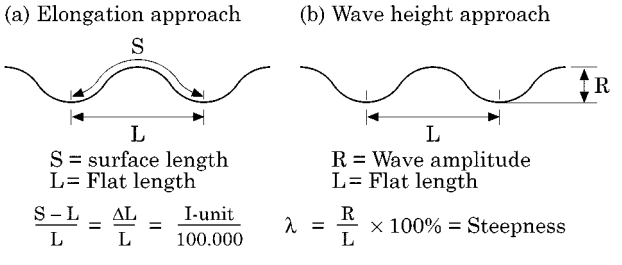

Figure 10. Two approaches to calculating flatness.

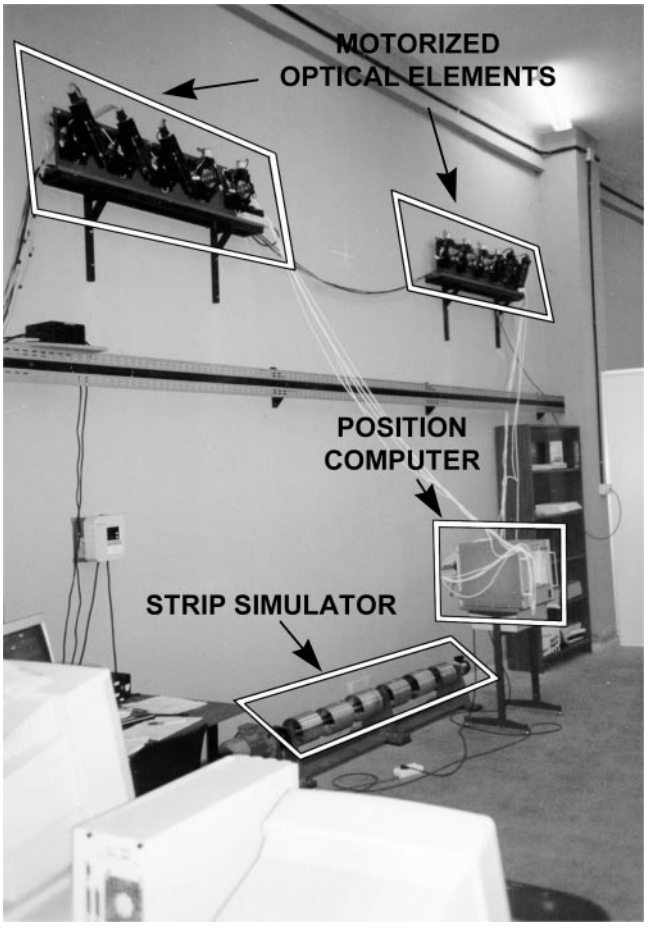

Figure 11. Flatness inspection system in the laboratory.

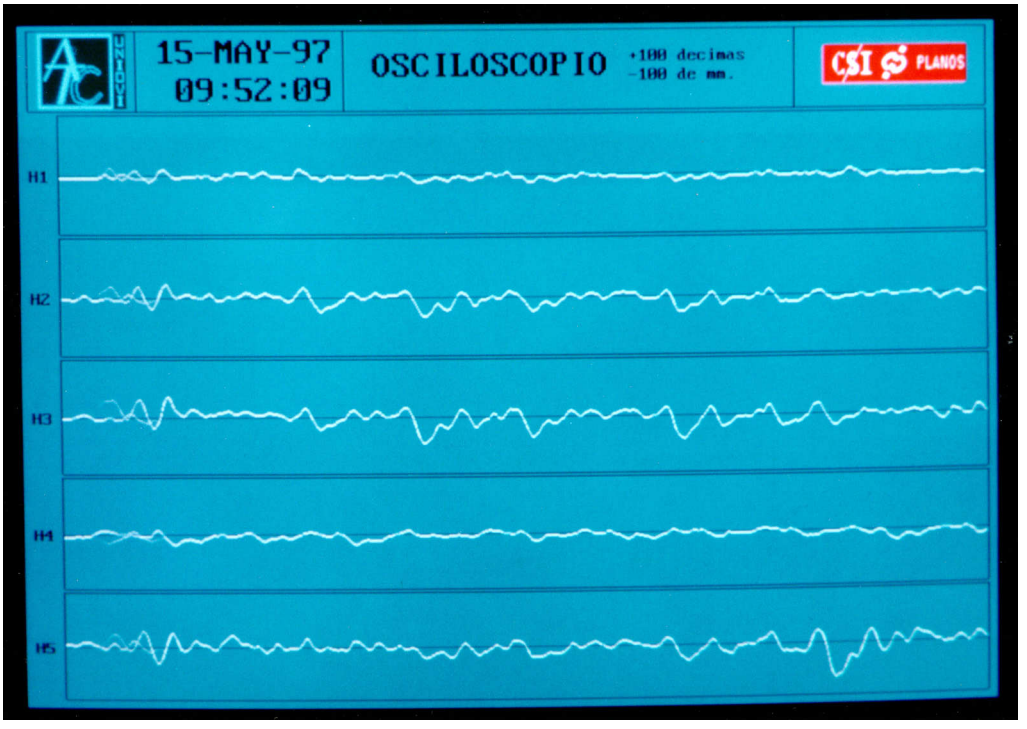

Figure 12. Strip profile reproduction.

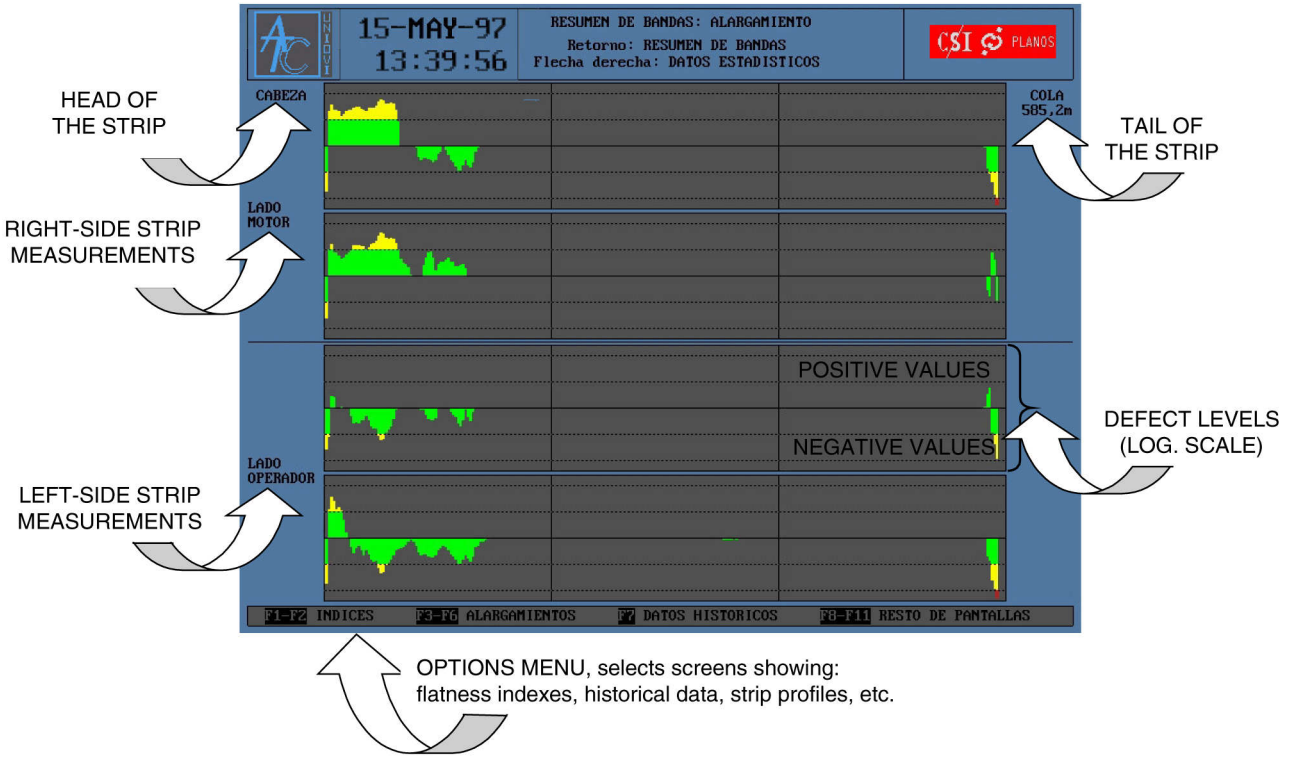

Figure 13. Typical flatness profile along the strip.

System implementation

Figure 9 shows the main components of the measurement system. Later, the task of each component is explained.

The flatness inspection system has five optical measurement lines, and these lines must adjust their positions over the strip surface in function of the strip width. A laser diode (670 nm, 50 mW) and a linear camera (EG & G Reticon LC1912) placed on either side of the strip path form each measurement line.

When the strip width changes, or when the system tracks a fiber, the optical components must change the point on the strip on which they are focussed. To make this possible, each element is mounted on a platform which can be rotated by a stepping motor. This motor enables the small, accurate movements necessary to position lasers and cameras.

In addition to receiving information about the strips to be manufactured from the process computer, and sending flatness information to the process computer, the system also interchanges information with the low-level instruments of the mill. It receives speed values of the strip and sends flatness signals to close the control loop.

The main objectives of this system are (i) to get on-line information about strip (flatness, this information is shown in the control cabinet and stored for further analysis); and (ii) to improve strip quality allowing the flatness control loop to be closed.

In order to fulfil these objectives, the sensor is made up of four computers, with two different architectures (PCs and a Sparc processor working on a VME bus), and three different operating systems. These are connected by a local area network using a standard protocol (UDP/IP), allowing all the computers to interchange data, and making flatness information available to other computers within the factory or elsewhere. Each computer performs a specific task within the global operation of the system.

Flatness computer. This is the main computer in the system. It hosts the camera vision boards (DT-2856), carries out the processing of the images to obtain heights from the strip, calculates flatness indexes, and makes them available to other computers in the network. Furthermore, it interchanges information with the process computer and the basic instruments of the mill, so it knows the characteristics of the strip to be manufactured and is able to feed flatness indexes back in order to correct defects. Finally, it maintains high level control over the operation of the flatness measurement system.

Position computer. This computer is based on a Sparc processor working on a VME bus. Its task is to modify laser and camera orientations to ensure that the correct fibers are selected over the strip whatever the strip width may be; and while the strip is being manufactured, to carry out dynamic tracking of a fiber in the strip. To do this, it controls the stepping motors, which move the platforms on which the optical components are mounted. Furthermore, it monitors the environmental variables of the global system (temperature and pressure inside the boxes where the optical components are enclosed, etc).

Monitor computer. This is the system supervision console. It receives information from the flatness and the position computers, which is represented using a graphical environment to show the state of the system, the position of the optical elements and the linear images obtained.

Operator computer. Here flatness measurements in the form of I-unit indexes are shown to the hot strip mill operator. There is also a complete set of graphic screens where different aspects of the strip quality can be seen (flatness index evolution along the strip, height profiles being measured, historical data, etc).

Results

In this section, the results obtained with the developed system are presented. These are broken down into laboratory and factory results.

Laboratory results

Resolution. Before examining resolution, the measurement range must be considered. Usually, the strip head (the first 100 m of the strip) is bouncing when it leaves the last rolling box. The system has to measure

strips under these conditions and the vertical movement of the strip must be included within the measurement range of the system. Unfortunately, the greater the measurement range, the lower the system resolution.

A trade-off between measurement range and system resolution must be established. A measurement range of 400 mm was requested by *CSI Planos*. The camera is equipped with an array of 2048 photodiodes (26.624 mm in length), which give a theoretical resolution of 0.2 mm per pixel. It works with a focal length of 260 mm. It must be considered that the strip height is not represented by one pixel, but by a group of pixels. If the middle point of the laser peak were taken as the height value, a resolution of 0.1 mm inside the laser peak would be achieved. This value would be even lower, applying Eqn (6) to calculate the gravity center of the laser peak.

Accuracy. System accuracy can be divided into two types: height measurement accuracy and flatness index accuracy. As was shown in Eqn (1), height is measured to calculate length, because using Eqn (4), flatness indexes are obtained from length comparison. An accuracy study similar to that developed in [5, 8] was carried out for this system.

Static measurements aim to establish height accuracy and establish the values of transformation constants. Several tests have been carried out measuring different elements of known height over various measurement ranges, obtaining reasonably accurate results. Absolute errors reach a value of 0.4 mm in the worst case. This occurs almost at the top of the measurement range, where the system will rarely have to work. Relative errors are small, reaching a value of 3.75% in the worst case. The accuracy required by the factory is 0.1 mm for low ranges and 0.5 for high ranges: the system fulfils these requirements.

Dynamic measurements are more important; they aim to establish the accuracy in calculating flatness indexes. There are two approaches to calculating flatness in order to measure the accuracy of the system, both are shown in Figure 10. In the elongation approach, flatness is represented as a length comparison, while in the wave approach, flatness defects are represented as waves whose length is similar to the width of the strip. There is a relationship between these two approaches [4, 7], which is given by Eqn (7). Based on this relationship, flatness indexes can be validated.

$$\frac{\text{I-unit}}{100\,00} = \frac{\Delta L}{L} = \left(\frac{\pi}{2} \cdot \frac{\lambda}{100}\right)^2 \tag{7}$$

To take this type of measurement, a strip simulator was built. It consists of several eccentric cylinders with known eccentricity. When these eccentric cylinders rotate, they generate for small eccentricities a curve to all intents and purposes, identical to a sine wave.

With the strip simulator, the eccentricity and wave length are established; by applying Eqn (7), it is possible to obtain the theoretical flatness index. In addition, the flatness inspection system measures the lengths generated by the eccentric cylinders and calculates the flatness indexes; system accuracy is determined by the difference between the theoretical flatness indexes calculated with Eqn (7) and the indexes obtained from the inspection system. The errors measured are below the value of 0.1 I-units, which is the factory requirement for low height ranges. For high ranges an error or 1 I-units is permitted. In Figure 11, a view of the inspection system in the laboratory is shown.

Factory results

When the system was installed in the hot strip mill, a limited set of trials was carried out for calibration purposes. During the manufacturing process, it is impossible to validate flatness indexes by measurement of fiber lengths with direct contact methods due to the high temperature and speed of the strip. After the manufacturing process, and when a strip has been coiled, the flatness of some pieces of strips are measured using physical methods. The measured indexes were found to be consistent with the real indexes.

A qualitative testing of the system was done by the hot strip mill operators themselves. Normally, in the course of their work they are able to identify several types of defects, which they can deliberately reproduce. A series of defects were produced by the hot strip mill operators, and the flatness measurement system proved effective in detecting and measuring them.

The system was also tested by the operators watching the profile reproduction. The system has a screen where

the profile of the strip is reproduced, as seen in Figure 12. The operators are able to compare the information shown on the screen with the real evolution of the strip in the hot strip mill. This test was passed successfully.

This inspection system proves its functionality daily, detecting and measuring flatness defects. The flatness histograms shown for the strips are representative of their real behavior: a great variation of flatness in the ‘‘strip head’’, almost a straight line while the strip is under the tension of the coiler and a small final variation in the ‘‘strip tail’’ the last 6 m.. One of these measured flatness histograms is presented in Figure 13. In Figure 14 a photograph of the inspection system in the factory is shown.

Conclusions

A reliable flatness measurement system has been developed. It presents good resolution and allows accurate measurements. The system can be integrated in the whole hot strip mill control system.

The main improvements introduced by this system are:

1. It works with a new disposition of the optical elements which permits the use of a smaller gauge room and increases both the quality and the range of measurements. It uses narrower angles of reflection, which practically eliminate errors due to strip height variation.
2. The constructed system is fast, accurate and reliable. It fulfils the factory requirements: error below 0.1 I-units for low ranges and 1 I-units for high ranges.
3. The computer system architecture, based on the distribution of tasks between different computers, permits the fulfilment of the system targets. All the computers are connected by a standard protocol, which allows any other computer in the factory to use the flatness measurements.
4. It uses standard computers, which makes it a cost-effective system. Furthermore, robust software has been developed, which allows the measurement system to function properly during temporary external failures.

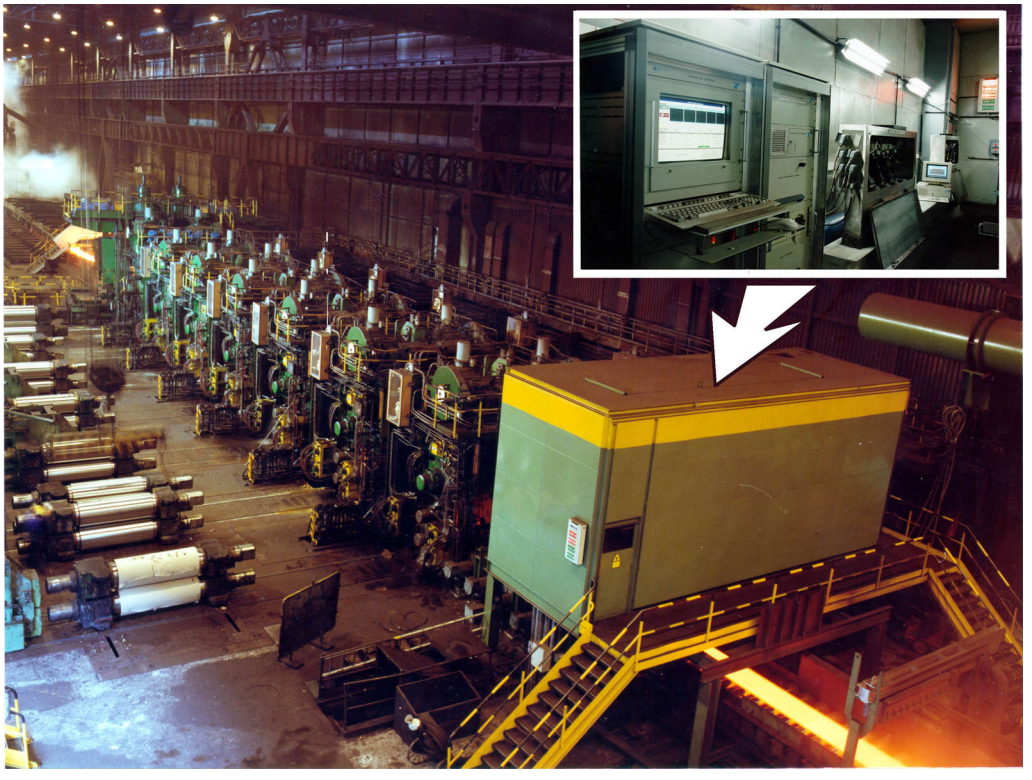

Figure 14. The flatness measurement system in the hot strip mill.

5. A comfortable user environment has been created, both for the presentation of results and for on-line system monitoring. A powerful graphical calibration tool has also been developed.

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