# DEVELOPMENT OF IMAGE PROCESSING TOOLS FOR MEASUREMENT OF BEAM STRAIGHTNESS

Fernando Ribeiro
Cranfield Institute of Technology
Cranfield

Frank Meyer
Integral Vision, Ltd
Bedford

## Abstract

The objective was to measure the straightness of steel beams as a non-contact mean and using image processing techniques. This work deals with the development of an image processing methodology to be employed in an inspection machine for measurement of straightness of moving steel beams. The method was embodied in a software that reads the position of the beams, correlates all the positions monitored by the cameras, and reports the quality of straightness of the beam.

The inspection machine uses computer vision technology as a non contact measuring device. Video cameras are used to log information about the lateral position and height of steel beams while rolling on a conveyor from the production process.

The number of cameras and the distance between them are user defined parameters. The technique developed is prepared to guarantee the measuring system operation if one camera is switched off or fails. This implies the ability of this system on using more than 3 cameras.

The system output is the non linearity deviation of the beam, compensating factors for lateral or angular movements in the horizontal measuring plane of the beam and the beam profile. The output is displayed in a computer screen, according to the line method and the least squares method.

## 1. Introduction

To meet an acceptable standards, the steel beams for the Civil Industry have to be inspected after their manufacturing. The actual task is made by hand and the steel beams are sampled which means that not all are inspected but just 10%. Two employees holding a string, connect the ends of beam and straighten the string. Another employee measure the largest deviation of the string from the steel beam. Some beams are 32 metres length in which is very difficult to straighten the string and so the resultant inspection is not very accurate. Therefore, a need to automate this inspection task was needed very urgent.
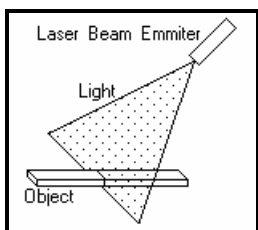


Figure 1 - Laser Beam Emitter

A prototype machine that uses image processing for analysing the steel beams was previously built by Anacleto (Ref. [1]). This prototype machine consists of three Reading Heads each of which comprises a video camera and a laser beam which are focused onto the Steel Beam; the laser beam takes the form of fan shaped slit of light which impinges onto the Steel Beam, as seen in figure 1. Each pair of Reading Heads is coupled to a slave computer which is used to analyse the video data.

The three video cameras are equally spaced and the computer reads the actual image from each camera and by analysing these pictures the computer is able to establish the edges of the beams and calculate the position of the beam in each picture according to a mathematical method in order to obtain the real profile of the beam. The beam profile is then analysed and compared to the appropriate British Standards, and if the beam does not meet these requirements it will be rejected.

## 2. The Prototype Machine

This prototype machine was being tested previously to this work but it just works with three cameras and it doesn't measure the height of the steel beams which means that if the steel beam is bent in the vertical direction that is not detected. The three cameras used have to be at the same distance between them which means that if one camera is not in the precise place the system will not work properly. Sometimes, due to the complexity of the straigthning machine not all the cameras can see the steel beam and so some parts of the steel beam were not analysed. It is therefore necessary to be possible to place the cameras at a different distances between them. These three aspects were taken in consideration to improve the inspection prototype machine and the errors were measured and analysed to observe the accuracy and precision of the system.

The Image processing Tool to extract the position of the steel beams were created by the author and it is called 'Caliper Tool'. The Maths to co-relate these co-ordinates was also created by the author of this paper. This technique was tested with some samples and it proved to be true.

## 3. Beam Profile Extraction

In all Digital Image Processing System it is necessary to have at least one camera, one VDU to show what the camera is observing and this VDU must be connected to a computer in order to carry out image processing. The computer will analyse

the picture and calculate various features of the image depending on the software program and the purpose of the system.

In a typical system the VDU is black and white and it has a resolution of typically 768 by 288 pixels or <u>pic</u>ture <u>el</u>ements. Pixels are the tiny areas (dots) that make up a computer graphics picture. The smaller the size of each pixel, the grater their number and thus the higher the resolution of the picture as noted by Zuech and Miller (Ref. [2]).

The computer used to analyse and process the image must be a relatively fast machine, because of the large amount of mathematical calculations necessary to interpret the image, analyse it and process it. The amount of computer memory is also an important feature of the system because images require a large amount of memory for their storage.

The proposed image processing system will consist of six Reading Heads each consisting of a Video Camera, a Frame Grabber and a Laser Beam, 4 computers (1 main and 3 slaves) and one TV monitor. All the 4 computers consist of a PC with a microprocessor 80486. Each one of the three slaves is responsible for 2 frame grabbers (it reads images from 2 cameras). The main computer is responsible for reading the global parameters of the system, calibrating the machine, performing the mathematical procedures and for all communication including that to the operator.

High accuracy is a fundamental aspect when extracting the points of the beam from the video information. A sub-pixel technique has been used by the author to increase the accuracy of the results.

The Steel Beam passes through the inspection system on a conveyor at a velocity of 2 metres per second which increases the difficulty of extracting the points to be measured. The Video Cameras observe the images projected onto the Steel Beam normally and the formation of these lines is entirely due to the inclination of the Laser Beam emitters.

The machine operator needs to decide which point or edge of the video image that the video processing system must watch for in particular. These points are recorded in the computer. Not all the edges are analysed because of the processing time which would be necessary. British Steel has about 500 different steel beams cross sections and therefore the operator has to decide the most appropriate point or pair of points to use for a particular Steel Beam cross section and then teaches the system to find this characteristic.

Figure 2 shows an example of extracting one particular point. The operator selects the area where the image can appear on the VDU screen by the use of a masking window. It is possible to move, increase or decrease the dimensions of the masking window from the computer keyboard. Four charts appear after the user has selected the appropriate window. Two charts appear at the bottom of the window and the other two charts on the left hand side of the window as shown in figure 2.
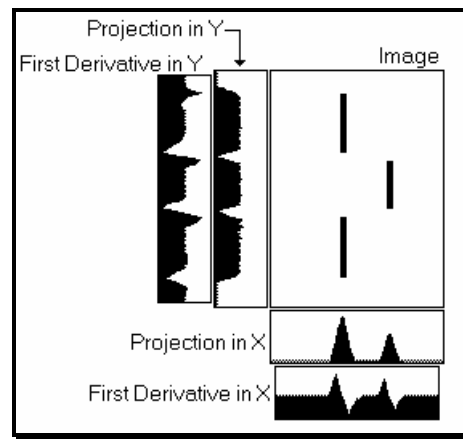


Figure 2 - Process to teach the system to extract points

It is firstly important to note that this figure represents an ideal case because real images frequently contain 'noise' and the edges are less than perfect. The main window shows the projection of the Laser Beam on a Steel Beam having a square cross section. The first chart at the bottom of the window and the first chart on the left hand side of the window represent the summation of the intensity of the black pixels in the X and Y directions. The peaks in these two charts represent the position at which the lines of the laser beam are situated.

The second chart at the bottom and on the left hand side of the window is a graphical representation of the derivatives of the first pair of charts. Each peak or trough in these derivative charts represent the edges of the lines. The peak represents an increase of black colour and it is the beginning of a black zone and the trough is a decrease of black colour and therefore represents the end of a black zone. Using this technique it is therefore possible to find the edges and the positions of the lines projected by the laser beam.

The reason for using the derivative chart is that the peak blackness value does not represent the centre of the Laser Beam line. The author decided to apply a statistical technique to the data in order to establish a more precise value and this technique enables sub-pixel accuracy to be achieved.
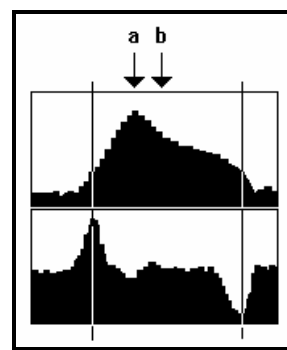


Figure 3 - Example of a peak in X direction

Figure 3 shows an example of two charts in the X direction in which the first chart represents the projection of the image and the second represents its derivative. In this example, *a* represents a peak blackness value but it does not represent the centre of the Laser Beam line. The derivative is therefore used to locate where the projection chart starts increasing its black value and where it starts decreasing its black value. The two lines

2

represented by the peak and trough of the derivative chart represent the limits of the area about which the average value can be determined.

After the statistical calculation procedure the true result is represented by average value **b** and not by the mode value **a**. The value of **b** can be determined to a precision value between two discreet pixel values. The resolution would be limited to the number of pixels if just the peaks values had been used.

The shape of the image on the Steel Beam caused by the Laser Beam always takes the form of a straight vertical line as observed by the Video Camera. Horizontal lines can never be formed by the Laser Beam and for this reason the statistical technique is only ever in the X direction. It is only necessary to find the edges of the lines in the Y direction and not their centre.

## 4. Caliper Tool

Caliper Tool is an image processing software tool developed by the author for locating the edges of images using the derivative characteristics described previously. The operator has to define what he is looking for to teach the system and then the system will give back an array of possible solutions as well as a score for each solution. The definition of what the user wants to find, is saved in a Configuration File with certain rules and an example of this file is given below:

> **PAIR=HORIZONTAL**
> **POLARITY=+-**
> **EDGE STRENGTH=50**
> **DISTANCE=10 80%**
> **ABSOLUTE POSITION=100 20%**

This is the file with the necessary information to look for a certain feature in an image. The first word indicates the number of points. The possible words to be used here are SINGLE or PAIR which simply means one or two points. The second word on the first line describes the axis of the search and this can be HORIZONTAL or VERTICAL. This statement has to be in the first line but the order of the other lines is not important.

In the second line the word POLARITY means the order of the points. In this example it means an increase of black density followed by a decrease in black density. The sign '+' means increasing and the sign '-' means decreasing. There are 4 possible and different combinations with these symbols for a PAIR of points which are '++', '+-', '-+' and '--'. For a SINGLE point there are just two possibilities, '+' or '-'. The second line is also compulsory.

In the third line the words EDGE STRENGTH represent the minimum height necessary to consider a value to be a peak. This means that for a value to be a peak it must exceed neighbouring peaks by an amount greater than the average plus the EDGE STRENGTH. This line is also compulsory.

The word DISTANCE is only applied when looking for a PAIR of points. This statement represents the distance expected between a pair of points in the image. The second number is a percentage which represents the importance attached to finding a particular feature of the image. In this case 80% implies that

the user is more interested in the correct distance between the two points rather than their ABSOLUTE POSITION (20%). The user can ignore this line if he is not interested in the distance between the pair of points. This line is therefore not compulsory.

The last line of the Configuration File is the ABSOLUTE POSITION and this is used when the position of the point or the first point when there are a pair of points, is expected to be in a certain position. In this case the point is expected to be in position 100 but the importance has been set at just 20% which means that it is not very important. The sum of these two importance percentage factors (DISTANCE and ABSOLUTE POSITION) must be 100%. The user can ignore this statement if he does not care about the absolute position. This line is not therefore compulsory.

When the system starts running it reads the Configuration File, analyses the image and gives a score to each one of all the possible solutions. The system then selects the best score and this will be the final result. The portion of image that the system has to analyse is also defined in the program but this is not a parameter in the Caliper Tool software.

## 5. Determination of Beam Shape

An important issue in this Section is to explain how the new mathematical technique operates. For this purpose it is necessary to understand the purpose of each Reading Head and how the Y co-ordinate points are extracted and used. The following figure will be used to illustrate this task.
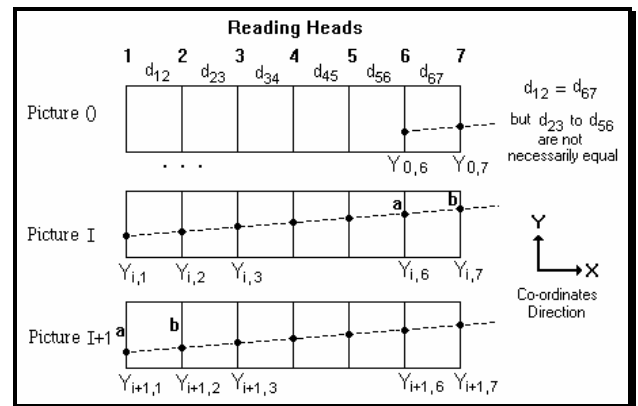


Figure 4 - Extraction of points using 7 Reading Heads

Where  $d_{ij}$ is the distance between cameras i and j.
$Y_{ij}$ is the Y co-ordinate in picture i in camera j.

Figure 4 represents a system with 7 Reading Heads and 3 sets of pictures though 2 of them are consecutive pictures. Picture 1 is at instant **0**, Picture 2 is at instant **I** and Picture 3 represents the instant **I+1**. Considering dynamic measurement, three movements have to be considered. The *Progressive Movement* of the beam in the X direction, the *Linear Movement* of the beam in the Y direction and its *Angular Movement* about the Y direction.

The *Progressive Movement* is the normal forward movement when the beam is on the conveyor and this provides the X position of the beam. It is assumed that the conveyor has

constant speed, but this could be measured more accurately by the use of a position encoder attached to one of the conveyor rollers.

The *Linear Movement* is the movement of the beam as it moves from side to side on the conveyor and this is a movement in the Y direction. This movement is measured by comparing the same point of the beam in two consecutive pictures. There is no *Linear Movement* if the Y co-ordinate is at the same point of the Steel Beam in two consecutive pictures.

The *Angular Movement* is the movement of the beam when one end moves more than the other, in other words it is when the movement causes the beam to make an angle with respect to the previous picture. This movement is calculated by comparing two points of the Steel Beam in two consecutive pictures. There is no *Angular Movement* if there is no difference between two Y co-ordinates in two consecutive pictures.

The last two Reading Heads are used to calculate the linear and angular movements between each picture and the previous one in order to calculate all the final Y positions read by the other Reading Heads. These points read on the Steel Beam have to be the same in two consecutive pictures and this is the reason why the distance between Reading Heads 1 and 2 must be equal to the distance between Reading Heads N-1 and N. It is important to note that this is the reason why just N-2 points are mathematically generated per picture where N is the number of Reading Heads.

The *Linear Movement* formula (1) does not depend on the distance between the cameras and the formula represents the difference between the Y co-ordinates between two consecutive pictures and the same point of the Steel Beam is measured in these two pictures. The linear movement value is equal for all the Reading Heads in one set of pictures. In Figure 4 point **a** is used to measure the linear movement. So, the general formula is:

$$LM_i = Y_{i,1} - Y_{i-1,N-1} \qquad (1)$$

To measure the angular movement it is necessary to consider two points at two different instants. There is Angular Movement if the difference between the points at one instant changes from the difference between the two points at the next instant. In the example shown in figure 4, points **a** and **b** are used to measure the angular movement between two consecutive pictures. The angular movement for the original system gave the following formula:

$$AM_{i+1} = \left( Y_{i,6} - Y_{i,7} \right) - \left( Y_{i+1,1} - Y_{i+1,2} \right) \qquad (2)$$

In this new work, there is a new concept which is that of Angular Displacement. It is now important to distinguish between Angular Movement and Angular Displacement. The A*ngular Movement* is the angle that the beam makes with respect to the previous picture and the *Angular Displacement* is the displacement in the Y axis caused by that angle per unit metre of Steel Beam, so the above equation must be divided by the distance between the Reading Heads. The formula for the *Angular Displacement* can therefore be represented by:

$$AD_i \ / \ \text{unit metre} = 1 * \left( \frac{Y_{i-1,N-1} - Y_{i-1,N}}{d_{N-1,N}} - \frac{Y_{i,1} - Y_{i,2}}{d_{1,2}} \right) \qquad (3)$$

The *Net Angular Displacement* formula consists of the summation of all the previous angular displacements before the current 'set of pictures'. It represents the Y co-ordinate of a straight beam that didn't move angularly. To find this value, the Angular Displacements since the first 'set of pictures' have to be added. This Net Angular Displacement value is used for all the Reading Heads in one set of pictures.
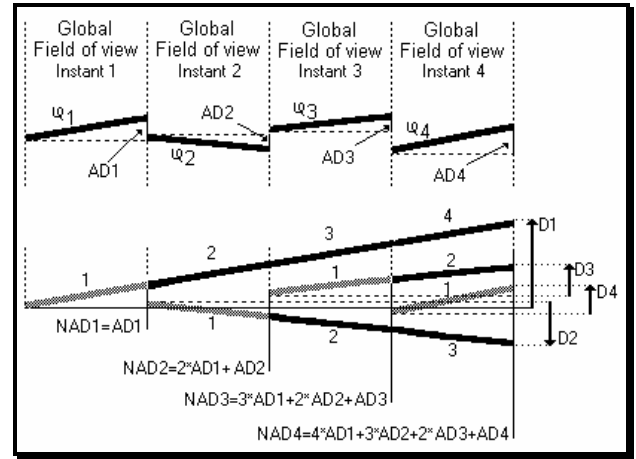


Figure 5 - Net Angular Movement

Angular Displacement (AD), top part of Figure 5, is next used to calculate the Net Angular Displacement (NAD), bottom part of Figure 5. Considering instant 1, NAD is now equal to the AD of instant 1. Considering instant 2, NAD is now 2*AD1 + AD2. Considering instant 3, NAD is now equal to 3*AD1 + 2*AD2 + AD3.

    NAD1 = 1*AD1
    NAD2 = 2*AD1 + 1*AD2
    NAD3 = 3*AD1 + 2*AD2 + 1*AD3
    NAD4 = 4*AD1 + 3*AD2 + 2*AD3 + 1*AD4

The general formula for Net Angular Displacement at instant i is therefore:

$$NAD_i = \sum_{j=1}^{i} \left( i - j + 1 \right) \times AD_i \quad \text{per i metres} \qquad (4)$$

where    i is the instant
         $AD_j$ is the Angular Displacement at instant j

By convention a positive Linear movement is in the upper or in the positive Y direction and a positive angular movement is anticlockwise.

The first picture in Figure 4 is referred to as Picture 0 and this is used to read the position of the Steel Beam and it is not observed by Reading Heads 1 to N-2. Just Reading Heads N-1 and N will be able to observe the Steel Beam. The position of the beam in these cameras is extracted and the values will be used to calculate the first *Linear* and *Angular* movements for the following picture which is Picture 1. For this reason no values are extracted from the last two Reading Heads in the last Picture because the Steel Beam has already passed through and the Reading Heads cannot see any part of the Steel Beam.

During the process, several 'sets of pictures' are taken depending on the length of the beam, and the Y co-ordinate is read after

each picture has been analysed. After the beam passes completely into the field of view of all the cameras, the beam shape co-ordinates are calculated according to the stored Y co-ordinates of the beam as seen by the cameras.

For each Y co-ordinate extracted from the image at a certain instant, it is necessary to introduce the following negative corrections to obtain the beam shape:

   **a)** the summation of all the linear movements given by formula (1)

   **b)** the summation of the all angular displacements or formula (3), multiplied by the distance between camera 1 and the current camera

   **c)** the summation of all previous angular displacements, which is the Net Angular Displacements or formula (4), multiplied by the distance between the first and penultimate cameras which represents the length of the beam analysed by each set of pictures

The reason for correction **a)** is to compensate the Y value when the Steel Beam moves in the Y direction. Correction **b)** is to compensate for the current angular movement since the last picture and this is multiplied by the distance between Reading Head 1 and the Reading Head under consideration because the Angular Displacement is per metre. This is illustrated in Figure 6 as distance D per each camera.
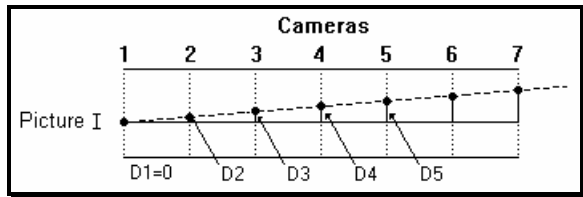


Figure 6 - Compensation for the current Angular Movement

Correction **c)** is equal for all the cameras in the same 'set of pictures' which occur at the same instant and it is necessary to compensate for all the angular movements which have occurred since the first picture as shown in Figure 5.

A general formula for the above corrections is given below:

$$YB_{i,j} = Y_{i,j} - \sum_{k=1}^{i} LM_k - Dist_{1,j} \times \sum_{k=1}^{i} AD_k - Dist_{1,N-1} \times \sum_{k=1}^{i-1} NAD_k \quad (5)$$

Where: $YB_{i,j}$ is the final Y co-ordinate of the beam shape in picture i by camera j

$Y_{i,j}$ is the Y co-ordinate extracted from the screen in picture i by camera j

$LM_k$ is the linear movement in picture k

$Dist_{1,j}$ is the distance between cameras 1 and j

$AD_k$ is the angular displacement per metre in picture k

$Dist_{1,N-1}$ is the distance between cameras 1 and N-1

$NAD_k$ is the Net angular displacement per metre in picture k

N is the number of Video Cameras

and j varies from 1 to N-2

After calculating the beam shape co-ordinates a graph is produced to show the overall profile of the Steel Beam and this result can then be compared with the relevant British Standards to check if the actual beam meets the required specification.

## 6. Case Study

The example illustrated here is that of an ideal straight beam with movement in the Y direction only. Table 1 shows the results obtained from this particular test. The first row shows the video camera number and the distances between them in metres. The distance between camera 1 and camera 2 is 0.40 metres, the distance between camera 2 and camera 3 is 0.50 metres, etc. The other 6 rows represent the points extracted from the camera pictures for each camera. Thus, in Picture 0 only the last two cameras observed the beam and the values extracted are 6.0 and 6.4 millimetres. In Picture 1 all the cameras saw the beam and the values extracted per camera are shown in that row, i.e. 8.0 - 10.0 millimetres.

| Cameras | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Distances | | 0.4 | 0.5 | 0.1 | 0.6 | 0.4 | |
| | | Y co-ordinates in millimetres | | | | | |
| Picture | 0 | | | | | 6.0 | 6.4 |
| Picture | 1 | 8.0 | 8.4 | 8.9 | 9.0 | 9.6 | 10.0 |
| Picture | 2 | 6.6 | 7.0 | 7.5 | 7.6 | 8.2 | 8.6 |
| Picture | 3 | 10.3 | 10.7 | 11.2 | 11.3 | 11.9 | 12.3 |
| Picture | 4 | 7.9 | 8.3 | 8.8 | 8.9 | 9.5 | 9.9 |
| Picture | 5 | 11.5 | 11.9 | 12.4 | 12.5 | 13.1 | 13.5 |

Table 1 - Example of image system readings with an ideal beam

After the mathematical technique had been applied, the resultant values in millimetres are as shown in Table 2:

| | | 1st cam. | 2nd cam. | 3rd cam. | 4th cam. |
|---|---|---|---|---|---|
| Picture | 1 | 6.0 | 6.4 | 6.9 | 7.0 |
| Picture | 2 | 7.6 | 8.0 | 8.5 | 8.6 |
| Picture | 3 | 9.2 | 9.6 | 10.1 | 10.2 |
| Picture | 4 | 10.8 | 11.2 | 11.7 | 11.8 |
| Picture | 5 | 12.4 | 12.8 | 13.3 | 13.4 |

Table 2 - Calculated values of the Steel Beam Y co-ordinates

These numbers represent the Y co-ordinates of the beam from each picture after applying corrections for any angular movements of the beam. The corrections in this case mean that the beam in each picture has been transformed into the position seen in the first picture.

Comparing the resultant values with the 'ideal' values, it can be observed that the difference is smaller than 0.08 millimetre per each 'set of pictures'. A table with these errors was created for each case and these are given in Appendix 3. With these values the beam profile can be represented as shown in figure 7 with the X axis is in metres and the Y axis is in millimetres. Figure 7 represents the beam profile as though it were always viewed from the first reading and it can be concluded that the beam is straight.
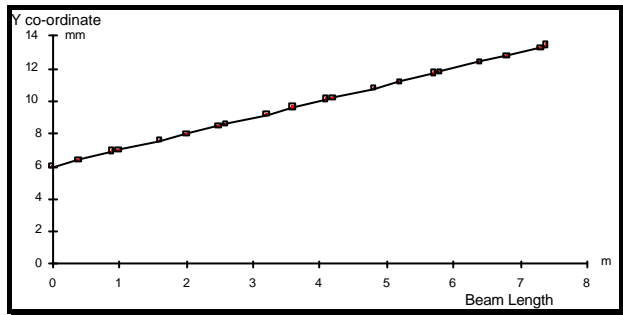
Figure 7 - Steel Beam profile after applying the mathematical technique

## 7. Conclusions and Recommendations

An image processing tool has been developed, validated and implemented in this application to a Steel Beam Inspection and Straightening Machine. The method developed also has potential for other types of application. The Image Processing method extracts an edge or a pair of edges having some pre-defined characteristics. This tool proved to be sufficiently accurate for this machine and the results obtained are very reliable. This tool is also very easy to use, simple to learn, and it has performed very successfully under test conditions.

A mathematical method of calculating the co-ordinates was also successfully developed. The number of Reading Heads and the distance between them is a parameter which can be set by the user and the only limitation is that the distance between the last two Reading Heads must be equal to the distance between the first two Reading Heads. These distances need to be accurately set and this is easy to carry out using a proper calibration procedure. The mathematical procedure is computer based and very fast. The problem of systematic and random errors has been fully investigated and these are small and therefore acceptable.

Sub-pixel resolution was achieved with success in the extraction of the Y co-ordinates by computer methods. This is an important technique because it makes it possible to improve the performance of the co-ordinates extracted instead of being limited to the discrete resolution of the video screen.

The mathematical technique and the image processing method was applied to a new Inspection Machine which was built and currently being commissioned by Integral Vision Ltd and Joseph Rhodes Ltd as British Steel Research. The machine will displace manual methods of measuring the straightness of the Steel Beams and also replace a sample inspection method by a total inspection method and this will eventually enable a total quality management system to be implemented.

## References

[1] ANACLETO, S.C., "*Dynamic Assessment of Beam Straightness by Non-Contact Means*" Thesis at Cranfield Institute of Technology, England, 1991.

[2] ZUECH N. and MILLER, R. K., "*Machine Vision*" The Fairmont Press, ISBN 0-88173-017-3, USA, 1987.

[3] GONZALEZ, R.C. and WINTZ P., "*Digital Image Processing*" Second Edition, Addison-Wesley Publishing Company, ISBN 0-201-11026-1, USA, 1987.

[4] PUGH A., "*Robot Vision*" International Trends in Manufacturing Technology, IFS (Publications) Ltd., ISBN 0-903608-32-4, UK, 1983.

[5] ADAMS, L.F., "*Engineering Measurements and Instrumentation*" The English Universities Press Ltd, ISBN 0 340 08342 5, Great Britain, 1975.

[6] CHAPRA, S. C. and CANALE, R. P., "*Numerical Methods for Engineers*" Applied Mathematics Series, Second Edition, McGraw-Hill International Editions, ISBN 0-07-079984-9, USA, 1988.