

A distortion corrected single camera-based weight estimation technique for industrial objects

Subhasis Chaudhuri,^a Anirban Mukherjee,^b Pranab K. Dutta,^b Amit Patra^b

^a*R & D Centre for Iron and Steel, Steel Authority of India Limited, Ranchi, India*

^b*Department of Electrical Engineering, Indian Institute of Technology, Kharagpur, India*

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Abstract

This paper describes a unique single camera-based dimensional measurement with a self-calibration method of image-based measurement. The system has been designed and implemented in one of the integrated steel plants in India. The purpose of the system is to obtain the frontal cross-sectional area of an ingot irrespective of its distance from the camera head. Automatic calibration is achieved by attaching a magnetic template of known area. This self-calibrating system is further refined to correct for the various distortions arising out of lens characteristics. The results obtained through field trials have been reported and found to be quite encouraging. © 2003 ISA—The Instrumentation, Systems, and Automation Society.

Keywords: Image-based system; Camera calibration; Dimension measurement; Lens characteristics

1. Introduction

The present market scenario in the steel industries is focused on product quality. The dimension of the product is one of the parameters that needs to be critically maintained for quality control. To cater to this market demand, thrust has been applied by industry for on-line dimension measurement and control to reduce production loss. With the development of high accuracy primary sensors, it is now possible to measure the dimension of complex objects precisely during a manufacturing process. A charged coupled device (CCD) camera, coupled with an advanced computer vision inspection system, makes it feasible to measure the dimension of the product accurately. However, the accuracy of the measurement greatly depends on how perfectly the camera is calibrated and also maintained. But in the industries where logistic problems do exist, it is difficult to adhere to the conventional camera calibration methods

[1–3]. Keeping in mind the implementation of camera-based measurement system in industry, an attempt has been made to develop an alternative method of camera calibration. This paper reports a novel self-calibrating image-based dimension measurement system, which has been implemented in one of the steel plants in India. This technique has been adopted in a visual inspection system, which estimates the length of the cut needed to achieve a specified weight (i.e., 530 ± 5 kg per block) of the piece/block from fluted ingots. The blocks are used for production of locomotive wheels through subsequent processing. The wheels thus produced require a very tight weight tolerance limit. These fluted ingots are 12 sided in cross section and tapered by an angle of about 0.3° in length (fairly constant throughout the length). Because of variation in frontal dimension of ingots, the weight per unit length is not constant. Therefore if fixed lengths of cuts are used, there is wide variation in the weights of the



Fig. 1. Typical views of the measurement table in the steel plant.

resulting blocks, giving rise to a large number of rejections. The manufacture of wheels is not possible if the block weight is less than 518 kg. Since measurement accuracy is the essence of the problem, the developed self-calibration technique needs to be industrially robust with a minimum frequency of calibration. The problem of radial distortion due to wide-angle characteristics has also been solved.

This paper is organized as follows: Section 2 describes the basic principle of operation of image-based dimension measurement system and the proposed self-calibration method and also covers how a distance invariant system has been developed with the help of a single camera. Section 3 elaborates the experimentation method and the results obtained. Section 4 reports the performance and limitation of the proposed technique.

2. Principles of operation

The system performs frontal area measurement of ingots by a matrix CCD camera. The camera takes the front view of every ingot for obtaining dimension of the cross section. A mathematical model is developed to provide the length of each cut of the ingot based on the data generated by the camera through image analysis. The system indicates the desired lengths of cut by a band saw for each block of ingot to achieve a targeted weight.

The ingot whose profile is to be measured is placed on the band saw table for initial front cutting to obtain a smooth frontal surface. After performing the first preliminary cut, the system operates in the following sequence:

(1) The ingot is moved forward on the measurement table, which can rotate at an angle of 90° (with respect to original position) clockwise and back. The measurement table as shown in the photos of Fig. 1 does not have any braking arrangement. The ingot is stopped at the specified location about 1.0–1.5 m away from the camera head.

(2) After performing the operations above, the front view of the ingot is captured by the CCD camera for further calculations. The camera is mounted on a bracket and is aligned with the measurement table to obtain clear front view of the ingot. An appropriate illumination arrangement is provided to obtain the required image clarity.

The scanned parameters are processed through a PC-based workstation, which calculates the required lengths (L_1 , L_2 , L_3) of each block (A, B, C) to be cut to obtain the target weight as shown in Fig. 2. The volume of the ingot is computed with the knowledge of the frontal area and a known tapering angle. The density of the ingot is considered constant, as it has been observed to vary negligibly ($<0.5\%$) between samples of different heats.

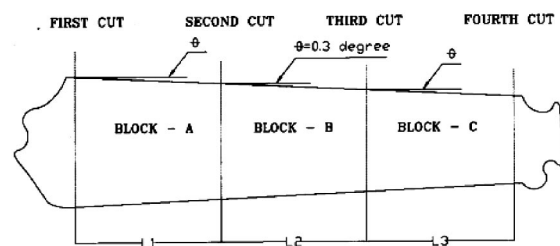


Fig. 2. Plan view of the fluted ingot.

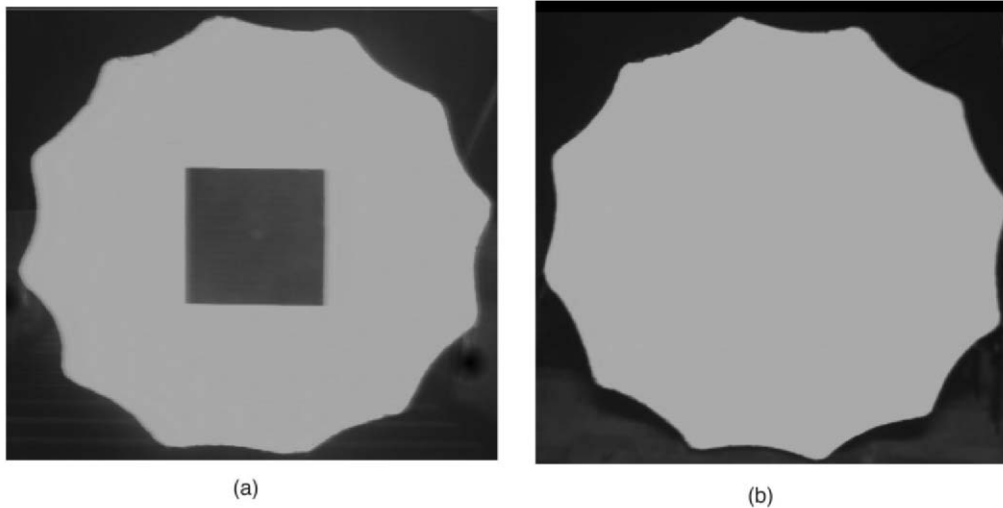


Fig. 3. (a) Image of the front of the ingot with magnetic attachment. (b) Image of the front of the ingot without magnetic attachment.

As it is apparent from the point of view of plant logistics, the images are required to be captured within only 1.0–1.5 m away from the camera head. Selection of the appropriate lens without foregoing the accuracy limit is a challenging task. The camera selected for this particular application was a Sony XC-75CE, 752(H)X582(V), CCIR, 6–12 mm variable focal length type. A superwide-angle lens has been selected due to the referred distance limitation. Hence the probabilities of image distortion as well as image vignetting effects are quite high, resulting in measurement inaccuracy. In order to counter the position dependency of image size as well as the lens distortion effect on measurement accuracy, a novel self-calibrating mechanism has been devised. A black reference plate with a permanent magnet fixed on one side is utilized as a template for the purpose of area calculation. The template, having known dimensions, is attached on the frontal portion of the ingots before capturing the frontal image. Fig. 3 shows the frontal image with and without attaching the disk. As the fluted ingots are at ambient temperature, the magnetic property is retained to hold the magnetic template. Also, no special tool is required by the operators for attaching the disk and the time required for attaching and detaching the disk is negligible.

Since the dimensions of template are known, a calibration factor $S = (\text{template area in mm}^2 / \text{template area in pixel})$ is computed for every cap-

tured image. The total computed frontal area is the product of calibration factor and the area of the frontal image calculated in pixels.

The system with the self-calibrating device is able to predict the weight and also estimate the length of the blocks quite accurately provided the ingots are placed at a fixed distance from the camera head for almost all the cases. However, variation in weight estimation has been observed when the ingot position changes with respect to the camera head even with the reference template. So some correction factor is necessary to counter this variation.

This scheme takes into consideration not only the variation of distance from the camera head but also the inclination of the frontal surface with respect to the camera head. Both the template and the frontal surface will be inclined at the same angle. Therefore, the area viewed by the camera will be projected by a factor, which is same for both the objects. Thus the inclination will not have much bearing on the calibration factor S . The calibration factor S will mainly be affected by radial distortion because the template area is much less than the frontal surface area.

It has been established that the depth information can be computed with the help of at least two cameras by stereovision principle [4,5]. However, in that case the camera coordinates with respect to a common coordinate system have to be known accurately. In any brown field project at times

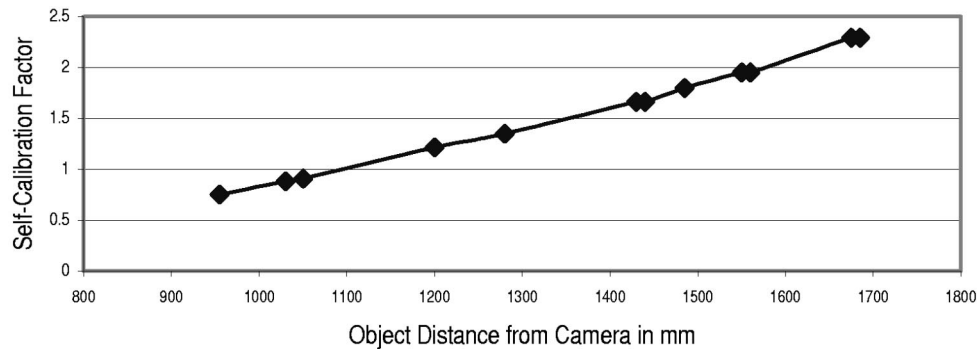


Fig. 4. Object distance from the camera vs self-calibration factor.

plant logistics may not permit implementation of all these aspects.

In this work an innovative self-calibrating mechanism is used to accurately estimate the frontal area of the cross section of fluted ingot, which is placed at different positions with respect to the camera. The novel feature of the system is that with the aid of only one camera, the distance of the object from the camera is computed based on a self-calibration factor.

A mathematical model for computing the distance of the object from the camera was developed by keeping a block of known weight at different distances from the camera head. This exercise was repeated by using a number of different blocks for tuning the model. This model has considerably eliminated the inaccuracy in estimating the area without knowing the depth information. Development of the model was essential, as the image capturing position could not be fixed all the time. A system for placing the ingots at a fixed position was even attempted by incorporating photo detectors across the measurement table. Due to the limi-

tation of the lens characteristics, area measurement is also sensitive to the object location from camera head.

3. Experimentation and result

The experiment has been designed based on the following conditions. The front diameters of the ingots were generally within the following ranges: crest to crest, 390–398 mm; trough to trough, 362–370 mm. The dimension of the magnetic attachment was 115.5×119.0 mm. The pitch of the roller of the measurement roller table was 125 mm. The CCD camera used was a SONY XC-75CE, 752(H)X582(V), CCIR, 6–12 mm variable focal length.

The experiments were conducted by capturing a number of images of a block of known weight by positioning it at different locations from the camera head. Initially area of the frontal surface was computed based on the self-calibration factor S generated by the template. It has been noticed that though the calibration factor is fairly linear (Fig.

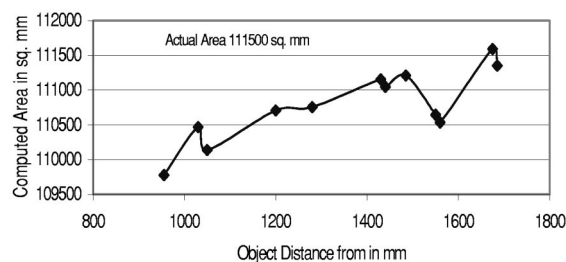


Fig. 5. Object distance from camera vs computed area with self-calibration factor.

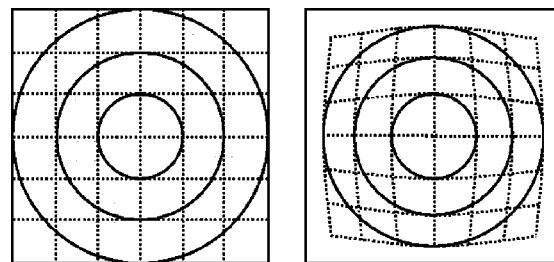


Fig. 6. Radial distortion example. The left image is an undistorted grid pattern, and the right image is the same pattern viewed after radial distortion.

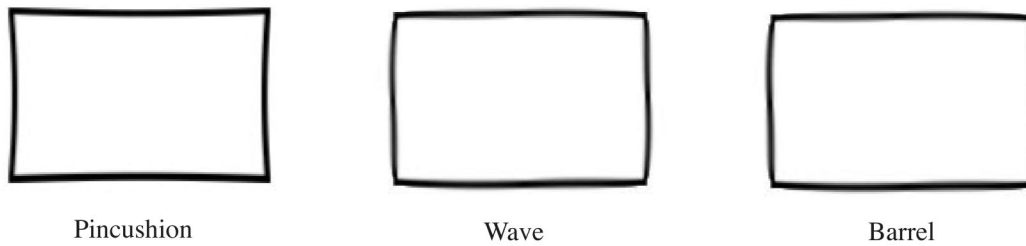


Fig. 7. Different types of common image distortions due to lens characteristic.

4) with respect to object distance from the camera head, variation in the area is quite appreciable as shown in Fig. 5.

This phenomenon is primarily due to the superwide-angle lens characteristics. The radial distortion is the most predominant effect in the wide-angle lens [6] as shown in Fig. 6. Radial distortion is a feature of lenses where the magnification is different at the edges than at the center of the lens. This distortion is a function of radius. The effect of the distortion is noticeable through most of the image. Most of the wide-angle lenses suffer from barrel distortion. It is clearly seen from the figure of the radial distortion example that the objects at small radii appear as they should, but further from the center of the lens and image, the perceived radius is smaller than the actual radius. At the same time, polar coordinate angles are unaffected, and so circles whose center corresponds to the center of the image remain circular with slightly smaller radius and lines through

the center of the image remain straight. However, lines that do not pass through the center tend to bow.

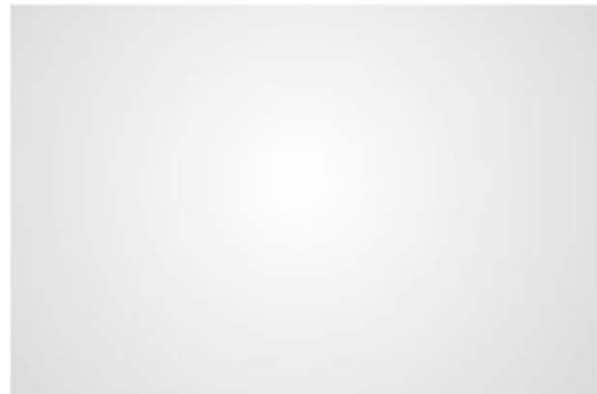
Since the template is attached in the middle of the image frame, image distortions such as the pincushion, wave, and barrel (Fig. 7) and the vignetting effect (Fig. 8) are negligible. But it is clearly visible from the figures that both distortions and the vignetting effect are quite prominent at the edges of the image. Though the vignetting effect may be reduced by controlling the aperture and also by controlling the luminance of the artificial illumination, this scheme may not be feasible for on-line systems. In order to address this problem, a radial distortion correction factor needs to be introduced in the measurement system.

The classical radial distortion model is a polynomial function such as

$$R = r + \alpha r^3 + \beta r^5, \quad (1)$$



Vignetting



No Vignetting

Fig. 8. Vignetting effect—wide-angle lens feature.

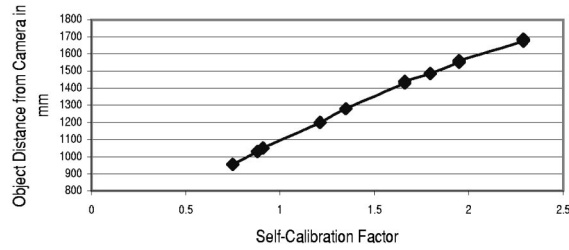


Fig. 9. Self-calibration factor vs object distance from camera.

where R and r denote the undistorted and the distorted radii, respectively, and α and β are coefficients of radial distortions. Since by adopting the classical distortion formulation, the distance information cannot be computed, instead an alternative model proposed by Pers and Kovacic [7] has been applied to compute the undistorted radius to obtain actual area for size estimation. The undistorted radius of the image is calculated by

$$R = \frac{d}{2} \frac{(e^{2r/d} - 1)}{e^{r/d}}, \quad (2)$$

where d is the distance of the object from the camera. The distance of the object from the camera has been derived by (a) plotting the self-calibrating factor with distance (Fig. 9), and (b) generating a least-square curve fit [8] with the data of the self-calibrating factor and the distance. A power equation $d = \gamma S^\phi$ is used for this purpose, where, γ and ϕ are the coefficients and the power that have been generated.

Initially the area of the frontal surface of the ingots is calculated based on the self-calibrating factor. The self-calibrating factor is measured by imaging technique, and the distance of the ingot from the camera head is computed by using the power equation $d = \gamma S^\phi$. To incorporate the radial distortion factor in a simple fashion, the object area has been approximated by a circular area of equivalent radius r . This is well justified for this case because both the ingot frontal surface and the template area are symmetric. Knowing the equivalent distorted radius r from the area calculated with self-calibrating factor and the distance d , the equivalent undistorted radius R is computed by applying Eq. (2).

The undistorted radius thus computed has been used for recalculating the area and subsequently for size estimation. The deviation of the computed weight with self-calibration factor and with radial distortion correction and the actual weight is shown in Fig. 10. It is quite clear from this figure that the radial distortion correction has significantly improved the performance of the measurement system. The ingot movement in the roller table is limited to ± 500 mm, it has been observed that twelve points for establishing the formula for $d = \gamma S^\phi$ is adequate to achieve the desired performance of the system. It has been seen that the estimated values of γ and ϕ are quite consistent in number of data sets. The goodness of fit for this form of equation to the data sets is around 99.9% in almost all the cases.

This scheme has been implemented in a

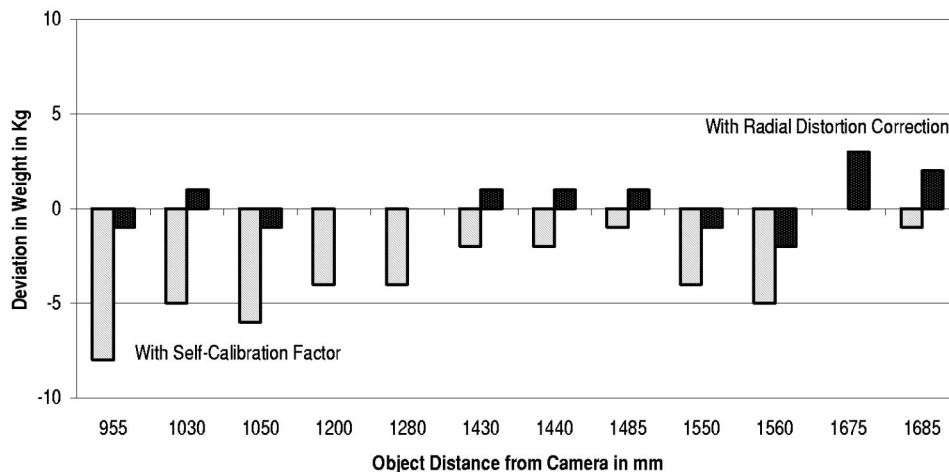


Fig. 10. Deviation in computed weight with self-calibration factor and with radial distortion correction.

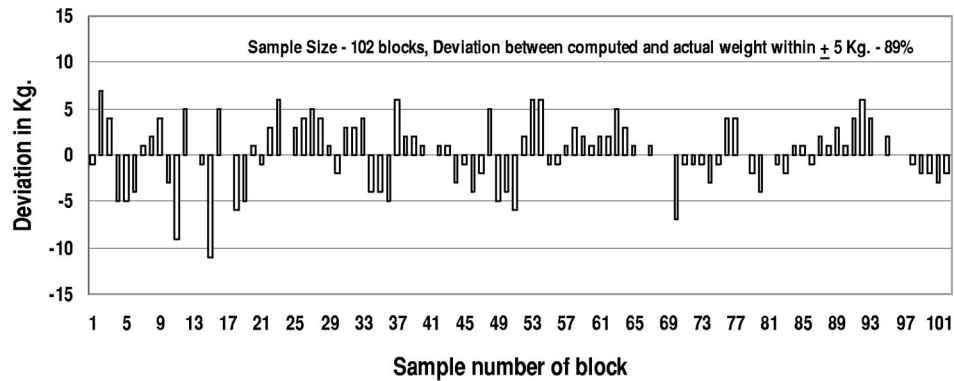


Fig. 11. Summary of field test results.

Pentium-based system under Windows NT environment. All related software has been developed in C.

Extensive field trials have been conducted and the results obtained are quite encouraging as shown in Fig. 11. The figure depicts that 89% of the blocks are within ± 5 kg, i.e., $\pm 1\%$ of the target weight (530 kg). In the case of off-line pre-estimated cutting, only around 66% of the blocks have been found to be within ± 5 kg of 530 kg.

4. Conclusion

An innovative single camera-based system has been developed for on-line image-based dimension measurement of steel ingots. This robust and operator friendly system has demonstrated a way of introducing a system that is adaptable in a brown field industrial application. The major feature of the system is a self-calibration mechanism that makes the measurement insensitive to the distance between the camera and the object. This is achieved by attaching a template of known area to the front of the ingot. To reduce the effects of lens characteristics, radial distortion correction has been implemented, and significant reduction of weight variation of same object placed at a variable location from the camera head has been achieved.

Due to the characteristic of superwide-angle lens, nonlinearity with depth of field is quite substantial. Linearity property of this type of lenses is limited to a narrow zone. The radial distortion correction has reduced the effect to a great extent, yet it is recommended to capture the image by avoiding the highly nonlinear zone to obtain the desired

result. Further study may reveal that an improved-quality lens provides better result, but selection of the lens will be a trade-off between the cost of the lens and the accuracy desired for the process requirement.

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Subhasis Chaudhuri received his M. Tech. in 1982 from Indian Institute of Technology, Kharagpur. He is currently working as Principal Research Manager in Research & Development Centre for Iron and Steel, Steel Authority of India Limited, India. His active areas of interests are process instrumentation and automation, especially in steel industries. His work in these areas resulted in more than 10 patents and patent applications.



Anirban Mukherjee received the B.E.E. degree in Electrical Engineering in 1998 from Jadavpur University, Kolkata. He did his M. Tech. in 2000 from Indian Institute of Technology, Kharagpur, where he is currently engaged in a Ph.D. program in electrical engineering. His current areas of interests are signal processing, image processing, and multimedia engineering.



Pranab K. Dutta has obtained B.E., M.E. and Ph.D. degrees, all in Electrical Engineering, in 1984, 1986, and 1992, respectively. Since 1993, he serves as faculty member in the Department of Electrical Engineering at Indian Institute of Technology, Kharagpur. He has active interests in technology development and participated in a number of industry-sponsored projects. His current areas of interest are signal processing, image processing (biomedical and multimedia), and optoelectronic devices. He has published more than 40 research papers. His work in these areas resulted in more than 8 patents and patent applications.



Amit Patra received B.Tech., M.Tech., and Ph.D. degrees from the Indian Institute of Technology, Kharagpur. He visited the Ruhr-University, Bochum, Germany as a Post-Doctoral Fellow of the Alexander von Humboldt Foundation. Since 1987 he is on the faculty of Indian Institute of Technology, Kharagpur. His research interests include discrete-event and hybrid systems, fault detection and diagnosis for industrial processes, control of machine drives, and industrial automation and control. He has published more than 75 research papers and a research monograph entitled *General Hybrid Orthogonal Functions and Their Applications in Systems and Control*, published by the Springer Verlag in 1996.

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