World Academy of Science, Engineering and Technology
International Journal of Physical and Mathematical Sciences
Vol:3, No:11, 2009

Double Aperture Camera for High Resolution Measurement

Venkatesh Bagaria, Nagesh AS and Varun AV*
Siemens Corporate Technology, India
*e-mail: varun.av@siemens.com

Abstract**—**In the domain of machine vision, the measurement of length is done using cameras where the accuracy is directly proportional to the resolution of the camera and inversely to the size of the object. Since most of the pixels are wasted imaging the entire body as opposed to just imaging the edges in a conventional system, a double aperture system is constructed to focus on the edges to measure at higher resolution. The paper discusses the complexities and how they are mitigated to realize a practical machine vision system.

Keywords**—**Machine Vision, double aperture camera, accurate length measurement

I. INTRODUCTION

MACHINE vision cameras are widely prevalent as inspection systems in many industrial manufacturing processes. This is because they pose the least amount of installation time, effort and do not hinder the existing processes and infrastructure down the assembly line. One such inspection application is the measurement of length of machined objects that are carried down a conveyor. Using a machine vision camera is easier than using mechanical devices such as vernier scales. While the latter would need to pick and place objects before measurement, the former would not need to disturb the flow of the objects as they are being assembled or manufactured. With such evident advantage, length measurement is also handed down to machine vision cameras.

A typical machine vision based measurement system for length measurement functions as follows. The camera is triggered to take an image by a field event such as proximity sensor detecting the presence of the object to be inspected or by the pulse of an encoder. After obtaining the image, image processing algorithms determine the extreme edges of the object. The vision software converts the distance between the end points from pixels to real world units using pre-calibrated data. If the measured dimensions are outside the tolerance limits the object is discarded from the conveyor, else it continues down the assembly line.

The measurement accuracy of such a system is dependant on not just the resolution of the camera, but the size of the object too. Let us suppose, a 1000x1000 pixel sensor measures a job of 10mm length, the expected accuracy is 10um, while a 100mm job only yields the length 100um accurate.

Increasing quality control norms demand high resolution dimension measurement of objects, however, even at higher camera resolutions the measurement accuracy has not been adequate. The accuracy further deteriorates when longer objects are inspected. Clearly, to improve the accuracy of such systems, the camera should not waste its pixels imaging the parts of the job not relevant to length measurement.

A significant increase in measurement resolution could be obtained if only the end portions (of interest) were to be imaged. The location of the ends could be obtained relative to each other and subsequently referenced to the total length of the object. A system can be designed which uses a pair of cameras focusing only on the extremities of the object, thereby measuring relative distances to get the overall length, once the distance between the two cameras are known. These systems require a stable operating environment to ensure that both the cameras do not move or tilt with respect to each other. In industrial operating conditions the practical problem of the set-up being disturbed during maintenance activities poses a hazard. The overall setup becomes larger, less compact and more expensive. Placing both the cameras too close to measure smaller objects is yet another problem; it would require redesigning the optics with multiple mirrors and beam-splitters.

To circumvent the above issues, a double aperture pinhole camera is constructed such that each end of the job is imaged to one-half of the imaging sensor. From the resultant image, the relative location of the ends from each half portion is found and this is referenced to provide the overall length of the job. This effectively renders a higher resolution as smaller areas at the ends are imaged at a higher magnification. Suppose light from a small section of 1mm at each end falls onto one half of the sensor, the effective accuracy is 1mm/500 pixels or 2um. In effect, a 1mm section of the two extremities of the object is imaged onto one half of the sensor. The relative position of the edges is found and referenced to the actual length of the object. In this manner, a single camera could measure the length of objects to very high precision and this technique is further discussed below.

Studies with similar philosophy on preservation of useful areas in the image while discarding the rest exist [3], however, they are targeted more towards shrinking and do not provide higher resolution information for measurement purposes

Venkatesh Bagaria, Nagesh AS and Varun AV are with Siemens Corporate Technologyh, India (phone: 91-9979260606; fax: 91-80-25112666; e-mail: varun.av@siemens.com).

Although multiple aperture pinhole cameras have existed, they are not common in industrial usage since a multitude of practical issues crop up. These issues need to be resolved to realize an industrial system using the pinhole cameras. However, pinhole cameras are known to produce a ‘soft-focus’ artifact in images which does not hamper the performance when the working distance is large. At smaller working a distance, the image quality deteriorates if the pinhole is not suitably manufactured, a problem which can be circumvented with the use of lenses to ensure sharp images. The hybrid dual aperture-lens camera system is also discussed below.

The alternate measurement method which simplifies the whole process and gives very stable measurements is described in section 2. Section 3 highlights the complexities that arise from using such as system and the limits placed on accuracy and usability. Some results are shown in section 4 with accompanied discussions. Section 5 concludes noting the advantages against existing systems and discusses future developments.

II. Double Aperture Camera for Length Measurement

The Double Aperture Camera System (DACS) is based on the idea of saving pixels by only imaging the two ends of the object and discarding the light from other parts.
The camera optics is modified by removing the lens and placing a dual aperture in front of the sensor. The aperture is specially designed such that it allows for certain features as detailed below. The aperture is an opaque disc consisting of two holes. The holes are placed in the disc such that light from one end of the object travels and fills one half of the sensor, while light from the other end fills the other half. Figure 1 explains the setup configuration of the camera. The double aperture slit houses two apertures A1 and B1 which allow light to fall on the image sensor. This system is placed to inspect the object.

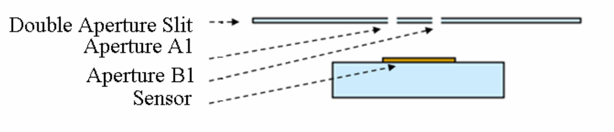

Fig. 1 Schematic of the double aperture camera

The image captured by the sensor only consists of the ends of the object at much higher resolution. For each half of the image, a reference position is marked and the edge position with respect to the reference is noted. The physical real world distances between the reference positions in each half are known, hence, the edge positions can also be ascertained with high accuracy.

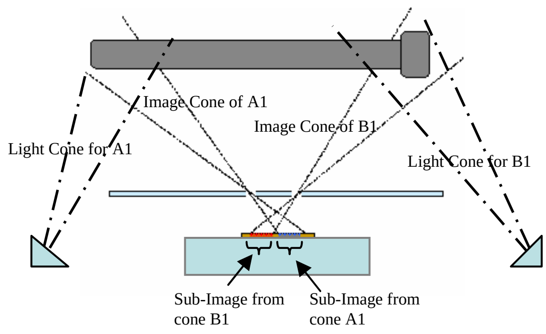

Fig. 2 Method of imaging a long object

Seen in figure 2, an object appears in front of the camera with the proposed double aperture. When the object is in the expected position, the camera is triggered to take an image and simultaneously lights are strobed to illuminate the areas of interest on the object. The illumination cones ‘Light Cones’ for A1 and B1 define the region of interest; light that reflects off these cones and travels through the aperture aids in image formation at different parts of the image sensor. If the entire scene was illuminated, the sub-images would not have formed at different parts of the sensor. The light cones fulfil two objectives. First, they precisely define the sub-images formed at the sensor. The image cone formed by each aperture A1 and B1 are defined only if the light cones A1 and B1 are fixed. Second, the quality of the composite image formed depends on the rejection of ambient light. Two distinct sub-images cannot form if ambient light floods the scene exposes the camera. However, the apertures are typically sized at f-stops higher than 100 and require an exposure time of few seconds to receive adequate light for image formation. If the exposure time is restricted to a fraction of a second, the contribution of the ambient light decreases, while the light cones, strobed at much higher intensities aid in image formation. This increases the signal to noise ratio, where-in the light cone intensity directly affects the not just the contrast of the image, but the quality of the sub-images too. Figure 3 shows the schematic of the image formed at the sensor. Each sub-image is inverted and care must be taken when calculating the relative distance of edges.

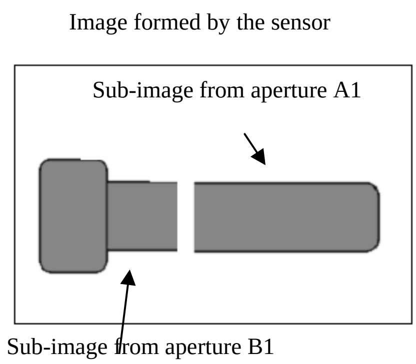

Fig. 3. The composite image formed with both the ends indicated as sub-images.

The edge location at each sub-image can be determined using standard edge detection algorithms and their relative distance found. This relative distance is referenced to the absolute length of the object. The camera is calibrated to convert pixel distance to physical distances. A standard job part of known length is imaged to obtain the reference relative distance.

III. COMPLEXITIES IN USING THE DOUBLE APERTURE SYSTEM

3.1 Soft Focus

Pinhole cameras inherently produce images that are not adequately sharp. This limits the accuracy of the measurement. Inadequately sharp images wherein the blurriness extends to a few pixels yield lower measurement accuracy. If the blurriness extends to a large number of pixels, say 10, the advantage of the system could be nullified. However, choosing the right focal length, wavelength of light and diameter could reduce the blurriness. It is not uncommon to see images which are sharp to the pixel level and hence the gain in advantage can be easily realizable.

Sub-pixel algorithms are often used to provide increased accuracy for applications like edge detection and pattern searching [2]. The possibility of sub-pixel accurate measurement is yet to be explored and if realized, the measurement accuracy would increase by a factor of 10.

Exposure, lighting levels and field of view

A sharp image requires a large f-stop. F-stops of above 100 are required, wherein heuristic exposure time of $1/60^{th}$ second produce sufficiently exposed images if the lighting levels match that found in bright sunny outdoor conditions. Light emitting diodes (LEDs) are conventionally used in machine vision. While generation of intense lighting becomes expensive and power consuming, the effective field of view of illumination has considerably decreased thereby reducing the overall power. Typical 1W LEDs delivers 50 lumen over an area 10mmx10mm produces considerable illumination to match bright outdoor conditions, therefore rendering lighting to be a facile issue.

Proximity Sensors

Image acquisition in the double aperture system is constrained since both the ends of the object should be placed well within their respective cones of view. Further, since exposure times are fairly larger, the frame rate effectively drops and more emphasis is now placed on the proximity sensor triggering as efficiently as possible. Short range proximity sensors can be used for this purpose, whose triggering range is smaller than the measurement cone width. Conventional short range proximity sensors are accurate to a few inches and this could pose a hazard; however, laser based sensors are more accurate and easily available.

Measurement in two dimensions

The concept can be extended into increasing measurement resolutions in two dimensions with two more pinholes with effectively partitioning the image sensor into 4 zones. While such designs are quick to develop, they have not been investigated yet and they pose the obvious trade-off in accuracy due to cannibalization of pixels between the zones.

Distance offset and Out of Plane Orientation

The pinhole camera projects a 3D scene onto a 2D sensor. While using cameras for measurement of length, an important parameter to consider is the distance of the object from the camera. Although this problem is not specific to the double aperture system and conventional cameras also experience the issue, we discuss ways of solving it since it affects high accuracy measurement even more.

Laser triangulation is a simple technique to predict the depth of each end; current triangulation systems provide the depth value accurate up to 50 um. The light cones when masked with opaque lines provide for a structured lighting solution to not just provide the depth of the object, but the out-of-plane orientation too.

Use of lenses to increase sharpness

While pinhole cameras are capable of producing images of good quality, the imaging scenario could produce conditions which result in degraded image formation. Short working distances i.e distance between the object and the camera often yield blurred images. The effects appear rather marked when using low resolution CCD or CMOS sensors. A facile circumvention of the problem is achieved with the use of lens in front of each aperture. The selection of lenses and the working distances are loosely constrained, lower quality lenses still provide good images and there is no harsh binding that the sensor is mounted exactly at the focal length of the lens. However, the Scheimpflug condition needs to be tackled due to the non-planar nature of imaging; which is elaborated below.

Effects of non planar imaging with the use of lenses (Scheimpflug condition)

The Scheimpflug condition [1] is a geometric rule that describes the orientation of the focal plane for given orientations of the lens and the camera sensor (image plane). When the lens plane and the sensor plane are not parallel, the focal plane must pass though the point of intersection of them. Shown in figure 4, is the double aperture system with lenses depicting that Scheimpflug condition would not be satisfied for imaging both ends of objects, subjecting the image to blur.

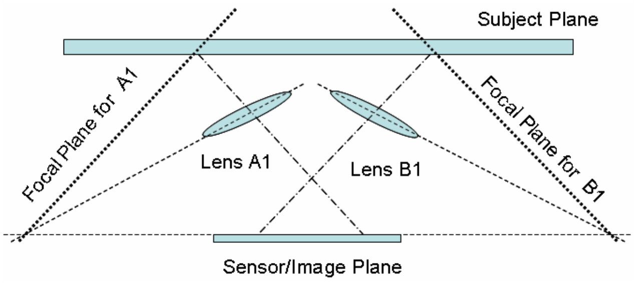

Fig. 4 Fully focused sub-images could be formed only if the ends of the subject were in the depicted focal planes for A1 and B1 respectively.

While the issue renders the image setup less viable for all distances as opposed to the natural pinhole system, the depth of field increases with the f-number. Increasing the f-number decreases the amount of light entering the camera; however, this reduction could be compensated by the lens which aids in collection of larger amount of light from the screen. Further, the ends of the object are magnified to a large extent and overall, the Scheimpflug constraint does not pose a large hurdle.

IV. RESULTS AND DISCUSSIONS

The camera is initially calibrated with an image of a scale. In figure 5, a metric ruler is imaged using the double aperture camera. The left and right sub-images show a magnified view around the markings 7 and 28. The central zone is the region that receives the least light since the light cones are designed to minimize exposure in the area.

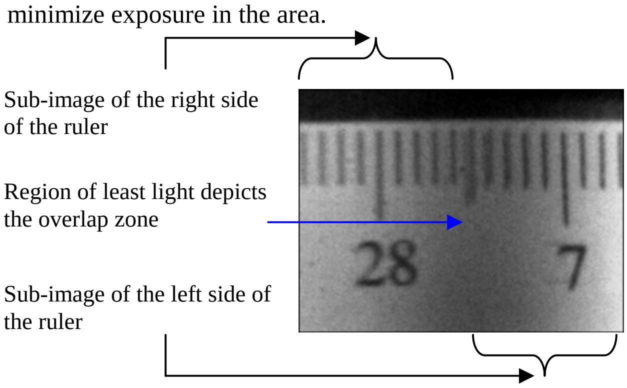

Fig. 5 The magnified ends of a metric ruler form a single composite image

Both the sub-images are in uniform focus; the depth of field is adequate and does not degrade the image for measurement purposes. Figure 6 shows a plot of the graduations on the ruler and their positions at both the 7 cm and 28 cm end. The calibration chart seen is linear implying that the depth of field is adequate for measurement purposes. Further, the calculated slopes are used for length measurement.

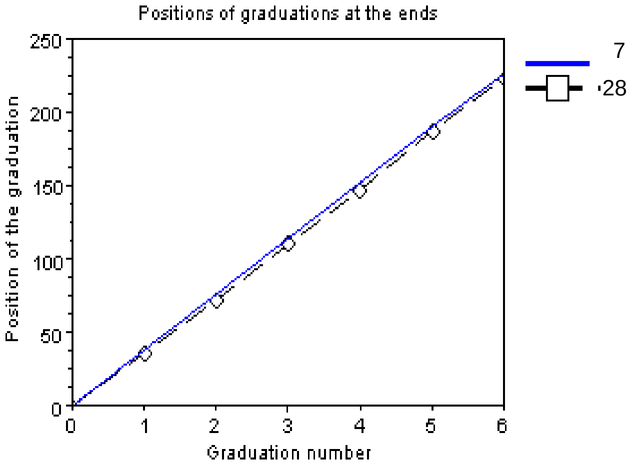

Fig. 6 Positions of graduations showing the linearity of calibration

To measure the length of a metal plate, roughly of the size 210mm, the proximity trigger is placed close to the 7 cm mark when the camera is triggered. The two ends of the metal plate appear at two sub-images. Edges are obtained and the positions in pixels noted. Using the calibration data, the length is calculated.

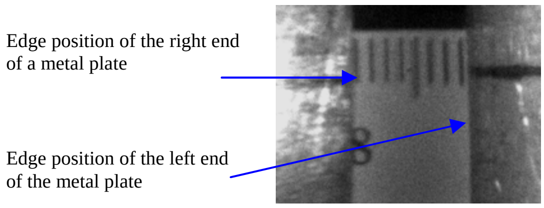

Fig. 7 The ends of a metal plate overlaid on the ruler

The sensor used has a resolution of 640x480 pixels. Suppose the entire ruler is imaged, the resultant accuracy with a 640 column imager measuring an object of 210 mm with 20 mm overall tolerance would be 230/640 = 360um. While in the current setup, roughly 10mm around each marking is divided into 320 pixels yielding an accuracy of 31.25um.

V. CONCLUSIONS

The paper presents a length measuring system which promises higher accuracy over existing cameras by using the double aperture combination. Optimal lighting cones enable the construction of the composite image, wherein each sub-image represents a magnified view of the end of the object. The edge locations are found at high resolutions thereby providing a higher resolution of the measurement of length. The out of plane orientation is a critical issue and must be resolved in order to obtain high accuracy. This problem can be solved using structured lighting or triangulation in a simpler fashion. With smaller working distances, the usage of lenses aid in obtaining sharp images, however, the Scheimpflug condition dictates a larger depth of field. The calibration image is shown, a long metric ruler is imaged such that the 7 cm and 28 cm graduation are visible in a magnified view at the right and left sub-image respectively. The system is linear and void of distortion, as seen in figure 6, hence ensuring precise measurement. With such practical issues being resolved, the double aperture camera promises a highly accurate length measurement system capable of serving the industrial vision market.

REFERENCES

[1] Stephen Walker Two-axes Scheimpflug focusing for particle image velocimetry. *Meas. Sci. Technol.* 2002 **13** 1-12

[2] Masao Shimizu, Masatoshi Okutomi. Significance and attributes of subpixel estimation on area-based matching. Systems and Computers in Japan, Published Online: 11 Sep 2003 Volume 34, Issue 12, Pages 1-111 (15 November 2003)

[3] Shai Avidan, Ariel Shamir Seam carving for content-aware image resizing. ACM Transactions on Graphics Volume 26 , Issue 3 (July 2007)

Venkatesh Bagaria, Nagesh AS and Varun AV are from Siemens Corporate Technology, India in Bangalore working as research engineers in the field of machine vision, computer vision and lighting for vision. Venkatesh Bagaria and Nagesh AS hold a masters degree in Electrical Engineering while Varun AV holds a masters degree in Aerospace Engineering.

Siemens Corporate Technology, India works in areas which involve adaptive optics and lighting for vision based problems in the context of automation. A recent contribution can be found in the publication *'Color Plane Slicing and Its Applications to Motion Characterization for Machine Vision'* presented at the 2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, which was given the best paper award.