Implementation of Low Cost Vision Based Measurement System: Motion Analysis of Indoor Robot

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***Abstract*—The current paper focuses on the development of a low cost vision based measurement system for obtaining the position, velocity, and trajectory of a mobile robot in an indoor environment using monocular camera. The developed method utilized color based feature extraction and blob analysis technique to detect and track the motion of the mobile robot. The equations for transforming pixel coordinate into real world coordinate were generated using polynomial surface fit. The noises in the measured data due to unaccounted source of errors were reduced by the use of median filter. The experiment utilized a commercial webcam to capture the robot motion thereby reducing the cost of the system. The experiments conducted on a two dimensional platform of size 1600 mm × 800 mm verified that the method can be effectively implemented for detecting mobile robots.**

***Index Terms*—blob analysis, image processing, mobile robot, motion analysis, object detection**

I. INTRODUCTION

Several measurement devices are available in the market to obtain the position, velocity, and trajectory of mobile robots. However in an indoor environment, it is expensive to build a reliable measurement system by assembling these devices. Some of the low cost systems like ultrasonic based and Lidar based systems fail to give accurate measurement in a laboratory test environment where workspace is small. With the developments in camera technology and availability of high speed processors, computer vision based measurement system is a viable solution in such indoor environments.

In recent years, computer vision has played a major role in many sectors such as medical image processing, currency inspection, surveillance, movement recognition, object detection and tracking, etc. A computer vision system usually comprises of one or more camera for capturing the images, processing hardware system (computer), and software for processing the captured image. The required data from the captured images are extracted, processed, analyzed and given as an input to the controller which is carrying out the specified task. Most of the commercially available camera based detection and tracking system comes with a cost between 5-10 lack Indian Rupees making it uneconomical in many situations. Thus, in the current paper a low cost vision based measurement system is developed for analyzing the motion of a mobile robot in an indoor environment.

Literature discusses and demonstrates many image processing techniques and algorithms for detection and tracking of static and mobile objects by utilizing their distinctive features depending upon the required application.

Techniques such as modeling of image-background scene and foreground can be used for detection and tracking of mobile objects [1], [2]. In these techniques a model of the background scene is subtracted from the captured image to detect the location of object which is not included in the background model. Another approach for detecting a target object is with the help of kernel based technique which compares a set of models of the target object with the objects in the image. Kernel based tracking proved to give good performance in most of the image sequencing scenarios, though this approach involves complex computation [3]. Use of tunable kernels can be utilized to increase the accuracy of kernel based tracking. This method can efficiently track human motion [4]. Multicolored objects can be tracked by using Gaussian mixture model [5]. Boundary based and region based information of the target can be utilized for tracking deformable targets like biological cells [6]. Spatial features such as shape, contour, edges, and color can be exploited for serving the purpose of object detection and tracking in a given scenario. Among them, color acts as a powerful descriptor to identify and track the objects of interest in a captured scene. Tracking of desired object by using its color feature has been very effective since color conveys a variety of rich information that describes the object [7]. Color histogram based tracking can be utilized for various challenging situations such as tracking a football player, measuring position and orientation of the target object etc. [8]. Another application of color based tracking system is for tracking

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movement of people. Color histogram technique can be used in this scenario for recognizing each person [9]. Thus, the distinct color of the target object can serve as a means for locating the object in the captured image with less computation. Therefore, color based detection and tracking technique was carried out in the current work and it proved to be very effective in the given indoor scenario.

When compared with foreground and background model based detection method, the current work does not rely on the model of the operating environment. Also, the present method utilizes only color information, thus making it much faster than kernel based detection method which requires comparison of scene with a set of target models for detecting the target. The velocity information of the robot was also calculated from robot position information.

However, an effective tracking algorithm needs to overcome many real circumstances which obstruct the processing stage and corrupt data extraction. Some of them are background clutters, occlusion, inappropriate illuminations, etc. Some of these problems are addressed in the next sections.

The paper is organized as follows: Section II contains the stepwise methodology utilized to detect and track the mobile robot. Section III elucidates the experimental set-up. The transformation of pixel coordinates into world coordinates (mm) is also detailed in this section. The results obtained from the experiments are discussed in Section IV. The conclusions of the work and its future scope are detailed in Section V.

II. METHODOLOGY

The movement of the mobile robot on a two dimensional (2-D) workspace was captured continuously using a camera mounted on the ceiling of the room. A red-colored label stuck on the mobile robot acts as a distinct feature (target) to be detected by the vision system. The image obtained was then processed through different stages of image-processing as shown in Fig.1. Feature extraction, binarization, filtering, and blob analysis were performed in these stages for detecting and obtaining the position coordinates of the target. The subsection below discusses each stage of processing the captured image.

- ***Image Acquisition:*** A commercial webcam Microsoft HD 3000 was utilized for image acquisition. Different settings related to brightness, exposure, saturation, focus, resolution etc. were adjusted ahead of acquiring the image to increase the clarity of the acquired image. As the mobile robot is moved, sequences of images were captured using the camera, as a video file at a frame rate of 15 frames per second (fps) and these images were stored in the system for processing and data extraction. Figure 2 shows the position of mobile robot in the sequence of captured image while the mobile robot is moving on the 2-D workspace of size 1600 mm x 800 mm. Figure 3 shows commercially available e-puck robot used for experimentation. This is a mini wheeled mobile robot used for educational purposes. The robot has a diameter of 70 mm. The main technical specifications are detailed in Table I and other details of the e-puck robot are also available [10].

Image Acquisition: Captures the image of robot moving on the 2-D platform using overhead webcam

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Feature Extraction: Brightens the portion of image with red tint thus brightening the red color target portion

↓

Binarization: Converts the portions in the image with intensity value same as that of the target intensity value into white color and all other portions into black color

↓

Filtering: Converts small white patches of noise in binarized image into black without altering large target portion

↓

Blob Analysis: Detects the target object and calculates its position in pixel coordinate

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Position, Velocity, and Trajectory Estimation: Converts pixel coordinate into real world coordinate with the help of calibration equations

Figure 1. Different stages of vision based measurement

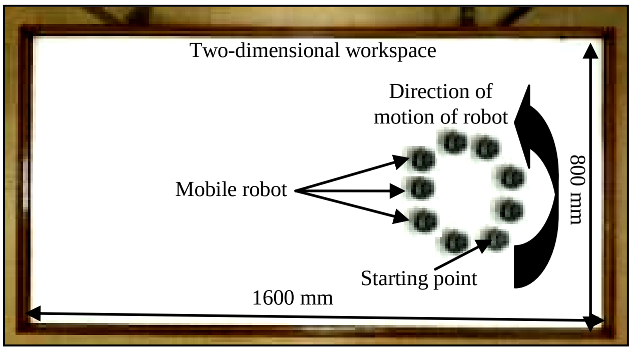

Figure 2. Position of the mobile robot in the sequence of acquired images for an experimental run of 30 seconds

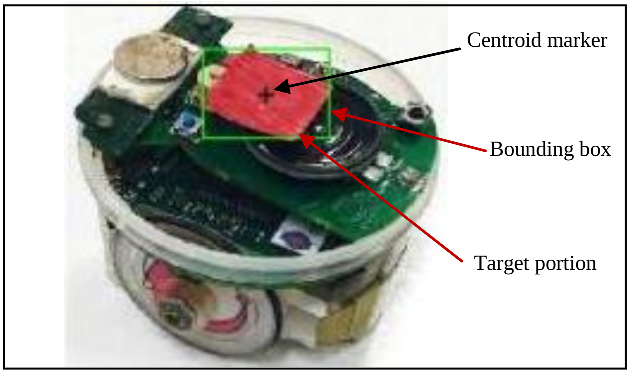

Figure 3. e-puck mobile robot

• ***Feature Extraction:*** Extraction of the relevant area from a given image is a crucial step to distinguish the robot from other objects in the same image. Feature extraction is utilized in this regard. However, selection of the required feature extraction technique according to the given input should be done with extreme care [11]. In the field of image-processing, the selection technique for feature extraction can be based on motion classification, object classification, or on spatial features such as texture, shape, size, edge, color, and so forth. The proposed method utilizes color (RGB model space) as the feature to be extracted from the captured image of the mobile robot. Many other researchers [5], [12] and [13], have also used color as a distinct feature for object detection and tracking.

The captured image has Red, Green, and Blue (RGB) intensities in different proportion, out of which the objective is to concentrate only on the particular color feature which in this case is red. For feature extraction, the grayscale intensity of each pixel in the image is subtracted from the corresponding red color intensity of the pixel. This extracts the red color feature of the target from the image and also compensates the variation in intensity of the red color due to irregularities in lighting. This step thus brightens the portions of the image having more reddish tint, and darkens the area having less reddish tint. Figure 4 shows zoomed view of the mobile robot before feature extraction and after feature extraction. The brightening of the areas having red color allows other stages of image processing to easily detect the target.

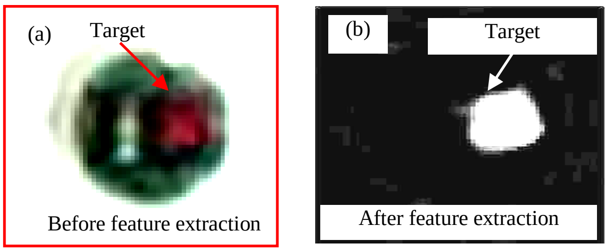

Figure 4. Zoomed view of the mobile robot (a) Before feature extraction (b) After feature extraction

• ***Binarization:*** Binarization is an operation in which the pixels in the image are converted into black or white by applying intensity threshold. The areas of image having intensity values greater than the applied threshold are converted to white color and areas having intensity values less than the threshold are converted to black. In the present scenario, binarization is applied to distinguish the target from other objects. The image output after feature extraction is binarized by applying an intensity threshold corresponding to the intensity of red color target. So, the area corresponding to the target will be converted into white color and other areas will be converted to black color as shown in Fig. 5. However, there can be areas other than that of the target which comes under the given color threshold. These areas will also be converted into white color and are usually of smaller size compared to the target point. Median filter is applied to remove these unnecessary portions. These portions can be considered as noises in the binarized image.

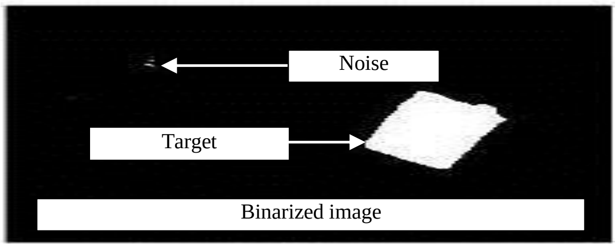

Figure 5. Binarized image showing the noise and the target

• ***Filtering:*** Filtering of noise is essential in image processing. To remove the noise from the extracted region, a 3 x 3 median filter was utilized. Median filter removes the noise by replacing each pixel by middle value of the sorted set of nearby pixel values [14]. Since the noise occupies small areas, this filter converts it into a value corresponding to black color, thus reducing the chance of next processing stage (blob analysis) in detecting this area instead of the target. The filter removes the noise in the detected region without disturbing the edges of the detected area thus maintaining the information about the shape of the object. Figure 6 shows the binarized image after removing the noise using median filter.

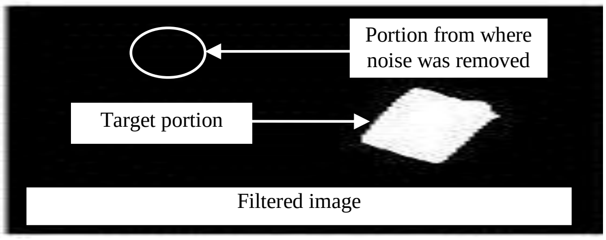

Figure 6. Filtered binary image showing the target portion

• ***Blob Analysis:*** The main objective of the current work is to measure the position and velocity of the mobile robot in the sequence of captured images. For this purpose, Blob analysis is the technique utilized; where 'Blob' stands for binary large objects. This is a technique that detects regions of image which maintain consistent specified criteria throughout. This technique is used in image processing mainly for detecting and classifying objects in the image. The term 'Blob' means a set of connected pixels in a binary image which is characterized as a single unit if all the pixels have specified feature. For detecting the blob, each pixel in an image is compared with other nearby pixels and, the matching ones are selected as a part of an object in the image. These selected pixels are then connected to form the blob. This ensures that each pixel of a detected blob will be similar to its neighboring pixels. A bounding box is placed enclosing the detected blob. The centroid of the extracted blob is calculated as the center of this bounding box, to obtain the information about the position of object in the image. In a given image, there can be more than one target object to be detected. Blob analysis can detect and separate these different objects in the image and also can calculate the location of all these objects. Some of the applications of blob analysis include detection of head and hands of a human body, identification of machine printed characters, detecting flaws on silicon wafers, and so forth [15].

In the current work, blob analysis has been performed on the filtered binary image. This enables the detection of area in the image which belongs to that of the target (white portion in binary image/Red label portion in RGB image). The algorithm places a bounding box enclosing the detected blob and the center of this box is considered as the centroid of the extracted area. The coordinates of the centroid is further exploited to obtain the velocity and trajectory tracked by the mobile robot. Figure 7 shows the detected centroid with bounding box enclosing the detected target (red-label) in the binarized image.

- ***Position, Velocity, and Trajectory Estimation:*** The centroids of the target in the consecutive frames are connected to obtain the trajectory tracked by the mobile robot. For real-time applications, the pixel coordinates are needed to be converted into world coordinate. For this purpose, numerical equation has been calculated through calibration phase. This equation is incorporated in the position estimation module. The calculation of actual position of the robot in millimeter is explained in Section III. To obtain the velocity of the robot, the difference between the robot positions in two consecutive frames is divided by frame rate.,

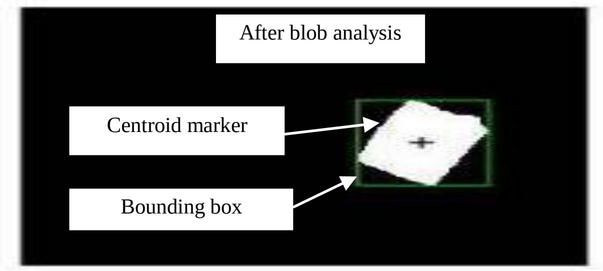

Figure 7. Image after marking centroid and bounding-box using Blob analysis

III. Experimental Set Up

The experimental setup used for testing the developed measurement system is shown in Fig. 8. It consists of a mobile robot, webcam, 2-D platform for conducting the experiments, and a FARO laser tracker for calibrating the setup. The specification of the components used for the experiment is listed in Table I. The 2-D platform (workspace) on which the experiments were conducted has a dimension of 1600 mm x 800 mm. The mobile robot is moved over the platform and the images are captured by the webcam. These images are sent to the processing system via USB 2.0. The camera was fixed on the ceiling, and faced the two-dimensional workspace. The camera has options to capture images at different resolutions starting from 160 x 120 pixels to 1280 x 720 pixels. The processing system has the image-processing software which processes and gives the position coordinates of the robot in pixels. The room was well illuminated for conducting the experiment. Laser based coordinate measurement system- FARO laser tracker was utilized for calibration of the setup

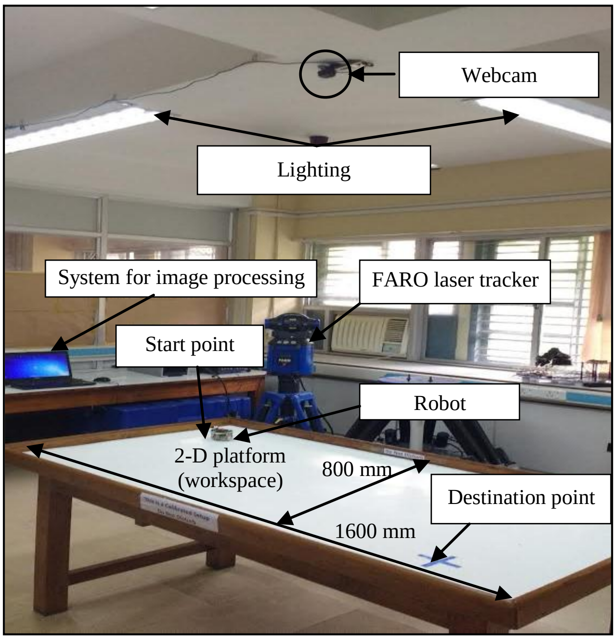

Figure 8. Arrangement of vision based measurement system

TABLE I. Specification of Components

Components	Specification		
Robot	Model	:	e-puck
	Diameter	:	70 mm
	Height	:	55 mm
	Weight	:	150 g
	Processor	:	dsPIC30F6014A
	Processor speed	:	60 MHz
	Type of motors	:	Two stepper motors
	Motor resolution	:	0.13 mm/step
	Speed	:	Max: 135 mm/s
	Robot to computer and robot to robot connectivity	:	Wireless communication using Bluetooth
	Battery	:	5Wh LiION battery
Webcam	Model	:	Microsoft HD 3000
	Sensor	:	CMOS image sensor
	Maximum resolution	:	1280 x 720 pixel
	Minimum resolution	:	160 x 120 pixel
	Resolution used	:	640 x 360 pixel
	Color space	:	RGB, 24-bit color
	Maximum frame rate	:	30 fps
	Frame rate used	:	15 fps
	Lens focal length	:	3.2 mm
Platform	Length	:	1600 mm
	Breadth	:	800 mm
	Surface	:	Flat and smooth
	Size of the red label	:	20 mm x 20 mm
Laser Tracker	Model	:	FARO
	Type of laser	:	Helium-Neon laser
	Accuracy	:	0.003 mm
	Range (radius)	:	0 mm to 35 000 mm

The extraction of relevant data within less time is an important factor to be considered. In the case of a visual data such as an image, more resolution means more number of pixels which gives added quality to the image. But, as the number of pixels increases, the processing time also increases. Thus, considering the quality and processing time of the captured image, resolution of 640 x 360 pixels with a frame rate of 15 fps has been used for experiments.

A. Calibration of the Mesurement System

The coordinates given in pixels by the image-processing algorithm should be transformed into world coordinates for any practical application of the proposed measurement system. Calibration was carried out in order to find this coordinate transformation equations which convert coordinate value from pixels to mm. For this purpose, the target (in this case, red color) was placed on the known locations of the platform. The world coordinates corresponding to these locations were obtained using FARO laser tracker. Then an image of the workspace was taken. This image underwent the earlier mentioned image-processing stages, and the position (centroid) of all the labels were obtained in pixel coordinates.

Polynomial surface fit has been used for mapping these measured pixel coordinates (X_p, Y_p) to actual (known) X coordinates (X_a) and actual (known) Y coordinates (Y_a). The measured points and fitted curve corresponding to X_a and Y_a coordinates are shown in Fig. 9 (a) and (b) respectively. The polynomial equations generated with the help of polynomial surface fit are shown in equations (1) and (2). These equations were implemented in the position measurement stage of the image processing. By substituting any measured pixel coordinates (X_p, Y_p) in (1) and (2), corresponding actual coordinates (X_a, Y_a) can be obtained. The value of constants mentioned in the equations (1) and (2) are given in Table II.

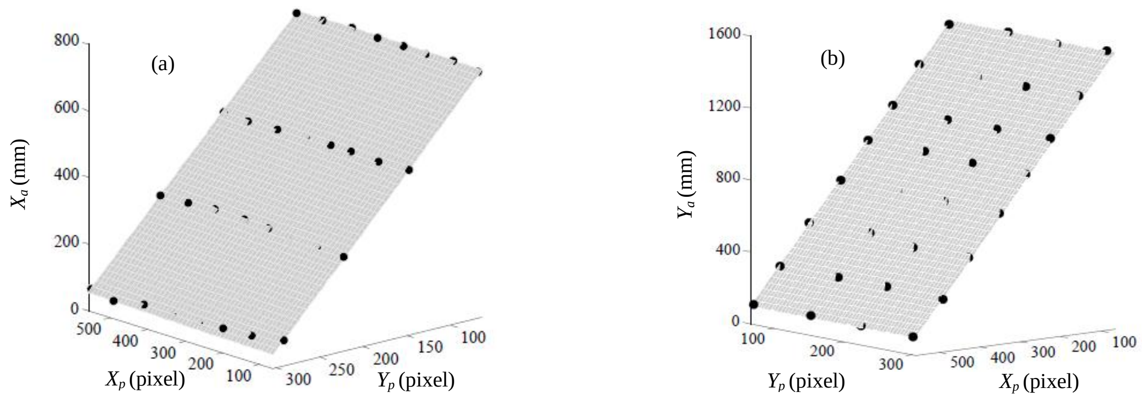

Figure 9. Calibration graphs (a) Actual X-coordinate X_a (mm) (b) Actual Y-coordinates Y_a (mm)

$$X_a = f(X_p, Y_p) = \begin{pmatrix} p_1 + (p_2 \times x_p) + (p_3 \times y_p) + \left(p_4 \times (x_p)^2\right) + (p_5 \times x_p \times y_p) \\ + \left(p_6 \times (y_p)^2\right) + \left(p_7 \times (x_p)^2 \times (y_p)\right) \\ + \left(p_8 \times (x_p) \times (y_p)^2\right) + \left(p_9 \times (y_p)^3\right) \end{pmatrix} \quad (1)$$

$$Y_a = f(X_p, Y_p) = \begin{pmatrix} p_{10} + \left(p_{11} \times (x_p)\right) + \left(p_{12} \times (y_p)\right) + + \left(p_{14} \times (x_p) \times (y_p)\right) \\ \left(p_{13} \times (x_p)^2\right) + \left(p_{15} \times (y_p)^2\right) + \left(p_{16} \times (x_p)^2 \times (y_p)\right) \\ + \left(p_{17} \times (x_p) \times (y_p)^2\right) + \left(p_{18} \times (y_p)^3\right) \end{pmatrix} \quad (2)$$

TABLE II. VALUE OF CONSTANTS

p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9
930.6	0.04674	-2.975	-7.4×10^{-05}	-2.8×10^{-05}	8.27×10^{-05}	3.49×10^{-07}	-3.1×10^{-07}	1.23×10^{-07}
p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}
1741	-2.964	-0.01281	4.48×10^{-05}	-3×10^{-05}	-9.1×10^{-05}	4.1×10^{-08}	1.71×10^{-07}	1.03×10^{-07}

B. Validation of Calibration

A validation phase was also conducted where the developed system is tested for measuring the position of target placed on new locations on the platform. In this phase the actual position X_a, Y_a of the target was obtained using the developed measurement system. This was then verified using the values obtained by coordinate measuring system-FARO laser tracker. For the validation experiments, the target was fixed at different new locations on the workspace as shown in Fig. 10. The measured coordinates (mm) of each target obtained through the developed system were compared with the corresponding actual coordinates obtained using the FARO laser tracker. The results are tabulated in Table III. It was observed that the minimum and maximum errors in measured *X*-coordinates are 0.1 % and 5.99 % respectively, and the average error was found to be 0.8 %, while the minimum and maximum errors in measured *Y*-coordinates were 0.0 % and 1.5 % respectively, with an average error of 0.27 %. These errors are within acceptable limits for analyzing the motion of the robot in the present scenario. It is also to be noted that the method can detect and predict locations of multiple target points with sufficient accuracy, thus making the system suitable for detecting multiple robots in a swarm of robots.

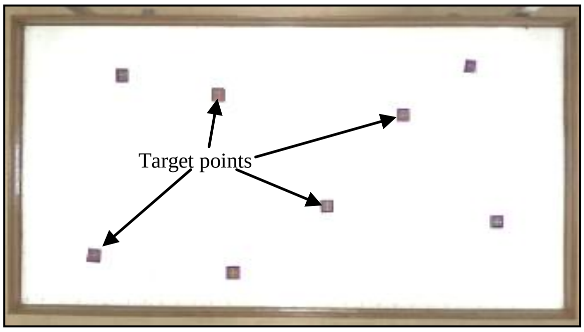

Figure 10. Location of the target point used in the validation phase

TABLE III. ERROR (%) BETWEEN MEASURED COORDINATES AND ACTUAL COORDINATES

Actual coordinates (mm)		Measured coordinates (mm)		Error (%)	
X	Y	X	Y	X	Y
142.8	1403.9	151.35	1401.32	-5.99	0.18
667.2	1325.9	668.40	1326.09	-0.17	-0.01
97.7	987.9	101.65	983.78	-4.05	0.41
615.4	1038.1	614.22	1036.57	0.19	0.14
291.1	708.9	293.44	708.87	-0.80	0.00
559.4	478	555.08	483.93	0.77	-1.24
250.9	200.3	242.82	200.62	3.21	-0.16
698.3	280.1	695.26	284.31	0.43	-1.50

C. Velocity Calculation

One of the objectives of the present work is to obtain the velocity of the robot. The position information obtained through image processing is utilized for velocity measurement. For obtaining the velocity (v) of the robot, the distance travelled (d) by the robot in between two adjacent frames of the video was divided by time interval (Δt) between frames as given in (3).

$$v = \frac{d}{\Delta t} \tag{3}$$

The distance (d) and time interval (Δt) are calculated as given in equations (4) and (5) respectively. Here, (X_i, Y_i) and (X_{i-1}, Y_{i-1}) are the position coordinates of the mobile robot in the current frame and previous frame respectively. The frame rate used in the experiments for recording the video was 15 fps. Thus the time interval (Δt) between frames is 0.067 s.

$$d = \sqrt{\left(X_{i-1} - X_i\right)^2 + \left(Y_{i-1} - Y_i\right)^2} \tag{4}$$

$$\Delta t = \frac{1}{frame\ rate} \tag{5}$$

During the trial experiments with the developed measurement system, frame to frame changes in detected centroids were observed even though the robot was not moving. Similarly, random oscillations were observed in the velocity although the robot was moving with a constant velocity. These random oscillations occur due to the unaccounted external disturbance such as uneven flatness of two-dimensional platform on which the robot moves, intensity variations due to variation in natural light, illumination error etc. Mean filter has been used to reduce these noises in measured data. The filter was applied on the position data as well as on the velocity data.

IV. RESULTS AND DISCUSSIONS

Experiments have been conducted to check the performance of the developed vision based measurement system for finding the position, velocity, and trajectory tracked by the mobile robot while tracking different trajectories. The trajectory tracked by the robot during the experiment was traced down (onto the 2D workspace) with the help of a stylus which was attached to the posterior of the robot. Simultaneously, the movement of the robot was captured and processed to obtain the position and velocity information using the developed measurement system. The trajectory traced by the stylus as well as measured by the measurement system are compared to obtain the effectiveness of the measurement system. The results obtained are as follows:

A. Experiment - Circular Trajectory

The measurement system was tested for analyzing the motion of the robot while tracking a smooth circular trajectory. For this purpose the robot was programmed to move in a circular trajectory of diameter 285 mm at a user defined velocity of 43.2 mm/s which corresponds to an angular velocity of 0.1 rad/s. Figure 11 (a) shows the actual circular trajectory traced by the stylus attached to the robot. Figure 11 (b) shows the trajectory obtained with the help of measurement system.

The diameter of the circular trajectory obtained through the measurement system was 283.8 mm which almost matches with the actual trajectory with an error of 1.2 mm. Fig. 11 (c) shows the comparison of actual velocity and measured velocity. It can be observed that the measured velocity fluctuates around the actual velocity (43 mm/s) within an error bar of ± 6 mm/s.

B. Experiment - Triangular Trajectory

The measurement system was tested for the measurement of a triangular trajectory to see the effectiveness in measuring non smooth trajectories having edges and corners. For this the mobile robot was programmed to track an equilateral triangle of side 170 mm with a user defined velocity of 23 mm/s. Measurements were taken similar to the circular trajectory tracking experiment. Figure 12 (a) shows the actual trajectory of side 170 mm drawn by stylus attached to the robot and Fig. 12 (b) shows the triangular trajectory of side 168 mm obtained through the measurement system. Figure 12 (c) shows the reference velocity (23 mm/s) and measured velocity (24 ±2 mm/s).The results show that the measurement system could be used effectively for measuring non-smooth trajectories also. Similarly, experiments were carried out with other types of trajectories such as rectangular trajectory, square trajectory etc. It was observed that the measurement obtained through the measurement system is within an error bar of 5 %.

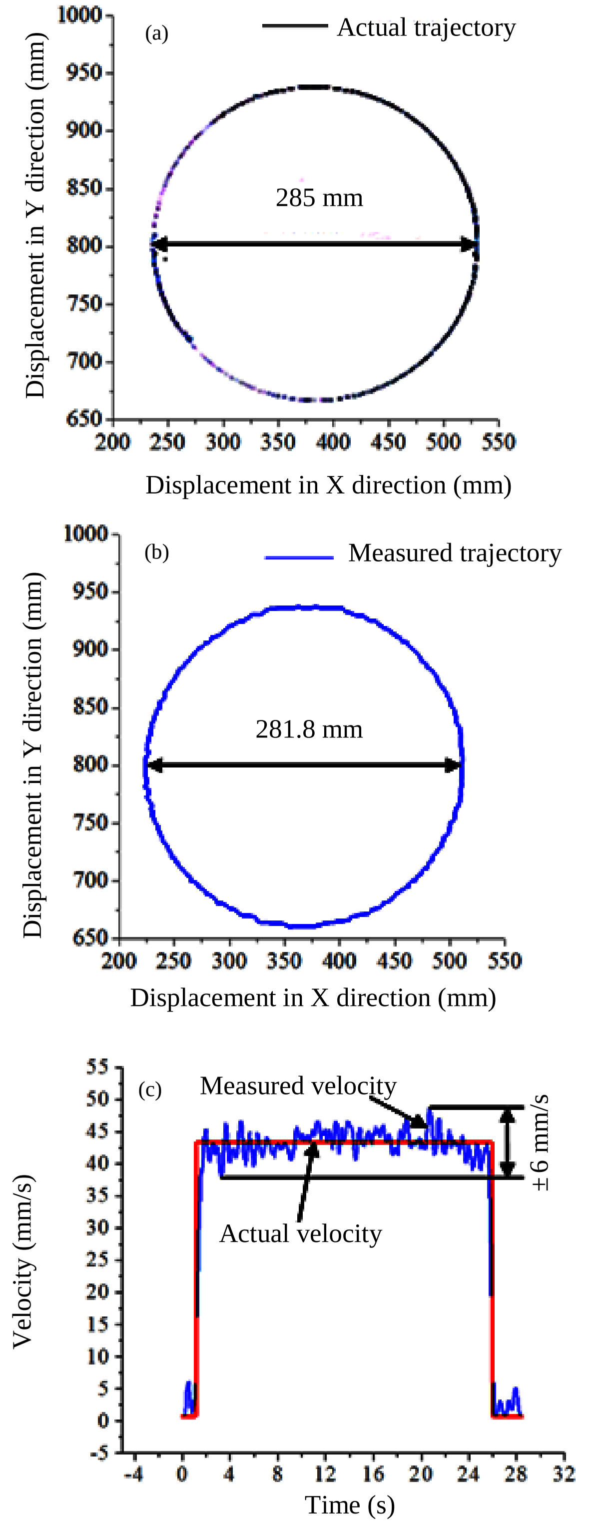

Figure 11. Result of circular trajectory experiment (a) Actual trajectory (b) Measured trajectory (c) Actual velocity and measured velocity for the circular trajectory experiment

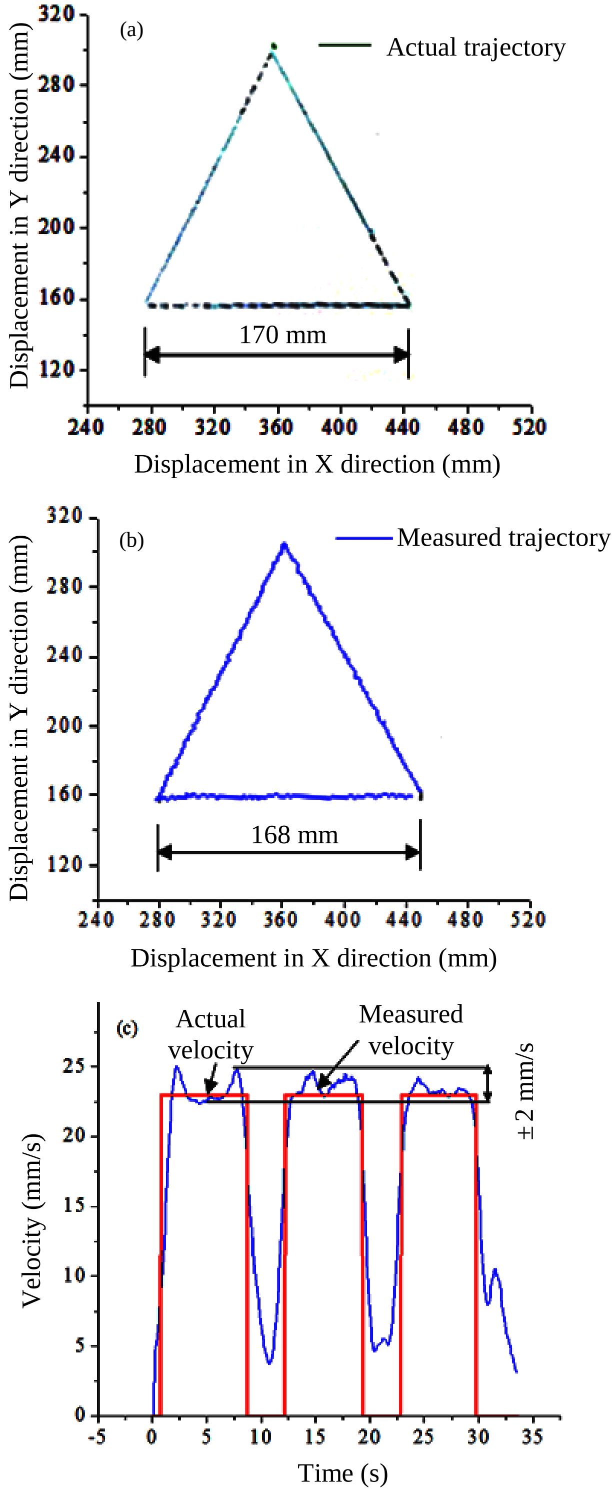

Figure 12. Result of triangular trajectory experiment (a) Actual trajectory (b) Measured trajectory (c) Actual velocity and measured velocity

V. CONCLUSIONS

A low cost vision based measurement system has been developed for motion analysis of indoor mobile robot. The system was tested for measuring the position and velocity of a mobile robot which is tracking different types of trajectories such as circular trajectory, triangular trajectory, rectangular trajectory etc. Following are the conclusions derived from the present study:

- The method which involved feature extraction and blob analysis was able to detect and track the mobile robot throughout the workspace of 1600 mm x 800 mm.
- The developed approach is computationally simple and takes less time in producing the measurements making it suitable for real time measurement.
- Maximum position measurement error was less than 5 mm and velocity measurement error was less than 6 mm/s. The trajectory of the mobile robot obtained through the measurement system was in agreement with the actual trajectory tracked by the robot.
- The method developed in this work may be implemented to analyze the motion of mobile robot along different geometrical trajectories.
- The overall cost of the processing system along with open source software and webcam is below 50000 Indian Rupees. However, the cost of the FARO laser calibrator is not considered in calculating the total cost since it is required only for calibration.
- With a few enhancements, this method could be extended for detection and tracking of multiple mobile objects in an indoor environment with much more accuracy.

The future work could include the development strategies for reducing the position measurement error and velocity measurement error. Real time motion analysis of multiple robots calls for a new paradigm.

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