Inspection of the Interior Surface of a Cylindrical Pipe by Omnidirectional Image Acquisition System

Md Rokibul Islam, A. S. M. Shihavuddin, M. A. Naser, S. M. Ferdous and Md. Ashraful Hoque

***Abstract*— Omnidirectional image acquisition sensor has become an integral part of robotic application such as navigation, surveillance, telepresence etc. In this paper, a catadioptric sensor is developed for inspection of the interior wall of a cylindrical pipe. The developed system provides 360° field of view and can be used as an onboard sensor of a robotic system where human intervention is not convenient or possible. The system simulates the camera image where defects of the specified size are imaged and located to the accurate precision. A suitable hardware setup is implemented to test the inspection ability of the catadioptric sensor based on the simulation of the total system. A hyperbolic mirror with a perspective camera lens is used to build the catadioptric sensor satisfying single view point constraint. Finally a comparative analysis is made between simulation and hardware based system.**

***Index Terms*— Catadioptric Sensor, Epipolar Geometry, Omnidirectional image acquisition, Single View Point, Image Unwarping**

I. Introduction

The capacity to capture large fields of view is often investigated in the vision systems of the animals. This feature motivated researchers to study and to replicate the systems from nature. For example, majority of the arthropods benefit from the wide field of view (FOV) provided from their compound eyes. The crustacean’s eyes are combinations of mirror and refracting surfaces that focus the light at different points of the retina. The study and research of omnidirectional camera or omnidirectional sensors is being explored from such examples. This type of camera has a full (360 degrees) azimuthal FOV. Omnidirectional cameras can be classified according to the type of lenses and mirrors mounted on it. Rotating camera system, camera with special lenses, using multiple camera system, combinations of cameras and mirror are several methods to obtain the azimuthal FOV. Different methods have their unique characteristics and features in various fields of application. Nowadays the combination of perspective lens and mirrors becomes the most popular area of interest.

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II. Related Work

Different types of methods were proposed and modified by many researchers to realize the idea of omnidirectional image acquisition system. Several researchers, for example in 1992 Ishiguro *et al.* [1] used panoramic images obtained from a rotating camera to recover range data. Similar rotating systems have been proposed by Murray [2] in 1995, Benosman *et al.*, [3] in 1996 and by Kang and Szeliski [4] in 1997. One effective way to enhance the FOV is to use the combination of lens and mirrors. Such combination is referred to as catadioptrics [5].

Many researchers worked on catadioptrics with different mirror size and shape and hence several implementations are found. One of the first uses of mirrors for stereo was by Nayar [6], where Nayar suggested a wide field of view stereo system consisting of a conventional camera pointed at two specular spheres. A similar system using two convex mirrors, one placed on top of the other was proposed by Southwell *et al.* in 1996 [7]. However, in this system the projection of the scene produced by the curved mirrors is not from a single viewpoint. As a result the pinhole camera model cannot be used and calibration became more difficult task. Investigation was being continued with single view point catadioptrics at that time, since it was an important property. Baker and Nayar [8] investigated the detailed geometry for single view point

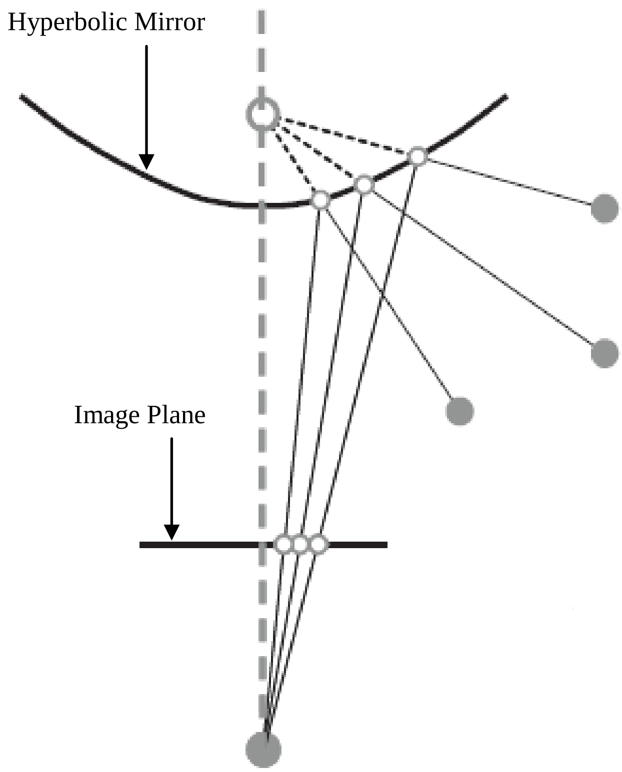

Fig. 1. Omnidirectional Camera with hyperbolic mirror satisfying single view point property.

catadioptrics for different size and shape of the mirrors in 1999. They showed that perspective images captured by the catadioptric cameras are geometrically convenient and accurate for modeling and analysis. Later on Hartley and Zisserman [9] in 2004 showed that the light rays coming into the camera can easily be calculated and combined in a multiview geometric framework if single view point camera is used.

Yamazawa *et al*. [10] first realized the prototype of Hyperomni, an omnidirectional vision sensor with a hyperbolical mirror. This provided a new scope of omnidirectional vision but at the same time images had a poor resolution. The orthographic camera with parabolic mirror may be the most suitable combination with single view point catadioptrics. S.K. Nayar [8] represented a prototype of such a camera showing the mapping between the image planes i.e. the mirror and the scene are independent from the translation of the mirror with respect to the camera. They highlighted the advantages of using folded optics namely size reduction and the removal of undesirable optical effects due to the curvatures of large mirrors.

Novel and innovative idea is being explored to implement the omnidirectional image acquisition system in different practical fields for single view point catadioptrics. This type of system has been utilized in many application areas such as surveillance in 2005 by Scotti et al. [11], telepresence in 2003 by Nagahara et al. [12] and 3D reconstruction in 2007 by Lhuillier [13].

This paper is the novel implementation of omnidirectional image acquisition system for inspecting defects and faults inside the surface wall of a cylindrical tube. The total work is simulated in Matlab and the hardware set up is developed keeping in mind the advantages and disadvantages of previously implemented catadioptrics.

III. CATADIOPTRIC SENSOR DESIGN

A. Resolution

There are several criteria to be fulfilled while designing the catadioptric sensor. Resolution is a very important factor in a large FOV and should be carefully considered to have enough resolution of the sensors. Resolution is not constant for the Single view point omnidirectional cameras. It is a distribution depending on the mirror size, shape and camera parameters. To do the comparing, the average value of the distribution would be used. Nayar [8] calculated the resolution of the catadioptric sensor by taking an infinitesimal area *dA* on the image plane and the corresponding solid angle *dv* encircled by it to form the following equation,

$$\frac{dA}{dv} = \frac{u^2(r^2+z^2)}{(c-z)^2.\cos\psi} = \left[\frac{(r^2+z^2)\cos^2\psi}{(c-z)^2}\right]\frac{dA}{d\omega}$$

Here, *u* is the distance from the focus point of the mirror to the center point of the image plane, and *u=2e* where *e* is the ellipticity of the mirror and *r* is the radial distance of the point on the surface of the mirror *x* and *y* coordinates. So the paraboloidal catadioptric with uniform resolution conventional camera has a highest resolution in its periphery. In this work the light rays coming from center of the mirrors are carefully omitted to get a better resolution.

B. Focal Length of the Camera

Another important system variable is the focal length of the system. The finite size of the lens aperture and the curvature of the mirror should be combined such a way that there is no blur present in the acquired image. The focal length of the camera is also adjusted depending upon the length and diameter of pipe. The flexibility of design will be enhanced if more focal length range is available in the camera. Here a canon 450D camera is used with 18-55 mm lens mounted on it. The maximum focal length 55mm is used during the time of image acquisition.

C. Shape and Size of the Mirror

The optimum size and shape of the mirror is determined from standard hyperbolic equation centered at the origin,

$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$ and specific size for this cylindrical pipe is controlled by the two parameter 'a' and 'b'. The ratio of $\frac{a}{b}$ is calculated to get the shape of the mirror.

IV. Cylindrical Pipe Design

To design the cylinder to the scale, the cylinder radius, number of threads, thread depth and width is needed to be known. A helix structure in cascading form is selected for designing a cylindrical pipe. For the design purpose here, every individual 3D point is created in space without using mesh surface. This gives the option to individually project every 3D point and find the line of sight point eligible to be plotted on the image plane.

In the practical hardware set up, a cylindrical pipe has been used with uniform thread depth and width throughout the body. Faults are distributed randomly along the interior wall of the cylinder.

TABLE I
SIMULATED CYLINDER SPECIFICATION

Cylinder parameters	Simulation values
Length of the cylinder	0.06 m
Radius of the cylinder	0.04 m
Width of the thread	0.002 m
Depth of the thread	0.002 m
Width of the groove	0.008 m
Number of points in 3d per meter along a line	0.001
Number of 3d poins in a single cycle of a helix	200
Color of the thread	[0 0 255]
Color of the groove	[255 0 0]
Width of the fault	0.001 m
Height of the fault	0.001 m
No of faults	25

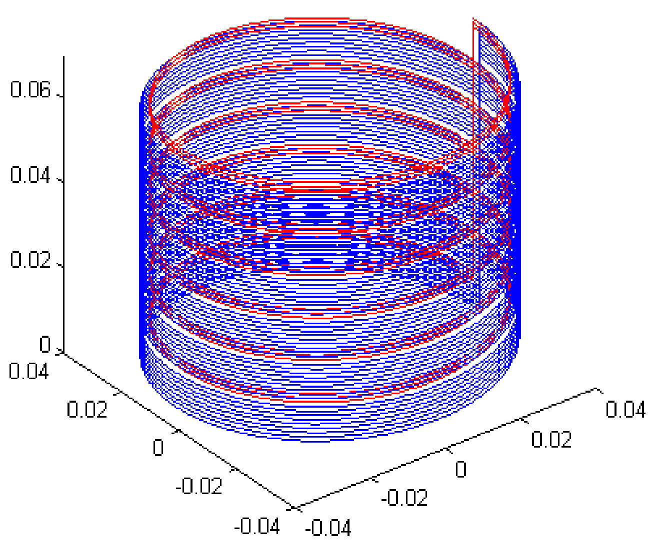

Fig.2. Simulated cylinder in helix structure with length 0.06 m and radius 0.04 m .

To complete the scanning the whole cylinder with good and equal resolution for all the body, the camera needs to be moved and several pictures from several positions must be taken. How many positions to be taken and what should be the shift difference between each position is an important design consideration.

V. Image Unwarping Technique

An omnidirectional vision system maps the surroundings into polar coordinates on the acquired image. The necessary remapping of the pixels of the image is necessary to get perspective image which is more comprehensible. This is known as "image unwarping" [14] technique. There are several methods present for this work to be performed. Here direct transformation is done from polar coordinates to rectangular coordinate to get the perspective image. The following equation is used for this method,

$$u = \frac{v_{pn} \cdot r_{pixel}}{V_{pn}} \cos\left(\frac{2\pi \cdot u_{pn}}{H_{pn}}\right)$$

$$v = \frac{v_{pn} \cdot r_{pixel}}{V_{pn}} \sin\left(\frac{2\pi \cdot u_{pn}}{H_{pn}}\right)$$

Here, u and v are the coordinates of a pixel in the original omnidirectional image that correspond to the pixel with coordinates u_{pn} and v_{pn} in the perspective image. The radial coordinate in pixels of the mirror rim in the original image is r_{pixel} and the height and width of the panoramic image are defined as V_{pn} and H_{pn}.

VI. Simulation and Analysis

The first approach of this work is to create a simulation environment in Matlab platform where objects are simulated in contrast to the real objects. A Matlab toolbox designed by Mariottini and Prattichizzo [15] is used to simulate omnidirectional camera. This toolbox has the options to change the parameters of the camera to match with the camera that would be used. An artificial image is created after projecting all the 3D points in the image plane. The artificial image resembles the real object image captured by the camera. Several artificial images are simulated at different positions to get better resolution along the whole surface of pipe. Then the omnidirectional artificial image is unwarped to get the perspective image which is the more convenient form of understanding. For this work, the implemented system uses a very simple idea of taking the periphery of outer circle in the effective area as the base width of the image. The width of the effective portion is the width in the perspective image. Some faults are also added in the interior wall for inspection purpose.

The final strip image is created by stitching all the effective portion of the unwarped image. This is the 2D view of the total interior wall of the pipe. A color detection algorithm in Matlab is used to find the tiny faults in black color.

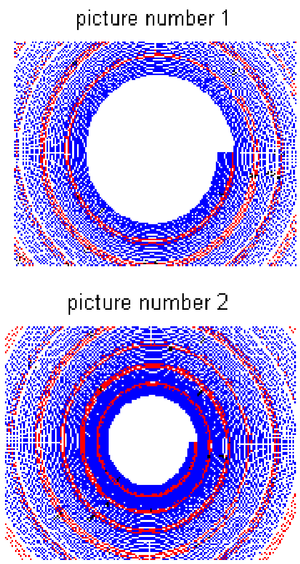

Fig. 3. Two picture taken at two different position of the omnidirectional sensor.

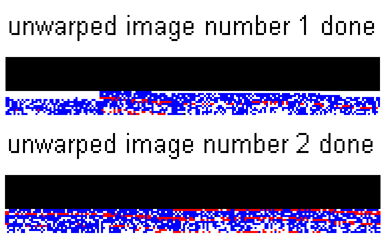

Fig. 4. Unwarped image at two different positions of the camera.

VII. HARDWARE DESIGN

The hardware set up is developed from locally available resources. A stainless steel cylindrical shaped pipe is chosen for internal inspection in which the interior wall is uniformly threaded. The hyperbolic mirror is attached with a galvanized iron pipe with a screw and the exterior part of the pipe is threaded so that it can move upwards and downwards inside the stainless steel pipe with the help of a socket. As a result the mirror can be shifted inside the pipe with a suitable step shift to get an optimum resolution. A very tiny plastic tape is randomly distributed as defects in the inside surface wall. A canon 450D camera with an 18-55mm lens mounted on it is kept fixed opposite to the mirror with help a camera stand. The omnidirectional image is then acquired by remote shooting of the camera using EOS utility software. A number of images are taken by moving the catadioptric sensor along the pipe.

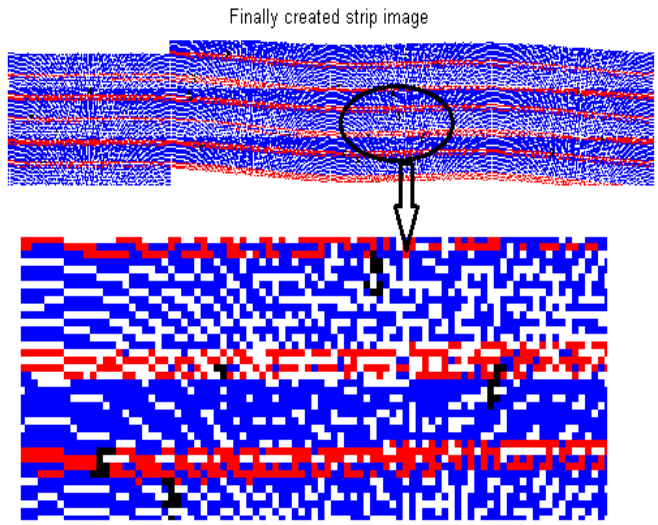

Fig. 5. A number of unwarped images are stitched together to get the final strip image and a small portion indicated by the circle is magnified to show the small defects of the pipe in black color.

The acquired omnidirectional image is then processed with Matlab in such a way that only the effective portions are cut out from the total image to remove the noisy part in the mirror-cylinder interior wall interface and get portions with higher resolution. An algorithm is developed to identify the small plastic tapes for defect inspection.

Fig. 6. Hyperperbolic mirror attached with a threaded pipe and socket.

VIII. Real Object Image Analysis

The simulation environment and the implemented hardware set up are not exactly similar. Fault sizes are uniform in simulation environment but in actual case the fault sizes vary in dimension. The thread and the groove are simulated with blue and red color for convenient analysis but the color of the thread and groove in the hardware is same.

Fig. 7. A part of the experimental setup with hyperbolic mirror placed inside the cylindrical pipe.

Due to uniform simulation of all the parameters, there is no sporadic and irregular behavior present in the simulation based approach. Real object image is not as uniform as the artificially created image. As a result, few discrepancies are found in defect inspection inside the pipe.

Fig. 8. A view of the experimental set up.

TABLE II
POSITIONS OF CATADIOPTRIC SENSOR

Images Taken	Distance from Lens to Top Surface of the Pipe (cm)	Distance from Top Surface to Perspective Camera Lens (cm)
IMG_01	8.2	7.2
IMG_02	8.7	6.7
IMG_03	9.2	6.2
IMG_04	9.7	5.7
IMG_05	10.2	5.2
IMG_06	10.7	4.7
IMG_07	11.2	4.2
IMG_08	11.7	3.7
IMG_09	12.2	3.2
IMG_10	12.7	2.7

There might be several reasons behind these irregularities. The inside surface is not smooth and clean causing mismatch with the original color. The intensity of the light also plays important role here. There is a black interface between mirror and interior wall present in the real object image which creates false identification of defects. This is why some error occurs between simulation and practical results.

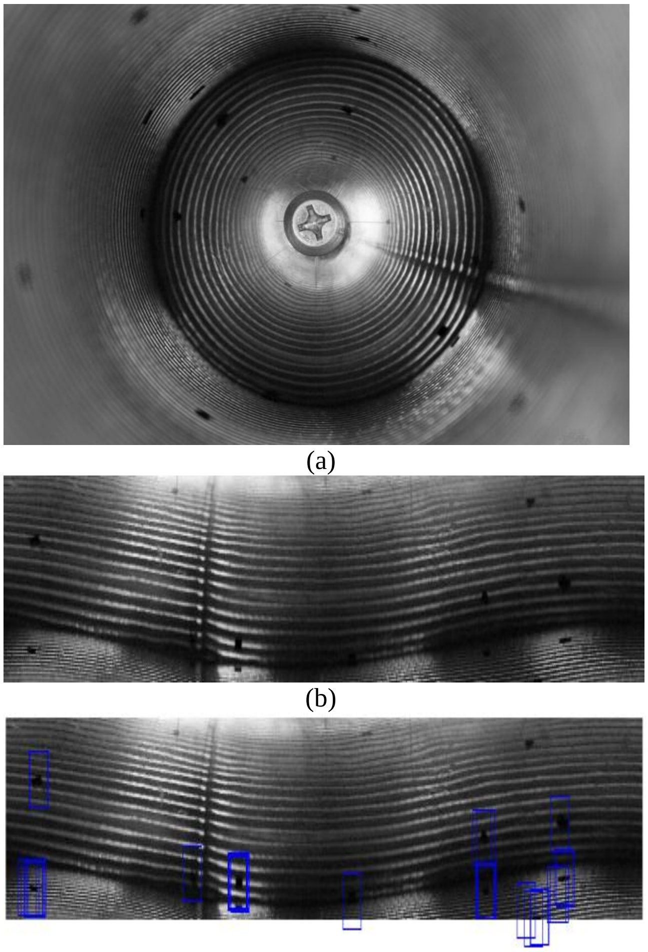

Fig. 9. (a) Omnidirectional image of the interior wall of the pipe reflected in the hyperbolic mirror inside the pipe. (b) The corresponding unwarped image to get the perspective image (c) Faults identified by the Matlab algorithm are indicated by blue rectangular box.

TABLE III
DEFECT ANALYSIS

Images Taken	Total Defects Present in the Unwarped Image	Identified Defects	Unidentified Defects
IMG_01	12	10	2
IMG_02	13	10	3
IMG_03	9	8	1
IMG_04	9	9	0
IMG_05	15	14	1
IMG_06	12	10	2
IMG_07	11	8	3
IMG_08	13	11	2
IMG_09	9	8	1
IMG_10	11	10	1

IX. Conclusion

This paper has implemented a complete Matlab algorithm for both simulation based analysis and hardware based set up. This work is another addition of gradually increasing application of omnidirectional camera system. The catadioptric vision technique will enable to analyze images with higher efficiency in a least possible time from a fewer captured image frames. The proposed system can be used in robotic vision technique to acquire image from a remote location. The system works in defect inspection precisely under proper light intensity. There is a scope of improvement in future by remodeling the system under any type of lighting condition.

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