Stereo Vision System for Live Submarine Inspection of Oil Pipelines and Equipments in Deep Sea

Lenildo C. Silva, Antonio Petraglia and Mariane R. Petraglia

Abstract— **This work presents a three-dimensional measurement system for inspection activities of submarine petroleum installations by remotely operated vehicles. A real-time stereo vision system is used for the acquisition of stereo pairs of images that, after preprocessing, by applying methods of image processing such as filtering, histogram equalization and edge detection, are submitted to dimensioning of objects through stereophotogrammetric computations using nonlinear least squares algorithms to obtain three-dimensional coordinates.**

Keywords— **stereo vision, image processing, photogrammetry.**

I. Introduction

THE activity of equipment inspection has the objective to follow the physical conditions of the equipments during their useful life, with the purpose of investigating the causes of possible accidents and solutions to prevent them. Some inspection methods are necessary in activities in which there are high risks to the security of the equipments and human beings, as is the case of submarine inspection, where the monitoring of pipelines and structures working under hostile conditions is needed, sometimes in high depths. For the inspection of these installations, several non destructive testing techniques have been developed, among which [1]:

- Ultrasound: the high propagation speed of the sound in steel, around 5.9 km/s, allows the use of this technique in cases where high speed of inspection is necessary;
- Measurement of electrochemical potential: the anticorrosive protection of ducts is carried out mainly by painting coverings and by systems of cathodic protection, such that the value of the electrochemical potential is the main parameter to be measured and controlled;
- Parasitic currents: is based on the introduction of electric current in the material to be inspected and on the observation of the interaction between currents and materials;
- Magnetic particle: it is based on the detection of discontinuities in magnetic materials, with the application of a magnetic field on a structure covered by magnetic particles;
- Visual inspections: it consists of the use of photographic devices to monitor ducts and equipments, and improve the efficiency of the operations of submarine intervention.

The method of visual inspections is the one adopted in this paper. Its methodology consists of suppressing objects that are not of interest from images of the structure to be evaluated, and to carry out a preprocessing of the image to obtain to greater reliability of the parameters to be extracted; after that, through techniques of analytical photogrammetry, the dimensioning of the objects of interest is performed. Based on this methodology, a modular integrated (software and hardware) three-dimensional vision system, which performs the acquisition and image processing, was developed to be applied to submarine inspection of pipelines and equipments.

The stereo vision system presented in this paper can be divided into three stages, as illustrated in Fig. 1. The **stereo vision system** consists of a pair of video cameras connected to digitizer cards, that acquire submarine images in real time to be shown in three dimensions. Images of interest are digitized and recorded in files on a personal computer in stereo pairs (two images, one each for a camera, of the same scene, taken at the same instant). The digitized images, before being effectively used, are submitted to the **preprocessing** stage, to adequate them to the process of dimensioning, which includes techniques of image processing such as histogram equalization and edge detection, with the objective of improving the accuracy of the parameters to be extracted from the images. Finally, the processed images are submitted to the **dimensioning** procedure, with the use of an algorithm that applies photogrammetric methods for the computation of three-dimensional coordinates, from the corresponding points in the bidimensional coordinate systems of each image of the stereo pair. The dimensions of three-dimensional objects can then be obtained from the computed three-dimensional coordinates.

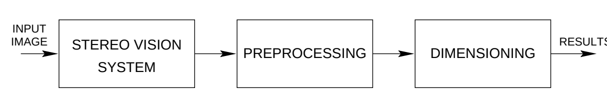

Fig. 1. Block diagram of the real-time stereo system.

The authors are with Programa de Engenharia Elétrica, COPPE/UFRJ, Caixa Postal 68504, Rio de Janeiro-RJ, Brazil. E-mails: lenildo@pads.ufrj.br, apetr@pads.ufrj.br, mariane@pads.ufrj.br.

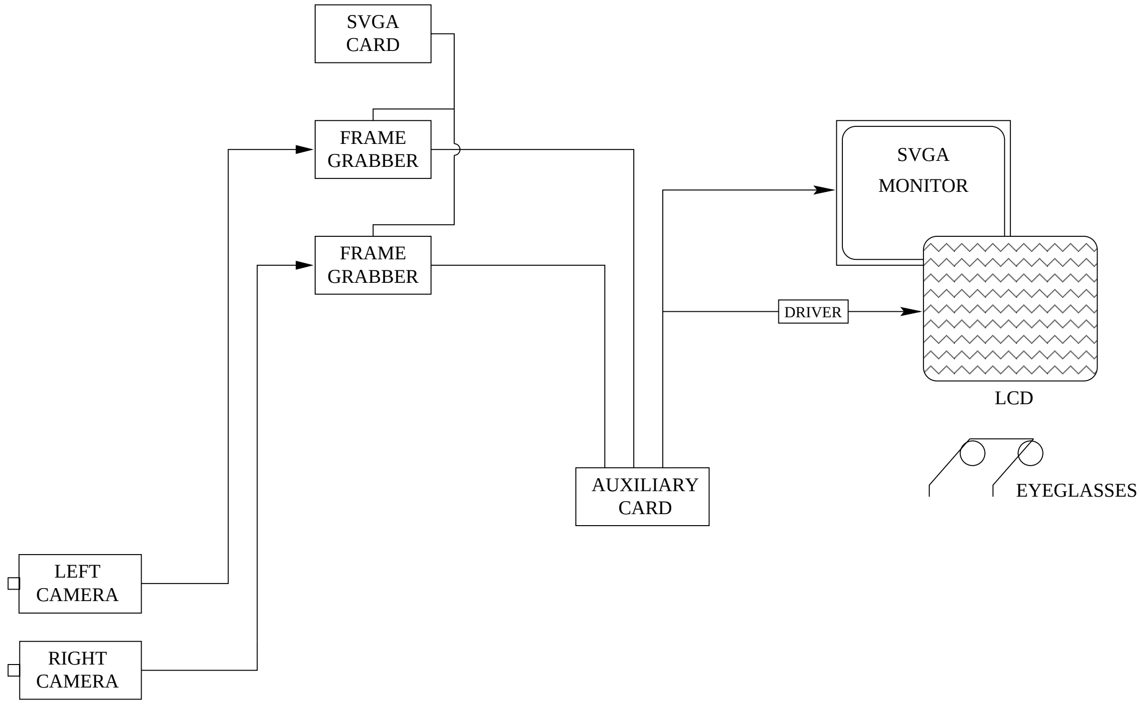

Fig. 2. Architecture of the stereo vision system.

II. Stereo Vision System

The acquisition of the images for the dimensioning process is made by a three-dimensional vision system [2] suited to submarine activities, such that it makes it possible the visualization in real time of the scenes to be investigated. The system, based on a personal computer, uses electronic video cameras and digitizer cards to allow the visualization and storage of images in computer files. This section describes the vision system, and its main components. Its architecture is presented in Fig. 2.

A. Cameras

The acquisition of the images is made by a pair of digital electronic video cameras. There are several types of digital cameras, and the most commonly employed ones (adopted in this system) are those that make use of CCD (Charge-Coupled Device) technology. These cameras allow a high quality visual inspection in real time due to the good resolution characteristics of the CCD arrays. The cameras have been assembled on a fixed base, lined up horizontally and spaced to correspond approximately to the distance between the eyes of an adult human being (typically, about 5.5 centimeters), to give the user the sensation of real stereo vision. Each camera generates a color video signal, in NTSC standard, and corresponds to a channel (left or right) in the architecture.

B. Digitizer Cards

The digitizer cards have the purpose of digitizing the video signals coming from the CCD cameras, transforming them into signals that can be shown in a SVGA monitor. The cards are frame grabbers, each of them receiving signal from a corresponding camera. Both cards are connected to an auxiliary card, that carries through the switching between the right and left images. Since the switching is performed externally to the digitizer cards, modifications can be incorporated by software to the original configuration, which would not be possible if the switching had been carried through internally to the digitizer cards.

C. Imaging Device

The stereoscopic imaging device, constituted of a LCD screen and passive eyeglasses, allows the visualization of the three-dimensional images from the composition of two bidimensional images, giving in this way the notion of depth.

D. System Operation

The basic function of the vision system is to perform the visualization of the images in real time. As the digitizer cards are on to the SVGA video card of the computer, overlay operation is possible, that is, the signal proceeding from the cameras can be sent directly to the output of the SVGA video card, allowing the use of only one monitor for the operation of the computer and for the operation of the software of the vision system. In addition to the visualization and acquisition of images, the software implements other operations, such as zoom, horizontal alignment, and convergence.

III. Preprocessing

After being acquired by the three-dimensional vision system, the images are submitted to the preprocessing stage, with the purpose of enhancing and adequating them to the dimensioning process. The enhancement procedure includes techniques such as histogram equalization and filtering. The use of techniques of edge detection allows a better characterization of boundaries of an image, which is useful in the determination of the necessary two dimensional coordinates. In this section some of these techniques are briefly reviewed, with emphasis given to edge detection.

A. Point Operations

Point operations [3] are zero memory operations where a gray level $u \in [0; L]$ is mapped into another gray level $v \in [0; L]$, such that $v = f(u)$. Examples of point operations are the negative transform, where a negative image can be obtained by reverse scaling of the gray levels according to the transformation $v = L - u$, and the histogram equalization, that allows the histogram modeling of an image to obtain a uniform histogram for the output image.

B. Spatial Operations

Spatial operations [3] in an image are performed in local neighborhoods of pixels, through the convolution of the image with an infinite impulse response filter called spatial mask. Examples of spatial operations are the low-pass filtering (an operation of spatial averaging, used for noise smoothing and interpolation), the high-pass filtering (used in extracting edges), and the band-pass filtering (used in the enhancement of edges).

C. Edge Detection

A problem of fundamental importance in image processing is edge detection [3], [4]. Edges characterize object boundaries and therefore are useful in segmentation, recognition and identification of objects in digital images.

The general paradigm in the process of edge detection is a two-step method. The first one consists of enhancing the presence of edges in the original image $f(x,y)$, thus creating a new image $g(x,y)$, where the edges are more evident. Large values of $g(x,y)$ indicate the likelihood of the presence of an edge. The second step consists of applying thresholds to $g(x,y)$ to make an edge/no-edge decision, yielding a binary edge map. For a continuous image $f(x,y)$ its derivative assumes a local maximum in the direction of the edge. Therefore, one of the techniques for edge detection is to measure the gradient of f along r in a direction θ (see Fig. 3).

The edge points of an image can be defined as the locations of abrupt gray-level change. For example, edge points in a binary image can be defined as black pixel tones with at least one white nearest neighbor. The edge can also be considered as being constituted

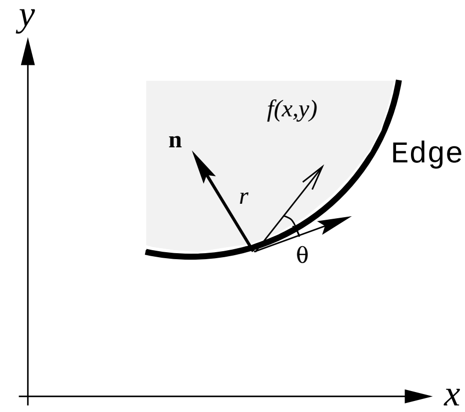

Fig. 3. Gradient of $f(x,y)$ along r direction.

of the points between two homogeneous regions of the image with different intensities of illumination. This definition implies that an edge corresponds to a local variation of illumination, but not necessarily the opposite.

For digital images, the edge detectors generally use discrete approximations of continuous derivatives with finite differences, that are considered linear and time-invariant operators, constituting the so-called masks of discrete convolution. The most common operators are the gradient operators, who are represented by a pair of masks that measure the gradient of the image $f(x,y)$ in two orthogonal directions, and the compass operators [3], who have the property of measure the gradient of an image in a selected direction.

IV. Dimensioning

After being acquired and later processed, the images are submitted to analysis, for the dimensioning of possible faults and/or defects in the structure being evaluated. The process of dimensioning is made through an algorithm to calculate three-dimensional coordinates, based in stereophotogrammetric methods, as described next.

The analytical photogrammetry [5]-[7] includes a set of techniques by which, from measurements of one or more 2D perspective projections of a 3D object, one can make inferences about the 3D position, orientation and lengths of the observed 3D object in a world reference. Fig. 4 illustrates the camera and world reference frames, showing a point in the three-dimensional space and its projection in the bidimensional references of each camera. The problem of inference can be modeled as a nonlinear least-squares procedure. Starting from one given approximate solution, the algorithm linearizes iteratively nonlinear functions around the current approximate solution, and solves the linearized problem that gives the adjustments to the current estimate.

The exterior orientation of a camera is specified by all the parameters that determine the pose of the cam-

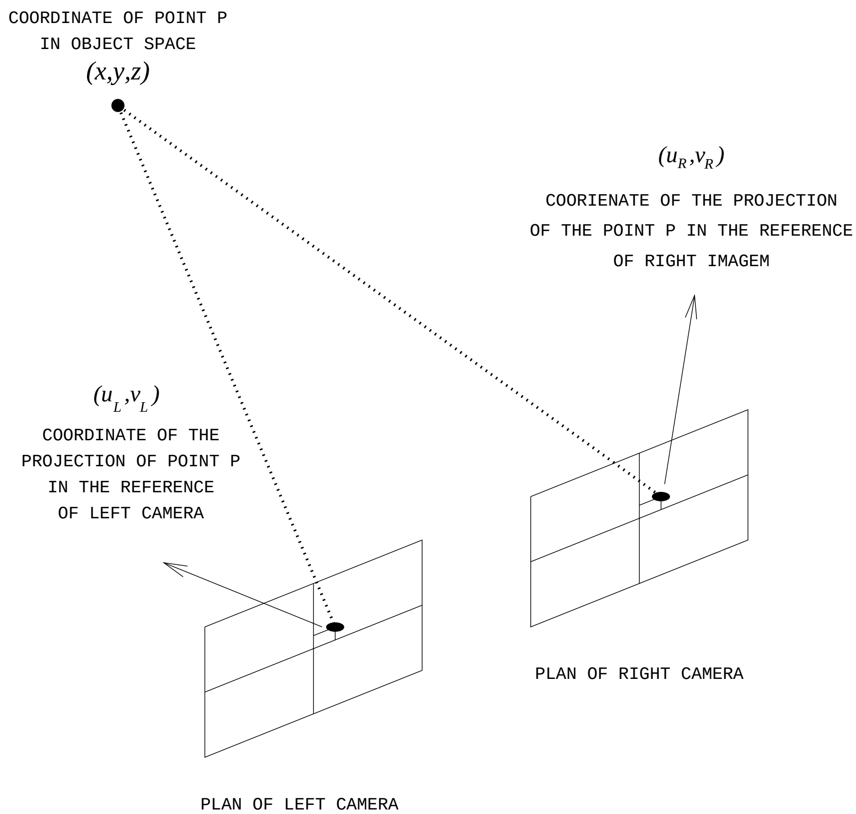

Fig. 4. Camera and world references.

era in the world reference. These parameters consist of the position of the perspective center and the direction of the optic axis. The specification of the exterior orientation is made from the 3D coordinates of some control points, whose corresponding positions in the image are known, and results in the evaluation of three rotation angles and three translation parameters. The interior orientation of a camera is specified by all the parameters that determine the geometry of a bundle of 3D rays from the measured image coordinates. The parameters of the interior orientation relate the geometry of the ideal perspective projection to the physics of a camera, and include the constant of the camera, the principal point (that is the point where the axis of the world reference frame intersects the image plans), and the lens distortion. The complete specification of the orientation of a camera is given by the interior orientation and the exterior orientation.

The relative orientation of a camera, that is the orientation of a camera relative to another one constitutes a stereo model and is specified by five parameters: three rotation angles and two translation parameters. When two cameras are in relative orientation, each pair of corresponding rays from the two cameras intersect in 3D space. The process of determining the relative orientation assumes that the interior orientation of each camera is known. The absolute orientation involves the orientation of a stereo model in a world reference, and requires the knowledge of seven parameters: a scale factor (that it is considered unitary in this case), the three translation parameters, and the three rotation parameters. The absolute orientation is obtained from the 3D coordinates of some central points whose position in the stereo image can be determined. The complete specification of the orientation of a pair of cameras is given by the specification of the parameters determined from the relative orientation and the absolute orientation.

A triangulation procedure is used for the inference of a point in the 3D space from the perspective projections of this point in each image of a stereo pair [5]. The triangulation procedure is a special case of the determination of a 3D point from the intersection of more than two rays. It makes use of parallax, that is the displacement in the perspective projection of a point caused by a translational variation in the position of observation.

V. Experimental Results

This section illustrates an application of the developed stereo vision system for the dimensioning of submarine objects. Several experiments with images of metallic pieces have been realized in a tank simulating the real conditions of use. The tests consist of the com-

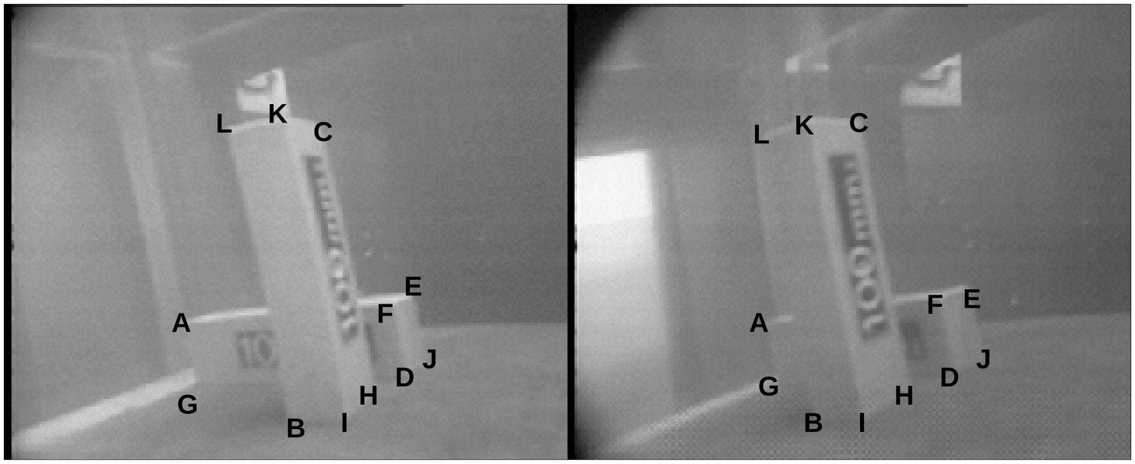

Fig. 5. Stereo pair.

putation of the three-dimensional coordinates, and the posterior calculation of the edge of the metallic pieces. Some results are presented below.

A. Acquired Images

The images used for the execution of the tests with the algorithms developed for the dimensioning of 3D objects have been acquired with the use of the three-dimensional vision system described previously. The tests have been made in a test tank, containing rectangular metallic pieces in a variety of positions, with the objective of simulating real submarine conditions with little luminosity. Some images have been obtained with the pair of CCD cameras. Results obtained with other stereo image pairs can be seen elsewhere [8]. The images of the stereo pair, presented in Fig. 5, show two identical metallic pieces, having dimensions $100 \times 30 \times 20$ (in millimeters). The images have originally a resolution of 640×512 pixels. They are here presented in reduced scale, and in gray-levels.

B. Preprocessing

The preprocessing, as mentioned earlier, consists of producing an enhanced version of the acquired images, through techniques of image processing, to adequate them to the 3D dimensioning stage. In the case of the images acquired for the tests, the application of edge detection techniques is necessary to get a clear visualization of edges of the metallic pieces used in the tests, and consequently to get exact acquisition of bidimensional coordinates from the images. Among the previous operators, the gradient operator presented the best results, being therefore the ones used in this experiment. The compass operators have also presented good results in determined directions, which it can be useful in certain cases, when it is desired to enhance the limits in a given direction only.

TABLE I
Experimental results.

Edge	Dimension		Error	
	Calculated	Real	Absolute	Relative
$\overline{AE}$	92,773	101,980	9,207	9,028 %
$\overline{AF}$	30,377	30,000	0,377	1,257 %
$\overline{AG}$	98,078	101,980	3,902	3,826 %
$\overline{BC}$	106,301	106,301	0,000	0,000 %
$\overline{BI}$	21,496	20,000	1,496	7,480 %
$\overline{BK}$	106,457	101,980	4,477	4,390 %
$\overline{BL}$	104,579	100,000	4,579	4,579 %
$\overline{CH}$	102,132	100,000	2,132	2,132 %
$\overline{CI}$	105,117	104,403	0,713	0,683 %
$\overline{DF}$	31,922	30,000	1,922	6,407 %
$\overline{DG}$	100,516	100,000	0,516	0,516 %
$\overline{EF}$	20,922	20,000	0,922	4,610 %
$\overline{EG}$	108,152	106,301	1,851	1,741 %
$\overline{EJ}$	27,999	30,000	2,001	6,671 %
$\overline{GJ}$	96,913	101,980	5,068	4,969 %
$\overline{HI}$	27,628	30,000	2,372	7,906 %
$\overline{HK}$	106,896	104,403	2,493	2,388 %
$\overline{HL}$	107,145	106,301	0,843	0,793 %

C. Practical Application

The results of several edge measurements of the metallic objects of the images of Fig. 5 are shown in Table I, where the real dimensions and the calculated ones are compared, as well as the errors obtained (absolute and relative) for each measure. The points used in each image for the calculations are vertices of the metallic pieces, and are labeled in Fig. 5 by capital letters. The measure of each edge has been estimated from the three-dimensional coordinates of the vertices that delimit it. For example, in the computation of the dimension of edge $\overline{AF}$, the coordinates of the vertices A and F have been initially estimated, and then the distance between these vertices has been obtained.

The errors observed in the tests, has in general been small, in the average between 3% and 6% with relation to the real dimension of each edge. These values have been considered satisfactory for the application in view, which is the inspection of submarine pipelines and equipments.

VI. Conclusion

This paper presented a system of three-dimensional measurement to be used in activities of submarine inspection of pipelines and equipments. The system was divided into three stages: three-dimensional vision, preprocessing and dimensioning. The vision system allowed the visualization of images in real time, with notion of depth, through an operation friendly interface. The use of edge detection algorithms allowed a better definition in obtaining the necessary points for the dimensioning process.

The method of three-dimensional dimensioning allowed the evaluation of three-dimensional coordinates of points in the 3D space, from bidimensional coordinates acquired from the bidimensional plan of each image of the stereo pair, through a program developed in C language, with the use of algorithms of analytical photogrammetry.

Although the system described here has been developed for applications in submarine activities, its features of low cost, reliability and remote operation in real time with telepresence sensation, extends its use in some situations where the automation of tasks is necessary, mainly in hostile environments for the technicians involved.

VII. Acknowledgments

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