A hand-held 3D laser scanning with global positioning system of subvoxel precision

Néstor Arias,*, Néstor Meneses, Jaime Meneses and Tijani Gharbi

1 GOTS-CENM, Escuela de Física, UIS, Bucaramanga, COLOMBIA
2 GOM, Departamento de Física y Geología, Universidad de Pamplona, COLOMBIA
3 Département D’Optique, FEMTO-ST, 16 Route de Gray, 25030 Besançon, FRANCE

*E-mail: nesariher@unipamplona.edu.co

Abstract. In this paper we propose a hand-held 3D laser scanner composed of an optical head device to extract 3D local surface information and a stereo vision system with subvoxel precision to measure the position and orientation of the 3D optical head. The optical head is manually scanned over the surface object by the operator. The orientation and position of the 3D optical head is determined by a phase-sensitive method using a 2D regular intensity pattern. This phase reference pattern is rigidly fixed to the optical head and allows their 3D location with subvoxel precision in the observation field of the stereo vision system. The 3D resolution achieved by the stereo vision system is about 33 microns at 1.8 m with an observation field of 60cm x 60cm.

1. Introduction
Numerous industrial situations arise in which it is required to digitize a 3D complicated surface with large dimensions, abrupt height variations and regions with difficult access to surface scanner. Most commercially available surface scanners employ mechanical scanning systems attaining high resolution images for reduced field of view. Therefore, in specific experimental situations is necessary to implement a surface scanner with extended depth of field, wide field of view, high resolution and high flexibility to access hidden areas [1-4].

This paper describes a 3D laser surface scanning with no mechanical scanning system. Instead, the optical device is hand-held and is manually scanned over the surface object by the operator. The device consists of an optical head that allows extracting 3D local information, and a global position sensor to determine the 3D global coordinates of the optical head. The proposed hand-held device designed to digitize a 3D surface imposes a condition: the resolution of the global position sensor must be less than or equal to the resolution of the optical head. Initially the calibration of the optical head is showed, which is composed by a classical laser triangulation device. Later, the calibration of the global position device is showed and tested, which is composed by a stereo vision system with subvoxel precision. Finally, some objects are reconstructed using the proposed hand-held device.

2. The system overview and architecture
The hand-held device consists of an optical device and a global position sensor. The optical head is a 3D reconstruction system based on standard technique of laser triangulation principle to extract 3D
local information. The coordinate values computed by 3D reconstruction system are represented in the laser coordinate system \(O_L(X_L, Y_L, Z_L)\). This coordinate system is rigidly associated with the hand-held optical head; any displacement value of the optical head cannot be measured by the laser triangulation device. The global position sensor allows extracting 3D coordinate values of the optical head, represented in the global coordinate system \(O_G(X_G, Y_G, Z_G)\) and are used to unify total surface information.

![Figure 1. Setup of hand-held 3D laser scanning.](image)

Figure 1 shows the hand-held device. This device is basically composed by a 3D binocular stereo vision system and a laser triangulation device. Each CCD camera of stereo vision system has an objective lens of 12 mm of focal distance placed at 1.8 m of object. In this experimental condition, a working area de 60 cm x 60 cm is obtained. The separation between cameras is approximately 90 cm. The optical head consists of a CCD camera (LC in Figure 1) with 8 mm of focal lens and a line laser generator (LD in Figure 1) to project a line pattern on the surface object. The two cameras of the stereo configuration (SC1 and SC2 in Figure 1) simultaneously observe a circle grid pattern (GP in Figure 1), coupled rigidly to the optical head, and is implemented using a 8x8 LED matrix of 5cm x 5cm with 5mm of dot diameter.

2.1. 3D reconstruction system

According to the triangulation principle, projecting a line pattern onto a 3D surface produces a line pattern that appears distorted from perspective camera, and can be used for a geometric reconstruction of the surface shape. In order to retrieve the surface shape information, an experimental relationship between deformed line pattern and height of surface object can be obtained. Traditionally, this experimental equation is obtained using a flat surface, called reference plane (RP in Figure 1), placed at \(Z=0\) and displaced at regular intervals [4]. The displacement direction defines the \(Z_L\) axis of coordinate system \(O_L\). For each \(Z\) position of reference plane, the position in the image of the laser line is shifted with respect to the position at \(Z_L=0\). Measuring the line displacement for each \(Z\) position, an experimental relationship between \(Z\) value in millimeters and line shift in pixels can be obtained and fitted to a polynomial function of degree 2, see Figure 2(a). The reconstruction procedure determines the displacement in pixels for each central point of deformed laser line image and calculates the corresponding \(Z_L\) value, using the experimental calibration curve.

2.2. Stereo vision system

In a stereo vision system, two image points in different cameras taken from the same point in space are projectively equivalent. According to epipolar geometry, Figure 2b, two rays from a point space \(R(X_W, Y_W, Z_W)\) intercept the image planes of each camera in \(r(u,v)\) and \(r'(u',v')\) following their specific centre of projection, \(O\) and \(O'\). \(O\), \(O'\) and \(R\) define the epipolar plane. Thus, central projection is a map from 3D space to 2D image space of each camera. Knowing the intrinsic and extrinsic camera parameters of each camera and the pixel coordinates of corresponding points \(r(u,v)\) and \(r'(u',v')\), the 3D coordinates
of R can be determined according to inverse central projection procedure [7,8]. A standard calibration procedure of computer stereo visions was utilized in order to calculate the intrinsic and extrinsic parameters of each camera in stereo configuration [11]. Usually the 3D coordinate of a point space are reported using the coordinate system \(O(X_C,Y_C,Z_C)\) of a camera, SC1 in Figure 1. This coordinate system defines the global coordinate system of our hand-held laser scanning \(O_G(X_G,Y_G,Z_G)\).

![Figure 2. (a) Calibration curve of laser triangulation system. (b) Epipolar geometry in stereo configuration.](image)

2.3. Global Position measure

The most difficult procedure in a stereo analysis is to solve the correspondence problem. Each corresponding point \(r\) and \(r'\) is traditionally calculated using a corresponding-detecting algorithm. The performance of detecting algorithm fixes the resolution of 3D coordinate values obtained from the stereo system. In order to determine the coordinates of a point in the image plane of each camera, the circle grid pattern was utilized as object of stereo vision system, Figure 3(a). The central point of each circle can be determined in pixels using a space-frequency analysis. Although each CCD records the grid pattern with a pixel of resolution, it is possible to calculate the center point of each circle with subpixel resolution using the spatial phase distribution of grid target [10,12].

![Figure 3. (a) Reference patterns using a 8x8 LED matrix. (b) Fourier transform of reference pattern](image)

Mathematically the intensity distribution of reference pattern recorded by each camera can be represented by two orthogonal periodic distributions. Using the first harmonic in the Fourier domain, Figure 3(b), the intensity distributions along the X and Y axes are given by:
where \( \phi_0 = 2\pi f_{wo,y} \) and \( \phi_H = 2\pi f_{wo,x} \). \( f_{wo} \) and \( f_{wo} \) are the fundamental frequencies in X and Y directions. The phase distributions are easily calculated using the Fourier transform algorithm\cite{9} from a regular pattern image. According to Figure 3a, the central position of a circle in the reference pattern image corresponds to a maximum value of intensity, and has a phase value of \( 2\pi \), where \( N \) is an integer, being \( N=0 \) the first column (or row) of circles and \( N=7 \) the last one column (or row). Thus, the center of circle labelled as P in Figure 3 corresponds to phase values of \( \Phi_V=6\pi \) and \( \Phi_H=6\pi \). Although the center of a circle does not generally coincide with a pixel, the calculated phase distribution using the Fourier transform algorithm can be interpolated in order to determine the subpixel position that corresponding to phase value. Phase interpolation can be calculated using a nonlinear mathematical function depending on the image distortion caused by the geometrical aberrations of the optical image-forming system. The mathematical model used was a linear fit, due to the low influences of geometrical distortions. Ref. 10 shows a detailed analysis of phase-sensitive procedure only for subpixel measurement of 2D positions.

The phase reference pattern is used to determine the corresponding points with subpixel resolution. These values in pixels are required by the previously calibrated stereo vision system in order to calculate the 3D coordinate values in the global coordinate system \( O_G \). Selecting the central positions of P, P\_x and P\_y circles, Figure 3a, it is possible to define a coordinate system \( O_M(X_M,Y_M,Z_M) \) coupled rigidly to the planar grid pattern and optical head.

When the operator achieve a displacement of the optical head, the stereo vision can determine the 3D position of origin and axis direction of coordinate system \( O_M \) with respect to global coordinate system, using the central position of P, P\_x and P\_y circles. In this way, the three coordinate values of position and three rotational values of orientation of the optical head are determined in the global coordinate system.

**2.4. 3D reconstruction procedure**

![Figure 4. Coordinate systems used in the 3D Reconstruction.](image)

Figure 4 shows the three coordinate systems used in the reconstruction process using the hand-held 3D laser scanning. \( O_L(X_L,Y_L,Z_L) \) is the laser coordinate system of the 3D reconstruction system. This coordinate system is not visible to the cameras of the stereo vision system. \( O_M(X_M,Y_M,Z_M) \) is the
coordinate system defined on the planar grid pattern and its spatial position and orientation are calculated using its phase information. \( O_G(X_G, Y_G, Z_G) \) is the global coordinate system defined by the calibration procedure of stereo vision system and allows the unified reconstruction framework. The position vector of point \( P \) on the surface object is calculated by the 3D reconstruction system in the laser coordinate system, \( r(X_L, Y_L, Z_L) \). A rigid transformation between \( O_L \) and \( O_M \) must be introduced, according to:

\[
\vec{r}_M = R_{ML} \vec{r}_L + \vec{T}_{ML},
\]

where \( R_{ML} \) is the rotation matrix and \( \vec{T}_{ML} \) is the translation vector between coordinate systems. \( R_{ML} \) and \( \vec{T}_{ML} \) are invariable parameters, and their values are calculated using the reference plane at \( Z_L = 0 \) and the optical head with the planar grid pattern. They are simultaneously observed by the stereo vision system. In this way, the position and orientation of \( O_L \) and \( O_M \) coordinate systems can be determined and used to calculate \( R_{ML} \) and \( \vec{T}_{ML} \). Their values were:

\[
\vec{T}_{ML} = \begin{bmatrix} -42.350 \\ 96.096 \\ 491.935 \end{bmatrix} \text{ (mm) and } R_{ML} = \begin{bmatrix} 0.9963 & 0.0855 & -0.0062 \\ -0.0097 & 0.1839 & 0.9829 \\ 0.0852 & -0.9792 & 0.1840 \end{bmatrix}. \tag{3}
\]

Similarly, knowing the orientation and position of \( O_M \) coordinate system with respect to global coordinate system, for a relative position of the optical head, the rigid transformation between \( O_M \) and \( O_L \) can be calculate according to:

\[
\vec{r}_G = R_{MG} \vec{r}_M + \vec{T}_{MG}. \tag{4}
\]

3. Experimental evaluation of 3D reconstruction device

3.1. Three-Dimensional Analysis of Global Positioning System

In order to quantify the error in the global position measurement, the circle grid pattern was placed in the working area on two-axis translation stages of 10 microns resolution and one rotation stage of 0.0166° angular resolution. One translation axis was placed parallel with \( Z_G \) axis and the other one in perpendicular direction. The rotation axis was placed parallel with \( Z_G \) axis. The translation axes were sequentially displaced at intervals of 50 microns until around 2 mm and the rotational axis at angular interval of 10° from -50° to 50°. Using the vision stereo system and the space-phase procedure, the accumulative distance for each stage was calculated. Figure 5 shows the results; a comparison between experimental and theoretical values gives an error with an arithmetic mean of -0.0325 mm and a standard deviation of 0.0156 mm for displacement measurement in \( Z_G \) axis. For perpendicular direction an arithmetic mean of 0.0184 mm and standard deviation of 0.0152 mm were found. Thus, the global position device based on stereo vision system and space-phase procedure determine spatial position of the optical head placed at 1.8 m with a precision of approximately 33 microns. Similarly, for the rotation axis the angles were determined using the orientations of \( X_M \) and \( Y_M \) axes with respect to the angular position of zero degrees. Comparing with the theoretical values an arithmetic mean of -0.02678° with a standard deviation of 0.1541° were found.
3.2. Three-dimensional reconstruction of objects

The circle grid pattern must be observed simultaneously by both camera of the stereo vision system and the laser line must be placed on the surface object and must be focused in the CCD camera of the optical head; these are the conditions of 3D reconstruction. The hand-held laser scanning has a working area of 60 cm x 60 cm and 180 cm of observation distance. An electronic device was designed to synchronize the image acquisition using a pulse switch, pressed by the operator when the laser line is displaced over the surface object. A graphical Matlab interface was designed to acquire, store and process the images. When the pulse switch is pressed by the operator, a total image acquisition and storage time of 0.98 seconds was obtained.

![Graphs showing experimental values of consecutive displacements](image1)

**Figure 5.** Experimental values of consecutive displacements for (a) Parallel to ZG axis, (b) For perpendicular to ZG axis and (c) Angular values for rotation stage with rotation axis parallel to ZG axis.

![Images acquired by the cameras and the accumulative reconstruction](image2)

**Figure 6.** Images acquired by the cameras and the accumulative reconstruction.

Figure 6 shows the images acquired by each camera for a given position of the optical head and the accumulated reconstruction image. Initially the reconstruction algorithm processes the image of the optical head to extract the 3D coordinate values of surface points that have intercepted the laser line. The calculated 3D coordinates in the laser coordinate system are transformed to the coordinate system OM using Eq. (2) and Eq. (3). Using the images of circle grid pattern in each camera of the stereo vision system, the corresponding points of circle P, PX and PY are calculated, according to the space-phase procedure. With this information, the spatial coordinates are calculated using the stereo vision system and the parameters RMG and TMG of Eq. (4) that transforms local topographic information to global coordinate system OG. Figure 7 shows the reconstruction of a human face.
Conclusions
In this paper a hand-held 3D laser scanning has been presented. The optical head was implemented using the linear laser triangulation principle. 3D reconstruction data is transformed into a global coordinate system, defined by a stereo vision system. The accuracy of stereo vision system is improved over the classical system using a circle grid pattern, coupled rigidly to the optical head, and implemented using an 8x8 LED matrix. This reference pattern is used to calculate with subpixel resolution the corresponding points in the images of each camera, using a space-phase procedure. The error in the global position measurement was experimentally calculated: 33 micron at 1.8m of observation distance.

Acknowledgments
The author acknowledges to The Administrative Department of Science, Technology and Innovation of the Colombia (Colciencias), for Financial Aid to make the first author's doctoral studies at the same time allow the realization of this work.

References
[1] Patete P, Riboldi M., Spadea M, Catanuto G, Spano A, Nava M and Baroni G 2009 Ann. Biomed. Eng. 37(9) 1877-85
[2] Bahmutov G, Popescu V and Mudure M 2006 Comp. Graph. Forum 25(3) 655-62
[3] Zagorchev L and Goshtasby A 2006 Computer vision and image understanding 1001(2) 65-86
[4] Harrison J, Nixon A, Fright W and Snape L 2004 British Journal of Oral and Maxillofacial Surgery 42(1) 8-17
[5] Romero L, Meneses J, Rodriguez A and Gonzáles O 2006 Revista Colombiana de Física, 38(2), 589-592
[6] Heikkila J and Silven O 1997 Proc. IEEE Computer Vision and Pattern Recognition (Washington: IEEE Computer Society) 1106
[7] Hartley R and Zisserman A 2003 Multiple view geometry in computer vision (Cambridge: University, Cambridge University Press)
[8] Zitnick C and Kanade T 2000 IEEE Trans. on Pattern Analysis and Machine Intelligence 22(7) 675-84
[9] Takeda M 1982 J. Opt. Soc. Am. 72 156-60
[10] Sandoz P, Bonnans V and Gharbi T 2002 App. Opt. 41 5503-11
[11] Bouguet J “Camera calibration for Toolbox of Matlab”
    http://www.vision.caltech.edu/bouguetj/calib_doc/
[12] Arias N, Suarez M, Meneses J and Gharbi T 2009 Revista Bistua 2(7) 70-6