

Calibration Procedure for 3D Surface Measurements using Stereo Vision and Laser Stripe

João L. Vilaça
joaovilaca@dei.uminho.pt
 Industrial Electronic Department,
 Minho University, Guimarães, 4800-058
 Portugal

Jaime Fonseca
Jaime@dei.uminho.pt
 Industrial Electronic Department,
 Minho University, Guimarães, 4800-058
 Portugal

A. C. Pinho
acpinho@dem.uminho.pt
 Mechanical Department,
 Minho University, Guimarães, 4800-058
 Portugal

Abstract

This paper proposes a new stereo vision calibration procedure and laser strip detection for 3D surface measurements. In this calibration procedure the laser plane is the one that matters, only one set of laser-coplanar calibration points is needed for image cameras calibration; and a dead-zone scan area is considered, since the digitalization arm is assembled in a 3 degree-freedom machine PC-based Motion Control with multiple scan paths. It is also presented some algorithms for 3D surface treatment.

Introduction

In reverse engineering, rapid prototyping or quality control with complex 3D object surfaces, there is often the need to scan a complete 3D model using laser digitizers [1]. These systems use a laser light and a camera for 3D measurements, the common procedure is to establish a relationship between 2D images coordinates and a 3D world coordinates using a triangulation procedure [8].

Complex 3D objects can cause information gaps in the model obtained. To overcome this problem, another camera can be used. Traditional calibration procedures for those systems normally result in a full 3D camera calibration, involving individual implicit camera parameters, a rigid motion equation relating the explicit cameras parameters of each camera and the intersection with the laser line [2][3][4].

This paper proposes a set of methods, techniques and algorithms to build a 3D scanning machine. It's organized in the following sections: System Architecture, stereo vision calibration procedure, divided in three steps: A - horizontal image correction, B - vertical image correction and C- real world coordinates correspondence, all these steps are based on polynomial correction; laser stripe detection and treatment; Data structures; Mesh Generation; 3D surface aliasing; 3D contour aliasing; results and discussion.

System Architecture

The main goal of this project is to develop a flexible control system to 3D machines. Know with

this system it is possible: to read the neutral format files of the CAD; to scanning models and generate CAD neutral files; In the future, use the scanning process to inspect the quality of the final product (CAI-computer assistant inspection) and generating trajectories automatically from the information of the neutral CAD files or the scanned data (Fig. 1).

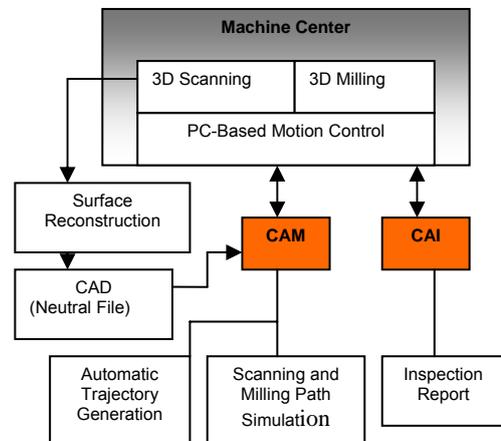


Fig. 1. System architecture

The work present in this paper is focalized in the 3D scanning system.

Mechanical Prototype

The built mechanical prototype is showed in Fig. 2 (a). It's a 3 degree freedom machine; with work-area dimensions of 1000x1000x500 mm. It's controlled by a PC-based Motion Control system.

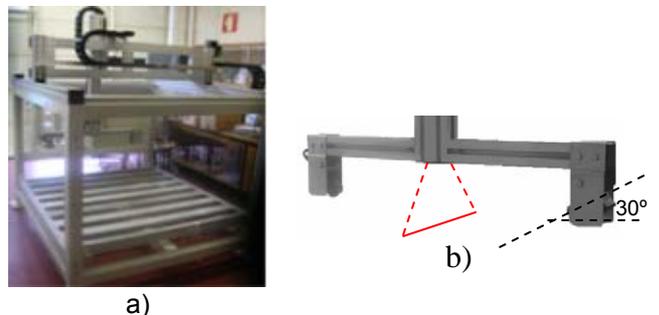


Fig. 2. Mechanical prototype: a) 3D machine b) scanning Arm.

Scanning Arm

The scanning arm is constituted by two CCD FIREWIRE cameras, with resolution 640x480,

using 8mm lenses and a laser with 1mW power. The laser is located at the same physical distance from both cameras, and the cameras are guided at 30° to the horizontal line (Fig.2 (b)).

Stereo Vision Calibration Procedure

Most of the techniques used for camera calibrations processes are normally based on the pinhole camera model. They define the calibration parameters R (rotation matrix) and T (translation vector), allowing, through a rigid equation, the transformation of the object world coordinate system to the camera 3D coordinate system. After this, they transform the 3D camera coordinate to an ideal (undistorted) image coordinate using perspective projection with pinhole camera geometry, calibrating the intrinsic camera parameters. They include modeling for lens distortion, which can be of two kinds: radial and tangential.

In the calibration procedure presented here only radial distortion will be considered, because it is that which needs to be considered in most of the industrial machine vision applications, and only for the laser plane.

In this system the laser is located at the same physical distance from both cameras, and the cameras are guided at 30° to the horizontal line (Fig. 2 (b)). Although mechanically the system is presented as calibrated (distances cameras-laser, camera angles and laser line parallel to both cameras), the comparison results from both images cameras showed that in the laser plane (plane studied for calibration) the system was far from calibrated, presenting the following problems:

- A point in the O_{laser} coordinated system corresponded to a point in the O_1 coordinated system and other point in the O_2 coordinated system, being the O_1 point different from the O_2 point.
- Perfectly visible radial distortion in some parts of the image, adding to the previous problem.
- Creation of image dead zones – problem caused by the relative angle of the cameras to the laser plane.

This angle means that in the upper part of the image, the horizontal distance was less than the horizontal distance in the lower part of the image, relatively to O_{laser} coordinated system. This problem only matters because the system to be calibrated will be assembled in a 3 degree-freedom machine that will carry out readings on parallel surface planes.

To avoid these problems a calibration procedure was developed. It calibrates each one of the images, verifying that a point in O_1 is equal to a point in O_2 , eliminating the radial distortion on the lenses and image dead zones.

For calibration a pattern was created with 10x5 mm rectangles. The pattern was printed on a

transparent sheet and placed between two glass plates with thickness of 1.2mm, for all the rectangles are co-planar and visible to both the cameras. The pattern was placed in the laser plane, becoming easy visualize the correspondence between both cameras image points, which is the basis of this calibration procedure.

The calibration procedure is divided in three steps: horizontal image correction (A), vertical image correction (B) and real world coordinates correspondence (C).

a) Horizontal image correction

The horizontal image correction for each camera is divided into five steps, in which the collected points in both cameras images will have to correspond to the same points in the laser plane:

1. Acquisition of a set of vertical image points which will be the horizontal zeros of the image after the horizontal correction.
2. Polynomial determination that translates the relation between the position (y) of vertical points and the position (x) of horizontal points (1).
3. Acquisition of a set of vertical image points, which will be the horizontal limits of the image after horizontal correction.
4. Polynomial Determination that translates the relation between the position (y) of vertical points and the position (x) of horizontal points (2).
5. Creation of a new horizontally corrected image, with horizontal dimension given by (3), where the position in x of each image pixel, relatively to the not horizontally corrected image is given by (4), maintaining equal the related pixel position in y.

$$x_{initial, cam}(y) = f(y) \quad (1)$$

$$x_{final, cam}(y) = f(y) \quad (2)$$

$$I_{Widthc} = W_{max\ rec\ tan\ gle} \times N_{rec\ tan\ gles} \quad (3)$$

$$x_{c, cam}(x, y) = \frac{x - x_{initial}(y)}{I_{Widthc} / (x_{final}(y) - x_{initial}(y))} \quad (4)$$

$$0 \leq x < I_{Widthc}; 0 \leq y < I_{Height}; 1 \leq cam \leq 2$$

b) Vertical image correction

Vertical image correction from the horizontally corrected image is divided into five steps, in which the points compiled in the horizontally corrected image will have to correspond to the same points in the laser plane:

1. Acquisition of a set of horizontal image points which will be the vertical zeros of the image after vertical correction.
2. Polynomial determination that translates the relation between the position (x) of the

horizontal points and the position (y) of the vertical points (5).

3. Acquisition of a set of horizontal image points, points these, which will be the vertical limits of the image after vertical correction.

4. Polynomial determination that translates the relation between the position (x) of horizontal points and the position (y) of vertical points (6).

5. Creation of a new vertically corrected image, with horizontal dimension given by (7), where the position in y of each image pixel relative to the horizontally corrected image is given by (8), maintaining equal the related pixel position in x.

$$y_{initial, cam}(x) = f(x) \quad (5)$$

$$y_{final, cam}(x) = f(x) \quad (6)$$

$$I_{Heightc} = H_{max\ rec\ tan\ gle} \times N_{rec\ tan\ gles} \quad (7)$$

$$y_{c, cam}(x, y) = \frac{y - y_{initial}(x)}{I_{Heightc} / (y_{final}(x) - y_{initial}(x))} \quad (8)$$

$$0 \leq x < I_{Widthc}; 0 \leq y < I_{Heightc}; 1 \leq cam \leq 2$$

Polynomial determination uses the method of the minimum squares to calculate the adjustment through points, using (9).

$$y = b + c_1x + c_2x^2 + c_3x^3 \quad (9)$$

b and c₁...c₃ are constants

c) Real world coordinates correspondence

The correspondence between the corrected image points and the points of O_{Laser} plane, in x coordinate, is given by (10), where k is a constant determined by the difference in distance between the two points in the corrected image and the distance between the two points in the pattern, points that will have to correspond to one of the rectangle vertices in the same horizontal edge of the pattern.

$$x_{Real} = k \times x, \quad 0 \leq x < x_{Widthc} \quad (10)$$

In y coordinate, the correspondence is given by (11), where f(y) is a polynomial. This polynomial is defined by the acquisition of a set of vertical points in the corrected image, points that will have to correspond to the different horizontal pattern edges visualized in the corrected image, making possible its correspondence with real values, given that the real distance between edges is known.

$$y_{Real}(y) = f(y), \quad 0 \leq y < Y_{Heightc} \quad (11)$$

Laser Stripe Detection and Treatment

Aspects such as optical properties of the surface, calibration, camera resolution, optics distortion and noise significantly determine the performance of the laser scanner [5], [6], [7].

The accuracy of a 3D reconstruction and measure using laser scanners is significantly determined by the detection of the laser stripe. The energy pattern of such stripe corresponds to a Gaussian profile.

In this section a laser strip detection method is proposed, its main characteristics are: strong immunity to light variations and to optical surface properties.

Image Horizontal 1st order Derivate

This method is executed in two steps.

The first step is taken before the stereo vision calibration procedure, and for each one of the camera images. It is characterized by the image horizontal first derivative calculation (Fig. 4). Thus, each image column is derived and detected the laser using three validation conditions:

1. Detection in the signal of positive for negative type transitions, and detection of the respective peaks;

2. To verify if the distance between peaks is greater than Δ_{Laser_Height} - maximum number of horizontal laser pixels;

3. Calculating the amplitude between peaks and verification if the amplitude is greater than $\Delta_{Laser_Intensity}$ - laser minimum intensity relative to the surface on which it occurs.

If the three conditions are validated, the vertical pixels of the analyzed column between transitions are placed in white and all the remainder in black. In the event of detecting more than one zone with validated parameters in the same column, the one with greater $\Delta_{Laser_Intensity}$ is chosen. The value of the parameter Δ_{Laser_Height} is attributed in function of the vertical resolution of the camera, the laser power and the distance camera/laser. The value of the parameter $\Delta_{Laser_Intensity}$ is defined through laser line intensity analysis over the material on which the measurements will be taken.

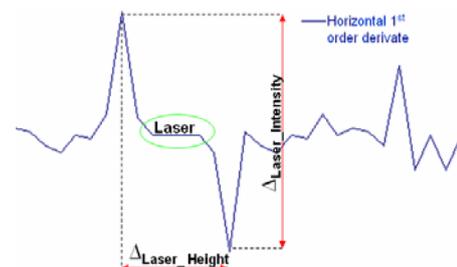


Fig.4. Representation of image horizontal first order derivative and laser line detection.

The second step of the laser line detection consists of detecting the laser line centre, which

corresponds to the average value between the maximum and the minimum values of the same. This step is carried out after step B and before step C of the calibration procedure. After laser line detection in both image cameras, step A and B of the calibration process are carried out. Then a logic operation is carried out between the two images resulting from calibration. In the resultant image of the logical operation, the laser line centre is detected. This image is then ready for the execution of C, the final step in calibration.

Laser Line Crack Correction

The so called crack problem occurs when some line points couldn't be saw by camera sensor, this problem is frequent on complex object surfaces. Some cracks may be geometric, where a hole exists in the surface, or topological, where T-junctions are created. Cracks may cause rendering artefacts, or introduce undesirable surface features that can adversely affect subsequent modelling operations such as decimation, connectivity analysis, or surface subdivision.

To solve de crack problem four crack correction methods where developed:

- After Point – the crack has filled with points; each point has the same z-value than the z-value of the first point after the crack (Fig.5 (a)).
- Before Point – the crack has filled with points; each point has the same z-value than the z-value of the first point before the crack (Fig.5 (b)).
- Linear - the crack has filled with points; it's established a straight line equation between the first point after the crack and the first point before the crack, z-value for each point is give by the straight line equation (Fig.5 (c)).
- Cubic – the crack has filled with points; it is establish a cubic equation (using the minimum squares to calculate the adjustment through points) between the tree firsts point after the crack and the tree firsts point before the crack, z-value for each point is give by the cubic equation (Fig.5 (d)).

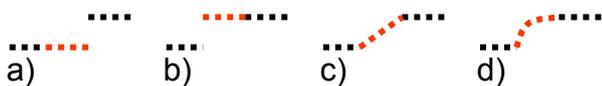


Fig. 5. Crack correction methods, a) after point, b) before point, c) linear and d) cubic.

Laser Line Aliasing

Laser strip aliasing is a technique that adjusts the z-value of the stripe data. The propose laser strip aliasing is to improve the strip appearance, preserving the line topology. This technique is applied in complex smoothing geometries, with continues first line derivate before Laser Line Crack Correction. This technique uses a weighing average to each line point across is neighbouring.

Data Structures

The CAD neutral file format chosen to store the information was the STL file format. The STL file is composed of unorganized triangles and their normal's associated unit.

In below, the data structures used in the implementation are presented. The information from the scanning process is store in this data structures, allowing:

- Easy surface reconstruction and contour aliasing – given by the hierarchical space organization set by the 3D scanning machine;
- Easy neighbouring find – for laser line aliasing and 3D surface aliasing;
- Easy STL format file import and export.

```
typedef struct Points3D{
    float x; //x axis value
    float y; //y axis value
    float z; //z axis value
    int n_triang;// number of triangles neighbouring triangles
    Triangles* pTriangles[8]; //pointer to neighbouring triangles
}POINT3D;
typedef struct Lines
{
    Points3D* points[CAM_WIDTH_RESOLUTION];
    //Hierarchical space organization
}LINE;
typedef struct class Triangles
{
    Points3D n; //unit normal vector
    Points3D* v1; //pointer to the first vertex of the triangle
    Points3D* v2; //pointer to the second vertex of the triangle
    Points3D* v3; //pointer to the third vertex of the triangle
    int select; //variable that allows select the triangle for some
    algorithms
}TRIANGLE;
```

Every triangle unit contains a normal vector unit, a pointer to each triangle vertex and a selection variable; the selection variable has different functions when associated to the developed algorithms. Each point unit is hierarchical space organized in lines and column. Every point also has associated itself a pointer for each triangle that belongs. This is important to find a point/vertex neighbouring.

Mesh Generation

A triangular mesh can be formed by repeated connection of a point of line to a point of another line by the use of the max-min angle criterion [9]. In Fig.6, for example, ∠bac is bigger than ∠adb, and triangulation (a) is preferred.

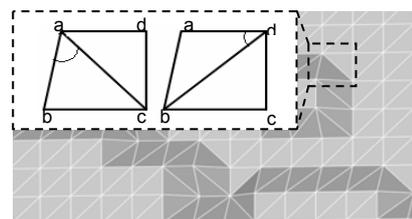


Fig. 6. Result of mesh generation using max-min criterion.

The algorithm developed for build the triangular mesh uses information provided by the hierarchal space organized matrix of points – set on lines data structure.

A polygon is set between two consecutives points, which belongs to the same line and two consecutives points which belongs to the next line. Then is applied the max-min criterion to build the triangles. If the number of points belonged to the created polygon are less than four, three situations can append:

- Point number in the created polygon equal to three - in this case, a triangle is automatically created with these points.
- Point number in the created polygon equal to two - in this case the neighbouring points are looked in the following lines.
- Point number in the created polygon equal to one - in this case the point is ignored.

3D Surface Aliasing

Mesh smoothing is a technique that adjusts the point-coordinates of a data set. The propose mesh smoothing is to improve the appearance of a mesh, and/or improve the shape of the data set cells. During smoothing, the topology of the data set is not modified only the geometry.

The must used smoothing technique is the basic Laplacian smoothing. It's based on the Laplacian flow (12).

$$I_z(x, y) = \nabla^2 I(x, y) \quad (12)$$

The discrete implementation is achieved by multiplying the Laplacian operator mask with a 3x3 mask (Figure7 (a)) to the data set.

Based on this technique were developed a set of smoothing surface filters. A Gaussian filter with 3x3 and 5x5 neighbouring (b and c) and a simple 3x3 average filter (d).

To preserve data set topology, a normal vector analyse is realised in each neighbouring of the analysed point. If the normal vector angle between the neighbouring is big enough, the smoothing technique isn't applied to the analysed point.

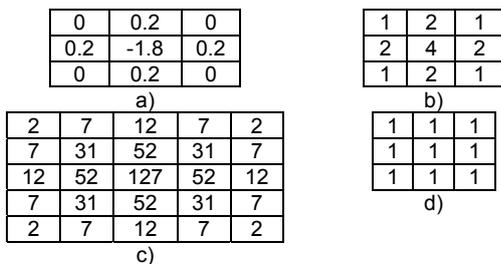


Fig. 7. Masks: a) Laplacian 3x3, b) Gaussian 3X3, c) Gaussian 5x5 and d) Average 3x3

The following images presents results from the 3D surface aliasing techniques.

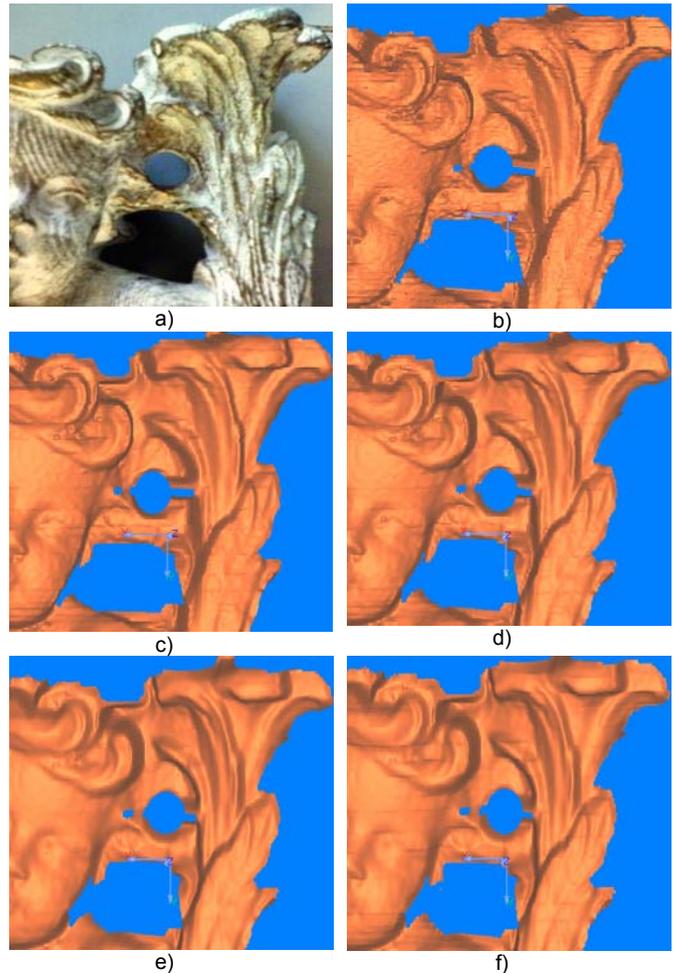
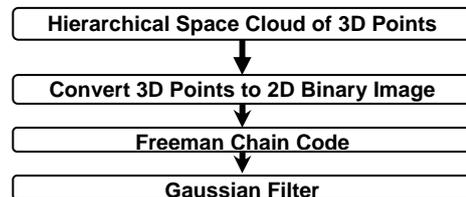


Fig. 8. Aliasing techniques: a) scanned object, b) scanned surface, c) Laplacian filter, d) Gaussian 3x3 filter, e) Gaussian 5x5 filter and f) average filter.

3D Contour Aliasing

The scanned object usually presents some imperfections in the contour as in show Fig. 9 (a). To overtake this problem it was developed the following algorithm.



The scanned points are hierarchical space organized in the line data structure, this structure is like a 2D matrix, each matrix cell have x, y space orientation and is filled with one if the point exist and zero if the point don't exist. This results in a binary image.

To find the binary image contour a Freeman Chain Code method [10] is applied, as result an organized set of contour points.

Then a Gaussian filter is applied to the organized set of contour points, aliasing the contour of the scanned object (b).

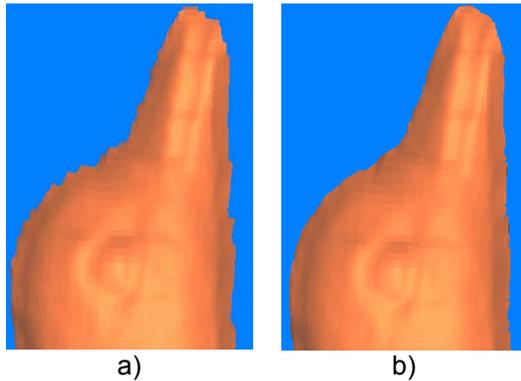


Fig. 9. 3D contour aliasing results: a) after and b) before

Results and Conclusions

This paper presents some developed methods, techniques and algorithms to build a 3D scanning system.

From the analysis of the results, it is possible to evidence that:

- The stereo vision calibration procedure has the following features: only uses laser-coplanar points, oriented towards laser line detection, permits the correspondence of two images on the laser plane without the use of a rigid motion equation.
- The maximum error is smaller than to 2 pixels, which set a system reading error smaller than at 0,5 mm (for 640x480 camera resolution and a 8 mm lens). The system error can be minimised using higher resolution cameras or lenses that reduce the view field.
- The system presents a 0.25 mm/pixel horizontal resolution and a 0.33 mm/pixel vertical resolution, in a view field of 170x160 mm.
- Ease of laser stripe detection in surfaces with high level of laser line absorption and complex geometry.

The results obtained validate the use of this calibration procedure in the system under development.

Future Work

The aim of this project is to develop a flexible quality control system for 3D object surfaces. The built system has a total scanning area of 1000 X 1000 mm and a field of vision of 170 x 160 mm. It will be necessary to integrate multiple range images and develop a complete set of algorithms that will allow analysis of 3D surfaces for generating quality control reports.

Acknowledgments

This work has being supported by “Fundação para a Ciência e a Tecnologia” (Portugal) through the PhD grant with the reference SFRH/BD/18155/2004.

References

- [1] Hong-Tzong Yau, Chun-Yan Chen, Robert G. Wilhelm, Registration and integration of multiple laser scanned data for reverse Engineering of complex 3D models, *int. j. prod. res.*, 2000, vol. 38, no. 2, 269± 285
- [2] J.J. Aguilar, F. Torres, M. A. Lope, Stereo Vision for 3D measurement: accuracy analysis, calibration and industrial applications, *Measurement Vol. 18*, No. 4 pp. 193-200,1996.
- [3] Barone, Sandro, Bruno, Stereo Vision and laser strippers for three-dimensional surface measurements, Andrea, XVI Congreso Internacional de Ingeniería Gráfica, 2004
- [4] F. Devernay and O. Faugeras. Computing differential properties of 3-D shapes from stereoscopic images without 3-D models. In *CVPR'94*, Seattle, USA, pages 208-213, 1994
- [5] Reimar K. Lenz, Roger Y. Tsay, Techniques for Calibration of Scale Factor and Image Center for High Accuracy 3-D Machine Vision Metrology, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 10, No. 5 September 1988.
- [6] R.Y. Tsai, A Versatile camera calibration technique for high accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses, *IBM Res. Rep. RC 51342*, May 8, 1985;
- [7] Heikkila. J., Silve' n O., “A four-step camera calibration procedure with implicit image correction,” *Proc. CVPR '97*, IEEE, 1997, pp. 1106-1112.
- [8] João G. França, Mário A. Gazziro, Alessandro N. Ide, José H. Saito, A 3D Scanning System Based on laser Triangulation and Variable Field of View, *Conference on Image Processing*, IEEE, 2005.
- [9] B.K.Choi, H.Y.Shin, Y.I.Yoon and j.W.Lee, “Triangulation of scattered data in 3D space”, *Computer-Aided Design*, 20(5), pp. 239-248, 1988.
- [10] Herbert Freeman. Computer processing of line-drawing images. *Computing Surveys*, 6(1):57-97, March 1974