3D High Precision Tube Bevel Measurement using laser based Rotating Scanner

Artzai Picón *, Arantza Bereciartua **, José Angel Gutiérrez ***, José Pérez ****
Dpto. INFOTECH / INFOTECH Dept.
ROBOTIKER, Corporación Tecnológica TECNALIA.
Parque Tecnológico, Edificio 202. E-48170 Zamudio (Bizkaia)
SPAIN
www.robotiker.com
* apicon@robotiker.es
** abereciartua@robotiker.es
*** josea@robotiker.es
**** jperez@robotiker.es

***Abstract.*- Quality control of products is everyday more and more demanding. Machine vision is becoming one of the most efficient technologies for the reliable and fast control of different types of products. The more classical techniques in machine vision 2D are valuables in lots of applications, but insufficient when it is necessary a three-dimensional data of the object to study. Classical linear 3D laser detection scanners are not optimized for revolution elements, since the features extraction algorithm needs to be different in each inspection zone and there are shadow zones where the inspection is not possible. In this paper, a novel 3D laser based rotating scanner is described (Patent Pending request nº ES-P200600068). This approach enables inspecting revolution elements avoiding the problems mentioned before. This rotating scanner implementation in a 3D Steel tube Quality Control Application is also described.**

I. INTRODUCTION

Quality control of products is everyday more and more demanding. Machine vision is becoming one of the most efficient technologies for the reliable and fast control of different types of products. This technology allows the obtaining of a big amount of information, superficial and dimensional, of the pieces at high speed. The more classical techniques in machine vision 2D are valuables in lots of applications, but insufficient when it is necessary a three-dimensional data of the object to study. To give this further step, several techniques for obtaining 3D information have been developed lately, such as optical triangulation, stereovision and combination of both. The objective of the present article is to present a 3D rotating scanner for the dimensional control of the metal tubes.

After different stages in their manufacturing process, these metal tubes present two sides with different finishes, bevels and dimensions. Each batch must fulfil the requirements established by the end user related to diameter and thickness of the tube; and depth, height and angle of the bevel. Another requirement of the system is a resolution higher than 0.1 mm.

Some of the features to measure, such as the bevel dimensions, require a 3D scanning of the tube.

Fig. 1. Example of tube with bevel

To obtain such a high resolution in 3D with the real field of view and distance conditions is not feasible with the conventional methods. This is why the optical triangulation methods and the laser as illumination source were chosen to be capable of achieving these services. Optical triangulation is one of the more extended techniques for 3D reconstruction which is based on the variation observed in the reflection of the light in an element taking into account the disposition of the set illumination - observer and the distance and angle to the object to observe as shown in figure 2.[1, 2]

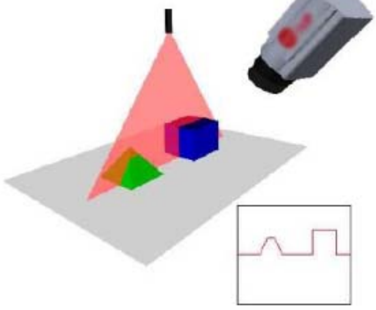

Fig. 2. Triangulation principle [3]

Moreover, the revolution nature of the object to inspect suggested the possibility of developing a revolving scanner instead of a linear one.

A novel 3D rotating scanner system based on triangulation techniques has been developed, whose architecture has into account the circular geometry of the metal tube, and performs a 180º turn, acquiring a profile measurement almost every grade. The acquisition of a big amount of data of the whole contour of every metal tube allows obtaining reliable results. The development of the acquisition and data processing algorithm was complex. It must be highlighted the difficulty in the calibration (translation from data in pixels of the camera to real millimetres), with complex methods of systems composition in the space and genetic algorithms. The reason for that difficulty is that the space is viewed from a different angle every measurement. Even if it is possible to calibrate quite easily the space, since the turning is not so precise as desired (due to mechanical constraints), the calibration of a rotary 3D space was difficult.

The advantages of this kind of system are clear: they assure the reliability and repetitivity of the result (facing up to the human limitations in the execution of quality control, besides subjectivity); and moreover, they imply an important time saving. The existing computing devices make it possible to carry out these tasks at high speed. The system that will be described in the present article achieves the inspection of each side of the metal tube in 1 second with tolerances of 0.01 mm.

The positioning of every tube is done by means of a robot, which will be able to interact with the output of the manufacturing process.

II. SYSTEM DESIGN

A. General description

Here it is the layout of the elements constituting the system in the industrial plan:

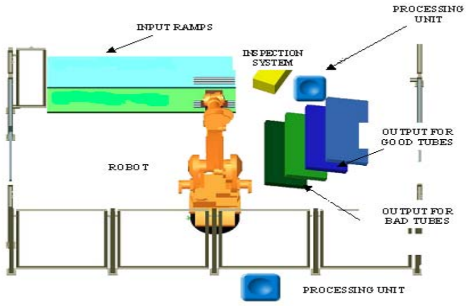

Fig. 3. Layout of the system

The different entities are:
1) The robot
2) The 3D inspection system
3) The processing unit
4) The input ramp
5) The output ramp for good tubes
6) The output ramp for faulty tubes
7) Electric, mechanical and security elements

The tubes coming from the input ramp are seized by the robot’s grip, and placed in a fixed point into the field of view of the camera. The robot communicates the inspection system that the tube is correctly placed. Then, the motor rotates 180º, and in this way, the camera can capture a profile every 1,3º.

This profile represents a chord of the tube (more exactly a pseudo-diameter) and 128 profiles are taken for reconstructing the tube. Three tubes are carried by the robot grip every cycle, and the inspection system and robot are fully synchronized to place the tube, rotate the motor while acquiring data, process the data and start again. The two sides of the tube are inspected.

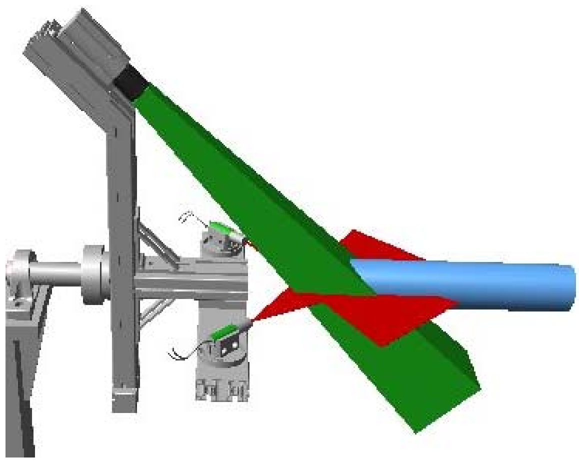

Fig. 4. Measurement subsystem

The measurement algorithm will be thoroughly described in the following section.

After the reconstruction of the 3D tube, and the calculation of the required values, such as radius, eccentricity, concentricity, roundness, bevel width and height… and its statistical data, the tube is classified as good or bad. The system indicates this to the robot, and consequently, every tube is transported to its corresponding output ramp. As soon as this action is finished, the cycle starts again.

III. MEASUREMENT ALGORITHM

A. Tube Profile Processing

The camera captures 128 profiles (one every 1.4º), which are pseudo diameters of the tube, as it can be seen in the following image.

The profile the camera captures is the intersection between the laser plane and the tube.

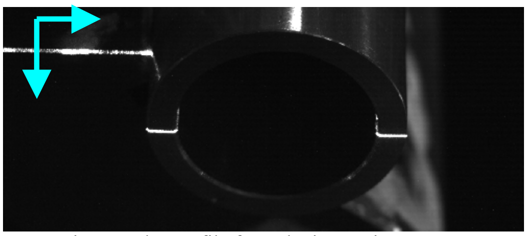

Fig. 5. Tube Profile from the inspection camera

A method based on subpixel accuracy is used to get the actual positions of the laser-tube intersections. This method increases accuracy 10 times.

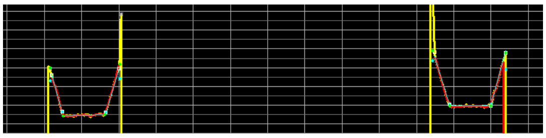

Fig. 6. Tube Profile after subpixel operation

Once the tube profile is obtained, signal processing algorithms are used to get the points of interest of the profile.

For this, filtering, line fitting, and nth derivate based peak detection methods algorithms are used to get the external point, internal point and the intersections between bevels and the front circumference.

The tube profile is filtered using mean and median filters. After filtering, each point from the 2^{nd} derivate of the filtered profile has been adjusted into a 2^{nd} degree polynomial using its N nearest points. Using this approximation, points of maximum pitch change are obtained. Empirical thresholding and criteria (minimum and maximum value of pitch, position of the point in the profile,…) are used to eliminate false peak points in noisy profiles (due to the brightness of the tube). Finally, the points of interest of every profile are obtained.

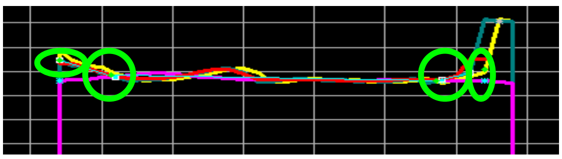

Fig. 7. Points of interest extraction of noisy profile (in green)

B. Laser Plane calibration

The obtained points belong to the inspection camera reference system as shown in figure 5 and their units are pixels.

The main goal is to convert every point in the inspection camera reference system into a 3D point belonging to a static global reference system.

For that, firstly, it is necessary to convert the points from the inspection camera (pixels) to their corresponding points in laser plane reference system as shown in Figure 8.

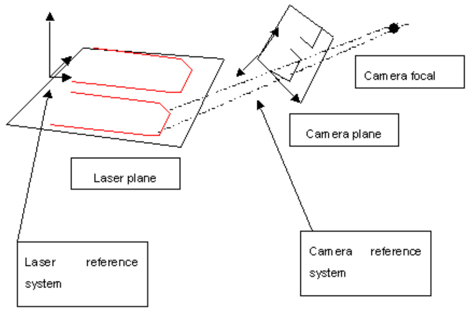

Fig. 8. Relation between inspection camera reference system and laser plane reference system.

To convert one point in the camera reference system (pixels) to a point related to the laser plane, a 2nd degree conversion function is used due to its good fitting with the geometrical camera model as described in [4].

$$Xmm = a_i \cdot Xpx \cdot Xpx + a_2 \cdot Ypx \cdot Ypx + a_3 \cdot Xpx \cdot Ypx + a_4 \cdot Xpx + a_5 \cdot Ypx + a_6$$
$$Ymm = b_i \cdot Xpx \cdot Ypx + b_2 \cdot Ypx \cdot Ypx + b_3 \cdot Xpx \cdot Ypx + b_4 \cdot Xpx + b_5 \cdot Ypx + b_6$$

The calculus of this function is made by using a calibrated element, specially designed for this application. This element is mounted into a precision positioning element. By moving this element in a axis of the laser plane, more than 500 pairs of relationships between laser plane and inspection camera are obtained.

Fig. 9. calibration element, used to calculate the coefficients of the camera2plane conversion function

Using these pairs of data, the coefficients of the conversion function are obtained. The conversion function appearance is shown in figure 10.

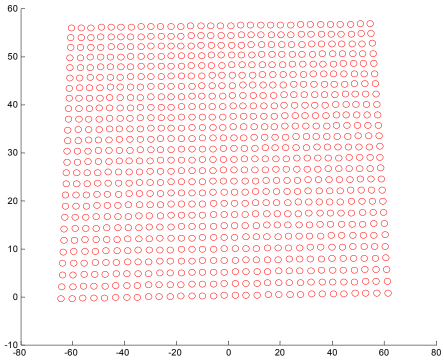

Fig. 10. Conversion Results from a square matrix of points belonging camera reference system into laser plane reference system.

C. Laser Plane Calibration

At this moment, the points are related to the laser plane reference system. If three-dimensional position and orientation of the plane were known, it would be possible to obtain the absolute 3D position of a point related to the system of reference of the plane. And, to complete the chain, the 3D position of a point related to the inspection camera reference system.

The only information known about the position of the plane is the encoder pulse, that makes it possible to get the angle rotated by the engine in any moment, and thus, the angle of the laser plane that rotates united to the engine.

If the laser plane belonged to the rotation axis of the system (Figure 11) it would be easy to get the 3D position of any point related to the laser plane reference system by applying basic trigonometric concepts.

$$X_{Absolute} = X_{laser} \cdot \cos(2 \cdot \pi \cdot n / N)$$

$$Y_{Absolute} = Y_{laser} \cdot \sin(2 \cdot \pi \cdot n / N)$$

$$Z_{Absolute} = Z_{laser}$$

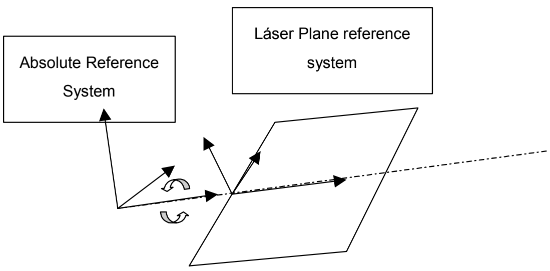

Fig. 11. Laser plane belonging to rotation axis

However, due to manufacturing constraints, the laser plane it is not in line with the rotation axis, and it is impossible to know directly the relationship between the laser plane and the rotation axis. For the high accuracy we are looking for, it is not possible to reject these manufacturing faults, since it will generate errors higher than 0.01 mm, so it is necessary to create a model that describes the plane movement

To make a model with the relationship between the laser plane and the rotation axis four parameters are defined: [X_0,Y_0, α , β].

The absolute reference system can be placed in any desired position. To improve simplicity in the formula, let Z axis from the absolute reference system matches the unknown rotation axis.

The laser plane reference system is translated X0 and Y0 related to the absolute reference system, and rotated α , β values.

A fifth value γ was added to avoid local minima in the search of the correct parameters of the plane, as shown later.

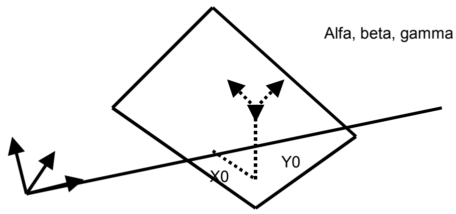

Fig. 12. Relation between laser plane and rotation axis

By using homogeneous 4x4 matrix for modelling rotations and translations in 3D, the relationship between the laser plane reference system and the absolute reference system would be:

$$AbsoluteCoordinates = f(LaserPlaneCoordinates, EncoderRotation, X_0, Y_0, \alpha, \beta, \gamma)$$

$$\left[Matrizparámetros\right] = \begin{bmatrix} 1 & 0 & 0 & X0 \\ 0 & 1 & 0 & Y0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Cos(\gamma) & -Sin(\gamma) & 0 & 0 \\ -Sin(\gamma) & Cos(\gamma) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & Cos(\alpha) & -Sin(\alpha) & 0 \\ 0 & Sin(\alpha) & Cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Cos(\beta) & 0 & Sin(\beta) & 0 \\ 0 & 1 & 0 & 0 \\ -Sin(\beta) & 0 & Cos(\beta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} Xabs \\ Yabs \\ Zabs \\ 1 \end{bmatrix} = \begin{bmatrix} Cos(EncoderRotation) & -Sin(EncoderRotation) & 0 & 0 \\ -Sin(EncoderRotation) & Cos(EncoderRotation) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \left[Matrizparámetros\right] \cdot \begin{bmatrix} Xlaser \\ Ylaser \\ Zlaser \\ 1 \end{bmatrix}$$

If the parameters representing the plane were known, it would be possible to convert any point referred to the camera reference system into its 3D absolute coordinates. With wrong plane parameters, it is not possible to get a correct reconstruction of a tube.

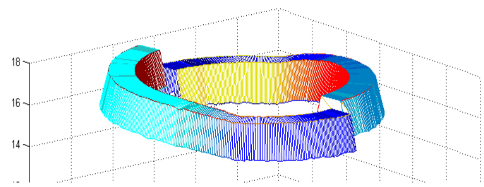

Fig. 13. Tube reconstruction with wrong plane parameters

D. Plane Parameters Estimation

It is necessary now to calculate the parameters of the plane taking in account that:

1) If the parameters were zero, the plane would contain the rotation axis.

2) The plane parameters should not be too different from zero

To obtain the estimation of the parameters of the plane, the following method is proposed. A mathematical function is created with the following conditions:

1) The parameters of the plane [X_0, Y_0, α, β, γ] are parameters of the function.

2) Data from a calibrated tube is also a parameter of the function.

3) 3D point values from the calibrated tube are obtained with plane parameters [X_0 ,Y_0 , α , β , γ].

4) The tube is divided into two half-tubes (left and right) which are well appreciated in figure 13.

5) From this 3D data of each half tube, 3D semi circumferences are obtained (fitting process is shown later).

6) By using these semi circumferences, some parameters are calculated:

- Normal vector.
- Radius.
- Distances among the centres of the circumferences.

If the parameters of the plane were correct, for every circumference:

1) The centres of the semi circumferences should match.

2) The radius of the two semi circumferences should be the same and their value should be the calibrated data.

3) Normal vector of all half-tubes should be the same.

Taking the previous point into account, the proposed function has to return an error value that increases with previous indicators.

$$Error = K_1 \cdot (Error_{radius}) + K_2 \cdot (Error_{centerdistances}) + K_3 \cdot (Error_{normal})$$

Where Error $_{radius}$ is obtained with the differences of the radius of the semi circumferences, $Error_{center\ distance}$ is calculated with the differences of position of centers of semi circumferences, and $Error_{normal}$ is calculated calculating the angle between normals using cross product.

With this function return value, and minimum search methods based on Genetic Algorithms and gradient based techniques are applied. The correct parameters were found after 40 minutes algorithm computing in a 2600 Mhz computer.

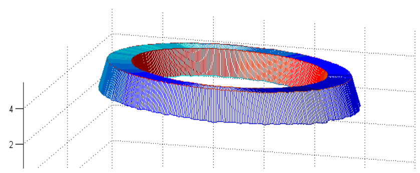

Fig. 14. Tube reconstruction with correct parameters

At this stage, 3D rotating scanner measurement algorithm principles have been described. The following section describes the algorithms needed to obtain the required specific measurements from the steel tubes, once the tube has been reconstructed in 3D with real values in mm.

E. Filtering and 3D ellipse Fitting

Once the 3D points have been obtained, some filters (median, mean) are applied to the arrays of X,Y,Z coordinates to eliminate spurious points and to smooth the data.

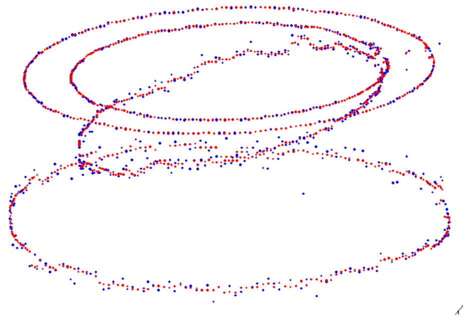

Fig. 15. Filtering of spurious points

After filtering the points 3D ellipse fitting is performed.

3D ellipse fitting is performed in a five steps way:

1) 3D plane fitting of the points to get the plane containing the ellipse.
2) Coordinate change into plane coordinate of the ellipse.
3) 2D ellipse square error function generation.

$$S = \sum \left[\frac{(X_i - X_0)^2}{R_x^2} + \frac{(Y_i - Y_0)^2}{R_y^2} - 1 \right]^2$$

4) Fitting 2D ellipse parameters using Levenberg-Marquardt algorithm [5].
5) Conversion of 2D ellipse features into 3D features (Coordinate reference change)

This way, four ellipses are obtained (external ellipse, internal ellipse, and two ellipses for the intersection of bevels).

F. Final measurement

The measures required by the end users are obtained from the study of the four ellipses of each tube. These ellipses are intersected by numerous perpendicular planes, containing the rotating line of the tube (regarding external circumference) and this plane turns every grade intersecting the different circumferences. The lines and points resulting from the intersections are analysed.

With this data the following measures are obtained:

- External Radius (Max, Med, Min).
- Internal Radius (Max, Med, Min).
- External Bevel width and height (Max, Med, Min)
- Internal Bevel width and height (Max, Med, Min)
- Angles of the external and internal bevels
- Eccentricity
- Concentricity
- Roundness

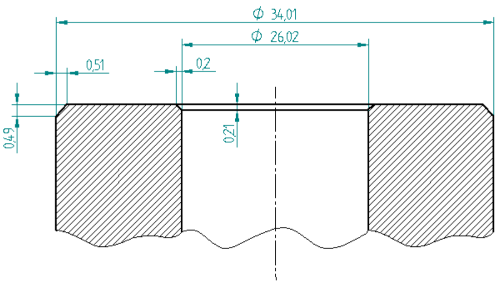

Fig. 16. Some Measures obtained from the tube

IV. MECHANICAL SYSTEM

The mechanical system consists of the following elements:

- Two lasers from LASIRIS, emitting in 685 nm wavelength,(1)
- One high resolution M50 camera from IVP.(3)
- Support element (2)
- Special Revolution axis with no looseness (4)
- Engine (5)
- Encoder (6)

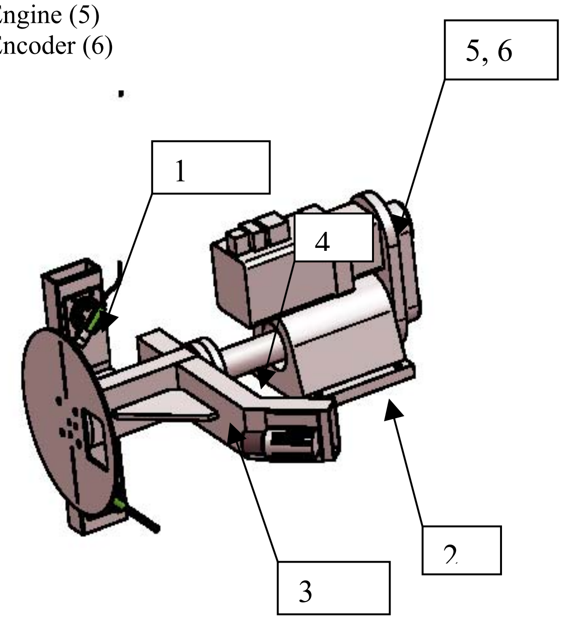

Fig. 17. Mechanical system

V. ROBOT SYSTEM

The manipulation needed for the inspection system has been carried out by a robot. The robotic cell is composed by the industrial robot, the load and unload stations and the inspection system.

Both the robot and other peripherals were available in TUBOS REUNIDOS. The model of the industrial robot is a IRB4400 of ABB manufacturer. It is mounted on a pedestal and has a vacuum gripper tool as an end-effector.

Fig. 18. Robot and gripper in the inspection location

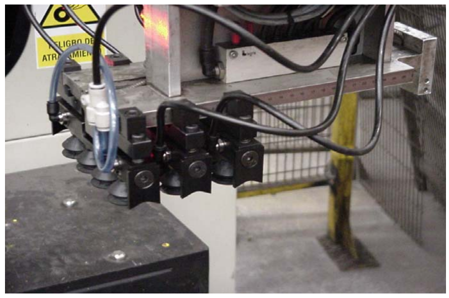

Fig.19. Vacuum gripper

Sequence of operations:

1) The robot receives information from the inspection system about the available cutting machines and the geometrical characteristics of the tubes.

2) The robot grips the tubes in the load stations of the different cutting machines (3 tubes every cycle)

3) The tubes are placed at the defined inspection point.

4) After tube inspection the robot turns to the unload stations. Tubes are dropped and classified depending on the machine they came from, and the result of the quality inspection.

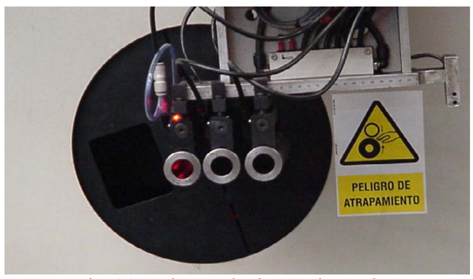

Fig. 20. Tubes at the inspection point.

The specific benefits of this robot investment are the automatic configuration of all the working locations to any tube size; the flexibility of the system due to future changes in the product or process or lay-out configuration; the digital input/output communication for process control; the serial port communication (RS232) for process configuration; the friendly interface in the operator panel; the high accuracy positioning at the defined inspection point due to communication between inspection system and robot; the reduced change over time and the increase of quality inspection (100%)

VI. SOFTWARE IMPLEMENTATION

The development tools used in this application have been:

- LabWindows CVI.
- Microsoft Visual C++
- Scientific software MATLAB.
- Robot programming language RAPID
- Simulation of robotized installations, ROBCAD
- Mechanical design software SolidEdge
- Electrical design Eplan 5.3 compact

All these tools have contributed to a modular development: acquisition of profiles, motor turn, data processing and 3D image reconstruction, communication with the robot by IOs, mechanical and electrical design, and finally all these modules have been integrated under a friendly user interface. It would be really long to describe all the functionalities of the software. The most important one is the automatic inspection cycle, whose results are visualized in the following panel.

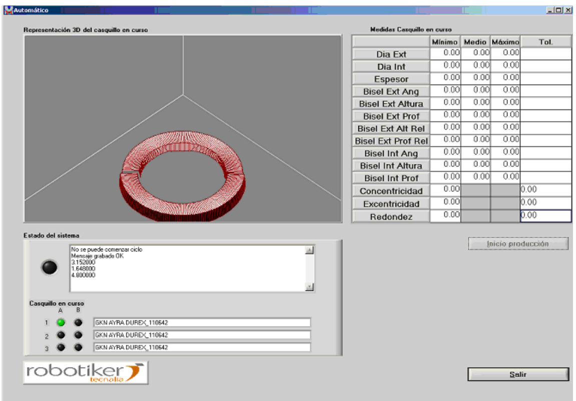

Fig. 21. Automatic inspection user interface.

VI. TESTS IN THE PLANT AND RESULTS

The application described in this paper has been successfully implemented in TUBOS REUNIDOS, a steel tube manufacturing company. In the first steps of the integration in the plant, there were lots of problems that were successfully solved. The 100% of the production is now inspected, and till the moment, the results are very good, and no deviations have been appreciated.

The test plan for validation of the project, once it was fully integrated in the factory gave the following results:

Results of the validation test		
Number of models of tubes tested	8	
Number of tubes of each model	± 50	
	Best Model	Worst Model
Repeatability (σ)	0.005 mm	0.01 mm
Accuracy (σ)	0.01 mm	0.02 mm

Table 1. Results of Validation tests

These measurement results are being checked every day with the quality tests made by TUBOS REUNIDOS and its customers of the manufactured tubes, using the measurement and statistical data which is stored automatically by the system,

The processing algorithm takes about 0.3 seconds per tube, and including the acquisition and positioning of the tube by the robot, it is approximately 1 second per tube.

Due to the innovation of this project, a patent request has been made: patent pending request nº ES-P200600068.

VII. CONCLUSIONS

As conclusions of this application, we can remark:

1) A new approach of 3D scanning triangulation has been proposed. In this case, a rotary scanning has been developed, trying to solve the limitations of a linear one for objects with revolution geometry.

2) By means of the sub pixel processing algorithm, it was reached a high resolution after signal processing and filtering as shown in Table 1 .

3) A new calibration method has been applied taking into account and minimizing the effects caused by the fact that the rotation axis does not belong to the laser plane, and that there can be looseness in the manufacture of the mechanical support for the motor.

ACKNOWLEDGMENT

We want to acknowledge TUBOS REUNIDOS for its cooperation and for having trusted ROBOTIKER in this project.

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