IMPLEMENTATION ISSUES REGARDING A 3D ROBOT – BASED LASER SCANNING SYSTEM

Theodor Borangiu, Anamaria Dogar, Alexandru Dumitrache

University Politehnica of Bucharest
Dept. of Automation and Applied Informatics

Abstract: This paper consists in the presentation of several implementing issues regarding the integration of short range laser scanner with a robot arm – the laser scanning system component of a multifunctional, autonomous, self-adaptive manufacturing platform. One of the most important aspects consists in the synchronisation between the data acquired from the laser scanner and the location data acquired from the robot controller. Another issue covered by this paper consists in the trajectory planning of the robot arm to optimally accomplish the complete scanning of object surface. There are proposed adaptive scanning strategies based on the surface features. .

Keywords: intelligent control, path planning, shape description, algorithms, simulation.

1. PROJECT DESCRIPTION

The objective of this complex project consists in developing a **multifunctional, autonomous, self-adaptive manufacturing platform** capable to perform the following three team-based activities, for single-product orders to large batch production:

1. Pre-production activities:
   - Scan complex object surfaces to provide their accurate digital 3D description from depth map images; compute iso parametric machining toolpaths by interpolating between image points of equal grey levels; generate G-code for CNC machine tools (*planning, reverse engineering*).
   - Directly download CAD files describing part geometry; post process CAD data to generate CNC toolpaths (*design, engineering*).
   - Prioritize activities according to rush orders; change class model description or toolpaths spec according to customer requests (*business*).
2. Production activities:
   - CNC machining (*roughing, finishing*).
   - Robotized mounting, grinding, polishing, cutting (*assembling, material conditioning*)
3. Post-production activities:
   - Automated visual measuring, defect detection (*inspection, quality control*).
   - Feature-based part qualifying, classifying, palletizing (*sorting, packaging*).

This versatile, multi-team based manufacturing platform was designed to integrate a short range, high-precision 3D laser scanning probe displaced by a 6-d.o.f. vertical articulated robot manipulator relative to a model (object) to be reproduced on a 5-d.o.f CNC milling machine, with automatic division of the material to be removed and adaptation of the feedrate and spindle speed during the roughing stage of part machining. The laser probe is able to measure distances from 70 to 250 millimetres, with an accuracy of achieving 30 µm. The robotic arm moves around the work piece – eventually placed on a rotary table with closed-loop position control – being scanned by computer-generated adaptive scanning paths (Fig. 1).

[*] This work is funded by the National Council for Scientific University Research, in the framework of the National Plan for Research, Development and Innovation, grant 69/2007.

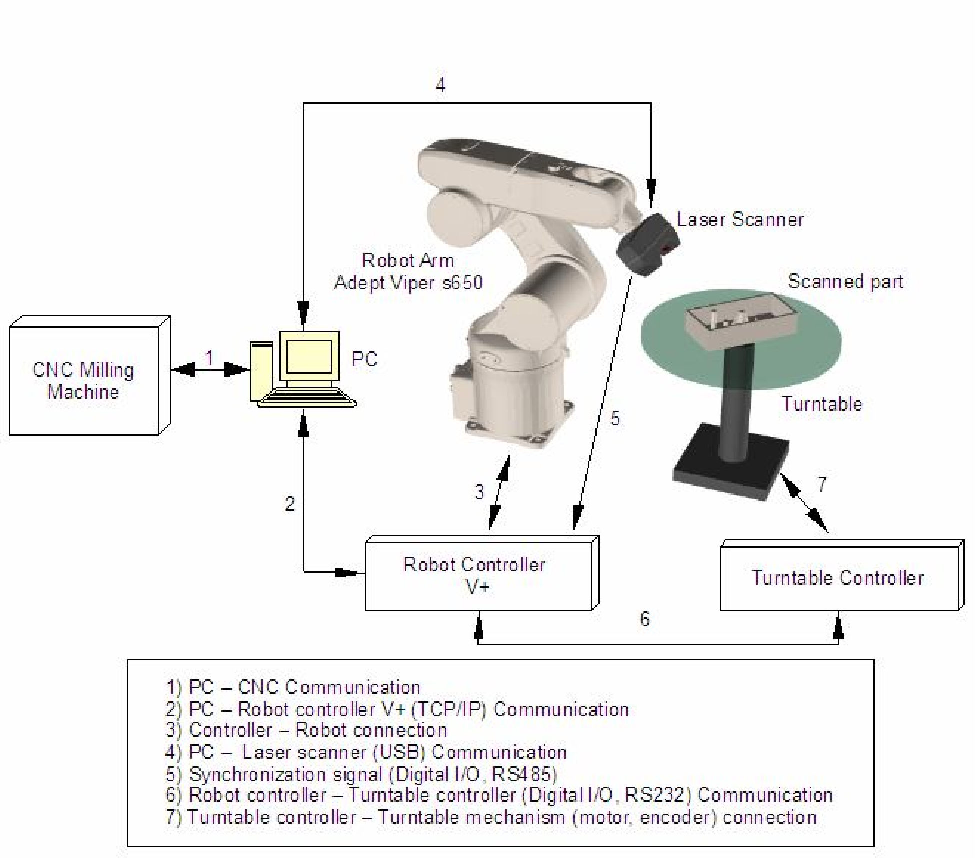


Fig. 1. Hardware architecture of the laser scanner-robot-CNC machine platform for *on-demand* reverse engineering tasks

These scanning paths are computed in real-time by the robot controller from a predefined motion pattern, while the range finder device generates depth map-type information describing the object's surface, synchronously with the motion of the laser scanner probe. The scanned 3D models will be then reproduced on a CNC milling machine for any ordered batch size.

The scanning device is a class-2, short distance, triangulation one, and has two CMOS sensors allowing the scanning of complex object surfaces. The optimal scanning distances range from 71 mm to 242 mm. The width of the scanning line varies between 31 mm and 83 mm, and the average measuring precision at point level is 31 μm.

The acquisition rate is between 50 and 150 frames per second, the number of points which are read on a scanning line being 480. The laser range finder system is interfaced to a 3.2 GHz IBM PC-type station by means of a standard USB input port, and uses additionally a digital RS485 line for synchronization with the robot controller.

2. INTEGRATION OF THE LASER PROBE WITH THE ROBOTIC ARM

To integrate the laser scanning and range finder system with the robot system, the following software modules must be developed (Fig.2):

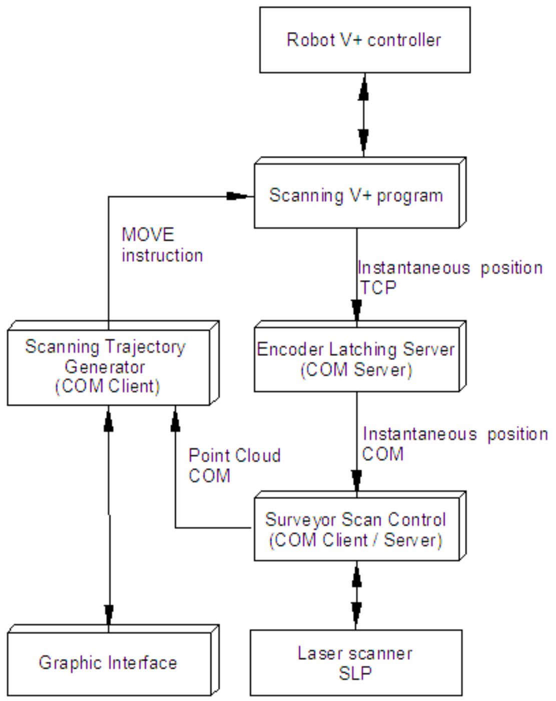


Fig. 2. Software architecture for laser object surface scanning and depth map image processing for toolpaths generation

- *Encoder Latching Server*: provides integration of the laser scanning control with the robot motion controller; the instantaneous Cartesian position of the Robot is transmitted to the distance acquisition software Surveyor Scan Control.

- *Scanning Trajectory Generator*: computes the robot paths along which scanning of the surface of interest will be done, according to the user defined strategy (motion pattern).
- *Graphical User Interface* (GUI): is installed and runs on the PC.

The scanning software proprietary to the laser probe – Surveyor Scan Control runs on the PC and allows integration with a robotic arm. It is necessary developing a program called Encoder Latching Server, which will act as a link between the robot controller and the scanning software. The latching server has to capture the instantaneous robot locations every time a measurement is performed by the laser probe. The interface between the encoder latching server and the scanning software is done using the Microsoft COM Interop technology, by implementing the latching server as a COM server.

The laser probe outputs a digital signal every time a measurement is performed. This signal is triggered in the middle of the exposure period, and it will be connected to a digital input port on the controller. The scanning rate varies between 50 and 150 frames per second, depending of the size of window of interest on the image processed by the laser probe. This implies that the delay between two successive measurements is between 6.6 and 20 milliseconds. The V^+ timer has a resolution of 1 millisecond, therefore it is suitable for synchronization purposes.

The robot controller offers the following possibilities for monitoring digital input signals:

- Continuous polling with the function SIG. The input signals are checked once every major cycle, which is of 16 milliseconds.
- Triggering a subroutine call at the transition of an input signal, with REACT or REACTI instructions. As the signals are checked every 16 milliseconds, Adept recommends that the signal should be active for at least 18 milliseconds in order to be detected.
- High-speed interrupts. The input signals from 1001 to 1004 can be configured as high speed interrupts, and a change in the input signal is detected with a maximum delay of 1 millisecond. The high speed interrupts can be configured with CONFIG_C utility, and monitoring of a signal in this mode can be done using the INT.EVENT and WAIT.EVENT program instructions.

The optimal solution is to use the high-speed interrupts. A V^+ program task will run in parallel with the motion control program, and it will monitor the input signal from the laser probe and save the instantaneous robot locations in a buffer. This task, called save_locations(), should run as high priority, in order to detect the signal transitions in real time.

The instantaneous locations are sent to the encoder latching server via TCP/IP by a second task, which has a lower priority, since the data acquisition software for the laser probe does not require the instantaneous positions in real time. The benefit of providing the instantaneous positions to the acquisition software is the ability to update in real-time the display of the 3D point cloud model of the workpiece being scanned.

The second task runs as a consumer, while the previous program is the producer, which is a classical problem for task synchronization. V^+ provides the test-and-set instruction, TAS, which can be used for this purpose.

The data is sent over TCP using fixed-length packets. Each packet begins with the signature "LOC" (4C 4F 43 in hexadecimal). The following two bytes are a 16 bit integer representing the zero based index of the packet. The following 7 × 8 bytes represent 7 double-precision values in IEEE floating point format, and their meaning is the timestamp followed by the six transformation components (*x*, *y*, *z*, *yaw*, *pitch*, *roll*) from the instantaneous location. After the data acquisition is complete, the program sends a packet containing the characters "FIN" (46 49 4E in hexadecimal) which mark the end of the transmission. These packets will be received by the encoder latching server, which will forward them to the data acquisition software.

3. ADAPTIVE SCANNING STRATEGIES. 2.5D SURFACES

Using a predefined strategy like raster or spiral gives the advantage of an easy implementation and can lead to very good results in many cases. There are cases when a predefined strategy will not be able to detect all the features of the analyzed object. In the case of molds, the scanning surface can be described as a $z = f(x, y)$ function, so it is s 2.5D surface. In this case it is possible the scanning using only trajectories in the *XY* plane, varying the distance of the scanner.

It is proposed a two stage scanning strategy. In the first stage of the scanning process, there is no information regarding the object; this laser scanning will be done at high speed rates, which implies a low resolution data set. In the second stage of the scanning process, there is an approximate model of the object and it can be computed an efficient scanning strategy. The scanning speed rate will be much lower, this is why the scanning paths used must be efficiently optimized. On the other side, the optimization in the first stage is not critical.

3.1 First stage scanning strategy

Let consider the mould profile in the Figure 3. It can be observed the trapezoidal region of the laser plane which is analyzed by the optical sensor. It can be noticed that the prolongation of the trapeze sides intersect in the point *O'*, which is not identical with the origin of the laser beam *O*. Also, there are parts of the laser beam which are not in the camera field of view.

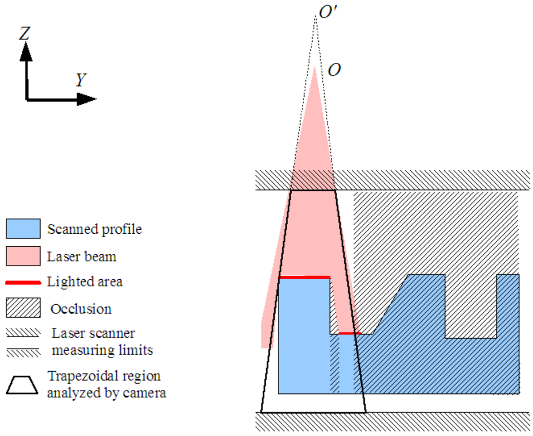


Fig. 3. First scanning of a profile

There appears an occluded region due to one vertical wall, for which a supplementary trajectory must be generated.

If in the first stage of the scanning process, the obtained cloud point is not analyzed, the next data acquiring pose is *X* (Fig. 4).

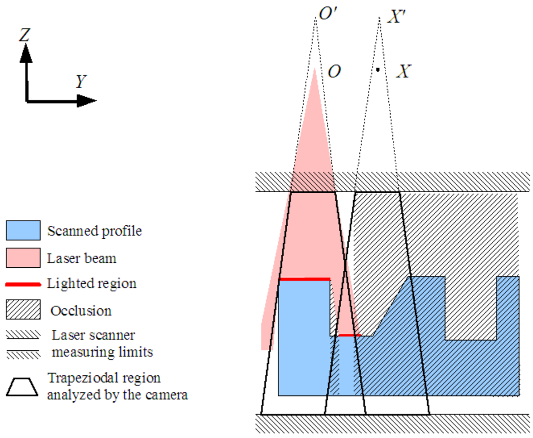


Fig. 4 The next trajectory in the scanning process

There can be observed that there is redundant data in the captured point cloud, so there must be eliminated the excess points.

In order to generate an optimal strategy for the second stage of the scanning process, the occlusions must be analyzed in the first stage. So a possible solution for the proposed profile is shown in the Figure 5, based on the following rules:

- if there is an occluded area, generate trajectory for scanning this area;

otherwise, generate the next path so that the up-left corner of the trapeze have the same horizontal coordinate as the last point detected in the previous scan.

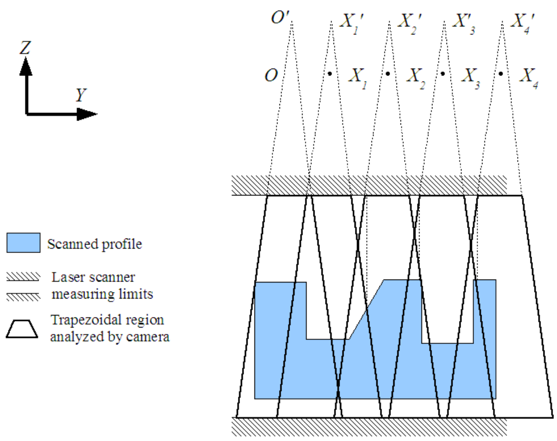
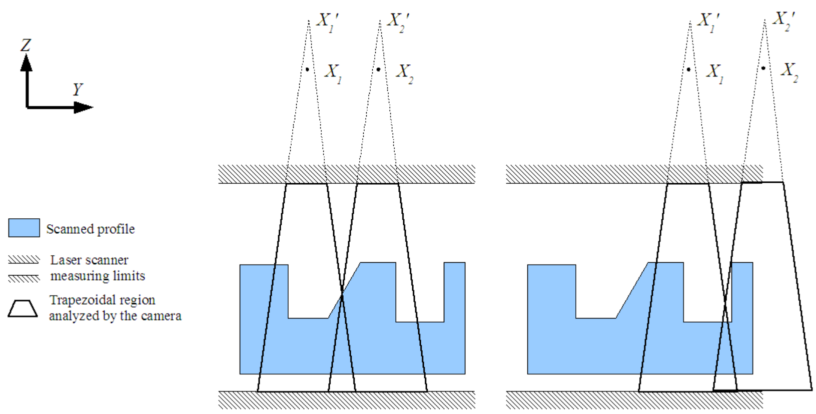


Fig. 5 Possible solution for adaptive scanning in the first stage

3.2 *Second stage scanning strategy*

In this second stage there is available an approximate model of the scanned object. This model is used for modeling the optimal strategy that will lead to the complete model of the object.

In the Figure 6, are presented two consecutive trajectories. In the *a)* case the intersection of the two trapezes sides on the profile surface does not create any occlusions. In the *b)* case the intersection of the trapezes sides on the mould surface will lead to an occlusion, in this case the trajectory must be placed so to be tangent to the vertical wall.



a) *b)*

Fig.6 Two consecutive trajectories for adaptive scanning in the second stage

For implementing this situation, it is useful a nonlinear transformation of the mould profile. This transformation is defined for circle of given center and radius (Fig. 7) and will be noted as **T**. Let be the circle $O = (x_0 ; y_0)$ and radius r, in the Cartesian plane XY, and a point $P = (p_x, p_y)$ that will be transformed in $P' = (p_x' ; p_y')$. Let be α the angle that is made by the segment OP with the axis Oy, and ρ the distance from P to O.

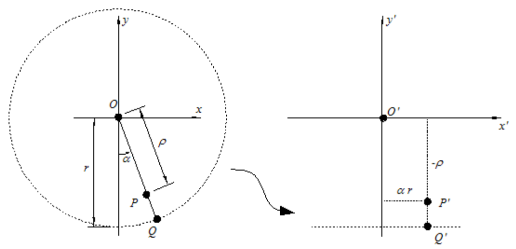


Fig. 7. Nonlinear transformation from circle to segment

The coordinates of the point P' will be for a circle with an arbitrary center:

$$p_x' = x_0 + \alpha \qquad (1)$$

$$p_x' = y_0 - \rho \qquad (2)$$

where

$$\alpha = \text{arctg}\frac{p_x - x_0}{y_0 - p_y} \qquad (3)$$

$$\rho = \sqrt{(p_x - x_0)^2 + (p_y - y_0)^2} \qquad (4)$$

The transformation **T** is not defined by the point O.

Using this transform, a circle with an arbitrary radius R and center O becomes a horizontal line at the level $y' = -R$, and a circle radius, becomes a vertical line $x' = \alpha$, where α is the angle between the radius and the Oy axis. So, the points P' and Q' from figure X will have the same abscise, since P, Q and O are collinear.
This transform facilitates the following calculus:

- applied with the center in the point X_1' from figure X, permits the computing of the intersection between the scanned profile and the side of the trapeze, by inspecting the y' coordinates of the scanned profiled points;
- applied in the X_i points, the origin of the laser beam, facilitates the detection of the vertical wall which lead to occlusions. This vertical wall, appear under this transformation as concavities.

4. SIMULATOR OF THE LASER SCANNER – ROBOT ARM SYSTEM. FUTURE WORK

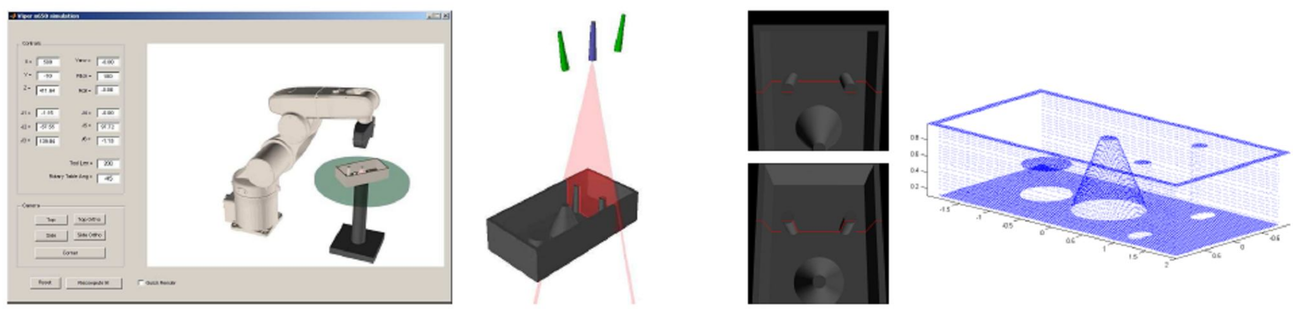
The simulator of the laser scanner – robot arm system is designed to be a development tool and test bench for the adaptive scanning algorithms developed. Using a simulation environment for designing the scanning algorithms has several advantages:

- The possibility of collisions between the robotic arm, laser probe and workpiece is eliminated. As the laser probe is an expensive device, collision avoidance is a very important point to consider;
- The system can be analyzed in ideal conditions, with no surface reflections, external light sources or perturbations in the measurements;
- The parameters of the scanning system components, like camera location, focal length, optical
- Sensor resolution, laser beam width, rotary table size and location, can be freely changed, and the influence of these changes can be analyzed thoroughly;

The software simulates the kinematics of the robot arm, and the interaction of the laser probe, composed by a laser beam and two cameras, with a virtual workpiece. From processing the rendered images, a cloud point representing the workpiece can be generated.

This work has been done in the Robotics and AI Laboratory of the Faculty of Automatic Control and Computers.

The close-future work includes developing the algorithms for complex 3D path following, optimizing and speed – up methods of the implemented algorithms.



a) Screen shot of the simulator b) Schematic view of laser probe c) Images from the two cameras d) Computed point cloud

Fig. 8. Laser scanner - robot arm system simulator

REFERENCES

Borangiu, Th. (2004). *Intelligent image processing in Robotics & Manufacturing*, Romanian Academy Publish. House, Bucharest.

O'Gorman, L. (1996). Subpixel Precision of Straight-Edge Shape for Registration and Measurements, *IEEE Trans. on Pattern Analysis and Machine Intelligence*, **18**, *11*, 57-68

Persistence of Vision Raystracer Pty. Ltd., POV-Ray Online Documentation

Adept Technology, Inc. Web Site, www.adept.com

Rahimifard, S., Semi-heterarchical production planning structures in the support of team-based manufacturing, International Journal of Production Research, **42**, *17*, 3369-3382, Sept. 2004.

Babiceanu, R.F. and F. Chen, Development and Applications of Holonic Manufacturing Systems: a Survey, Journal of Intelligent Manufacturing, **17**, 111-131, 2006.

Ratcheva, V. and S. Vyakarnam, Exploring team formation processes in virtual partnership, Journal of Integrated Manufacturing Systems, **12**, 512-523, 2001.

Valckenaers P., Van Brussel, H., Wyns J., Bongaerts L. and P. Peeters, Designing holonic manufacturing systems, Robotics and Computer-Integrated Manufacturing, **14**, 455-464, 1998.

Van Brussel, H., Wyns J., Valckenaers P., Bongaerts L. and P. Peeters, Reference architecture for holonic manufacturing systems: PROSA, Computers in Industry, **37**, 255–274, 1998.

Leitao, P. and F. Restivo, ADACOR: A Holonic Architecture for Agile and Adaptive Manufacturing Control, Computers in Industry, **57**, *2*, 121-130, 2006.

Cheng, F.-T., Chang, C.-F. and S.-L. Wu, Development of Holonic Manufacturing Execution Systems, in Advanced Robotic Systems International, 77-100, pro literatur Verlag, Mammendorf, 2007.