INTEGRATING 3D QUALITY CONTROL FUNCTION INTO AN AUTOMATED VISUAL INSPECTION SYSTEM FOR MANUFACTURING INDUSTRY

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Lucrarea prezintă realizarea unui sistem de control de calitate integrat în celule flexibile de fabricație. Sistemul propus combină mai multe componente, cu scopul de a furniza o soluție eficientă pentru măsuratori complexe în timp real. Sarcinile standard de inspecție vizuală sunt efectuate de către sistemul de vedere artificială 2D. Datorită creşterii complexității aplicațiilor de inspecție vizuală, procedurile standard 2D nu sunt întotdeauna suficiente pentru a atinge standardele de calitate cerute. Sistemul de control al calității sistemului oferă funcția de inspecție 3D prin integrarea unui dispozitiv de scanare laser montat pe un robot cu 6 grade de libertate.

This paper presents an integrated quality control system for manufacturing industry. The proposed system combines several components in order to provide an efficient solution for complex realtime measurements tasks: image processing system which can be adapted to specific requirements, monochrome video cameras and a laser scanner probe, all integrated in a flexible manufacturing cell. Standard visual inspection tasks are performed by the 2D vision system. Due the increased complexity of inspection applications, standard procedures do not always suffice to achieve given quality standards. The quality control system provides the 3D solution by integrating a 6 d.o.f. robot mounted laser scanning device.

Keywords: automatic quality control, laser scanning systems, flexible manufacturing cell

1. Introduction

The quest for agility and re-configurability requires a new class of production control systems, characterized by: (i) a set of distributed, autonomous and intelligent building blocks, designated as control units; (ii) autonomy of each control unit which has its own objectives, knowledge and skills; (iii) global decisions are obtained by the cooperation of more than one control unit; (iv) control units adapt to changes without external intervention; (v) control units of mechatronic devices such as machine tools, robots, conveyors and vision sensors, are part of reconfigurable, fault-tolerant planning, control and test architecture of

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global manufacturing system; (vi) input data and formats for part processing are subject to increased diversity, requiring both high-speed cooperation between external sensors (range finder, machine vision), intelligent robots and CNC machine tools, and easy reconfigurable, task-driven software systems capable to detect, recognize, locate, qualify, inspect complex objects and accurately represent in digital form their 2D/3D surfaces/shapes [1].

Today, quality requirements in industry are higher and keep increasing. But today economic situation affects the budgets and consequently time schedule are more constrained. The manufacturing industry must provide products as fast and cost-effective as possible, and in the same time keeping high quality.

The proposed solution has the objective of enabling a complete quality control of manufactured components. Assuring the quality of machined parts is a key competitive issue for manufacturing industry; a small part can easily cause a reject of thousands of euros.

The proposed system combines several components in order to provide an efficient solution for complex realtime measurements tasks. The system is composed of an image processing system which can be adapted to specific requirements, monochrome video cameras and a laser scanner probe. This solution offers the flexibility of the system in order to adapt to specific visual inspections tasks and high accuracy measurements performed.

The proposed system is suitable for manufacturing industries under a strong pressure to provide a 100% quality control, from low-cost to complex quality sensitive products. The inspection and measurement of machined parts may raise serious challenges if 3D features must be checked. The selected 2D machine vision system provides measurement accuracy up to 0.007 mm. For higher accuracy measurements or different aspects such as conical features, inner or outer heights or other critical dimensions, the chosen solution consists in an arm-mounted the laser scanner on a 6 d.o.f. robot manipulator. This provides the flexibility and adaptability of the quality control system, and also accuracy of tenths of microns.

An important aspect of the proposed system is its adaptability across the whole product range, covering components which have a variety of sizes and shapes, the inspection system has the flexibility to incorporate further inspection and measuring tasks corresponding to the definition of new products. The system combines several components to provide an effective solution for complex, realtime measurement tasks, such as:

- image processing framework
- conveyor belt
- arm-mounted and fixed monochrome cameras for 2D measurements
- arm-mounted laser scanner for flexible 3D measurements

2. Integrating Quality Control System into Flexible Manufacturing Cell

The flexible manufacturing cell is composed by a number or robotic resources, interconnected by a closed-loop transportation system - conveyor. (Fig.1) The final product results by executing a number of mounting, joining and fixing operations by one or several of the networked robots. The operations are scheduled off-line or rescheduled online by a holonic bidding mechanism. The set of specific production operations is extended to on-line part conditioning (locating, tracking, qualifying) and checking of relative positioning of components and geometry features.

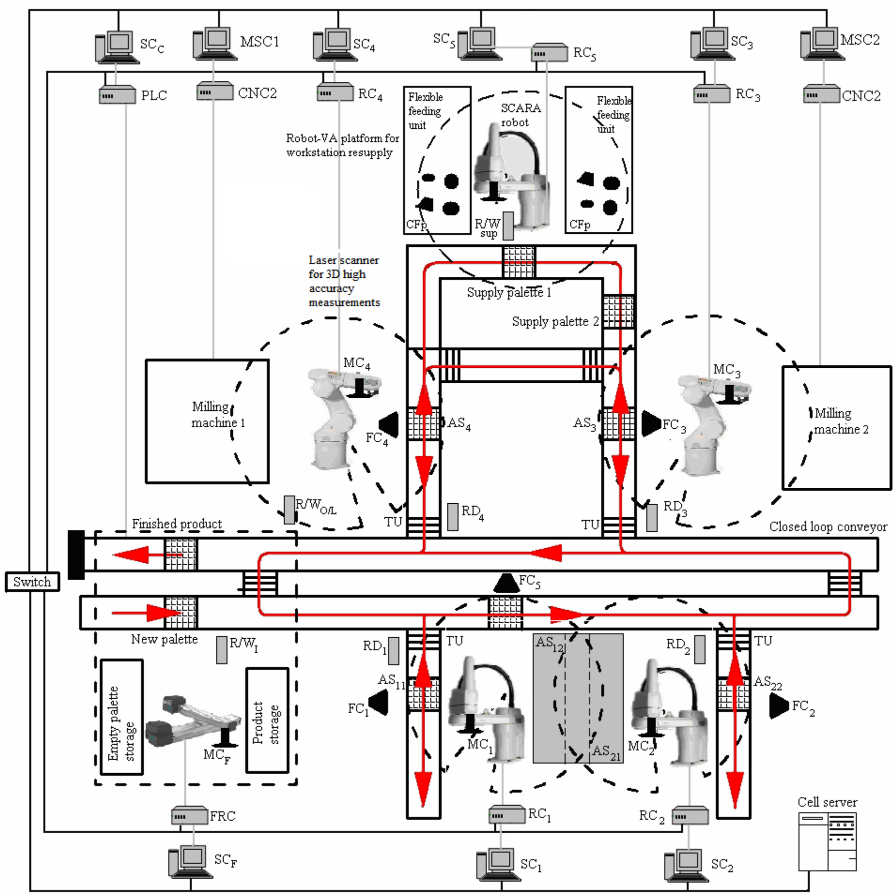

Fig. 1. Implemented architecture of the flexible manufacturing cell

These functional extensions may be supported by artificial vision either integrated with motion control (Guiding Vision for Robots - GVR) or as stand alone, computer vision (Automated Visual Inspection – AVI). In both cases, vision is used online to check for proper geometry features and presentation of assembly components in view of robotized mounting, and for inspecting the product in its intermediate and final execution stage – positioning, alignment and completeness.

Traditional networked assembly structures have either a *hybrid* or *heterarchical* architecture. The first one, derived from the hierarchical architecture, allows cooperation and sharing of information between lower-level (robot) controllers; a supervisor initiates all the activities and then the subordinates cooperate to perform them. The second is formed by a group of independent entities called *agents* that bid for orders based on their status and future workload [2].

Fig. 2. The flexible manufacturing platform

There is no master-slave relationship; all the agents including the manager of a particular order are bidding for it. Due to the decentralized architecture, the agents have full local autonomy and the system can react promptly to any change made to the system. (Fig. 2) However, because the behavior of an order depends on the number and characteristics of other orders, it is impossible to seek global batch optimization and the system's performance is unpredictable. In order to face resource break-downs, networked assembly structures should use robot controllers with multiple-network communication facilities allowing for fault-tolerance: targeted data saving and task redistribution.

3. 2D Automated Visual Inspection System

The 2D visual information management process is carried out according to a systemic, closed loop "Look-and-Move" robot-vision cooperation. This systemic model is partially replicated in case the robot is equipped with multiple physical cameras or when the inspection tasks require the creation of multiple virtual cameras and the optimal set up of the extended vision environment. Also, guidance vision for material-handling tasks is implemented through: statistical pattern recognition based on feature analysis, cluster and pattern construction; blob- and model-based recognition and locating; modelling the scene-robot, scene-object, robot-object and robot-scene parameters; visual conveyor tracking for on-the-fly robot access to moving parts. [10]

Automated Visual Inspection techniques based on Artificial Intelligence – AI and Vision Tools (Area of Interests – AOI, point-, line- and arc finders, linear and circular rulers), polar- and linear offset signatures, and skeletonization have been developed and tested and in the framework of the holonic manufacturing control with integrated product inspection.

The PROSA abstract suggests that any manufacturing system can be broken down into three basic holons, the Resource Holon, the Product Holon, and the Order Holon. Each of these holons may exist more than once to fully define the manufacturing cell. A holonic structure easily be compared to object orientated programming. A holon designs a class containing data fields as well as functionality. Because of this remarkable similarity it is fairly easy to integrate the structure into program code. Beside the information part a holon usually also possesses a physical part. A holon may even be part of another holon [3].

The 2D Visual inspection system is one component of the Resource Holon. (Fig. 3) The 2D vision system consists in fixed and mobile cameras (arm mounted cameras), and the vision framework system AdeptSight™. AdeptSight™ is an easy-to-use, standalone vision guidance and inspection package. The software includes a powerful framework that can be used to develop customized vision guidance and inspection applications. The vision framework allows developing and adding vision capabilities that help deal with smaller parts and tighter tolerances, and achieve higher quality products. The implemented robust vision algorithms are tolerant to poor lighting, noise, and occlusions. [11]

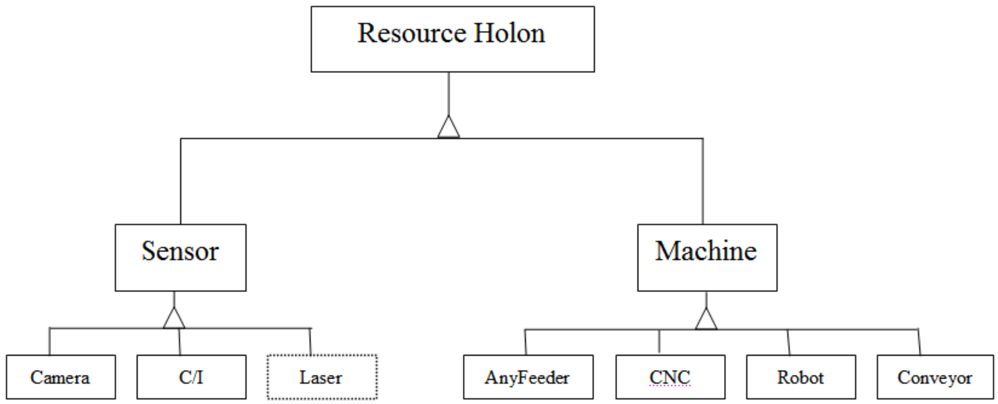

Fig. 3. Diagram class structure for the RH.

When implementing a 2D vision inspection system special care must be paid to the illumination systems and lens to be used. Inappropriate chosen illumination solution may lead to unstable or errors inspections results. Also software cannot correct the effects of poorly chosen lens.

Inspection operations fall into several categories: performing measurements or gauging, recognizing and identifying specific features (pattern matching), reading characters or encoded (bar code) information, detecting the presence of an object or marking, comparing objects or matching an object to a template, and guiding a machine or robot.

The following functions are performed by the integrated 2D vision system: image acquisition, image enhancement, feature detection, recognition and extraction, object analysis and recognition, visual guidance for robots. (Fig. 4)

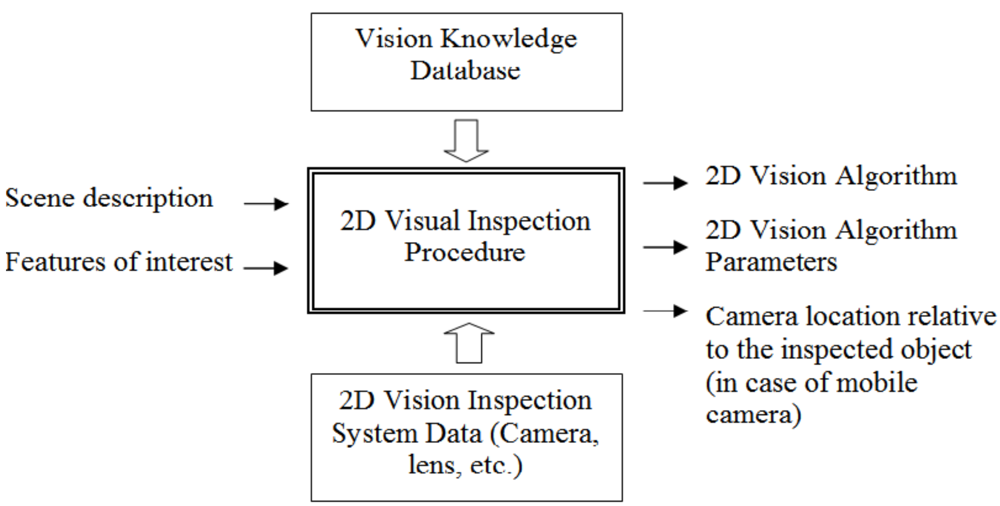

Fig. 4. 2D Automated Visual Inspection System architecture

4. Integrating 3D Visual Measurements into the Manufacturing Cell

Due the increased complexity of inspection applications, standard procedures like the two-dimensional optical inspection don’t always suffice to keep or achieve given quality standards. The standard procedure of the two-dimensional inspection shows weaknesses, since normally the inspection is limited to the top view. Errors like tilted and soldered components (so called tombstoning) cannot be found, because the top view doesn't show the differences between a correct and a faulty soldered component. Using the third dimension within the inspection leads to the detection of undiscovered errors and consequently to an increased product quality.

- *Laser scanning system*

The task to integrate a short range, high-precision 3D laser scanning probe displaced by a 6-d.o.f. vertical articulated robot manipulator into the versatile, multi-team based manufacturing platform presented in section 1, raised several implementation issues to be presented in this section. (Fig. 5)

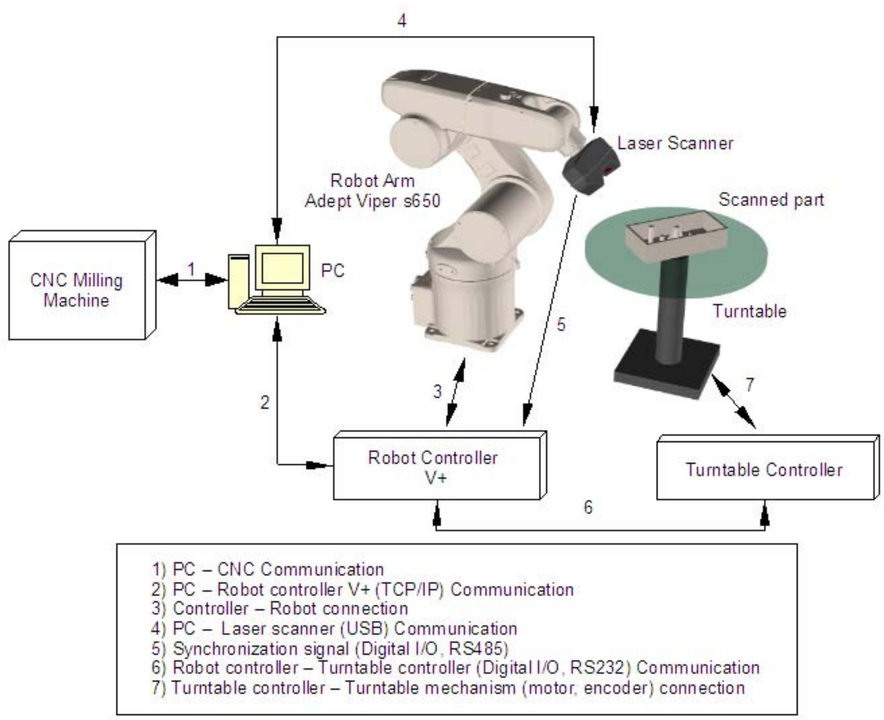

Fig. 5. Hardware architecture of the laser scanner-robot platform for *on-demand* high precision quality control and reverse engineering tasks

The main component of the 3D vision system resides in the laser sensor, called the Rapid Profile Sensor, or RPS. The line range laser sensor collects thousands of points of data per second, making digitizing significantly faster than conventional noncontact measuring technologies without sacrificing accuracy. Line range means that the laser beam is spread out into a plane with passive beam spreader optics which forms a line of light on the object being scanned. The sensors in the probe take measurements over the whole line at the same time instead of measuring just one point of light, as with a point range sensor. This reduces scanning time dramatically.

By using the principle of triangulation, the sensor gathers extensive part profile geometry quickly and precisely. The laser in the RPS probe produces plane of light that intersects the part to be measured. (Fig. 6)

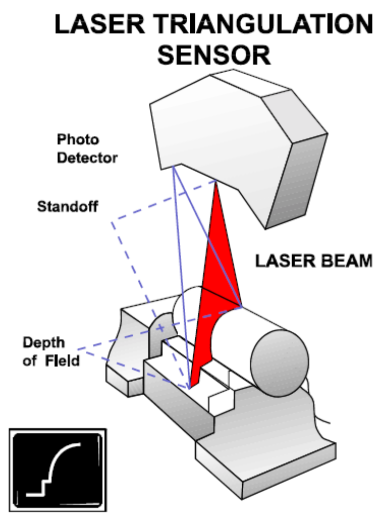

Fig. 6. Triangulation based laser scanner

To integrate the laser scanning and range finder system with the robot system, the following software modules were developed:

- *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 [4].

- *The constraints for the 3D vision system*

For measuring a point on the surface using a laser scanner, several constraints must be satisfied [5]. For explanation, some notations are introduced. *Pi* and *Ni* denote a point on the surface and the unit normal vector of that point, respectively. *Bi* is the bisector of the laser stripe and *L* denotes the laser probe (Fig. 7). All the notations are defined on the plane on which the laser beam lies.

The defined constraints in the robot system are of two types: hard constraints and soft constraints. The hard constraints must be kept at each step of the motion planning in order to ensure a valid path. The hard constraints consist in: known obstacles in the robot workspace, articulated robot singularities and articulated robot joint angle limits. The defined soft constraints are laser scanner imposed constraints (like keeping the minimum allowed scanning distance towards the scanned object), flexible reach (avoiding "un-comfortable" positions of the robot arm) and following the computed path.

The laser scanner imposed constraints considered are the following:

- The view angle constraint must be satisfied at every measurement that the laser scanner is performing. The angle between the incident laser beam and the surface normal of a point being measured should be less than the minimum incidence angle α (20 degrees).
  $d_i \cdot N_i \geq cos(\gamma)$, where $d_i=(L - P_i)/\left| L - P_i \right|$
- The object to be measured must be in the field of view (FOV) of the laser scanner. This implies additional constraints on the laser scanner position. The measured point should be located within the length of a laser stripe.
  $(-d_i) \cdot B_i \geq cos\ (\delta/2)$, where δ is the FOV angle
- Depth of field (DOF): The measured point should be within a specified range of distance from the laser source.
  $l_{STAND} - l_{DOF}/2 \leq \left\| L - P_i \right\| \leq l_{STAND} - l_{DOF}/2$ where l_{STAND} and l_{DOF} denote stand-off distance and DOF length.
- The incident beam as well as the reflected beam should not interfere with the part itself [6].

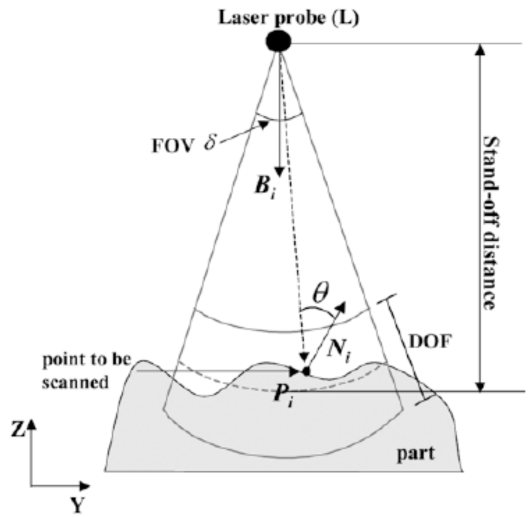

Fig. 7. Optical constraints for the laser scanning system

Also the laser probe should travel along a path that is collision – free. A very important aspect of the implementation consisted in avoiding the existent obstacles in the robot working area. These predefined obstacles are: the turntable, the object to be inspected / modelled, the conveyor and the CNC machine.

Using the utility SPEC of the V+ operating system, one can define up to 4 Cartesian obstacles and clearance distances. There must be defined parameters used to avoid collisions with the existent static obstacles in the workspace. The path of the robot tool tip is automatically tested to ensure that it does not collide with defined obstacles under the following circumstances: when the robot is being moved in WORLD or TOOL manual control mode; when the destination of each motion is being planned; and while straight-line motions are being performed.

Each obstacle is defined by its shape, location, and size. The shape of an obstacle can be a box, a cylinder, or a sphere. The location of each obstacle is defined with respect to the base reference frame of the robot when its BASE transformation is null.

- *Generating scanning paths for 3D visual inspection*

In the first stage of the proposed 3D visual inspection procedure, the surface information is extracted from the existing CAD model. The CAD model can be from various resources (previously modeled free form models, engineering data, etc.). Based on the required measurements, the second stage consists in generating the scan directions and scan regions by analyzing the normal vectors. The region growing method can be used in order to find the best suitable scan direction and the related scan region. These can be varied by modifying the size of the view angle in the allowed maximum angle.

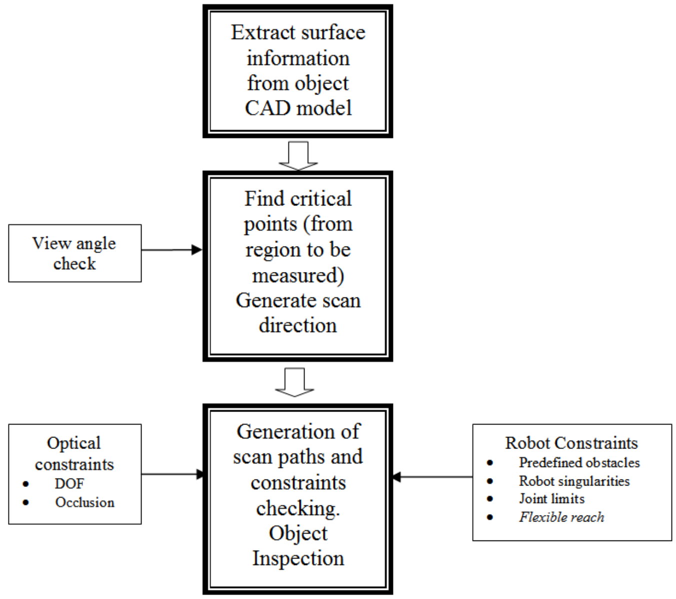

Fig. 8. Laser scanning paths generation

The final step of the proposed procedure consists in generating the scanning paths. The scanning paths should be validated according to the laser probe and robot defined constraints [7]. Quality control inspection is performed based on the generated scanning paths; the data collected being compared with the quality parameters imposed. (Fig.8)

The automatic generation of the scanning plan will enable the inspection operator to build a consistent and efficient scan plan that can avoid erroneous and unnecessary user interactions. It will also facilitate the generation of an optimal plan for a part with freeform surfaces. Even for a skilled operator, this may not be possible by manual inspection planning owing to the complexity of the part surfaces. By automating the generation of the scan plan, the cost and time for the inspection operation can be significantly reduced compared to that for manual operations.

The accuracy and speed of the laser probe make them ideal for rapid inspection and verification application, like: measuring gaps, sectional profiles, feature heights, cores and cavities, etc.

To the present the scanning system can scan the parts with any orientation of the laser sensor that can be achieved physically with the mechanical setup [8].

The resulted data can be compared to the quality parameters for assuring high precision of the machined part. (Fig. 9)

(a) (b)

Fig. 9 Laser scanner resulted 3D data. Original part (9a) and resulted point cloud (9b)

It has been developed a simulator of the laser scanner – robot arm system designed to be a development tool and test bench for the scanning algorithms to be developed. Using a simulation environment for designing the scanning algorithms has several advantages: the possibility of collisions between the robotic arm, laser probe and inspected object is eliminated; 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 **s**ensor resolution, laser beam width, can be freely changed, and the influence of these changes can be analyzed thoroughly [9].

The software simulates the kinematics of the robot arm, and the interaction of the laser probe with a virtual object.

6. Conclusions

While cost pressure remains intense, high quality within the production process is essential for survival. Therefore better methods of testing are needed: old test methods have to be completed to eliminate residual risks. In the meantime optical tests became standard and are improved constantly. The optical inspection on the basis of 2D images cannot detect all possible production defects. Only the third dimension provides the important information. This paper presented the initial work of integrating a 3D visual inspection system in a manufacturing flexible cell.

Future developments will be implemented regarding optimal generation of scanning poses and paths according to the feature of interest to be measured. Other factors also need to be considered for fully automated inspection systems, such as automatic acquisition of tolerance information, further investigation of jigs and fixtures for part orientation, and integration with other existing types of inspection devices.

Fig. 10. 3D Visual Inspection System – physical implementation

The overall 3D visual inspection system features are: in-line 3D measurements can be performed at very high speed; high flexibility in measurements; μm measurements; scalable in function and inspection speed; easy extendible with new measuring components, measuring range extendible due to the robot arm.

R E F E R E N C E S

[1] *Th. Borangiu*, Intelligent image processing in Robotics & Manufacturing, Romanian Academy Publish. House, Bucharest, 2004

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

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

[4] *Th. Borangiu, A. Dogar, A. Dumitrache*, Integrating a Short Range Laser Probe with a 6-DOF Vertical Robot Arm and a Rotary Table, Proceedings of RAAD 2008, Ancona, Italy, ISBN 978-88-903709-0-8, pp. 14

[5] *J.H. Kim. and et al.*, Collision Avoidance Planning of Jointed Robots using Configuration Space, Korean Society of Automotive Engineering, **Vol. 2**, No. 6, 1994

[6] *S. Son, S. Kim, K.H. Lee*, Path planning of multi-patched freeform surfaces for laser scanning, Int J Adv Manuf Technol 22:424-435, 2002
[7] *K.H. Lee, H. Park, S. Son*, A framework for laser scan planning of freeform surfaces, Int J Adv Manuf Technol 17(3):171–180, 2001
[8] *Th. Borangiu, A. Dogar, A. Dumitrache*, Flexible 3D Trajectory Teaching and Following for Various Robotic Applications, The 9th International IFAC Symposium on Robot Control - SYROCO'09, Gifu, Japan, September 9-12, 2009
[9] *Th. Borangiu, A. Dogar, A. Dumitrache*, Modelling and Simulation of Short Range 3D Triangulation-Based Laser Scanning System, Proceedings of ICCCC'08, Oradea, Romania, Int. Journal of Computers, Communications & Control (IJCCC), **Vol. 3**, No. Supl. Issue, pp. 190-195, ISSN 1841-9836, E-ISSN 1841-9844
[10] *F.D. Anton*, R&D collaboration portal and communication platform for remote robot control, U. P. B. Sci. Bull., Series C, **Vol. 70**, No. 2, 2008 ISSN 1454-2342
[11] *S. Anton*, Integrating vision tools in robotic tasks for signature analysis, part measurement and recognition, U. P. B. Sci. Bull., Series C, **Vol. 70**, No. 2, 2008 ISSN 1454-2342.