AUTOMATED ROBOTIC INSPECTION CELLS FOR QUALITY CONTROL

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Abstract: Currently, intelligent robotic systems have become essential for industries. This paper presents two integrated quality inspection cells designed to be used in the manufacturing industry. The proposed systems combine several measurement technologies, robotic systems, and feeding systems, in order to provide an efficient solution for complex measurements tasks: an image processing system, contact measurement systems, a thread measurement system, non-destructive testing (NDT) principles – all integrated in flexible inspection cells. Additionally, the paper presents the design methodology of the two flexible inspection cells.

Keywords: Automatic Quality Control, Robotics, Robotic Cell, Modular Inspection Systems, Collaborative Robots.

1. Introduction

In the era of automation and digitalization, there is an evident transformation of manufacturing. Rapid changes in process technology trigger the need to generate production systems which are easily upgradable and into which new technologies and new functions can be easily integrated [1]. Transition to the smart manufacturing era requires the adoption of a number of technologies including Cloud computing, Information and Communication Technology (IT), Internet of Things (IoT), Artificial Intelligence (AI), Virtual Manufacturing Systems (VMS), and Flexible Manufacturing Systems (FMS) [2-4] [5].

Interconnected manufacturing operations and the ability to control the entire production process in complex industrial environments, represent a major goal in the Age of Industry 4.0 [6]. Interconnected manufacturing systems leads to considerable operational improvement and economic benefits. In this context, the automation of inspection operations is of upmost importance for intelligent manufacturing systems. Intelligent industrial production processes require automated measuring cells for better planning, total quality control, and higher repeatability. Automated robotic inspection cells are essentially a flow shop, which contains a feeding device, an output device, a series of workstations (measurement/control stations, sorting stations, etc.), each repeatedly performing a certain operation in a fixed sequence, and one or more robots that transport the parts inside the cell.

Nowadays, robots have become essential for industrial processes' automation. The robotic solutions are usually applied for complex repetitive tasks. Figure 1 shows the number of industrial robots installed in 2019 in factories in Top 15 countries around the world.

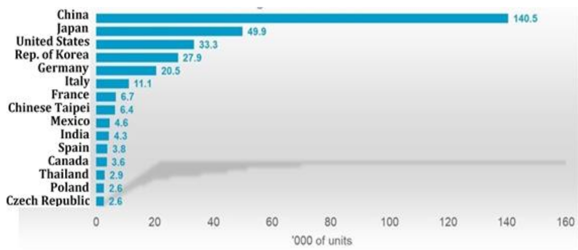


Figure 1: Annual Installations of Industrial robots in TOP 15 countries (Source: World Robotics 2020 Report)

For small and medium-sized enterprises (SMEs), any gain in productivity can have a huge impact. Automation offers significant advantages, but many SMEs believe that robotics is out of their reach. Since SMEs provide more than 55% of the value added by the manufacturing industry in the European Union [European Commission, 2020], it is vital to allow them to introduce efficient and easily flexible robotic solutions to ease and speed up the product manufacturing. These robotic solutions must have a modular construction (a structure consisting of modules or components that can be combined in a flexible way across a system). Besides, a major benefit of modular working systems is flexibility.

Over the years, many studies and research efforts have tried to find a solution for optimising the robotic working cells design. Thus, aspects related to the robotic cell layout optimisation [7-8], simulation tools for processes optimisation [9], and robot trajectory planning optimisation [21] were analysed.

Nowadays, inspection is an area of factory operations in which there is a significant interest in automation by using robots, in order to develop reliable solutions to speed up repetitive inspection of large numbers of components [10][11]. Although robots have been widely used in the automation of various manufacturing processes, such as assembly, drilling, painting and material handling, the low positioning accuracy is a serious drawback in the use of industrial robots in measuring systems. Industrial robots have good repeatability (i.e., from ±50 µm to ±300 µm), but their positional accuracy can have errors of several millimetres [12]. Robots error sources include, but are not limited to:

- Commissioning errors: tool centre point (TCP) offset, workpiece and robot spatial relationship;
- Manufacturing/mechanical errors: linkage length, axis perpendicularity, eccentricities, linkage elasticity, backlash.
- Dynamic and inertia-based errors.
- Temperature based errors: robot warm-up, ambient temperature influences.

The potential of using robots in dimensional control increases with the development of new sensors, vision processing equipment, micro-controllers, and computers, with better performance at lower cost. The flexibility of robots in combination with more accurate, high-performance sensors will provide efficient solutions to different inspection tasks [13]. Dedicated studies present some examples of automatic inspection systems involving industrial robots and laser scanners or 3D vision sensors [10][12] [14–16]. However, the current literature does not present automated solutions that involve a combination of a robot and contact measurements, in which the robot replaces the operator of the measuring machine [15].

In this paper, we present two integrated quality inspection cells for the manufacturing industry, developed as modular systems, which combines several measurement technologies, robotic systems, and feeding systems, in order to provide an efficient solution for complex measurements tasks. The two inspection cells are robot-centred: one including a 6-axes articulated robot and the latter featuring a combination of an articulated robot arm and a linear YZ gantry robot.

2. Design of a Robotized Inspection Cell

The purpose of the research presented in this article is to present two cases study for the design of flexible cells intended for:

1. Inspection of the ball pivots, components of the automobile steering systems

Area of inspection: automotive components manufacturing

Inspection tasks:

- dimensional control: ball pivots torx hole depth (L1); length L2; (figure 2)
- thread integrity control at distance L=L2-L3 (figure 2);
- eddy current non-destructive (NDT) inspection.

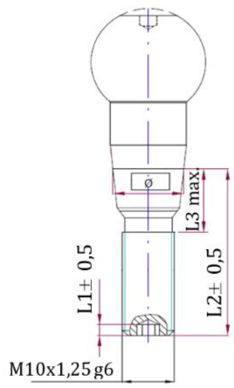


Figure 2: Ball pivot for automotive steering system

2. Form and dimensional inspection of small and medium size CNC machined parts

Area of inspection: automotive, aerospace or other manufacturing industries

Inspection tasks: form and dimensional deviations of outer and inner surfaces.

Measurement performances:

- resolution ≤1 µm;
- repeatability ≤±2 µm
- accuracy: ≤ ±0.01 mm

Figure 3 shows some examples of parts to be measured.

Figure 3: Examples of parts to be measured, manufactured on CNC machine-tools

The design of a flexible robotic cells for inspection purpose is a complex process which requires several factors to be considered.

In this section, we present the methodology used to design the two flexible inspection cells.

Figure 4 depicts the main steps involved in the design process of the two robotic inspection cells.

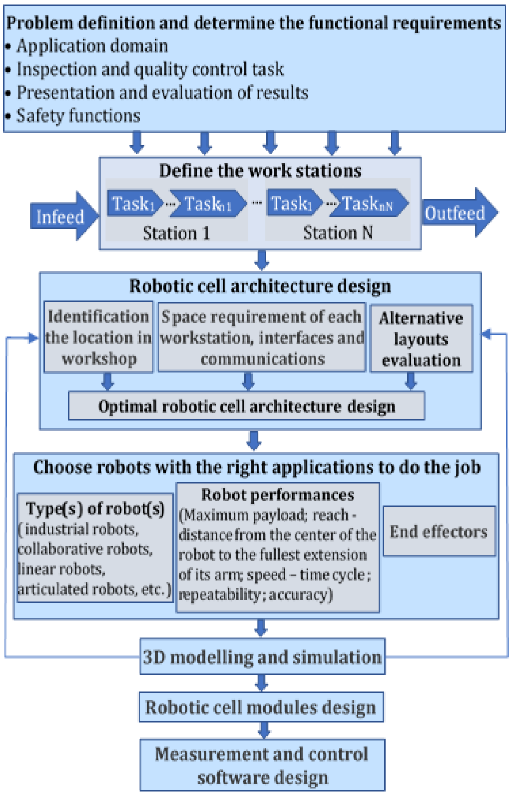


Figure 4: Design process flow chart

The first step was to analyse the functional requirements and the tasks of the system to determine all the components required for the cell to operate properly. This analysis was based on the customer needs, characteristics of parts to be inspected, and the manufacturing process [18]. From these analyses, we could draw specific lists of tasks to be performed automatically, performance requirements, the sequence of the tasks (tasks relations), and a distribution of tasks between workstations/ component modules.

Both inspection cells have modular structures. The modular structures give the flexibility of the robotic inspection cells.

There is no universal structure for a robot-based work cell. The most basic and important components present in a robot-based inspection cell are:

- N inspection stations (equipment) (IS)

$$IS = \{IS_i \mid i = 1,2, ..., N\} \tag{1}$$

- n robots (IR)

$$IR = \{IR_j \mid j = 1,2, ..., n\} \tag{2}$$

- a number k of buffers (BF) for feeding, sorting and outfeed the inspected products

$$BF = \{BF_l \mid l = 1, 2, ..., k\} \tag{3}$$

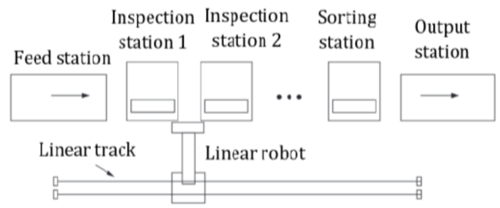
Other components of the flexible inspection cell are: a robot end effector, safety elements, a controller for controlling the cell.

For all these modules, the integration requirements (communication, relationship, interfaces) must be defined.

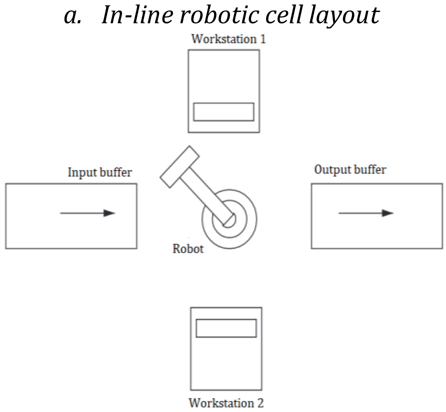
The second step was to design the system architecture. All workstations should be positioned relative to each other in a way that allows rational use of production space, optimizes the inspection cycle, guarantees operator safety and provides easy access for maintenance.

Robot-based work cells can be organised into various arrangements or layouts. In our work, we have considered two basic types (in line and circular robot cells) and combinations of them. In figure 5.a is presented the in-line robotic cell type and in figure 5.b is shown the circular (robot–centred) type.

At the end of this stage overall robot cell dimensions and how parts get in and out of the cell are identified precisely.



a. In-line robotic cell layout



b. Robot-centred cell layout

Figure 5. Robotic work cell layout examples

For each of the two inspection cells, optimal design, different alternatives were preliminarily analysed, taking into account different parameters such as: optimal use of the space, reduction of the time cycle, different types and numbers of robots, etc. For evaluating the alternative solutions are used a number of criteria, such as: cost; flexibility; cycle time; overall length of the robotic motion.

The next step was the robot(s) and the end-effector(s) selection. The selection of the robot(s) was influenced by several factors including: payload capacity, workspace, positioning accuracy, repeatability, joint type, kinematics, weight of the robot, speed of the robot, programming flexibility, and total cost.

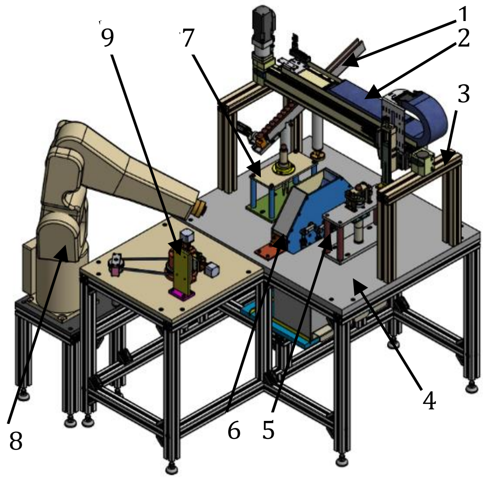
For end-effector selection the following aspects were considered: application (the shape, size, texture and rigidity of the handled parts), payload and gripping force, gripping range, gripping speed, compatibility with the chosen robot, cost.

Based on the 3 steps presented above, 3D models of flexible inspection cells were designed and computer simulations were performed (using Autodesk Inventor program) to analyse the kinematics of the designed systems.

The design process was completed by the detailed design of all hardware and software modules of the inspection cells.

3. Flexible Cell for Inspection and Sorting the Ball Pivots

In figure 6, is presented the architecture of the flexible cell for inspection and sorting the ball pivots.



1. Feed/output station; 2. Cartesian robot (Linear gantry YZ - FESTO); 3. Base frame for cartesian robot supporting; 4. Base table; 5. Thread integrity control station, 6. Station for non-compliant parts sorting; 7. Station for dimensional measurement (length and torx hole depth); 8. Spherical (6 axes) robot – IRB 1200 - 7/07; 9. NDT testing station

Figure 6: Architecture of the ball pivots inspection and sorting cell

Layout of this robotic inspection cell results as a combination of an in-line and a robot-centred working cells structures. This inspection and sorting robotic cell is composed of distributed quality control devices and handling elements.

A programmable logic controller (PLC SIEMENS S7-300 with a central processing unit CPU 315-2 PN/DP) continuously monitors and controls all of these devices. Each of the functional devices of the inspection and sorting cell constitutes independent entities, which can operate independently (in the different phases of the process) and is subordinated to the cell controller. The PLC has digital input / output modules and it is set as a MASTER system (PROFIBUS). The programming language used is STEP 13.

The use of intelligent measurement systems allows overlapping execution times of some operations and thus, the entire process time cycle can be reduced.

The block structure of the system is shown in figure 7.

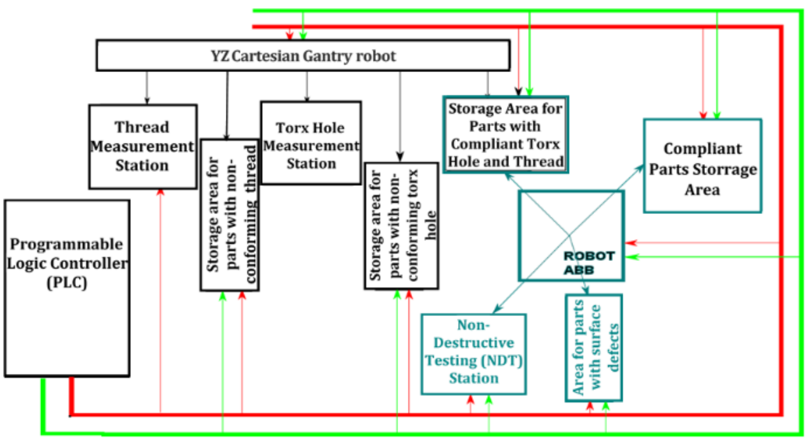


Figure 7: Block structure of robotic cell for ball pivot inspection and sorting

The operating cycle is shown in figure 8.

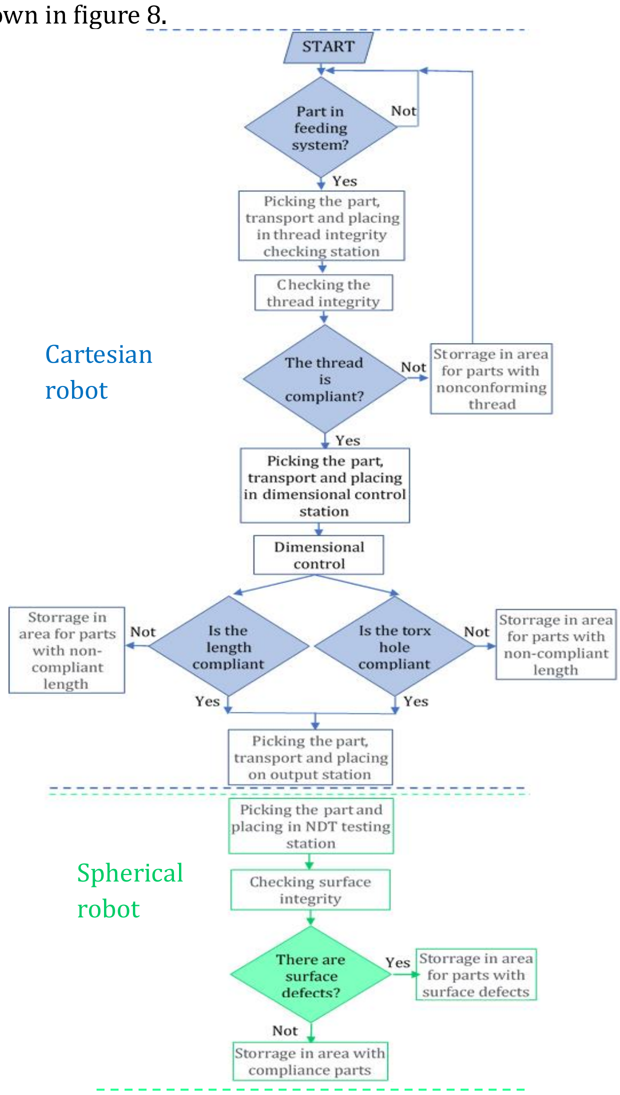


Figure 8: Operating cycle of the robotic cell for ball pivot inspection

4. Flexible Cell for Inspection CNC Machined Parts

The architecture of designed inspection cell for automatic multi-parametric quality inspection of parts manufactured with CNC machine-tools is shown in figure 9.

This is a flexible inspection system, easy to set up for the production requirements. The compact design allows for in-process placement on the workshop floor.

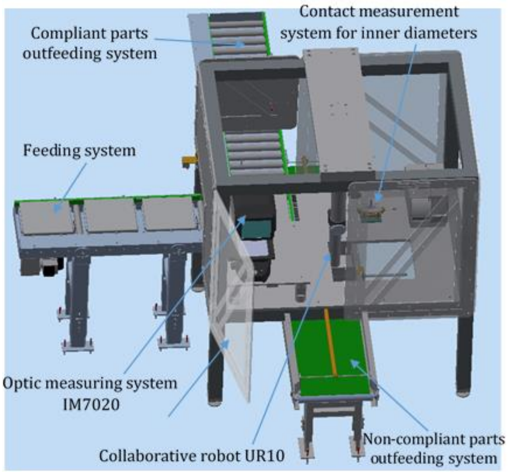


Figure 9: Inspection cell architecture

This is a flexible inspection system, easy to set up for the production requirements. The compact design allows for in-process placement on the workshop floor.

It is generally known that robot-centred cells are preferred in practice because they reduce the required physical space. This flexible inspection cell is built around a manipulator robot type UR10 (a collaborative robot). It ensures the handling of the parts inside the cell, picking the parts from the feeding system, positioning the parts in the measuring stations, and placing the measured parts on the outfeed systems (for either compliant or non-compliant parts). The UR10 has 6 joints with 360 degrees of rotational freedom, a working radius of 1.3 m and can support 10 kilograms. The Polyscope software interface allows quickly and easily programming. According to Universal Robots UR10 has a repeatability of 0.1 mm.

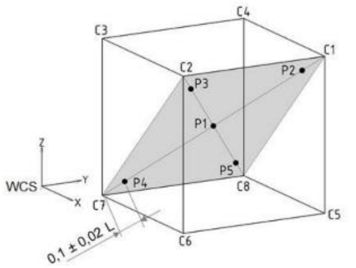
The benefits of using collaborative robots include: they increase the safety of employees, are easily programmable, quick to set up, flexibly applicable and quickly amortized.

Collaborative robots are characterized by very good repeatability, but not very good accuracy. The positioning accuracy is influenced by wear in joint connections, friction, transmission errors in gears, accuracy of the manipulator elements execution, mechanical stiffness, computational errors, work environment, elastic effects of components and mounting method, and other static and dynamic factors. [19][20]

Because of the fact that the accuracy of the industrial robots is not always very good, calibration and repeatability are essential for achieving the desired functions. The standards most suited for the robot performance evaluation are: ISO 9283 and ANSI / RIA R15.05.

According to the ISO 9283 standard, all the testing should be performed inside the so-called ISO test cube (the largest cube that can fit inside the robot workspace). Furthermore, position accuracy and repeatability should be measured at five different configurations (Points P1…P5) (figure 10).

The measurement consists of 30 measuring cycles, within which the TCP point moves to points P1…P5. Coordinates of each point are measured after reaching its pose and then accuracy and repeatability is calculated.



L = diagonal length (mm)

Figure 10: ISO 9283:1998 cube

A digital gauge, with a resolution of 0,1 μm, was used for the measurement. The measurements were performed in three perpendicular directions, parallel to the coordinate axes of the robot base. The 5 points P1…P5 were determined for a cube with a side of 780 mm, via a simulation in Autodesk Inventor. The coordinates of the 5 points are:

- P1 (0,0,390)
- P2 (-312,70; 852,64;702,65)
- P3 (312,70; 852,64;702,65)
- P4 (- 312,70; 227,37;77,35)
- P5 (312,70; 227,37;77,35)

The repeatability assessment was performed for a load of 1.2 Kg (Robotique 2F-140 gripper weight) and a load of 3.7 Kg (gripper weight + a payload of 2.5 Kg).

The robot arm was manually moved to a position corresponding to the approximate coordinates of one of the five measuring points (figure 11), and the position of the digital comparator was adjusted on the X measuring axis. The position of the robot was recorded and the automatic return of robot arm was commanded, 30 times, in the same position, on the same trajectory. The indications of the digital gauge have been registered. A similar procedure was performed for the Y and Z directions, for all the five points.

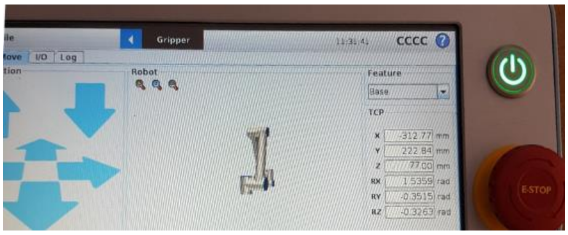


Figure 11. Coordinates of the measured point P4 on UR10 robot teach pendant

The mean coordinates of the measured poses are calculated using equations (4)-(6).

$$\overline{X_F} = \frac{\sum_1^n x_{i(F)}}{n} \tag{4}$$

$$\overline{Y_F} = \frac{\sum_1^n y_{i(1,2)}}{n} \tag{5}$$

$$\overline{Z_F} = \frac{\sum_1^n z_{i(F)}}{n} \tag{6}$$

Where:

- x_i, y_i, z_i are measured coordinates
- n is the number of measurement cycles
- $\overline{X_F}, \overline{Y_F}, \overline{Z_F}$ are the mean coordinates of the measured poses
- F is the load

The repeatability of the positioning for each of the 3 coordinate axes, for a load of F (kg) are calculated using equations (7)-(9).

$$S_{X(F)} = \sqrt{\frac{\sum(X_{jF} - \overline{X_F})^2}{n-1}} \tag{7}$$

$$S_{Y(F)} = \sqrt{\frac{\sum(Y_{jF} - \overline{Y_F})^2}{n-1}} \tag{8}$$

$$S_{Z(F)} = \sqrt{\frac{\sum(Z_{jF} - \overline{Z_F})^2}{n-1}} \tag{9}$$

The analysis of the results showed that the repeatability of UR10 is not significatively influenced by the payload on the X and Y directions.

For the Z direction, repeatability increases with payload (increase from 0.031 mm, at a load of 1.2 kg to 0.073 mm at 3.7 kg).

The results show that the UR10 robot is suitable for handling parts inside the designed inspection and sorting cell.

The functional scheme of the inspection cell is presented in figure 12.

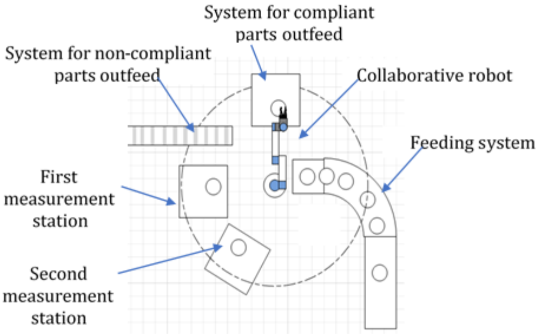


Figure 12: Functional scheme of inspection cell

This inspection cell includes two types of measurement equipment:

- an optical measuring system based on digital image dimensions measurement (figure 13)
- a contact measurement system for inner surfaces (figure 14).

The optical measurement system (IM – 7020 - Keyence) has the following advantages:

- automated detection of a part's position and orientation on the stage
- versatile programming for parts inspection
- accurate and repeatable measurements (Repeatability up to ±1 µm; Accuracy up to ±2 µm)
- automated focus adjustment and lighting settings
- capacity to measure a wide range of part sizes (Field of view = 200 mm × 200 mm).

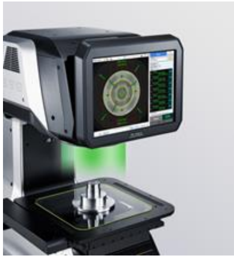
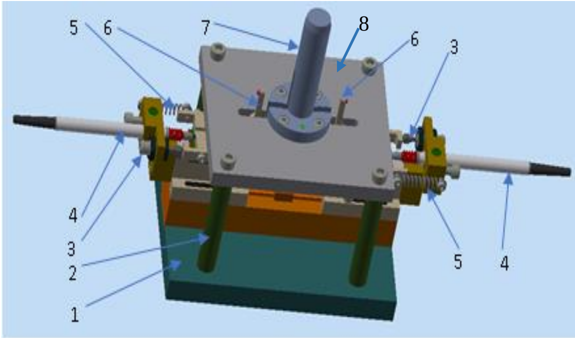


Figure 13: Optical measurement system (IM – 7020 - Keyence)



1. Base plate; 2. Upper plate support columns; 3. Pneumatic microcylinders; 4. Displacement digital transducers; 5. Springs; 6. Interchangeable probes; 7. Centring mandrel; 8. Upper plate

Figure 14. Inner diameter measurement system

According to figure 14, the system for measuring the inner diameters consists of: a mandrel (7) for centring the measuring parts; 2 measuring probes, diametrically opposed (6), symmetrical to the centring mandrel; digital transducers (4), with a measuring range of 12 mm and an accuracy of 0.002 mm; springs (5) that ensure the measuring force; pneumatic cylinders (3), with a stroke of 20 mm, for retracting the probes after measurement; base plate (1) for positioning the measuring system; the upper plate (8) on which the centring mandrel is positioned.

The head of the centring mandrel has a conical portion to allow easy positioning of the part in the measuring station by means of the robotic arm (figure 15). The mandrel and measuring probes can be changed depending on the dimensions and geometry of the measured part.

Figure 15: UR10 robot with a 2F-140 adaptive gripper

The digital transducers used for measurement have a module for RS-232 C serial communications.

Feeding and outfeed systems consist in motorized conveyors, easily adaptable to the configuration of the production line.

5. Conclusions

Product-quality and process control are gaining influence in the process industry and are an inherent part of Industry 4.0. Robotic inspection cells increase measurement systems capability and manufacturing quality reducing or eliminating the human-operator influence on the measurements.

In this paper, we present the drawing process for two robotic cells, with applicability in total and efficient inspection process of automotive, aerospace, and industrial components. We also discuss a systematic way to design a robotic cell, with clearly defined tasks and objectives in terms of time and cost efficiency. The proposed system combines different measurement and quality control techniques with in-line or spherical robots and feeding/ out feeding systems, in order to provide efficient solutions for the automation of inspection processes involving parts with complex geometry.

Moreover, the presented inspection cells have modular structures, as the modular construction gives flexibility to the inspection cells.

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