Design of a Positioning System for Cylindrical Parts

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Abstract: *This paper presents the design, development and testing of a semi-automatic inspection machine for cylindrical parts dedicated to the automotive industry. The system integrates an optical micrometre and multiple smart cameras along a linear rail positioning mechanism. The paper attacks the industrial challenges and motivations, the evolutions of quality control machines, from conveyor and rotary based solutions to robotic arms and linear rail systems. The machine contains a Keyence TM-3000 optical micrometre with four Keyence IV-2 cameras, supported by a poka-yoke like positioning base. The technical principles of measurement and visual inspection are analysed in detail to provide a wider understanding. Experimental testing was realised through PneuAlpha, validating the accuracy and repeatability of the proposed system. The economic evaluation demonstrates a payback period of approximately two years, making the system viable for mass quality control in the automotive sector.*

Keywords: *Quality control, positioning system, machine learning, mechatronics*

1. Introduction

In industrial manufacturing, the role of quality control has become increasingly critical over the last decades. As markets become more competitive and product lifecycles shorter, companies are under pressure to increase productivity and also guarantee that every product is up to standards before leaving the factory. This is particularly evident in the automotive industry, where safety is of up-most importance to avoid recalls, warranty claims and lost customer trust that can reach millions of euros in loses [1].

Traditionally, quality inspection was performed manually by trained operators. While manual inspection is flexible and low in initial investment, it is subject to human variability, fatigue, and limited repeatability [2]. These limitations have become dealbreakers in industries that require micrometric-level tolerance and continuous production flow. Consequently, automation has become the dominant trend in inspection, supported by technological advanced in mechatronics, sensors, and machine vision [3].

The beginning of Industry 4.0 has further accelerated this transition. Modern inspection systems are no longer isolated islands, but are integrated into digital manufacturing ecosystems, providing real time data for process optimization, predictive maintenance, and closed-loop control [3]. Automated inspection is not only a tool for detecting defects, but it can also improve overall equipment effectiveness to try and achieve zero-defect manufacturing [4].

This led to evolution of hybrid inspection systems that combine dimensional metrology with visual defect detection. Dimensional deviations represented by out-of-tolerance diameters or lengths, can be captured with the high precision optical micrometre, while visual anomalies such as scratches, iron feelings or incomplete machining can be identified through the smart cameras from Keyence that are supported by machine learning algorithms [5]. When these subsystems are integrated into precise positioning mechanisms, the result is a powerful inspection machine that meets the dual requirements of speed and accuracy.

This paper presents the design and validation of such a system, dedicated to cylindrical parts used in automotive applications. The installation combines a Keyence TM-3000 optical micrometre with four Keyence IV-2 smart cameras mounted in circle on a linear rail positioning system. The purpose is to demonstrate that merging advanced measurement equipment with a good positioning solution, it is possible to achieve reliable, repeatable, and economically viable inspections.

2. State of the art on quality control machines

The evolution of quality control machines has followed the trajectory of industrial manufacturing itself, progressing from purely manual checks performed by trained operators to complex automated installations. As the need for accuracy and repeatability has increased, industries have moved away from human-centred verification to machine-centred inspection, where sensors, actuators and a software replace the eyes, the hands and the brain of the humans [6].
Modern quality control machines can be classified according to the type of transport and positioning system used to bring the part into the inspection area. While the inspection principle may vary, depending on the product, the effectiveness of the inspection depends heavily on how consistently and precisely the part can be positioned relative to the sensors. In this field, four main categories of positioning systems stand out: conveyor-based systems, rotary table machines, robotic arm solutions, and linear rail systems. Each category has its own domain of application, advantages, and limitations.

2.1. Conveyor-based machines

Conveyor-based machines are among the most widely used solutions in the large-scale manufacturing, particularly in industries where parts must be inspected at high speed in continuous flow. The basic principle relies on a belt or a chain conveyor that transports parts through one or several inspections stations. At each station, measurements or visual checks are performed by sensors or cameras synchronized with the conveyor motion.
These systems are common in the electronics, packaging, and food industries, where large volumes of products pass through identical inspection routines. The advantage of conveyors includes easy integration into automated production lines, and relatively low mechanical complexity. However, positioning accuracy is often limited by vibrations, belt slippage and difficulty to stop the parts for high-precision checks. This makes conveyor systems better suited for simple surface and dimensional checks rather than micrometric-level inspections [2].

2.2. Rotary table systems

Rotary table inspection machines use a circular platform divided into multiple stations, with parts placed in fixtures mounted around the table perimeter. As the table rotates step by step, each part sequentially passes through various inspection points, such as dimensional measurement, surface analysis, or functional testing.
These machines are particularly efficient when multiple inspection operations must be performed in sequence within a compact footprint. Their cyclical operation ensures consistent cycle times and repeatability. Rotary tables are frequently encountered in small component manufacturing, such as connectors, small auto parts and precision moulded parts. It's a compact machine that can realise multiple inspections at the same time in a small space, that facilitates using this type of machines in a small size factory that has a higher production.
The main advantage of rotary table systems are their compact design, high productivity, and ability to integrate several tests within one rotation. However, limitations include wear of the rotating mechanism, the need for precise synchronization of sensors, and reduced flexibility for handling parts of significantly different geometries [7].

2.3. Robotic arm systems

Robotic arm systems represent the most flexible approach to automated inspection. Equipped with multi-axis manipulators, grippers, and advanced vision systems, robotic arms can handle parts of varying geometries and place them precisely in front of different sensors. They are often combined with coordinate measuring machines or high-resolution cameras to perform complex inspections.
The key advantage of robotic arm systems lies in their adaptability: a single installation can inspect multiple product types simply by changing the inspection program. This makes them well suited for high-mix, low-volume production environments. In addition, robotic systems integrate easily into Industry 4.0 ecosystems, with connectivity to manufacturing and real time data analytics platforms.
Despite their flexibility, robotic arm inspection machines come with drawbacks. Their acquisition cost is significantly higher than that of a conveyor or rotary system, and their operation requires

specialized programming and maintenance expertise. In addition, cycle times are generally longer due to the need of precise movements, making them less efficient in high-throughput scenarios [8].

2.4. Linear rail systems

Linear rail systems have emerged as highly precise alternative for applications where accuracy and repeatability are important. These machines rely on a guided linear motion, typically supported by ball bearing rails, to transport parts to the inspection zone. The motion can be driven by stepper motors, servo motors or pneumatic actuators, with belt or screw mechanism providing power transmission.

The main advantage of linear rail machines is their ability to provide stable, repeatable positioning of parts, even at high speeds. For cylindrical or prismatic parts that must be measured under strict tolerances, linear motion eliminates many of the uncertainties associated with conveyors or rotary systems. Furthermore, linear rails are mechanically simpler than robotic arms, while still offering flexibility in integrating different types of sensors or cameras along the inspection path.

Applications of linear rail inspection machines include the automotive, aerospace, and medical device industries, where product reliability depends on micrometric precision. The installation presented in this paper belongs to this category, as it combines optical and vision sensors within a linear rail positioning framework [9].

3. Description of the proposed installation

The developed inspection machine integrates dimensional and visual inspection subsystems into a single installation. The dimensional verification is achieved using the Keyence TM-3000 optical micrometre, which uses telecentric optics and high-speed scanning to capture profiles with a micrometric accuracy. Visual inspection is performed by four Keyence IV-2 smart cameras, with 3 of them mounted at 120° relative to each other, to eliminate blind spots, and a fourth camera above the part to check its upper profile. These cameras utilize machine learning algorithms trained with datasets of conform and defective parts, enhancing accuracy against variable surface finishes.

The cameras are mounted inside a lightproof chamber to eliminate interference from external illumination. This ensures repeatable conditions across inspection cycles. The micrometre and cameras are synchronized through a central control system, which coordinates measurement acquisition with the movement of the positioning system.

Fig. 1. General view of the semi-automatic inspection installation

4. Positioning system analysis

The positioning system represents the backbone of the inspection machine, as the reliability of the measurement process depends directly on how accurately and consistently the part can be placed under the sensors. Any deviation in positioning introduces uncertainty in both dimensional and visual inspection, which is unacceptable in applications requiring micrometric-level tolerances [10].
To minimize these risks, the installation was equipped with a support for the parts based on the poka-yoke principle. This represents the first layer of inspection as an undersized cylindrical part will not be able to fit on the support, also it won't be able to fit, if the part is flipped as the base is wider than the top of the cylinder, thereby eliminating operator error. Through this constrains of geometry, the cylindrical components are going to arrive in front of the sensors under identical conditions, which guarantees consistency across repeated inspections.
The translational movement of the support is achieved using a linear rail with recirculating ball bearings. This solution provides low friction and high stiffness, which are essential characteristics for precision positioning. The rail guides the part smoothly along a single axis, aligning it with the optical micrometre and camera system.
Motion is generated by a NEMA 17 stepper motor, chosen for its balance of torque, compact dimensions, and ease of integration with digital drivers. The motor is controlled through a micro-stepping driver, which allows smooth movement and high-resolution positioning. Power is transmitted by a GT2 timing belt, tensioned with a spring-loaded mechanism to prevent slack and eliminate backlash effect. This arrangement ensures that the system maintains table and repeatable displacement, even at higher speeds.
Alternative solutions were considered during the design stage. Ball screw mechanism, while capable of providing higher rigidity and precision, involve greater mechanical complexity and increased costs. Pneumatic actuators were also analysed as a low-cost alternative, but their limited control and lower repeatability made them unsuitable for micrometric inspection tasks. The final choice of a belt-driven linear rail represented probably the best compromise between precision, reliability, and economic feasibility.
Comparable approaches, where numerical optimization and CFD simulations support the validation of high-precision mechatronic systems, are reported in a research on centrifugal pumps for spacecraft cooling systems [11].
Experimental validation confirmed the performance of the chosen design. The system demonstrated the ability to achieve speeds of up to 180 mm/s without loss of steps, maintaining accurate synchronization with the acquisition cycle of the micrometre and cameras. The repeatability of the positioning system ensured that the inspections process could be performed under controlled and stable conditions, which is a critical requirement for industrial adaptation.

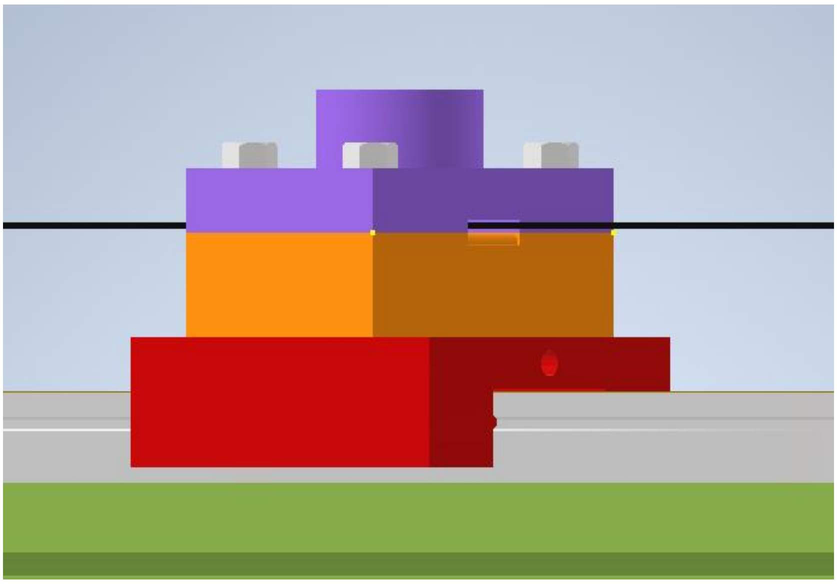

Fig. 2. Positioning system mounted on the linear rail

5. Experimental testing with the PneuAlpha

Validation simulations were carried out on the PneuAlpha app, which replicates production-like conditions. The objective was to better understand and simulate the steps of the system when checking one cylindrical component. The Keyence IV-2 cameras were trained with datasets of both conform and non-conform parts, and the algorithm parameters were adjusted to minimize false positives and negatives. The system consistently detected defects such as scratches and pores with high reliability, while dimensional results from TM-3000 confirmed deviations within tolerance limits.
Similar validation procedures combining numerical modelling with experimental tests have been successfully applied in optimization of aerospace pumping systems [11].
Future experiments will involve an extended data sheet with more defect types and deliberately introducing environmental variations, such as lighting changes and vibration, to further test adaptability.

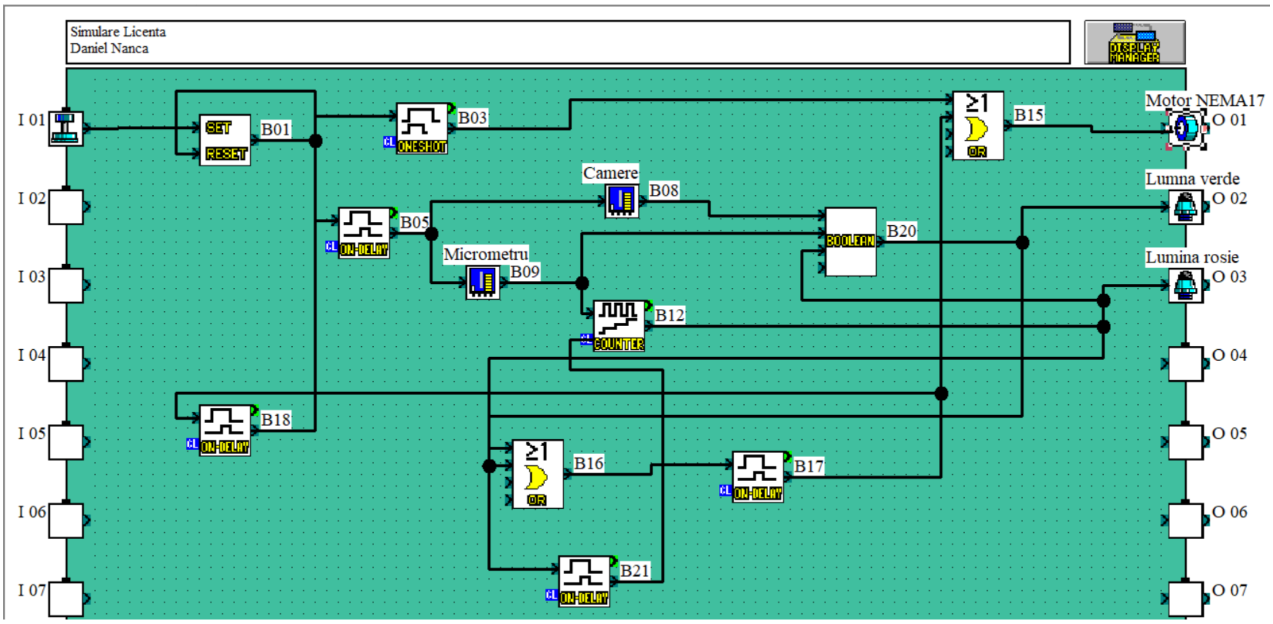

Fig. 3. Experimental setup with the Pneu Alpha stand

6. Economic efficiency evaluation

From an economic perspective, the main costs of the installation derive from acquiring the optical micrometre, smart cameras, and the positioning system components. However, these are offset by reductions in operator involvement, inspection cycle time, and defect-related losses. The estimated payback period is approximately two years, which aligns with industry benchmarks for automation investments; in addition, indirect benefits such as improved customer satisfaction and reduced warranty claims further enhance the economic case.

7. Conclusions

This project presents the design, analysis, and validation of a semi-automatic inspection machine for cylindrical parts. By integrating a Keyence TM-3000 optical micrometre with IV-2 smart cameras in a linear rail positioning system, the solution demonstrated micrometric accuracy and reliable defect detection. Testing the model on the PneuAlpha app, confirmed repeatability, experimenting with the visual cameras confirmed accuracy, while economic analysis indicated a favourable return on investment. Future developments will focus on extending automation towards a fully autonomous inspection line and broadening the detection capabilities with additional sensor integration.

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