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AN INNOVATIVE SOFTWARE INTERFACE SOLUTION FOR INDUSTRIAL APLICATION OF MACHINE VISION ON A SMART ASSEMBLY /DISASSEMBLY MECHATRONIC LINE

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Abstract: ***This paper presents a revolutionary approach to image analysis, specific to quality testing (QT) processes performed in industrial manufacturing processes, which integrates specific concepts of Industry 4.0 and Industry 5.0. The results of the research were translated into an innovative software interface, finally customized for testing the manufacturing quality on the mechatronic assembly and disassembly lines. The QT control structure, subordinated to the new technologies of Industry 4.0 and Industry 5.0, proposes that the acquisition sequences, analysis, decision-making and historical recording of quality data, be implemented through a server application (SA) and remotely through client applications (CA). Additionally, the system's hardware configuration and embedded software components function analogously to an Internet of Things (IoT) sensor, providing a framework for real-time process analysis and control. The QT system is structured as a Machine Vision (MV) framework, leveraging advanced image processing techniques to extract relevant information, thereby enhancing the reliability and detail of quality assessments. In this setup, the mechatronic line is seamlessly integrated with cutting-edge analytical and control functionalities, enabling robust production monitoring and remote-control capabilities through the SA. Concurrently, the CA software offers enhanced flexibility for customizing production orders in response to customer demands. Following the implementation of this MV-based control structure, which utilizes the developed software interface for image analysis, a series of performance tests were conducted to validate system efficacy and adaptability within an automated production environment.***

Keywords: SMART Assembly / Disassembly, Quality Test Management System, Machine Vision.

1. INTRODUCTION

Currently, in large production series, the aim is to increase productivity and production quality, by making maximum use of production resources and minimizing losses. Moreover, given the massive integration of Industry 4.0 and Industry 5.0 concepts into industrial processes, manufacturing systems offer remote access monitoring and control functions on computer systems connected through communications networks [2].

Mechatronic production systems are designed to adapt to different product typologies - flexible manufacturing, using the same hardware resources with the reconfiguration of interconnected stations, or through new control algorithms developed to reconfigure the flow of the production process, served by robotic systems for handling and transport operations [6].

In modern production systems specializing in assembly operations, the goal of production management is that the assembly process must be faster and faster, and quickly adapt to production requirements with a high degree of manufacturing flexibility. There are rules of good practice used to raise the flexibility level and the efficiency of assembly process: using an appropriate material handling system according to the production process (conveyors, autonomous vehicle, autonomous robots etc.), using as many robotic arms as possible in the production flow, using autonomous processes and using the concept of disassembly in the production process [1].

The assembly process can be divided into three categories: mechanical fastening, adhesive bonding and joining methods. Each category is fitting, according to necessity, to a specific production process. In the case of the product assembled from parts designed for assembly and disassembly, the most used method of assembly is mechanical fastening [7].

Autonomous mobile robots are integrated to improve the disassembly process in the production process. The use of collaborative robot structures, connected in parallel or alternative control structures, lead to the reduction of effective production times or auxiliary times, generated by handling and transport operations. Therefore, they bring an economic advantage by minimizing the cost [14].

Thus, this paper proposes a software solution developed for the control of a quality assurance system on a flexible mechatronic manufacturing line with component recovery. The research presented in this article was carried out on a mechatronic assembly and disassembly line, which can be adapted to the production of products with monolayer typologies or multilayer typologies, obtained through recurrent assembly operations. In order to determine the compliance of the products with the imposed standard, it was necessary to integrate a quality management system. All aspects of these topics have been detailed in chapter two. In the third chapter, the following aspects were detailed: the architecture of the MV system, the hardware structure proposed for the MV system, and the algorithm used for image processing using the MV acquisition system. The fourth chapter presents the decision-making algorithm already implemented and the software developed in C# programming language. Chapter five is reserved for testing the software application and for evaluating the degree of applicability in the field.

2. LITERATURE REVIEW

2.1. Flexible Manufacturing Systems (FMS) in context of Industry 4.0 and Industry 5.0 overview

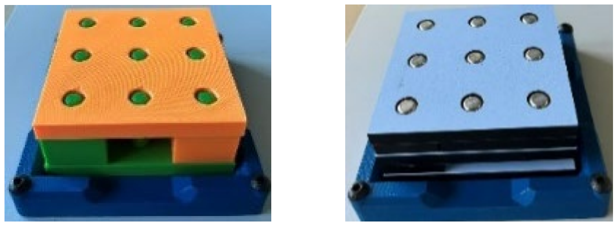
The SMART Assembly/Disassembly mechatronic line (A/DML) represents a sophisticated, adaptable production system featuring workstations served by robotic manipulators specialized for assembly and disassembly tasks, alongside mobile robots designated for handling and transport operation systems operate within advanced control frameworks engineered to coordinate and synchronize tasks, optimizing resource utilization across the production line. Achieving high product quality within the A/DML production process is closely tied to the integration of an autonomous quality management system.

Figure 1: A/DML production system side view

In the A/DML production system, the final product is achieved through a continuous workflow progressing sequentially across up to seven workstations, each facilitated by a SCARA robot and a mobile robot. Each workstation integrates a material handling system and is assigned a specific task, while interdependencies between tasks at each station are governed by the manufacturing flow dictated by the workpiece (see Figure 1). This structured flow ensures precision and consistency, aligning with the objectives of efficient and high-quality production.

To enable production across multiple workflows, the A/DML system has been designed with flexible manufacturing capabilities. In the context of A/DML, flexible manufacturing encompasses the ability to produce two distinct product types that can be assembled in varying configurations using common components, alongside adaptability in product configuration [3].

Production outcomes on the A/DML line include products with differing internal structures, which can be classified into two main categories: Product A and Product B (see Figure 2). Specifically, Product A is composed of an upper layer, a single inner layer, and a basal layer, whereas Product B includes an upper layer, three inner layers, and a basal layer (see Figure 2). This flexible configuration approach allows the A/DML system to efficiently cater to diverse product requirements within a unified production framework.



a) b)

Figure 2: A/DML product types: a) product A; b) product B

2.2. Integrating a decision node capable of dynamically altering the production flow within the A/DML

The A/DML workstations can be categorized based on their roles within the assembly and disassembly processes. Specifically, workstations dedicated to the assembly of the basic product include WS1, WS2, WS4, and WS5, while those involved in assembling the complex product include WS3, WS4, and WS5. Workstations WS7 and WS3 are designated for disassembly operations (Figure 3).

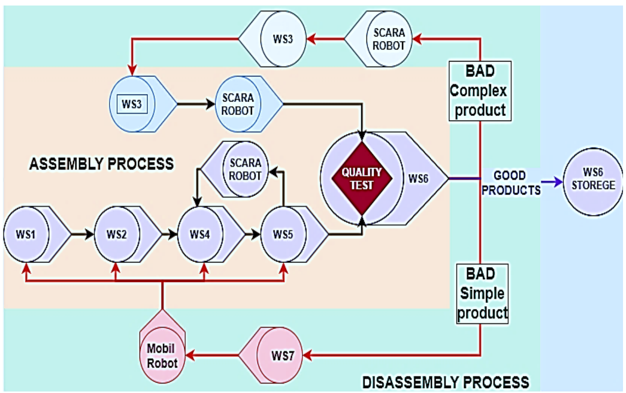


Figure 3: Schematic representation of the A/DML workflows

Based on these workstation functions, five distinct production flows can be established along a single assembly and disassembly line. To optimize these flows, the concept of pseudo-parallelism was employed, which enhances the system's capacity to assemble or disassemble various product types on the same line, thus increasing production efficiency [18].

The quality assurance system is pivotal within the production process, as it independently determines whether each product meets specified quality standards [12]. Based on its evaluation, products deemed satisfactory are directed to storage at WS6, while those identified as defective are sent to WS7 for disassembly.

2.3. A/DML a customer-oriented system

In response to significant market changes, assembly lines must now possess the ability to swiftly adapt to evolving customer requirements [19]. There are instances when the profitability of one product exceeds that of another produced on the same line, prompting a strategic shift from a product-centric to a customer-centric approach [4].

To effectively implement this customer-centric concept within the Assembly/Disassembly Manufacturing Line (A/DML), the integration of a SCARA robot into the assembly and disassembly processes was essential. This robot not only facilitates the transport of products between workstations but also complements traditional conveyor systems, enhancing operational flexibility.

Adopting a production system specifically tailored to customer needs yields numerous advantages, particularly in terms of production efficiency and economic viability. When this approach is aligned with the implementation of a Material Requirements Planning (MRP) application, it can significantly enhance the production capacity of the line. The synergy between customer-centric design and advanced planning systems allows for optimized resource allocation and responsiveness, ultimately leading to improved overall performance and profitability.

III. MACHINE VISION SYSTEM

The quality management system is required to meet specific criteria tailored to the Assembly/Disassembly Manufacturing Line (A/DML) production process, namely high speed, accuracy, and accessibility. To fulfill these requirements, the quality management system must establish real-time communication with the workstation control system, ensuring seamless integration and responsiveness throughout the production process [9].

III.1. Design and Development of a Machine Vision System

Machine Vision (MV) systems incorporate computer vision principles to address a broad spectrum of industrial applications, primarily for the visual inspection of products [10]. The advantage of deploying MV systems lies in their rapid task execution, enabling the high throughput testing of numerous products within a minimal time frame [11]. This efficiency significantly enhances production line performance and quality assurance in fast-paced industrial environments [8].

Integrating an MV system into the A/DML production process necessitates compliance with specific conditions dictated by the production line's architectural requirements (Figure 4). These conditions include dimensional constraints, the nature of interaction with products, and the complexity of the inspection tasks [13].

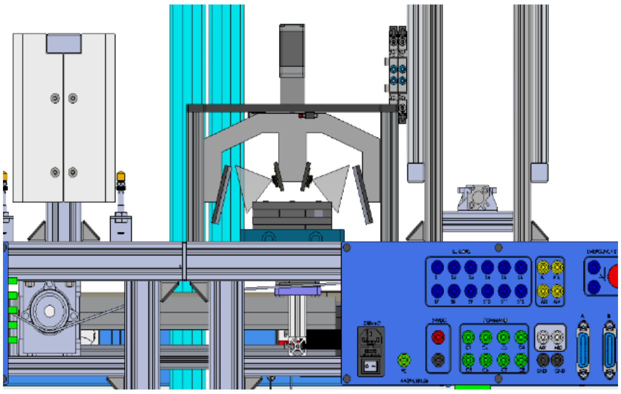


Figure 2: Acquisition system architecture designed in Solidworks

The electromechanical system responsible for image acquisition comprises two cameras, a stepper motor with a reducer, two mirrors, a support structure, and various electronic components. This setup facilitates precise positioning and image capture, aligned with the operational demands of the A/DML process (Figure 5).

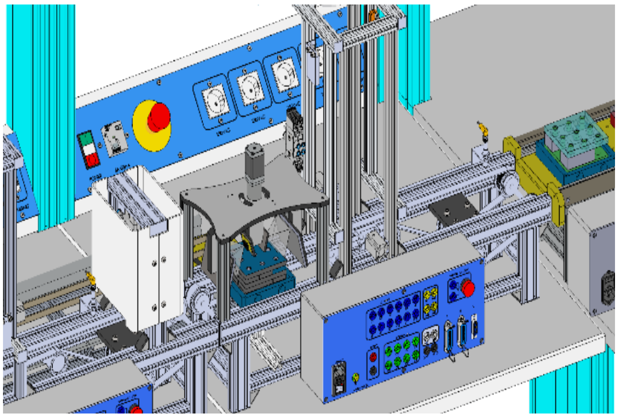


Figure 5: Acquisition system architecture Solidworks in WS6

III.2. Hardware architecture of Machine Vision system

The Machine Vision system utilized on the production line comprises an image acquisition subsystem, a control and processing unit, a monitoring system, and an electromechanical system (see Figure 6). Building on the approach introduced in the previous study, an enhanced version of the Machine Vision system was developed. This improved design integrates a computer to handle both process management and image processing tasks, offering a substantial performance upgrade over the previous model, which relied on a Raspberry Pi 3 microcontroller. Due to the limitations in processing power and memory of the Raspberry Pi 3 compared to a standard laptop [17], this transition was necessary.

Implementing a machine vision system with two webcams, a Raspberry Pi 3 B+, a Tic T834 driver, a motor and MATLAB code involves balancing cost with performance gains. Hardware costs are relatively low (about 300 EUR), but software costs vary—MATLAB with Computer Vision Toolbox can range from 200 EUR to 2,000 EUR, while open-source alternatives like Octave reduce costs but require more feature development effort. Training and integration can add additional costs, depending on complexity.

After conducting extensive testing in Python, C++, and MATLAB, it was determined that significantly improved performance could be achieved by upgrading the hardware architecture. The original processing unit—a Raspberry Pi 3 B+ microcontroller featuring four Cortex-A53 processors, each operating at 1.4 GHz—was replaced by a laptop with dual Intel i5 processors, each with a maximum processing frequency of 2.7 GHz. This modification results in a marked reduction in execution time.

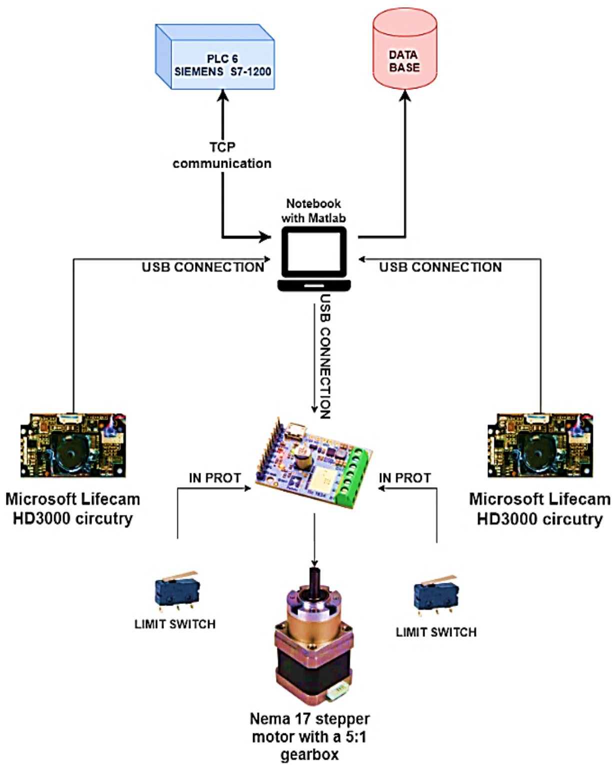


Figure 6: Schematic representation of the hardware structure of Machine Vision system

The image acquisition system includes two Microsoft LifeCam 3000 cameras and a laptop. These cameras feature a 1280x720 image resolution, 24-bit color depth, a maximum video resolution of 1280x720, and a 30fps frame rate. Additional specifications include 4x digital zoom, a CMOS sensor, and a USB 2.0 interface (Figure 7).

The processing and control subsystem is supported by custom-developed software designed to manage the image acquisition stages with optimal safety and efficiency. This software employs a specialized algorithm that processes images and, through its analytical components, delivers a verdict on each product's quality.

The monitoring system is implemented via an application developed in C#, which allows seamless connectivity to the Machine Vision device from any internet-enabled computer. This application continuously exchanges data with the server, enabling the operator to adjust essential production parameters remotely with a single action. By providing full system accessibility from any networked computer, this software aligns closely with the core principles of Industry 4.0 and Industry 5.0, promoting connectivity, flexibility, and real-time control in the production environment [15].

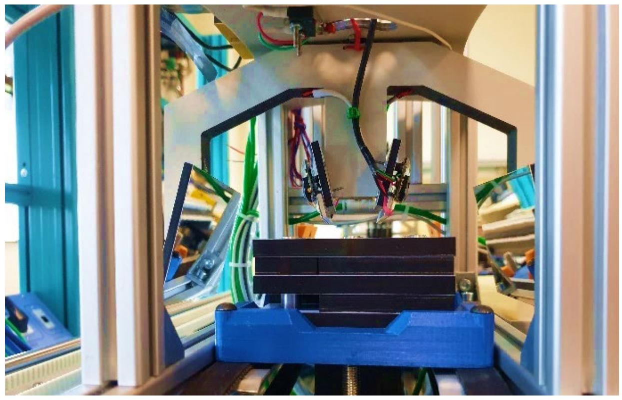


Figure 7: The mecanical and aquisition subsystems of the Machine Vision system

The electromechanical subsystem is purpose-built for the A/DML production process (refer to Figure 7). The electrical components of this subsystem include limit switches, a driver, and a stepper motor, all of which define the operational boundaries within the working areas. The mechanical components comprise bearings, an HPL (High-Pressure Laminate) support structure, and mirrors positioned at a 75° angle relative to the horizontal axis. These elements collectively enable precise control and positioning are essential for high-accuracy operations within the production line.

IV. THE ALGORITHM APPLICATION

The algorithm proposed in [17] integrates several well-established image processing techniques to make decisions. These include Gaussian and sharpen filters, an edge detection algorithm, the M sample estimator (MASC), and normal cross-correlation (NCC). The decision-making process follows a series of sequential steps, executed in a predetermined order, to ensure accurate and efficient outcomes.

No	Algorithm Step
1	*Image capture*: Acquire an image using the designated acquisition system.
2	*Filtering*: Apply filters to both the captured image and the template image.
3	*Image alignment*: Align the captured and template images based on a feature matching algorithm;
4	*Edge detection*: Execute the edge detection algorithm on both the captured and template images;
5	*Index map generation*: Utilize the normalized cross-correlation (NCC) algorithm to generate an index map;
6	*Decision-making*: Determine the product's quality based on the maximum index from the index map: *if (the maximum index is higher than 0.80) then the product is good* *else product is defective*

IV.1 The core of the algorithm

The defect detection algorithm primarily relies on the percentage of the maximum value of the normalized cross-correlation (NCC) index for decision-making. The effectiveness of this method is constrained by the ability of image processing techniques to reduce noise and ensure the geometric alignment of the products within the images. The cross-correlation algorithm takes as input a template and an image captured by the machine vision (MV) system. Prior to their use in the algorithm, both the template and the captured image undergo pre-processing. This pre-processing involves applying noise-reduction filters, an edge detection algorithm, and a geometric alignment algorithm to align the products within both images.

The algorithm can be adjusted according to the type of product analyzed by the machine vision system, using specific conditional structures. The identification of the product type during the quality test process is carried out by the RFID integrated in the transport tray, thus allowing the automatic adaptation of the inspection parameters and the optimization of the accuracy of the analysis.

IV.2 Implementation of Machine Vision Control Structures in MATLAB

MATLAB is a software platform offering a wide range of toolboxes applicable across various fields. Its proprietary programming language facilitates optimal integration with external devices connected to a computer, making it an effective solution for developing both machine vision (MV) system control programs and implementing image processing algorithms.

In controlling the MV process, MATLAB leverages built-in functions to transmit commands via serial communication to a stepper motor driver, interfacing with the laptop's command prompt control panel. This enables precise control of the MV system's operations.

For image preprocessing, MATLAB supports the execution of functions and provides the MATLAB App Design utility, which allows the creation of standalone applications. An interface was developed using this utility to facilitate edge detection in images, enabling users to adjust edge detection parameters dynamically and efficiently (Figure 8).

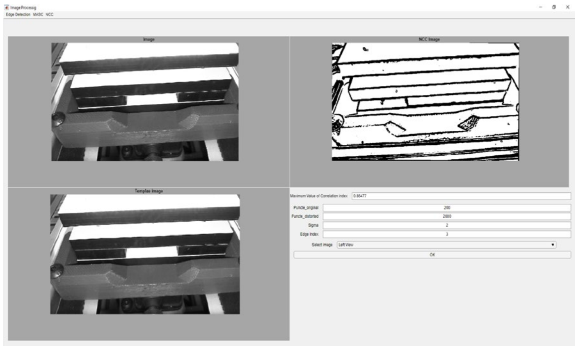


Figure 8: Design a software application in MATLAB App Designer of the Edge Detection algorithm

IV.3 The software application developed in C#

The software application is an integral component of the management subsystem within the machine vision (MV) system, designed primarily to oversee the decision-making activities conducted by the MV system. This supervision can be executed by an operator or through dedicated supervisory software [16].

Both the user interface and the operational core of the application are developed within the Microsoft Visual Studio programming environment, which supports the creation of portable executable applications across various programming languages. Among the languages available in this suite, C# is particularly noteworthy. C# offers a range of capabilities, including graphics development, server-side application development, and hardware control applications, making it well-suited for this application's requirements.

The MV system management application encompasses all the functionalities of a database management system. This software interface enables users to access, retrieve, store, save, and define database information [5].

To enhance data security, a multi-user policy has been implemented within the system. Each operator is assigned a user account and password, granting them secure access to the application and its features. This approach ensures that sensitive data remains protected while allowing authorized users to perform necessary operations effectively.

Upon successful entry of a username and password, the application grants access to the main window, which incorporates an SQL function to query the database at regular intervals or in response to user actions. The database is continuously updated by a secondary application, which records the status of products in production. The process monitoring interface retrieves this data from the database and visualizes it through progress containers. This enables the user to track key production metrics, including the number of parts in storage, the location of individual parts in the production process, the position of the mobile robot, and the percentage of completion for the Quality Test (Figure 9).

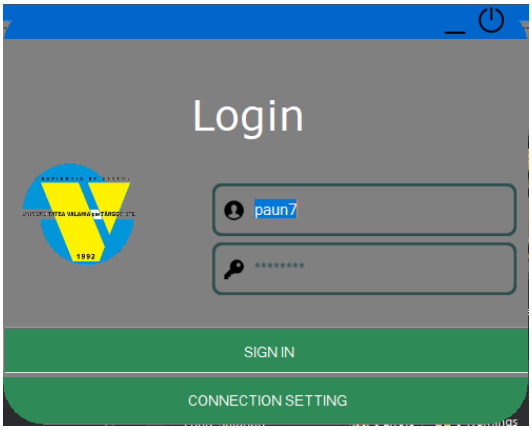


Figure 9: Login interface of quality management system

The main window features an interactive menu, accessible by pressing the "Menu" button located in the upper left corner. Activating this button expands a vertical panel on the left side of the window. The menu offers access to the following options: Overview, Quality Test, Statistical Information, and About. Each menu button dynamically updates the content displayed in the main window (Figure 10).

By accessing the "Quality Test" button opens a window titled "Quality Test," which presents important details about the QT process. This includes the total number of products tested, the number of defective products, the number of defective products reported in the last 10 products, and the number reported in the last 100 products. All of this data is retrieved via SQL queries performed on the database. In addition to displaying this information, the window also provides functionality for modifying QT settings and viewing all captured images (Figure 10).

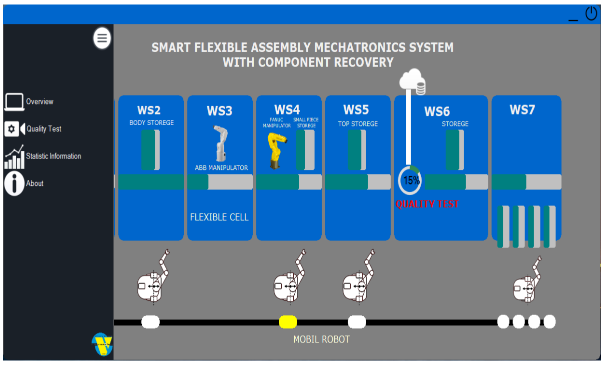


Figure 10: Software application of QTS. Overview

The "Statistical Information" button in the application menu opens the Statistical Information window, which offers a feature for generating charts tailored to the operator's specifications. These charts can be created for data from a specific day, a particular month, or the entire operational period of the QT system. Additionally, the "Clear" button allows users to remove all data displayed on the chart (Figure 11).

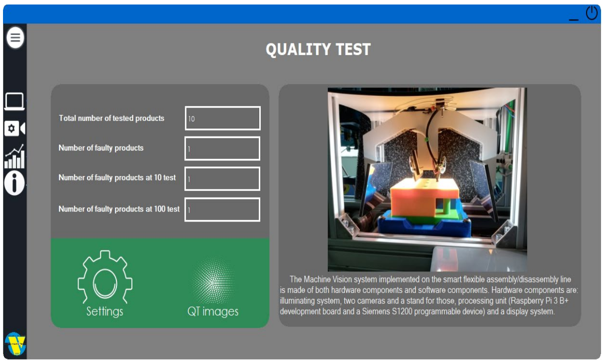


Figure 11: Quality Test window

V. EXPERIMENTAL TESTS RESULTS

The algorithm of default detection works based on Normalized Cross-Correlation and obtains the result by directly comparing a template with an image, being sensitive to variations such as rotation, scaling and illumination. This algorithm requires manual adjustments for each transformation and is inefficient for large images or extensive databases. If we compare this algorithm with an algorithm based on convolutional neural networks (CNN), it can be appreciated that these networks possess the automatic learning characteristic, being more robust to variations and noise. However, CNNs require a large number of images, long training time and high computational resources. Tests performed on A/DML pictures using the system demonstrated a detection accuracy of 98.56% [17].

Performance testing carried out with Microsoft Visual Studio revealed that the application, on average, consumes 118 MB of RAM during runtime, while utilizing a maximum of 12% of the CPU capacity. Notably, user interactions do not lead to significant fluctuations in resource consumption. Additionally, resource usage was found to be higher during the initialization phase compared to steady-state operation (Figure 12).

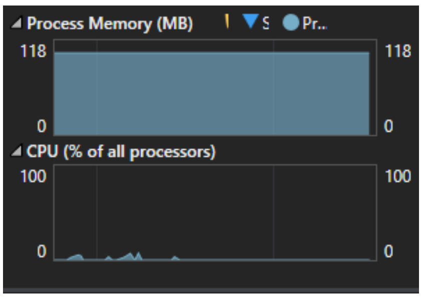


Figure 12: Application resource consumption

The provided performance metrics illustrate the computational load of the process, specifically in terms of memory consumption and CPU utilization. The process maintains a stable memory footprint at 118 MB, indicating predictable allocation patterns. The observed CPU usage remains near 0%, suggesting minimal computational demand under current conditions. As production volume increases, memory consumption may rise due to higher data throughput or concurrent processing demands, necessitating adequate RAM provisioning.

VI. CONCLUSIONS

The results presented in the conducted research demonstrate that a QTS (Quality Testing System) implemented on a production line offers numerous benefits, particularly when, in addition to the defect detection algorithm, remote monitoring and control applications are also implemented. In this scenario, the QTS can conceptually be assimilated to an 'IoT' sensor based on Industry 4.0 technologies. The implementation of a client-server model for the QTS allows for easy interpretation of QT results. The system provides real-time information about the volume of manufactured products, statistics on defective products, details regarding stock failures, or potential defects in the manufacturing process, which will trigger warning alarms. Simultaneously, the monitoring application allows for interventions in production planning when the process is in a critical operational state.

The software interface, designed with a client-server architecture, allows for seamless interpretation of machine vision data, offering a user-friendly experience through interactive menus and detailed graphical representations. This solution supports dynamic adjustments in production planning, especially during critical operational states, thereby improving the adaptability and resilience of the manufacturing process.

Resource usage tests indicated that the application operates efficiently, with minimal impact on system memory and processing power, ensuring stability even during complex operations. The ability to generate statistical reports and visualize progress in real-time adds further value to production management, optimizing decision-making and enhancing quality control.

The developed software interface is a robust and scalable solution that aligns with modern industrial automation requirements, promoting improved productivity, reduced downtime, and enhanced product quality in smart manufacturing environments.

VII. REFERENCES

[1] Hoda A. Elmaraghy, W. H. Elmaraghy, "Smart adaptable assembly systems." Procedia CIRP, 2016, 44, 4-13;

[2] Eugenia Minca, Adrian Filipescu, Alina Vodac, "Modelling and control of an assembly/disassembly mechatronics line", Control Engineering Practice, 2014, 31, 50-62.

[3] Eugenia Mincă, Henri George Coanda, Florin Dragomir, Otilia Dragomir, "Cycle time optimization of Reversible A/DML Served by Mobile Robotic System", 19th International Conference on System Theory, Control and Computing (ICSTCC), Cheile Grădiștei, 2015, 99-104;

[4] Gary, Cokins, "Measuring and Managing Customer Profitability", Strategic Finance, 2015, 96(8), 23-29;

[5] Gunjal, Bhojaraju, M. Koganurmath, "Database Management: Concepts and Design", In Proceedings of Knowledge Management in Special Libraries in Digital Environment: XXIV All India Conference of IASLIC, 2003, 15-18;

[6] Octavian Duca, Valentin Gurgu, Eugenia Mincă, Adrian Filipescu, Florin Dragomir, Otilia Dragomir, "Optimal control of the complete assembly/disassembly cycle for a mechatronics line prototype", 23rd International Conference on System Theory, Control and Computing. Sinaia, 2019, 621-625;

[7] Olga Battaïa, Alexandre Dolgui, Sunderesh S. Heragu, Semyon M. Meerkov, Manoj Kumar Tiwari, "Design for manufacturing and assembly/disassembly: joint design of products and production systems", 2018, International Journal of Production Research, 56(24), 7181–7189;

[8] Remigiusz Labudzki, Stanislaw Legutko, Pero Raos. "The essence and application of Machine Vision." Tehnicki vjesnik - Technical Gazette, 2014, 21(4), 903-909;

[9] S, Sathiyamoorthy, "Industrial application of Machine Vision", International Journal of Research in Engineering and Technology, 2014, 3(7), 678-682;

[10] A. Sharma and A. Kulkarni, "Vision System for Smart Manufacturing: A Review", *2023 IEEE Engineering Informatics*, Melbourne, Australia, 2023, 1-9;

[11] Mohd Javaid, Abid Haleem, Ravi Pratap Singh, Shanay Rab, Rajiv Suman, "Exploring impact and features of machine vision for progressive industry 4.0 culture", Sensors International, 2022, 3, 100132-100143;

[12] Allashyam Charan, Chundu Karthik Chowdary, Peddagowda Komal, "The Future of Machine Vision in Industries- A systematic review", IOP Conference Series: Materials Science and Engineering, 2022, 1-7;

[13] V. Nandini, R. Deepak Vishal, C. Arun Prakash, S. Aishwarya, "A Review on Applications of Machine Vision Systems in Industries", Indian Journal of Science and Technology, 2016, 9(48), 1-5;

[14] Pérez, L.; Rodríguez, Í.; Rodríguez, N.; Usamentiaga, R.; García, D.F., "Robot Guidance Using Machine Vision Techniques in Industrial Environments: A Comparative Review", 2016, Sensors, 16, 335-359;

[15] Viorel Miron-Alexe, Gabriela Mantescu, "Retrofitting outdated pyranometer for IoT integration towards a circular economy model", Journal of Science and Arts, 2023, 23(4), 1081-1094;

[16] Ionuț-Cătălin Munteanu, Emil Cazacu, Lucian Petrescu, "Predictive-adaptive maintenance applied for optimizing the performance of industrial electrical systems and equipment", The Scientific Bulletin of Electrical Engineering Faculty, 2024, 24(1), 8-14;

[17] M., A. Păun, E., Mică,, A., Filipescu, A., Filipescu, O. Duca, "Improved Image Processing Algorithm for Quality Test on a Flexible Manufacturing Mechatronic Line," 2020 24th International Conference on System Theory, Control and Computing (ICSTCC), Sinaia, Romania, 2020, pp. 819-824;

[18] F., Dragomir, E., Mincă, O., E., Dragomir, A., Filipescu, "Modelling and Control of Mechatronics Lines Served by Complex Autonomous Systems", Sensors 2019, 19, 3266.

[19] Ş., Barutçuoğlu, M., Azizoğlu, "Flexible assembly line design problem with fixed number of workstations", International Journal of Production Research, 2011, 48(12), 3691-3714;