Digitization of Industrial Quality Control Procedures applied to Visual and Geometrical Inspections

Giuseppe Antonio Setem Davanzo - 46699

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Work oriented by:
Prof. Paulo Leitao
Prof. Jorge Aikes Junior

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Dedication

I dedicate this work to my family and friends, especially to my parents Marcos Cesar Davanzo and Maria Cristina Setem Davanzo. Who always supported me and inspired me to continue challenging myself and persevering in my studies.

Acknowledgment

First of all, to my parents Marcos Cesar Davanzo and Maria Cristina Setem Davanzo, for supporting me at all times, inspiring me to persevere in my education.

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Abstract

Industries quality control procedures are usually dependent on gauge inspection tools, and these tools are used to inspect visual and geometrical tolerance conformity. Operators are guided during an inspection by using paper tutorials that assist them in performing their tasks and registering the result of the performed analysis. This traditional method of registering information may be misleading, lowering the effectiveness of the quality control by providing inaccurate and error-prone inspection results. This work implements a system that uses emergent technologies (e.g., Human-Machine Interfaces, Virtual Reality, Distributed Systems, Cloud Computing, and Internet of Things (IoT)) to propose a cost-effective solution that supports operators and quality control managers in the realization and data collection of gauge inspection control procedures. The final system was deployed in an industrial production plant, with the delivered results showing its efficiency, robustness, and highly positive feedback from the operators and managers. The software may offer a quicker and efficient execution of analysis tasks, significantly decreasing the setup time required to change the inspected product reference.

Keywords: Cyber-Physical Systems, Quality Control, Inspection Systems, Industry 4.0, Virtual Reality.

Contents

List of Tables

List of Figures

Acronyms

ABMS Agent-Based Modeling and Simulation.

AGD American Gage Design.

AR Augmented Reality.

CAD Computer-Aided Design.

CAE Computer-Aided Engineering.

CDN Content Delivery Network.

CLI Command-Line Interface.

CMM Coordinate Measuring Machine.

CPPS Cyber-Physical Production System.

CPS Cyber-Physical System.

DOM Document Object Model.

DT Digital Twin.

E2E End-to-End.

ECMA European Computer Manufacturers Association.

ES6 ECMAScript 2015.

EU European Union.

FaaS Factory as a Service.

FR Functional Requirements.

GLTF Graphics Language Transmission Format.

HCI Human-Computer Interaction.

HiL Human-in-the-Loop.

HiLCPS Human-in-the-Loop Cyber-Physical System.

HMD Head Mounted Devices.

HMI Human-Machine Interface.

HTML HyperText Markup Language.

HTTP Hypertext Transfer Protocol.

ICT Information and Communications Technology.

IoS Internet of Services.

IoT Internet of Things.

IPA Intelligent Personal Assistant.

JS JavaScript.

JSON JavaScript Object Notation.

JSX JavaScript XML.

MTUI Multi-touch User Interfaces.

NFR Non-Functional Requirements.

NPM Node Package Manager.

ORM Object Relational Mapper.

OS Operational System.

OTA Over-The-Air.

PWA Progressive Web Apps.

SPA Single-Page Application.

SQL Structured Query Language.

SUS System Usability Scale.

TLS Transport Layer Security.

TS TypeScript.

UI User Interface.

UX User Experience.

VR Virtual Reality.

WoW Window on Word.

XML Extensible Markup Language.

Chapter 1

Introduction

In this chapter, we will present the fundamentals of this work. Firstly, we will show the background and motivations for the presented work, also it's relevance to the research community (Section 1.1). Subsequently, we'll reason about the objectives which we propose to accomplish (Section 1.2). Finally, mention the contribution produced by the development of this work (Section 1.3) and demonstrate the structure of the document (Section1.4).

1.1 Background

The industry 4.0 initiative takes a pioneering role in the current manufacturing industries scenario, enabling technologies to transition from traditional systems to a cyber-physical paradigm where embedded systems, semantic machine-to-machine communication, Internet of Things (IoT), and Cyber-Physical Production System (CPPS) technologies are integrating the virtual space with the physical world [1]. Each industrial revolution inferred efforts to increase the manufacturing quality, scalability, and efficiency in the manufacturing of goods. From steam-powered plants to computerized production facilities, the fourth iteration of this process is nevertheless an evolution to make manufacturing increasingly intelligent, thus, more adaptable, automatable, and flexible [2].

This new wave of industrialization uses data as a means to optimize its process applying technologies, e.g, IoT [3], big data [4], cloud computing [5], and Augmented Reality (AR) [6] as frameworks to improve decision making, in a decentralized manner at production time as mentioned by Egger and Masood [2]. Industry 4.0 relies on CPPS to seamlessly connect cyber and physical counterparts, the systems are organized in a distributed network and interact with each other to achieve a common goal [7].

Human resources are an essential part of CPPS, since they allow flexibility and validation to the performed operations, demanding that human-centered technologies play a special role in the design of these systems. Many technologies support the Human-in-the-Loop Cyber-Physical System (HiLCPS), helping the humans integration into the cyberspace, e.g, AR, Virtual Reality (VR), and Intelligent Personal Assistant (IPA). All these technologies enable the augmentation of the original human capabilities increasing its abilities to perform tasks [7].

As shown by Nunes, Zhang, and Silva [8], although these interconnected and intelligent systems communicate with each other without any human involvement, human technology is made by humans, for humans. Effective tools acknowledge the before-mentioned statement, demanding efficient and intuitive usage of technology to provide context-awareness. We can define context-awareness as the application of the context to delivery task-relevant information and/or services to a user [9]. In HiLCPS, human behavior is no longer perceived as an external and unknown circumstance but enhances an essential part of the system instead. For example, modern aircraft pilots still decide for themselves when to engage the autopilot or assume manual control of the plane [8].

In a 2015 report by the European Parliament, AR has already been classified by the European Union (EU) as one of the main technologies that will drive the development of smart factories, as a medium to allow increased flexibility in production, providing better interaction between humans and machines [10].

As Yao, Zhou, Lin, *et al.* [11] mentioned and Egger and Masood [2] quote, AR technology shines when a large number of data produced by a CPPS aim to provide contextual-awareness toward humans, as a real-time resource to achieve greater efficiency.

There are several ways to display content in VR, each one of these techniques will allow one to experience the immersion within one's world in different ways [12]. In this document, we will use the term VR for both 2D and 3D solutions, stationary or mobile, that enable humans to access digital information through a layer of information [2].

With significant transformations in the global geography of the automotive industry, Europe continues to be one of the world's main production regions, being the third-largest commercial vehicle production region in the world, only behind Greater China and North America [13]. In 2020, the automotive sector provides direct and indirect jobs to 14.6 million Europeans, representing 6.7% of total EU employment [14] and 8.5% of EU manufacturing employment [15].

EU is the second-largest producer of passenger cars, increasing its global market share from 20.5% in 2018 to 21.3% in 2019, only behind China [13]. This gives the automotive manufacturers one of the crucial positions between industries in the EU, principally when also considering its trade balance of €71.3 billion in 2019 and spending of €57.4 billion in 2019 on research and development, Europe's largest private contributor to innovation, accounting for 28% of total EU spending [13].

This work uses modern software development technologies to create a distributed system that enables operators to perform quality control checks more efficiently. Implementing an Human-Machine Interface (HMI) that uses simple VR techniques to guide the operator through quality control inspection tasks, while registering and analyzing the obtained data providing information to the quality control managers and storing it for future use. Our primary goal is to develop a reliable software, as before described, and test it in a real-world scenario investigating users' perception, stability, and overall integration with the current process provided by the application.

1.2 Objectives

This work was deployed in the Catraport's factory located in Bragança (northern Portugal) that produces components for the automotive industry through a cold molding process. The solution was applied in the quality control process facing the challenging of an industrial production line. The main objectives of this work are:

1. Develop a mobile application that will empower operators with tools for quality control;

2. Develop a web application for data visualization at production process inspection level;

3. Apply the developed solution in a industrial environment;

4. Identify advantages of the application use in a production environment.

The solution should also be reliable and cost-effective ready for use in a production environment without creating issues and bottlenecks in the process. The developed system seeks to improve the current state of many industries by digitizing the use of paper in the mission-critical quality assurance process.

1.3 Contributions

This work will produce several contributions to different communities, such as Industry 4.0 researchers, software engineers, HMI researchers, seeking to provide to the automotive industry a cost-effective way to move towards digital transformation.

For Industry 4.0 researchers, this project offers a real-world case for a distributed system that uses a Human-in-the-Loop (HiL) during quality control. For software engineers and HMI researchers, the work shows the development and use of a cloud computing system that interacts with operators and their managers through an HMI that uses 3D to better guide users in the factories process. For industries, this work offers an alternative for moving towards an Industry 4.0 era cost-effectively while gathering data to understand better processes and improvements that can be made to ensure quality.

1.4 Document Structure

This work will present its content in the following order. First, the technical knowledge and context necessary for understanding the terms and concepts used in work are presented in Chapter 2. Next, the case study and the problem analysis are demonstrated in Chapter 3 with a rough idea of how to approach problem-solving. In Chapter 4, materials and methods used during the work development are listed and detailed. Chapter 5 presents the architecture and implementation of the developed solution, demonstrating what technologies were used to create the final system. Finally, Chapter 6 analysis the results and open a discussion on positive and negative aspects found in this work. Chapter 7 wraps all the before mentioned topics to conclude the work and present a future direction for this project.

Chapter 2

Context and Technologies

In this chapter, the basis of our project is presented. Firstly, Industry 4.0 is contextualized demonstrating the history, techniques and components utilized in its implementation (Section 2.1). Next, quality control and gauge tools' usage on industrial components inspection are evaluated (Section 2.2). This chapter then describes Human-Machine Interface (HMI) guidelines and concepts applied to 3D and Multi-Touch displays (Section 2.3). Finally, we detail Virtual Reality (VR) (Section 2.4) and Usability Test instruments (Section 2.5).

2.1 Industry 4.0

The industry remains one of the most critical parts of the global economy. Provide material goods in a profoundly mechanized and automatized method is a driving force to the fourth industrial revolution. From the beginning of industrialization, technological leaps guided changes in the behavior of industries operation. These paradigm shifts now are entitled "industrial revolutions" [16].

In the period 1760 to 1830, the First Industrial Revolution was happening confined to Britain. Aware of their head start, the British banned the exportation of machinery, skilled workers, and manufacturing techniques. Although the British monopoly could not last forever, industrial methods were brought to continental Europe, transforming the economy from west to east. Those industries embodied the employment of steam-powered machines in the production of goods [17].

In the mid-nineteenth century and first half of the twentieth century, the Second Industrial Revolution occurred, the modern industry began to utilize many natural, and artificial resources not formerly used [17](e.g., lighter metals, new alloys, synthetic products like plastics), and the excessive usage of electricity in the production [16].

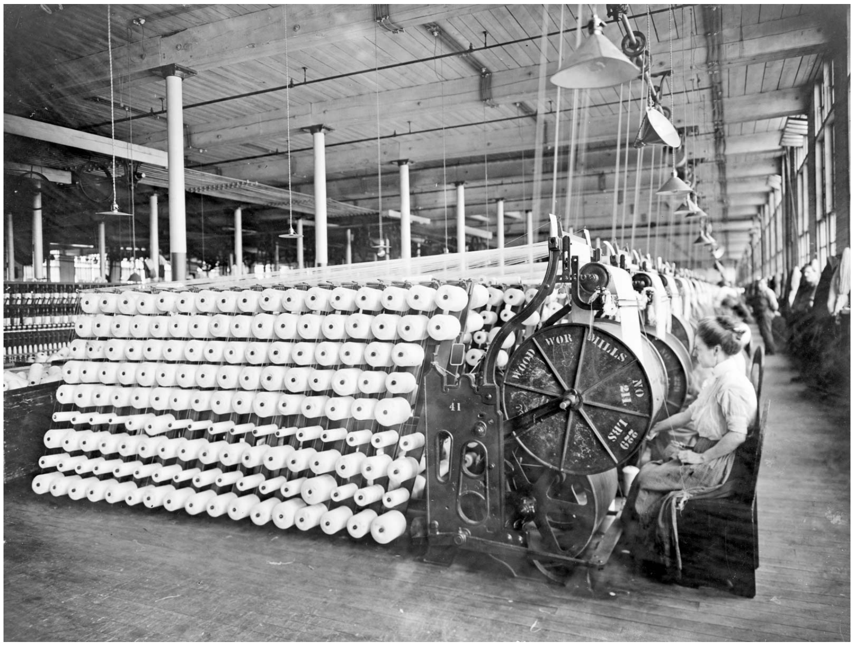


Figure 2.1: Industrial revolution factory workers. Boston, C. 1912. [17]

At the end of the twentieth century and the beginning of the twenty-first century, the Third Industrial Revolution had a meaningful impact as the First Industrial Revolution had in the nineteenth century and the Second Industrial Revolution in the twentieth century [18]. It fundamentally transforms every slant of the way we work and live. Great pillars of the Third Industrial Revolution are the shift to renewable energy, the buy and sell of energy on an interactive power grid, internet technology usage, and the widespread digitalization in industrial facilities [16].

The advances in digitalization within factories and the combination of internet technologies oriented to an intelligent factory appear to result in a new fundamental paradigm transformation in industrial production [16]. This future envisions a modular and efficient manufacturing system where dynamic business and engineering processes allow last-minute adjustments to display and deliver the capacity to react flexibly to disruptions and failures. They are powered by an end-to-end provider over the manufacturing process, facilitating optimized decision-making [19].

The expression Industry 4.0 was first used at the Hannover Fair in 2011 and has been noticed by many parts, from academics to government officials worldwide. It is not only a technological-related challenge to the relevant industries, but Industry 4.0 will also have far-reaching organizational implications, presenting a chance to generate new business and corporate models, facilitating more inclusive employee engagement [19].

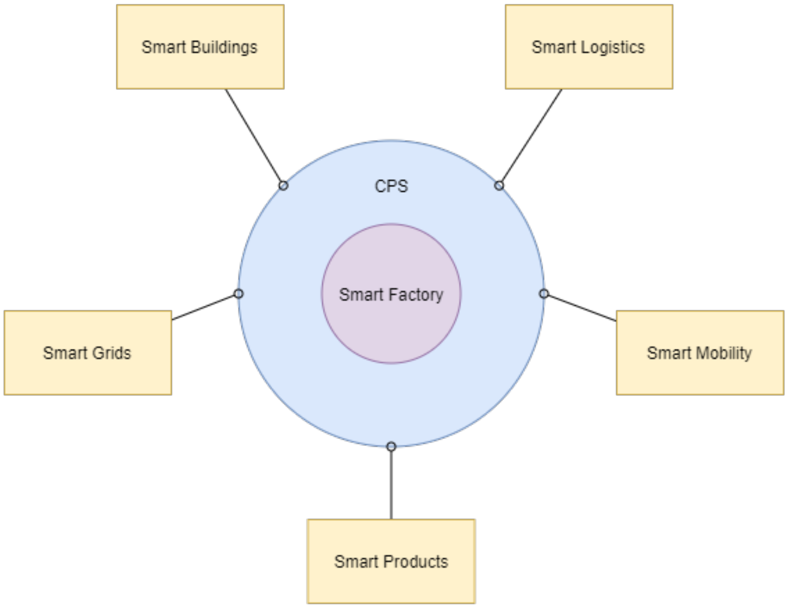


Figure 2.2: Smart factories as part of Internet of Things and Internet of Services. Adapted from [19].

2.1.1 Components

To enable this engaging environment while enabling an intelligent, networked world, Industry 4.0 relies on multiple components to implement smart factory plants. Thus, improving the capability to manage complexity, less inclined to errors, and more efficient manufacturing goods. By decentralizing the production logic in multiple components, Industry 4.0 products can comprehend the aspects of their manufacturing process and logistics (Figure 2.2), transforming the traditional value chains and business models [19]. Some of those components are [20][21]:

- **Cyber-Physical Systems (CPS)**. A CPS integrates the computational and physical process. They are embedded computers and networks liable to watch and manage the concrete process and provide feedback on consequences in a physical or computational process. This component relies on identification technologies (e.g., RFID tags), decentralized services for storage and analytics, and sensors compatible with networks;

- **Internet of Things (IoT)**. IoT allows "things" and "objects" (for example, RFID tags, sensors, smartphones) to interact with each other, cooperating with other smart components in a network to achieve a mutual purpose. IoT is a network where CPS collaborate to accomplish a specific objective;

- **Internet of Services (IoS)**. It allows vendors to offer services via the internet and combine it within the production chain. IoS allows a new way of dynamic variation of the distribution of individual value chain activities, supporting both functional and technical features;

- **Smart Factories**. It is a context-aware factory that assists people and machines in executing their tasks. Indicating that the system can consider contextual data like an object's position and status, performing their duties based on physical and digital information.

As described by Hermann, Pentek, and Otto [20] the intelligent factory "base on the definitions given for CPS and the IoT, assist people and machines in the execution of their tasks...". One project that implements such a system is the SMART FACE under the "Autonomics for Industrie 4.0" program initiated by the German Federal Ministry for Economic Affairs and Energy. The project supports using a modular assembly station that acknowledges the customer-specific configuration and can decide autonomously which working steps are needed, individually composing the necessary process through the IoS network.

2.1.2 Design Principles

Design principles support companies in identifying possible Industry 4.0 projects, which then can be implemented [20]. A straightforward approach is necessary for identifying variables and model an advance in the business implementation towards Industry 4.0. In essence, Industry 4.0 design principles are fundamental concepts that describe this phenomenon and promote its accomplishment [22][20][19]:

- **Interoperability**. The capacity of two or more systems to coexist, interact, and interoperate, for example, sharing resources. In companies that implement Industry 4.0, communication standards are a crucial factor for a successful implementation. Enabling vertical integration with different company systems at a different hierarchical level (e.g., physical, software, a business process). Also, horizontal integration consists of inter-company integration of IT systems, both within and across an organization;

- **Virtualization**. It monitors CPS physical process by associating sensor data with a virtual plat virtual representation, allowing for real-world events visualization in a digital form. Virtualization is essentially associated with information transparency and enabling technologies such as CPS, VR, AR, and Digital Twin (DT);

- **Decentralization**. It implies that one system network is not centrally managed.

Embedded systems should allow CPS to choose their process based on an identification key provided by the product to the machine before performing its tasks, shifting the paradigm from the central planning and controlling;

- **Real-Time Capability**. It enables real-time data-driven decision-making supported by gathering data and analysis in real-time events. Applying this principle, the plant can permanently track and analyze its components and react to this by making smarter data-diving decisions;
- **Service Orientation**. Provides organization to focus on selling services instead of products, known as Factory as a Service (FaaS). By identifying product-specific processes that compose customer-specific requirements into a final product;
- **Modularity**. A modular system should adjust to changes in its requirements by supplanting or extending individual modules. Modularity applies to many stages of the production cycle, enabling mass customization, flexibility, and fast manufacturing.

Implementing these patterns, advancements within factories, and the combination of internet technologies oriented to an intelligent factory appears adjusting industries into the 4.0 paradigm. It may maximize the advantages of its production capacity while improving the volume and quality of its service.

2.2 Quality Control

The objective of an independent evaluation of product and process quality as a fundamental element of quality control is an accomplishment that can only be achieved with monitoring measurement technologies [23]. As Albers, Gladysz, Pinner, *et al.* [23] paper quotes from Kovac, Maňková, Gostimirović, *et al.* [24], it is impossible to monitor these manufacturing processes' conditions directly. This is why measurable indicators have to be identified and implemented to conclude the quality state so that industries can have quantitative measures of the production quality, comprehending the process issues present in the plant to improve the product quality.

As mentioned by Teti, Jemielniak, O'Donnell, *et al.* [25] and quoted by Albers, Gladysz, Pinner, *et al.* [23]. The gains of intelligent quality control systems using sensors and indicators haven't succeeded in practice yet. The principal cause is the inevitable regulations that need to be applied to sensors on specific applications and the proper techniques to create suitable indicators.

To maintain quality, Petritoli, Leccese, and Spagnolo [26] paper proposes that "through an accurate analysis of the production processes and an appropriate flow of post-product test data, it is possible to correct the quality drift of the product during the production itself without waiting for the lot to run out".

To have a uniform quality assurance system is essential to start with the preparation of development down through the put in service. It is necessary to reduce potential problems from the production process. Consequently, checkpoints need to be established to prevent an item considered feasible to induce failure from reaching the next process step [26].

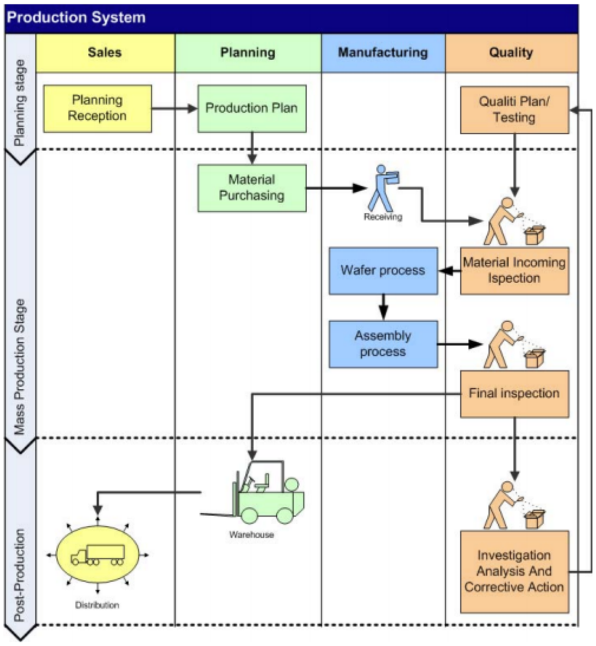


Figure 2.3: Production stages of a semiconductors production process. The figure shows the production stages and their relationship with the quality control stages [26].

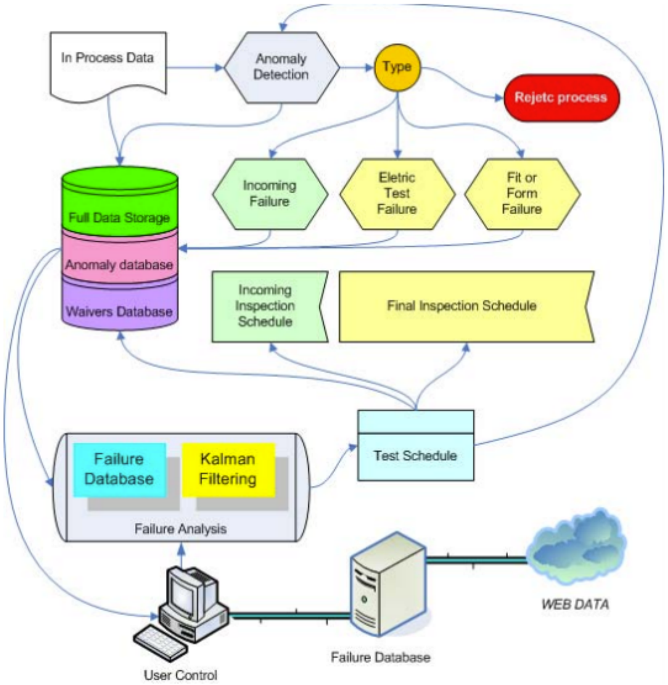


Figure 2.4: Quality processes in production systems [26].

One example of the application of quality control automation in Industry 4.0 is the Petritoli, Leccese, and Spagnolo [26] paper. The author applies quality control systems in a semiconductors production process (Figure 2.3) to correct the product's quality during the production itself. The author implements an online quality control system based on the process data coming from multiple stages of the production process in which the components are tested.

The data flow, represented by Figure 2.4, processes the data when it enters into the general database then sent to the Anomaly Detection layer, which detects non-conformities and classifies them. The failed component is marked by test failure (Incoming, Electric Test, or Fit/Form) and stored in the Anomaly Database, used during later Failure Analysis. By analyzing the production and quality processes, the author was able to test a reasonable number of electronic components leading to a significant increase in operational availability, thus reducing extraordinary maintenance interventions [26].

2.2.1 Geometric Inspection

Quality control inspection methods aim to evaluate products by creating metrics and measurements to monitor the process quality. This process is essential to identify the product defects and calibrate the machines' disposal along the production line. These traditional inspection processes (e.g., geometric inspection techniques) present some problems, primarily the loss of time and occurrence of errors when the inspection procedure is unknown and the manual collection of data related to detected defects.

Conventional tolerancing methods have been in use since the middle of the 1800s to ensure conformity in produced goods. Complex components are formed by several characteristics (e.g., planar, cylindrical, spherical, etc.). The machining process during the fabrication of all these features may impact the entire construction's overall accuracy. To guarantee that dependent pears will work together after the parts go through the production process. Techniques like Geometric Dimensioning and Tolerancing (GD&T) and Coordinate Dimensioning and Tolerancing (CD&T) are used to provide quantitative and qualitative measures for the quality of the pieces [27][28].

2.2.2 Types of Geometric Inspection

GD&T and CD&T are practiced to ensure quality in an industrial environment by examining manufacturing components with gauges. When the design of a component is used as a guide for its manufacturing process, the designer defines the piece limits of size, shape, and composition with dimensions, specifications, and tolerances present for every specification in the workpiece's drawing project [27][29].

Coordinate Dimensioning and Tolerancing (CD&T)

Since the middle of the nineteenth century, the industry has been using the plus or minus tolerancing system for tolerancing drawings. CD&T uses the plus or minus tolerancing system to represent the tolerance found in the piece [27]. In Figure 2.5, an example of the CD&T is shown to demonstrate the metric usage. Note that the dimension may be located anywhere within the gray rectangle [29].

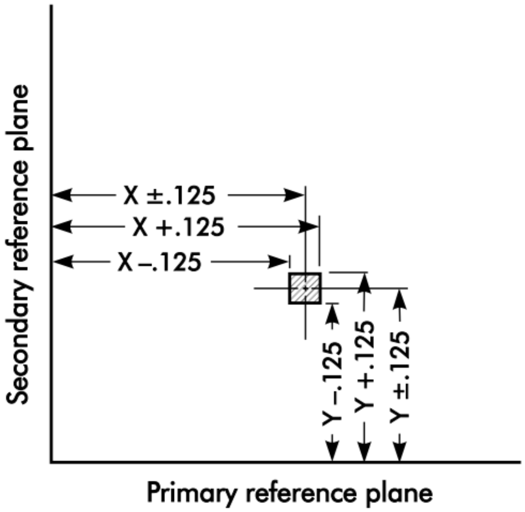


Figure 2.5: Example of CD&T applied into a object [29].

When handing cylindrical shapes, like a hole, for example, the center of the hole's tolerance can be determined by the difference of the X and Y coordinate tolerance measurements. After calculating the dimensions shift, the difference can be visualized in the intersection of the 45 degrees diagonal line to calculate the cylindrical tolerance (Figure 2.6)[29].

This method creates rectangular tolerance zones that are not precise when handling cylindrical objects or holes in a piece, differing in values when two measurements are applied. Another limitation of the CD&T is not representing size variation of shapes. For example, if the hole increases in size, it has more location tolerance, but there is no way to specify additional tolerances with the plus or minus tolerancing system [27].

Geometric Dimensioning and Tolerancing (GD&T)

GD&T is a representative language. It is utilized to define the size, shape, form, orientation, and location of features. When verifying the tolerance of complex objects, the features brought by the GD&T allow the identification of straightness, flatness, circularity, and cylindricity that can be incorporated into the piece in the form of errors [27][28].

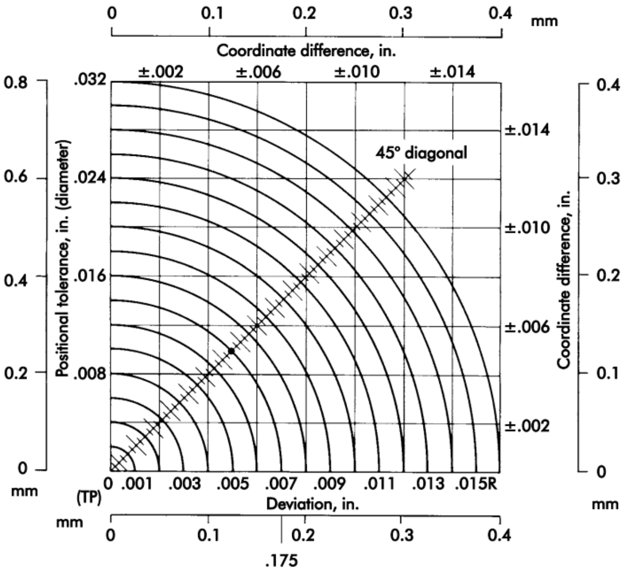


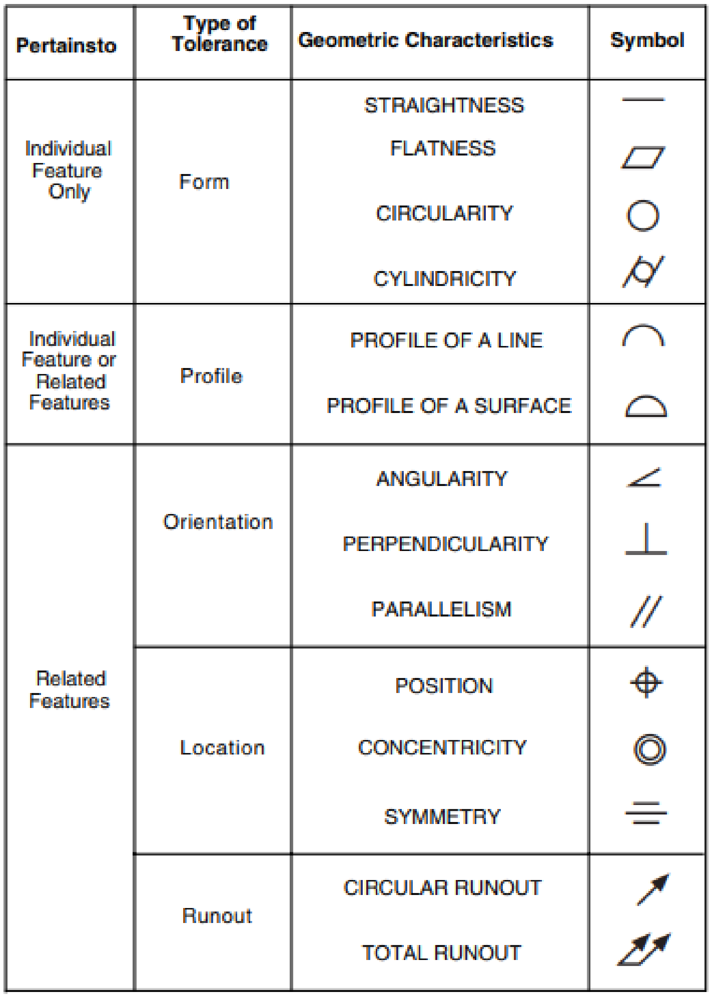
Figure 2.6: Guideline to calculate cylindrical tolerance [29].

To represent the object's characteristics more effectively, GD&T defines a series of symbols, terms, and rules to clarify a piece's conformities. Figure 2.7 demonstrates the symbolic language characters used to describe the tolerance type (e.g., form, profile, orientation, runout, and location). In Figure 2.8 feature control frame is illustrated, showing the meaning of each of its components. GD&T uses uppercase letters to identify the "faces" of the piece geometry (also know as datum), instructing the manufacturer by representing datums in order of presence and importance [27].

When compared to the CD&T, GD&T shows a more descriptive approach to dimension and tolerancing representation, allowing industries to have more context during complex components examination. Thus, impacting directly the quality of the final product produced by factories.

2.2.3 Concepts of Geometric Inspection

To understand the guidelines provided by CD&T or GD&T, it is necessary first to understand the methods and needs they try to solve.



Pertainsto	Type of Tolerance	Geometric Characteristics	Symbol
Individual Feature Only	Form	STRAIGHTNESS	—
		FLATNESS	▱
		CIRCULARITY	○
		CYLINDRICITY	⌭
Individual Feature or Related Features	Profile	PROFILE OF A LINE	⌒
		PROFILE OF A SURFACE	⌓
Related Features	Orientation	ANGULARITY	∠
		PERPENDICULARITY	⊥
		PARALLELISM	//
	Location	POSITION	⌖
		CONCENTRICITY	◎
		SYMMETRY	⌯
	Runout	CIRCULAR RUNOUT	↗
		TOTAL RUNOUT	⌰

Figure 2.7: GD&T symbols, tolerance types and their characteristics [27].

Tolerance

Tolerance implies the full measure in which a dimension could range from a specified size. It is not feasible in an industrial process to produce many components with precisely the same dimensions. Thus, working with tolerances is needed [29].

When verifying a part's tolerances, the designer delimits each feature's characteristics and their relationships with other of the piece features. They are acknowledging that two workpieces, distances, or quantities can not be exactly alike. Therefore, the designer specifies an ideal condition and calculates a degree of error that a component diversion can be tolerated [27][29].

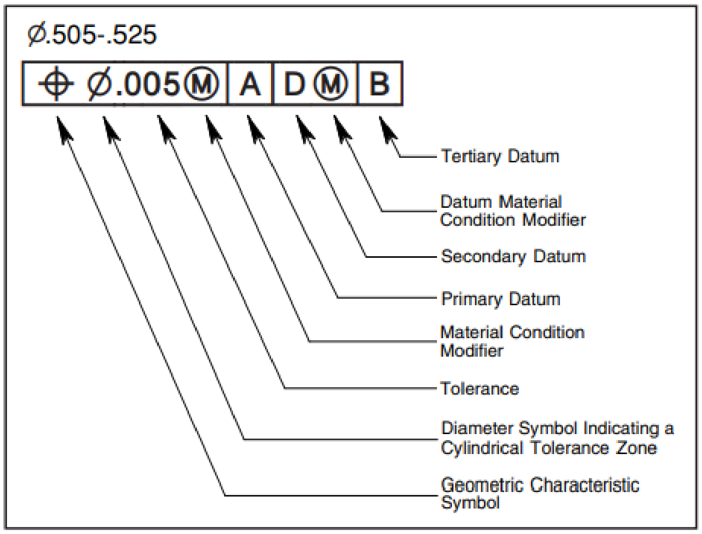


Figure 2.8: The feature control frame with description labels [27].

Gauging Principles

Gauge tolerance is usually planned based on component tolerance amount. For some gauges, the 10% rule is typically applied to limit the measure of gauge tolerance. Consequently, with the nonexistence of a specified gauge tolerance threshold, the maker will use 10% of the component tolerance as the gauge tolerance amount for a working gauge [29].

Next, the direction in which the allowance is should be determined. Two basic systems exist, bilateral and unilateral, but variations are commonly used, based on the product and facilities. When choosing an allowance system, the objective aims to reach the economical production of 100% usable parts as possible, accept suitable components and reject bad ones [29].

- **The bilateral system** (Figure 2.9.a) has the gauge tolerance zone divided into high and low limits of work tolerance. The gauge tolerance zones, in this case, are half plus and half minus concerning the high or low limit of the work tolerance zone;
- **The unilateral system** (Figure 2.9.b) has a work tolerance zone that includes the gauge tolerance area. This causes the work tolerance to be smaller by the sum of

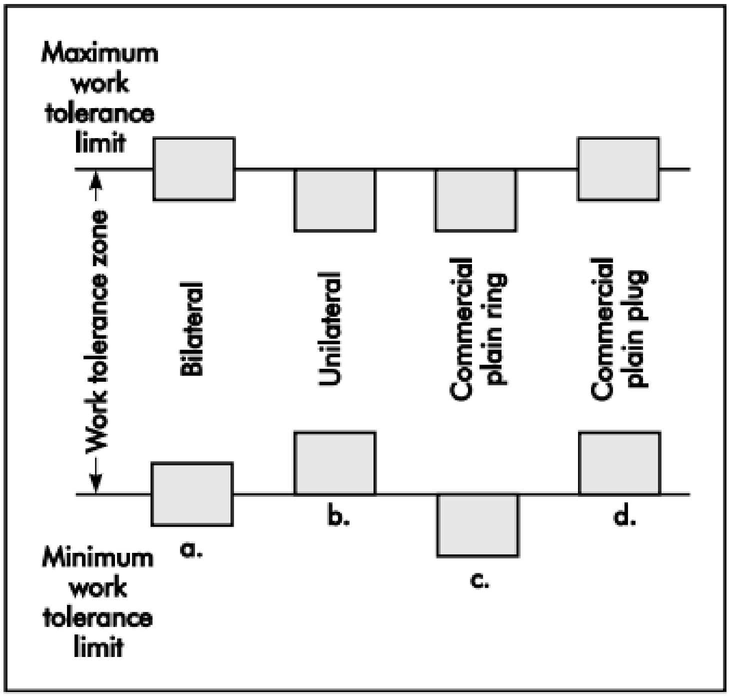


Figure 2.9: Different systems of gauge tolerance allocation [29].

the gauge tolerance, but guarantees that all parts passed by such a gauge will be inside the work tolerance zone despite the quantity of the gauge size variation;

- **The commercial plain ring** (Figure 2.9 c) and d) are commercial variation of the two basic systems. The product and the facilities should determine modifications.

Industries broadly use gauging to identify unwanted tolerances in the manufactured pieces. Although some standardized systems exist (Figure 2.9), the gauge may vary according to the product need in order to guarantee the final piece's best quality.

Gauging Wear

As Nee [29] demonstrates in his book, no gauges are perfect. If an ideal gauge existed in the real world, it would be imperfect after just one examining operation. The gauge wear amount during only one analysis operation is hard to measure, but several analysis operations' total wear can affect the measurement's precision. A gauge can fade past usefulness, so some allowance should be built into tolerance value. All gauge tools have an expiration date and should continually be verified previous to each inspection.

Gauging Materials

The materials utilized to make gauge tools may vary according to the production which it runs. Medium production usually uses hardened alloy steel to the wear surface of gauges. In higher demanding production, chromium-plated are typically used instead. When a gauge needs to have a higher degree of accuracy in long and wear excessive use, tungsten-carbide contacts often are used on gauges. The worn gauges surfaces can be ground down, chrome-plated, reground, lapped to size, and put back into service [29].

2.2.4 Tools for Geometric Inspection

Tools are needed to inspect the geometric dimensions and tolerances of a manufactured piece. Although the final tooling will always depend on the workpiece necessities, those pieces' testing methods may vary from traditional gauge tools to computerized automated systems.

Gauge tools

A gauge tool is typically built with two parts. One part is described as a "go" end. This end should allow clearance throwing the gauge tolerance zone. And another end is called "no-go," which should be more significant than the tolerance threshold. Many types of gauge tools exist to test many aspects of machined component conformity, e.g., custom commercial gauge (Figure 2.10.a), screw pitch gauge (Figure 2.10.b), plug gauge (Figure 2.10.c), ring gauge (Figure 2.10.d), among others [29].

Most gauges are standardized by norms, like American Gage Design (AGD). Although an exclusive gauge may be designed to inspect a particular component, AGD serves as a guideline for the tooling design [29]. For example, AGD standards generalize three types of plug gauge:

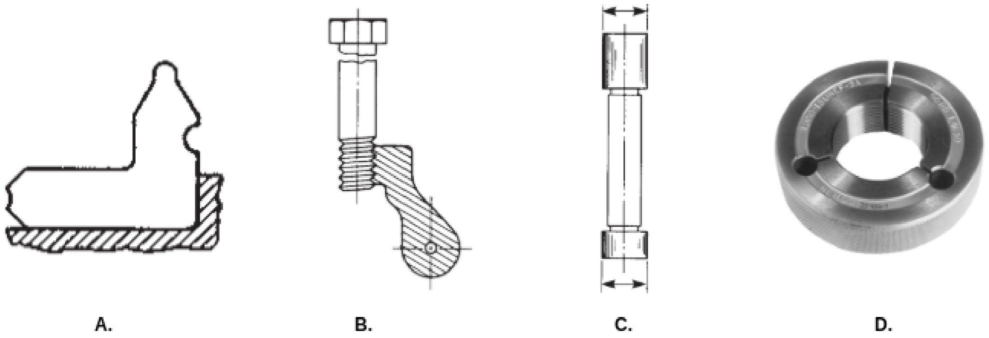


Figure 2.10: Types of gauge tools used by industries. Adapted from [29].

- **Single-end plug gauge**. This type of gauge consists of two separated gauge parts (a "go" and "no-go"), with each one of them having its handle (Figure 2.11.a);
- **Double-end plug gauge**. his is a single handle gauge tool with one gauge member (a "go" and "no-go") on each end (Figure 2.11.b);
- **Progressive gauge**. A single handle gauge with both parts (a "go" and "no-go") mounted on the same end. Both inspection ends are put together with the "go" part mounted in the front of the "no-go" end (Figure 2.11.c);

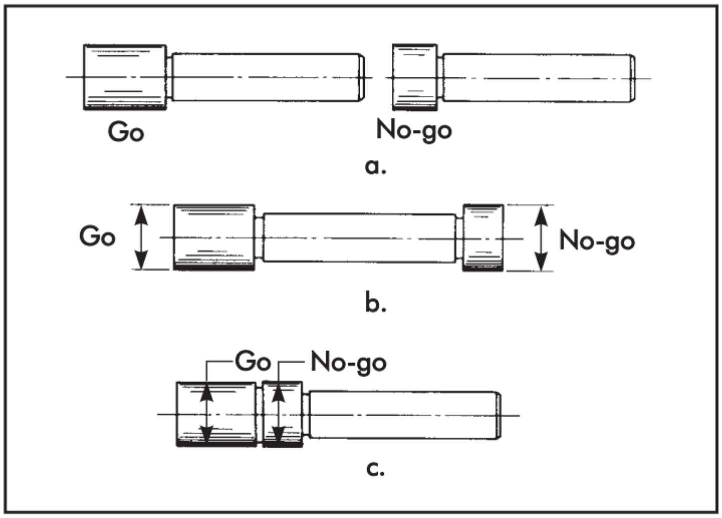


Figure 2.11: AGD cylindrical plug gages used to inspect the diameter of holes [29].

The usage of traditional gauge tools is a straightforward and manual process, depending on human operators to use the gauge tool and test it correctly. Standards help the design in developing gauges for testing manufactured pieces.

Coordinate Measuring Machine (CMM)

The Coordinate Measuring Machine (CMM) is an automated tool utilized by industries as a critical component of manufactured components inspection. CMMs enable Computer-Aided Inspection to increase accuracy and precision, emphasizing modern manufacturing qualities. CMMs are equipped with a touch probe that extracts high accurate data from surfaces which can then be compared with CAD files, utilizing the features information as metrics for the inspection [30].

Although extensively used in industry, To integrate CMMs in the industrial quality inspection process, the elaboration of an inspection planning strategy is needed to produce an optimum inspection strategy achieving more accurate and faster inspection results. CMMs deliver high accuracy with a slow measurement speed causing bottlenecks in the industry productivity. CMMs also highly depend on experienced operators to plan an effective strategy, which may be problematic and complex. The execution of the planning task will directly impact the inspection's measuring time, cost, and errors [30][28]

3D Scanner

In [28] paper, a 3D scanner to automatically check the geometric tolerance of parts is proposed. The author used the 3D scanner device to compare the scanned model with the tolerance specified by the components' tolerances, usually provided by a CAD file. The difference found when comparing with the specified tolerance is accepted or rejected according to the piece conformity with the guideline, generating a report with all the discoveries in the end. Although the author defines this approach as reliable and reproducible, the use of this technique depends a lot on highly experienced workers and excellent planning to perform the analysis correctly. The solution also isn't affordable and has been implemented in a controlled environment.

Cameras

In [31] paper, the authors approach the quality control of a badminton shuttle manufacturer by developing a solution that analysis the geometrical features of the feather used by the shuttles, identifying inconformities during the laser cut process. The solution uses multiple cameras to detect and measure unconformities in irregular-shaped objects and compares it with a 3D model of its real-world counterpart before the laser cutting operation. The laboratory prototype built presents a possibility for reduction of the time and power on handling faulty materials. However, implementing these automatic systems is not the proper solution for all processes since they usually require a high investment and/or present a high implementation complexity is dependent on the inspection process. In this sense, traditional quality control systems may face difficulty using automatic tools on the production line.

Although very promising, most of the state of the art solutions using emergent technologies remain highly experimental and mainly tested in a laboratory environment with only specific parts being used and not considering the industrial requirements. Another disadvantage for the before-mentioned approaches is their high implementation prices, a problem for small and medium-sized companies that aim to make the transitioning to use more digital geometry inspection methods.

2.3 Human-Machine Interfaces

Human-Machine Interface (HMI) can be described as the process by which humans interact with machines, implying in any machine or device used to perform or support individuals in their tasks [32]. An effective HMI solution is one that handles machine operations efficiently by humans without potential errors [33]. As Hollifield [34] states and Gregorio, Nota, Romano, *et al.* [32] quotes, in an industrial context, a satisfactory HMI should provide an operator means to identify and intercede effectively and quickly on irregularities within a process before they turn into a real emergency.

HMI is widely adopted by Industry 4.0. It can help industrial factories decrease the number of emergencies and accidents by providing operators with a macro view of their surroundings and rapidly reacting to situations. Powered by data and supported by assistance systems, humans can benefit when using the HMI for decision-making. The human-machine interface reduces the complexity of the process and makes them more manageable for users [32][33].

2.3.1 Principles and Guidelines

User interaction is a progressive field where new technology has always been employed to facilitate human-machine communication. Guidelines and best practices exist to support designers in building great HMI, presenting recommendations that may benefit the achievement of a good HMI design [35][36].

General principles are those that deal with common User Interface (UI) principles. This principle can be applied in most systems that rely on a UI to interact with a user. Some of those principles are [35][36]:

- **Consistency**. This is defined as the uniformity of system semantics across similar situations. This can be a consistent template, interaction method, term, and/or operation that is commonly used throughout the whole system;
- **Visibility**. Delivering important information prominent and easily detectable to the user. Users should quickly find tools and/or important information for their task;
- **Feedback**. The system should always give feedback to user's actions. For example, when a user interacts with a button visual feedback should be presented;
- **Recoverability**. Systems should provide users with options that enable them to recognize and recover from errors.

Although general principles can be applied to many systems, when handling 3D modeling and visualization, another set of regulations is suggested to be utilized. These principles are used by software, such as Computer-Aided Design (CAD), to better interact with the 3D spaces in 2D software [35]. Some of those 3D specific guidelines are:

- **Maximization of Workspace**. Interfaces should provide maximum screen space for modeling and viewing 3D models;
- **Graphical Richness**. Usage of graphical information, such as images and animation, enhance user comprehension when not over-utilized;
- **Direct Manipulation**. The HMI may provide the user with a direct operation to manipulate an object or scene within the 3D space. One example is the usage of the pinch gesture to apply zoom in a 3D dimension.

By applying the General and 3D specific principles, the software achieves more excellent usability and integration of its features. But when developing HMI is also needed to think about the user's support that will interact with the UI. For these, best practices show how to handle user support [35][36]:

- **Familiarity**. Take into consideration the users' experience in the real world and with other software when interacting with a new system. Maintain conformity with operating system conventions, 3D modeling system conventions, or similarities with the users' work;
- **Customizability**. Support users to modify the interface or operation of the system based on their preference;
- **Assistance**. Provide the user explicit assistance with tutorials and implicitly, by giver the user clues in which direction to follow;
- **Minimalist design**. The HMI should keep the user interface design simple, minimizing redundancy, and eliminating information that may confuse the user;
- **Context recognition**. The system should identify the context of the user and automatically modify the interface and/or operation to the one that best suits the user.

A more usable UI will be achieved by following the guidelines and improving the software's final UX. Empowering users, the HMI will reduce complexity and makes the cognitive load caused by complex information more manageable by the user.

2.3.2 Multi-touch User Interfaces (MTUI)

Multi-touch User Interfaces (MTUI) enables the user with more intuitive interactions than the keyboard and mouse inputs would provide. One example of the usage of this paradigm would be a photo gallery that uses the finger's "swipe gesture" on the display surface to browse the collection [37].

Many use cases may require the human-machine interfaces to provide visualization and interaction of 3D objects in touch-sensitive devices. The Fiorella, Sanna, and Lamberti [37] paper evaluates multi-touch interaction methods seeking an effective approach to this problem. The MTUI presented by the author results in the usage of the following gestures to interact with the 3D environment:

- **Picking gesture** is used to select an object (Figure 2.12.a);
- **Pinch gesture** enables the user to modify the scale of the object (Figure 2.12.b);
- **Two-finger gesture** allows translating the object (Figure 2.12.c).

These multi-touch interactions, when compared to traditional button-based user interfaces, received more positive feedbacks. The paper author concludes that most of the experiment subjects find the handheld device suitable for 3D graphics application [37]. Proving that is possible to translate 3D computer graphics applications to the 3D mobile application, by using MTUI instead of mouse input for dragging, rotating, and zooming [37].

2.3.3 HMI concepts applied to Industry 4.0

Industry 4.0 demands smart factories with all process equipped with support to interconnected data. Machines and industrial equipment will mature to more autonomous and

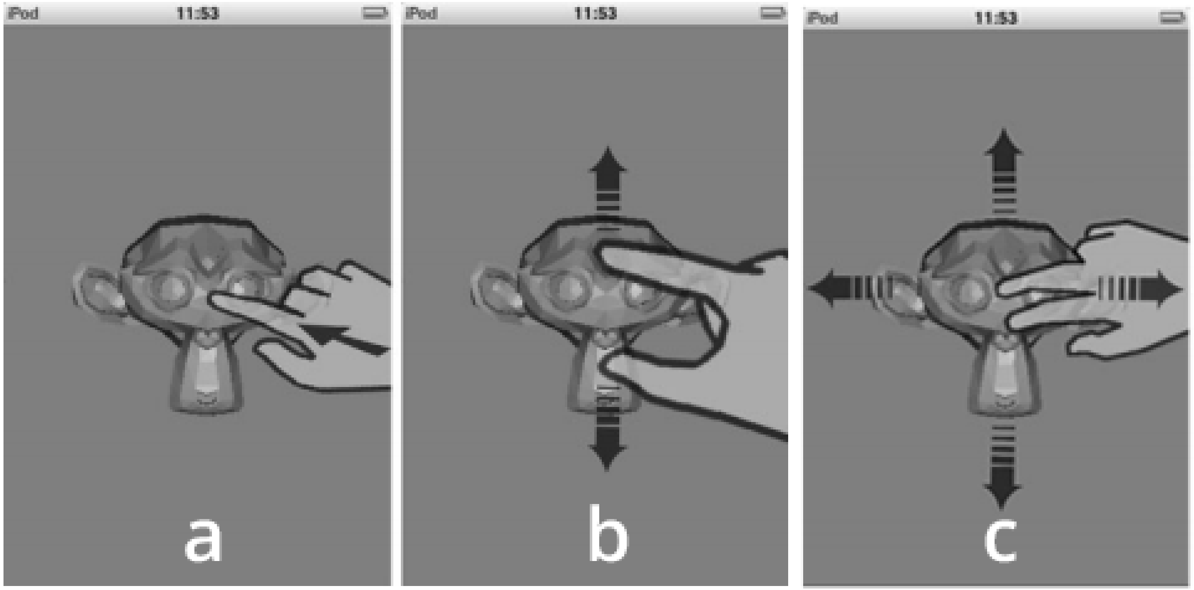


Figure 2.12: The designed Multi-touch User Interfaces: Picking gesture (A); Pinch gesture (B); Two-finger gesture (C) [37].

self-organizing, making one complex manufacturing process more manageable [33]. A key component for the reduction of complexity is the Human-Machine Interface, which can be integrated with industry-related data to provide humans with tools that can aid digital decision making [33].

The development of industrial-grade HMI will always depend on organizational specifics [33]. The collection of experiences, skills, familiarity, and motives that make operators handle job-related duties and challenges requires the process to adequate two important aspects:

- The technical competence that enables successful user-friendly HMI innovations [33];
- The worker competence to operate in a highly autonomous and interconnected environment [33].

According to Lodgaard and Dransfeld [33], the success of an HMI integration into Industry 4.0 will differ for each manufacturing company. Identify the maturity level of those companies is crucial to managing the integration in those digital transformations.

Useful and user-friendly HMI requires the development of approaches based on a company maturity level.

2.4 Virtual Reality (VR)

As cited by Bishop and Fuchs [38] and quoted by Mazuryk and Gervautz [39], Virtual Reality (VR) can be defined as “Real-time interactive graphics with three-dimensional models, combined with a display technology that gives the user the immersion in the model world and direct manipulation.” - i. e., an advanced UI that enables the user to navigate and interact in a three-dimensional environment.

Virtual Reality portrays to the user an experience characterized by the coexistence of immersion, interaction, and involvement [40]. An immersive VR experience may provide a person with a virtual environment with the feeling and experience of being in the actual environment. This can be achieved by the usage of display gear (i.e. output devices) and devices that introduce other senses to the virtual environment (i.e. input devices) [40].

2.4.1 Immersion

Immersion is the feeling of being part of the environment. There are two types of VR visualization, the immersive and the not-immersive [40].

The immersive VR experience can be achieved by the usage of display gear and/or devices that introduces other senses to the virtual environment. Although vision is our main sense when working with VR, another stimulus like sounds and touch response can be used to better the user perception of the digital environment [40].

In another way, the non-immersive VR usually utilizes monitors to visualize the 3D scene. If compared to immersive solutions, the main positive point of the non-immersive technology is the affordable cost and straightforward usage. Although the advantages of non-immersive VR are clear, immersive VR is the tendency of most future Virtual Reality applications because of the immersive capacities brought by the technology and extensive research been used in the field [40].

2.4.2 Levels of Immersion

As Slater, Usoh, and Steed [41] explains and Mazuryk and Gervautz [39] quotes, the Virtual Reality system is responsible for delivering sensory feedback to the user. The quality of the experience immersion will be determined by the feeling of presence in the virtual environment. In a perfect world, a VR experience will always be high-resolution, high-quality, and consistent on the displays, with the information being stimulated to all user's senses. However, in reality, the VR immersion does not always fill the given requirements and will be classified by the level of immersion that the solution provides to the user.

- **Desktop VR**. Also known as Window on Word (WoW) systems, the Desktop VR is the simplest type of VR application. It uses a conventional monitor to display the virtual world, without supporting sensory output;
- **Fish Tank VR**. These systems are an evolution of the Desktop VR with support to head tracking, which improves the user immersion. The display technology is still provided by conventional monitors and does not support sensory output;
- **Immersive Systems**. It is the more immersive system, placing the user in an immersive computer-generated world. This paradigm uses HMD, stereoscopic view, audio, haptic, and sensory to enhance the user experience.

2.4.3 Virtual Reality in The Industry 4.0

There are several simulation-based approaches available in literature being employed in the context of Industry 4.0, e.g. VR, AR, Agent-Based Modeling and Simulation (ABMS), Digital Twin (DT), and others [22]. As Hermann, Pentek, and Otto [20] mentioned and Paula Ferreira, Armellini, and Santa-Eulalia [22] quote, although there is no consensus on the definition of Industry 4.0, some of its core technological components and design principles can be identified and used to support the implementation of Industry 4.0 scenarios in companies, like, real-time capability and virtualization.

Real-time capabilities, i.e. real-time data collection, analysis, and support to data-driven decision making, will transform work content, work processes, and the working environment, connecting people, objects, and systems [19]. In [42], an approach for modeling and assessing the performance of manufacturing systems is proposed, using a virtual model to increase the performance of the real system. The proposed framework combines modeling of hybrid systems with plant floor data extracted using IoT to solve some of the synchronization and performance challenges faced on digitally representing a real industry. This can be achieved by monitoring machine and system-level variables with synchronous operation between the real and virtual environments, supporting manages on the floor plant with their decision making.

Virtualization, as quoted from Paula Ferreira, Armellini, and Santa-Eulalia [22], is the virtual replication of a physical system by linking sensor and actuators' data with a digitized factory model [20]. A virtual system is effective for issues such as training and conducting the workforce while performing manual processes, diagnosing, and predicting faults, and guiding maintenance tasks to fix failures [43]. Moreno, Velez, Ardanza, *et al.* [44] paper shows a study case on the virtualization process of a metal punching machine. The article exemplifies the application of virtualization with Digital Twin, addressing the creation of a DT of a material removal machine so that it can be used within a simulator to collect valuable information without wasting resources. The digital representation uses an Extensible Markup Language (XML) file to arrange the 3D model representation with data provided by Ethernet/IP (TCP/UDP connections) from the real machine. The simulator may warn the user about potential risks by comparing the program trajectories and their linear speeds with the trap's location and state.

Virtual Reality (VR) is a powerful tool when combined with real-time data and virtualization, enabling a more immersive interaction in manufacturing, increasing a user's perception and interaction with the real world, supporting different activities such as training, assembly, and maintenance [22]. Pérez, Diez, Usamentiaga, *et al.* [45] demonstrate an integrated human-robot interface using commercial gaming technologies and real robotics hardware and software to create a VR-controlled robot, in an immersive interactive environment where the operator can be trained. The innovation of the proposed approach is that it combines training, simulation, and control in a safe and non-expensive integrated application. Results show that the immersive experience succeeds in increment the efficiency of the simulation processes with a cost-effective solution, although the Head Mounted Devices (HMD) might cause sickness during intensive use, as shown by the author which finds out that 88.33% of the user's felt sick during the experiment.

A 2020 survey about industrial augmented reality studies realized by Souza Cardoso, Mariano, and Zorzal [46] reveals a notable use of AR technology by many general mechanical industries, generally producer of small components for other companies, largely in the automotive segment. The most meaningful use of AR in the examined period was by HMD and the primary benefit was the reduction of performance time, accompanied by improvement in quality and increase in learning, circumstances that contribute to costs reduction. From every one of the subjects examined only 5% were implemented in a production environment, offering a great area for research of disruptive solutions.

In [47], the author introduces a discussion on the use of AR in industrial shop-floors, for the experiment were built four prototypes adopting different display technologies, next tested in an industrial company workforce, and finally, the pros and cons of each approach were compared. The prototypes were:

1. Video-based glasses, an Oculus Rift [1] mounted with two cameras that stream video into the screen. This solution provides a hand-free solution, but was heavy to wear and had the operator's vision completely digitalized which can be to risk in an industrial environment;

2. Optical Glass, a C-Wear glasses connected to an Android-based device as computing unity with the augmented reality implementation. As result, a hand-free tool with non-obstrusive visualization of the real-world was offered, but as a counterpoint, image updating at head moves sometimes lag, the solution difficult to use the glasses

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[1] Oculus Rift Website

if already wearing ordinary glasses, and the weight of the optical glasses started to be perceived after some time;

3. Video-based tablet, a hand-held tablet that uses the device camera in combination with an augmented reality software. Its pros were a high familiarity perceived by the operator, while the cons were that the solution either occupies the operator's hands or, if placed in a stand, obstruct the operator's field of view, another problem was that in case of an object comes in the way of the camera the virtual objects disappear;

4. Spatial projector implements augmented reality by disconnecting the display from the user and integrating it into the environment. This method achieved a hand-free solution without affecting the operator's sight and without carrying additional weight. Although it depends on hardware permanently installed in the working environment and sometimes the information can become invisible if something came in the way of the projection.

As result, most of the participants believed that the prototypes were easy to understand and use. Another positive aspect revealed by the study was that most participants perceived increased efficiency with AR. However, the complexity of the task must be high enough for the operator to sense that it is deserving of using the augmented reality system.

2.5 Usability Test

A usability test is a process used both during and after the development of a product. It aims to test the prototype through an interactive process with constant user feedback. The usability test depends on consistent communication between usability specialists, product designers, and consumers [48]. As shown by Rubin and Chisnell [49], this might require constant task-based prototype testing, research, interviews, and survey to achieve a more relevant analysis.

2.5.1 Instruments and Measures

Peres, Pham, and Phillips [48] state that is developing questionnaires require many aspects to consider to create good instruments. Their paper describes several steps to take for quality control of a survey before its administration. Some useful guidelines like the length of the questionnaire, the qualitative item analysis, expert review, and pilot test are an excellent way to assert the survey quality. In their study, Peres, Pham, and Phillips [48] used the following instruments to measure the effectiveness of their survey:

- **Convergent Validity**. Describes the relationship between two different measures that aim to capture the same construct. This instrument consists of ten items, on which usability is rated on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree);
- **Divergent Validity**. Divergent validity refers to items that should not be related. That is, measures should not conceptually relate to the items. As a result, divergent estimates expect a low correlation between items;
- **Criterion-related Validity**. This instrument is a relationship between a measure in question and an external objective measure, i. e., a performance measure. When comparing to an objective performance measure, Peres, Pham, and Phillips [48] studies show that a medium-size correlation is expected;
- **Reliability**. The reliability measure describes the internal consistency of a survey by analyzing how the items of a questionnaire related to each other;
- **Sensitivity**. This topic refers to which differences can be detected by an instrument when an independent variable, for example, usability, is manipulated. By grouping means of the high-usability conditions with the low-usability conditions, the sensitivity can be assessed;
- **Respondent Workload**. The workload put to the subject of the test can be asserted by using a single-item scale such as "It was exhausting for me to respond

to the questions.", representing the participant fatigue during the survey;

- **Respondent Motivation**. A test subject's motivation may be analyzed by adding items that may show interest and pleasure using words that indicate fun, joy, and/or interest while completing the questionnaire;

- **Questionnaire Completion Time**. Online surveys can be used to record the completion time of each item.

2.5.2 System Usability Scale (SUS)

When working with Human-Computer Interaction (HCI), it is common sense to use usability evaluation tools to address the recommended solution's quality. Assila, Oliveira, and Ezzedine [50] describes usability evaluation as a well-defined and well-studied subject utilized to make systems easy to use and learn. Shackel [51] states and Assila, Oliveira, and Ezzedine [50]. quotes that "usability is the capability to be used by humans easily and effectively and associated with five criteria, i.e., effectiveness, learnability, retention, error, and attitude".

Although there are plenty of distinct great options to usability test (Table 2.1) [52], Assila, Oliveira, and Ezzedine [50] review on HCI literature found out that most of the studies on usability are focused on comparing one or more survey systems with the System Usability Scale (SUS), investigating the correlation between them. The general usage of SUS occurs by the fact that it is utilized as an industry standard for a usability test, performing a more quick and general usability assessment.

Survey name	*Number of questions*	*Availability*	*Interface measured*	*Reliability*
After Scenario Questionnaire (ASQ)	3	Non-proprietary	Any	0.93
Computer System Usability Questionnaire (CSUQ)	19	Non-proprietary	Computer based	0.95
Poststudy System Usability Questionnaire (PSSUQ)	19	Non-proprietary	Computer based	0.96
Software Usability Measurement Inventory (SUMI)	50	Proprietary	Software	0.89
System Usability Scale (SUS)	10	Non-proprietary	Any	0.85
Web Site Analysis and Measurement Inventory (WAMMI)	20	Proprietary	Web based	0.96

Table 2.1: Summary of available usability surveys (adapted from [3]).

Chapter 3

Case Study and Problem Analysis

The study considered in this work is related to gauge tools to perform the quality control of parts produced in a steel cold stamping factory plant. In such a process, the operator uses a pre-configured testing bench, as illustrated in Figure 3.1, to inspect the geometry compliance of a particular produced part. These testing benches provide gauge tools for the component-specific inspection, guides (for instructions and component conformity specifications), and expiration dates for the tools' effectiveness for each component series.

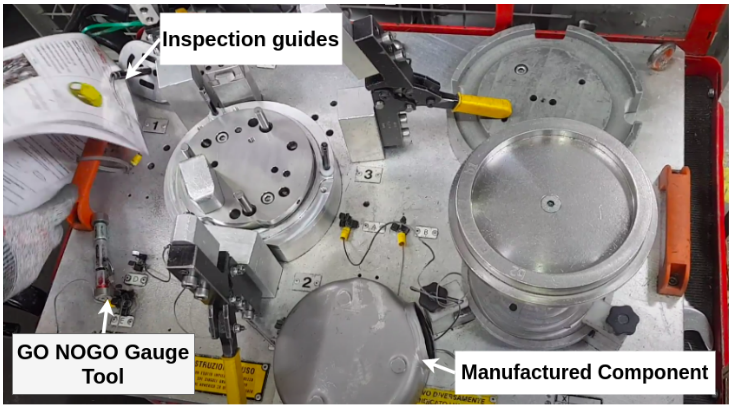


Figure 3.1: Test bench used by operators during the inspection process.

3.1 Quality Control

Quality control inspections are usually carried out many times in a day with the intent to test as many components as possible minimizing production failure. The specified interval between each analysis may be defined by quality control management, and at each interval, a partial or complete inspection may be executed.

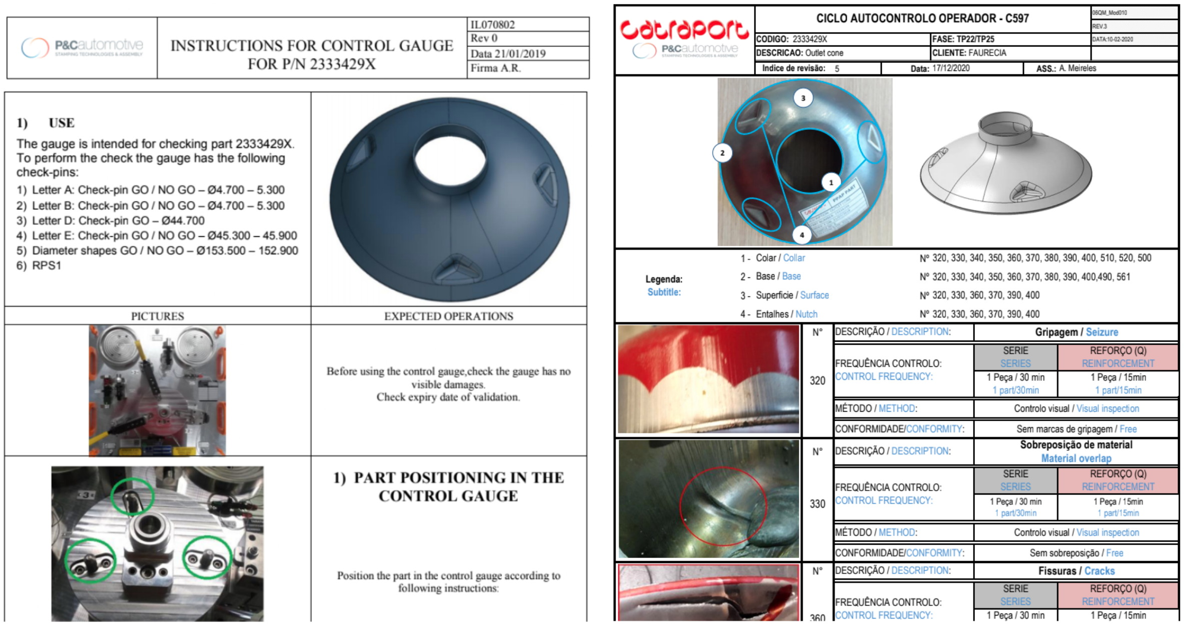
In our study case, these inspections can be divided into two categories visual and geometrical. Visual inspection frequencies are more often and faster to be executed, increasing the number of inspections to detect visible damage present in the produced piece.

The geometrical inspection is often less frequent and happens after a visual inspection. This technique utilizes "go" and "no-go" gauges to inspect the components' geometric conformity, a common among factories. This process involves executing a step-by-step analysis to inspect a component with tools that may or may not enter the tolerance specified.

For both analysis methods, guidance through the visual and geometrical inspection process is provided to the operators via tutorial papers. The test bench usage guide (Figure 3.2.a) provides step-by-step information on how to use the test bench during the inspection, the operation control guide (Figure 3.2.b) shows common failures, tolerances, and inspection methods used during the inspection.

Once the operator finishes the inspection, the results are recorded in the paper spreadsheet. It offers insights into the non-conformities found during the inspection. The recorded information is sent to quality control management, which will use the data to register metrics and better understand the production problems.

The main problem with this approach is the execution time and the number of errors that can exist due to the operators' difficulties in memorizing and executing the entire inspection sequence for the different part references correctly. This difficulty can become more evident in changing part reference, especially when the operator starts the inspection procedure and requires time to adjust the inspection routine.



INSTRUCTIONS FOR CONTROL GAUGE FOR P/N 2333429X	IL070802 Rev 0 Data 21/01/2019 Firma A.R.

1) USE

The gauge is intended for checking part 2333429X. To perform the check the gauge has the following check-pins:

1) Letter A: Check-pin GO / NO GO – Ø4.700 – 5.300
2) Letter B: Check-pin GO / NO GO – Ø4.700 – 5.300
3) Letter D: Check-pin GO – Ø44.700
4) Letter E: Check-pin GO / NO GO – Ø45.300 – 45.900
5) Diameter shapes GO / NO GO – Ø153.500 – 152.900
6) RPS1

PICTURES	EXPECTED OPERATIONS
	Before using the control gauge,check the gauge has no visible damages. Check expiry date of validation.
	1) PART POSITIONING IN THE CONTROL GAUGE Position the part in the control gauge according to following instructions:

A.

CICLO AUTOCONTROLO OPERADOR - C597		06QM_Mod010 REV.3 DATA:10-02-2020
CODIGO: 2333429X	**FASE: TP22/TP25**	
DESCRICAO: Outlet cone	**CLIENTE:** FAURECIA	
Indice de revisão: 5	**Data:** 17/12/2020	**ASS.:** A. Meireles

Legenda:
Subtitle:

1 - Colar / Collar	Nº 320, 330, 340, 350, 360, 370, 380, 390, 400, 510, 520, 500
2 - Base / Base	Nº 320, 330, 340, 350, 360, 370, 380, 390, 400,490, 561
3 - Superficie / Surface	Nº 320, 330, 360, 370, 390, 400
4 - Entalhes / Nutch	Nº 320, 330, 360, 370, 390, 400

Nº			
320	DESCRIÇÃO / DESCRIPTION:	**Gripagem / Seizure**	
	FREQUÊNCIA CONTROLO: CONTROL FREQUENCY:	SERIE SERIES	REFORÇO (Q) REINFORCEMENT
		1 Peça / 30 min 1 part/30min	1 Peça / 15min 1 part/15min
	MÉTODO / METHOD:	Controlo visual / Visual inspection	
	CONFORMIDADE/CONFORMITY:	Sem marcas de gripagem / Free	
330	DESCRIÇÃO / DESCRIPTION:	**Sobreposição de material** **Material overlap**	
	FREQUÊNCIA CONTROLO: CONTROL FREQUENCY:	SERIE SERIES	REFORÇO (Q) REINFORCEMENT
		1 Peça / 30 min 1 part/30min	1 Peça / 15min 1 part/15min
	MÉTODO / METHOD:	Controlo visual / Visual inspection	
	CONFORMIDADE/CONFORMITY:	Sem sobreposição / Free	
360	DESCRIÇÃO / DESCRIPTION:	**Fissuras / Cracks**	
	FREQUÊNCIA CONTROLO: CONTROL FREQUENCY:	SERIE SERIES	REFORÇO (Q) REINFORCEMENT
		1 Peça / 30 min	1 Peça / 15min

B.

Figure 3.2: Guides used by operators during the inspection: Test bench usage guide (A); Operation control guide (B)

The traditional method also creates a loss of time when converting the inspection report into digital support. Changing the test bench reference also implies changing all the paper guides used, creating a more time-consuming task. Additionally, using a paper spreadsheet to record data can be misleading once the data recorded may be wrong or incomplete, needing the future treatment to register more efficiently in a digital means, creating an additional loss of time to the operators writing the report.

3.2 Solution Requirements

The presence of Information and Communications Technology (ICT) and IPA, as the proposed work, are increasing in the industry. To digitize this inspection process, this works contributes to improve the inspection speed and the operator's perceived comfort by using a 3D environment to enhance the inspection process learnability, easing the operator's workload. Furthermore, using reliable storage to store and collect analysis data digitally from the beginning of the user interaction is essential to enable an automatical reporting functionality, without depending on operators to specify failures, besides including the photos of visual non-conformities (Figure 3.3).

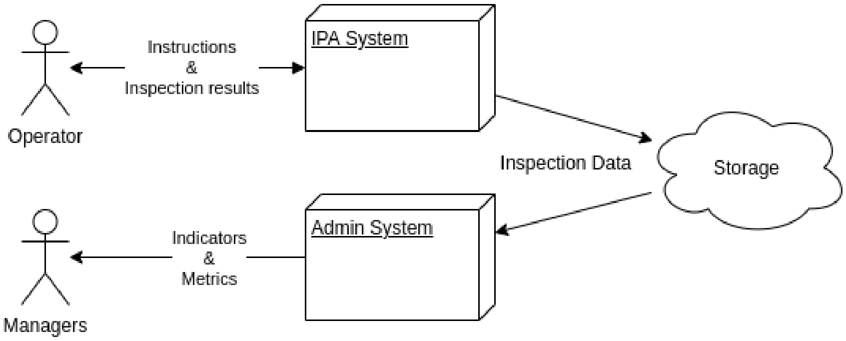


Figure 3.3: Diagram illustrating proposed system. It connects operators inspection results to managers while empowering operators with enhanced instruction data.

The collected data should be accessed in real-time by externals systems, e.g., management personnel that can visualize and analyze the results using proper metrics and better understand-conformities, contributing to identify earlier failure trends and proceed with machine calibration. As the result of the solution implementation is expected that the system improves the inspection quality control by offering: A more friendly HMI enabling operators to easily understand their tasks; Registering inspection information's more reliable; Reduce the inspection time by eliminating the data collection process; And improving quality control times by removing the need to change paper guides for every test bench replacement.

3.3 Development Strategy

To begin the software developed in this work is necessary to define the application's required functionalities. Thus, gathering the industry requirements and use cases is needed to understand the industrial process better. Therefore, the software engineering concept of iteratively creating use cases and prototypes is necessary to establish a common ground with the stakeholder. The methods described below are represented by Figure 3.4.

First, a visit to the industrial facility was made to understand better the quality control process and the key personnel behind those processes. All the crucial details were registered with notes, photos, and videos. Next, the content of those entries was analyzed to create a report explaining the factory inspection process. This report was used to contextualize all the project participants and create an environment prosperous for ideas. During an online meeting, brainstorm was carried out with the project participants'. Finally, ideas were collected, elaborated, and then proposed as possible solutions to the stakeholders.

With the possible solutions presented to the stakeholder, the process understanding was again refined, and the viability of each idea was discussed to find a more effective solution. After the meeting, notes took from the discussion were molded into functional and non-functional requirements using a spreadsheet to register it. Next, the requirements were transformed into use cases, and a diagram was drawn to represent them. Finally, screen prototypes were created with Figma using the use cases as guidelines.

The meetings with the industry personnel were frequent and happened during many stages of the development of this work. After each new iteration (e.g., brainstorm, requirements gathering, prototyping, and development), the project direction was validated with the industry responsible to ensure the work conforms with their needs. During this process, the understanding of the business logic was improved, and the communication of each of the project parts (e.g., developer, advisor, industry personnel) became more evident.

As defined by the prototypes and use cases, the implementation began by using those as guidelines to develop the solution with NodeJs, React, and React Native. Next, tests were executed with Jest to identify application failures before shipping to production. Finally, the application was deployed to the cloud using GitHub Actions to make continuous deployment on Vercel, Heroku, and Google Cloud, enabling secure external access to the software. During the whole application development and eventual bug fixes, this process was repeated, fully automated to create a fast and reliable release pipeline.

Digitization happened when the software requirements needed to create the manual were implemented. The process consists of using Fusion 360 and Blender to import, export, optimize, texture, and animate the final object to render in the mobile application. The final GLTF model is exported with the manual content into the web application to create a digital copy of the analog guide. This process is repeated until all the requested manuals are made and their content fully digitized.

After development and content creation, the application was presented to a control test group, and their answers were registered in an online SUS form. This group did not work in the factory and presents a diversified range of knowledge about software usage and industrial quality control. Next, the application was introduced in the industrial environment, integrated with the quality control process by fixing the tablet near a test bench. Moreover, managers were instructed on how to handle the application and apply the tests to the operators. During the production environment experiments, the online form registered their answers and related them with the email used during the device authentication.

Finally, the user test results were collected as a CSV file, imported to a spreadsheet, and analyzed to understand the user's perception better while handling the software and how this affected their work. Also, bug statistics were collected in order to check the application stability during production usage.

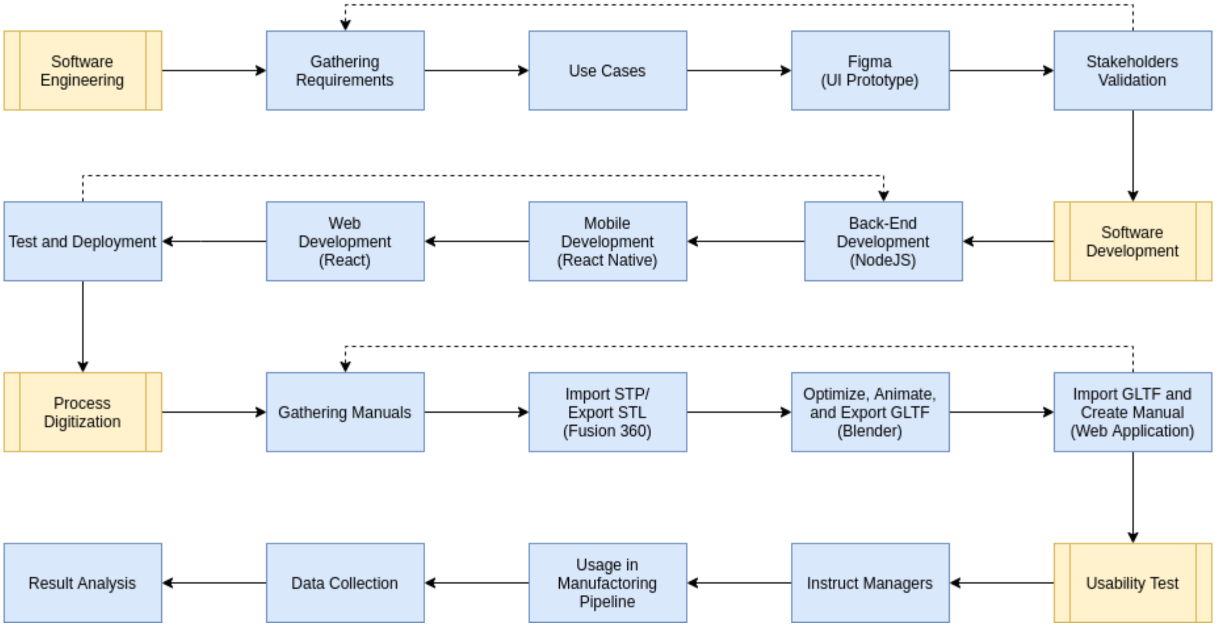


Figure 3.4: Diagram illustrating the strategy used during this work development.

Chapter 4

Technologies And Software Description

This chapter aims to present and explain the technologies utilized in this work and describe the reason for their usage during this project's application development. Technologies presented in Sections 4.1, 4.2, and 4.6 were used before and during all the applications development. The Sections 4.3 to 4.5 were used in both web and mobile apps. To create the digitized guides Sections 4.7 to 4.9 were applied. Finally, to deploy the application into production and provide infrastructure were utilized technologies described in 4.10 and 4.11. In the next chapter more details will be given in how these tools are used to solve the problem.

4.1 NodeJS (14.15.5)

NodeJS[1] is a JavaScript (JS) runtime built on top of Chrome's V8 JS engine. It was developed to enable JS to be executed in computers by a Command-Line Interface (CLI), allowing JS applications to be used as executables. Although more common concurrency models use the available Operational System (OS) threads to execute parallel computing, NodeJS employs an asynchronous event-driven strategy using a single thread in a

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[1] NodeJS Website

non-blocking event loop. This design allows creating network-based applications more efficiently than traditional thread-based alternatives, free from dead-lock and I/O blocks, using the event loop's ability to perform JavaScript callback functions after completing other work.

4.1.1 Node Package Manager (NPM)

Another advantage of NodeJS is the Node Package Manager (NPM)[2], which eases the import and configuration of libraries and frameworks for the runtime and makes the development process even more straightforward by improving the developer experience. NPM is also one of the package repositories with more contributions, with more than 1500000 modules available for development usage in the NPM public registry. The available packages vary from application-specific uses like ExpressJS, enabling NodeJS to receive Hypertext Transfer Protocol (HTTP) calls, and development-specific like Babel and ESLint, providing developers with better tooling for the task.

4.1.2 JavaScript (JS)

JS is a lightweight, interpreted, or just-in-time compiled programming language with multi-paradigm (e.g., object-orientation, imperative, and functional) and dynamic types. JS was first submitted to the European Computer Manufacturers Association (ECMA) to be used as a standard to implement scripting across multiple browser vendors. In the current NodeJS version, not all modern JS features are enabled by default (e.g., import/export, async/await, object deconstruction), only supporting the ECMAScript 2015 (ES6) specification.

4.1.3 TypeScript (TS)

Transpile languages into JavaScript is a common practice in the JS ecosystem. It uses a more developer-friendly language to increase productivity without losing compatibility

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[2] NPM Website

with older standards achieving a greater user-base. During the application development, Babel (version 7.12.1) was imported via NPM to allow TypeScript (TS) (version 4.0.2) to be used during the application construction to improve development further. TS extends the latest JS version by adding a strong type system, validating the JS ahead of time (i.e., providing errors and fixes before the code be executed). During the application execution, Babel transpile and optimizes the TS files into ES6 standards and then runs it in the NodeJS runtime.

4.2 Jest (26.6.3)

Jest[3] is a JS testing framework. Its usage aims to grant correctness to code features, describing test cases for each use case, thus improving the service's reliability. The tests executed by Jest are decoupled from the business logic and run in a parallelized manner by performing in a separate runtime process. Jest is an open-source tool-agnostic technology that integrates with Babel, TS, Node, React, Angular, Vue, and others.

4.3 React (16.11.0 - 17.0.1)

React[4] is a JS framework for developing web apps, Progressive Web Apps (PWA), mobile apps, and desktop apps. React is based on business logic componentization and declarative views, allowing for a predictable and straightforward UI implementation. Another advantage produced by the React framework is its multi-platform capability, allowing the reusability of code and knowledge in many target platforms (e.g., Android, IOS, MacOS, Windows, Linux, Web Browsers). React was used for both mobile (version 16.11.0) and web (17.0.1) development. The main difference from those targes is the additional React Native package only present in the mobile version.

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[3] Jest Website

[4] React Website

4.3.1 React Dom (16.11.0 - 17.0.1)

React uses React DOM to bind the Document Object Model (DOM) global methods into React and render JS elements on the screen. The DOM is accountable for connecting web pages to scripts by representing a document's structures (i.e., HTML) in memory. This allows JS to manipulate the document in a logical tree, where the script language can control this tree structure, style, and content.

The DOM provided by the browser usually suffers from performance issues when handling many manipulations at once. This happens because of the re-rendering of the UI that occurs to the manipulated element and its children. This step is computationally expensive, and excessive writes to the DOM have a significant impact on performance. React DOM solves this problem by creating an immutable Virtual DOM, which computes the necessary changes using an in-memory version of the DOM with a Diff algorithm and re-renders the minimal amount required to display the UI change (Figure 4.1).

4.3.2 React Native (Expo SDK 38.0.2) & Expo (38.0.8)

React Native[5] is used exclusively in mobile development. It allows the creation of native apps for Android and IOS using React. It combines both React and Javascript to build business logic and interface components reusable for any platform. Expo[6] is a set of tools and services built around React Native to improve developer experience on developing, building, deploying, and simulating Android and IOS applications.

Expo offers advantages from traditional React Native boilerplates by providing:

- **Multi-Platform Build.** Expo provides services to build the final application in the cloud. It allows developers to deploy for Android and IOS without having an XCode or Android Studio in their development environment;
- **Over-The-Air (OTA) Updates.** It provides OTA channels by default to developers deploying updates to the application. Whenever client device connects to the

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[5] React Native Website

[6] Expo Website

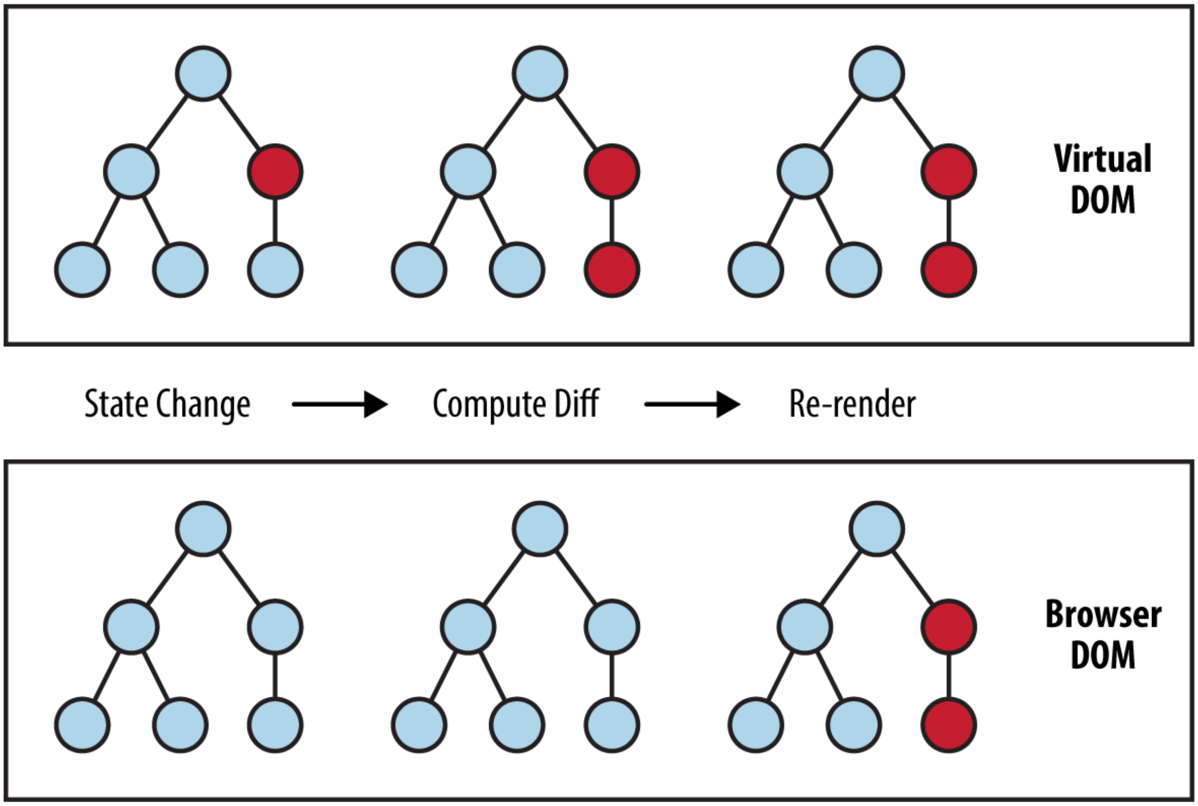

Figure 4.1: Virtual DOM Performing calculations compared to Browser DOM [53].

network, available updates are checked, downloaded, and installed;

- **Application Sharing.** Expo provides a development client that can be downloaded on any device, enabling testers to access the application anywhere during the development. It facilitates the sharing of the application, increasing feedbacks on the application's functionalities and implementation.

These advantages make Expo tooling an excellent option when working with React Native by increasing the developer's productivity.

4.4 ThreeJS (0.123.0)

ThreeJS[7] is an open-source, cross-platform, general-purpose 3D library. The project was created aiming to help web developers to work with 3D on the Web. The current stable version includes a WebGL renderer, but WebGPU, SVG, CSS3D, and OpenGL (Expo Three) bindings are also available to be used with the platform.

ThreeJS is developed with JavaScript and distributed via NPM, enabling any JS project to access and extend its functionalities easily. Some of the functionalities brought by the ThreeJS package are:

- THREE object abstraction around the traditional WebGL calls;
- Import and Export 3D files and textures (e. g., GLTF, COLLADA, OBJ, among others);
- Orbit Controls for manipulating the camera around the orbit target;
- Animation rendering, mixing and importing;

By offering many abstractions from the traditional WebGL, ThreeJS improves the developer productivity by including utilities for working with 3D. The library's counterpoint is the procedural coding style when handling the 3D scene, which difficulties its integration with more declarative frameworks, like React.

4.5 React Three Fiber (5.3.10)

React Three Fiber[8] abstracts the ThreeJS by simplifying the code when working with React and React Native. It implements a 3D scene with declarative and reusable components that allow the React framework to address 3D Objects, Light, Cameras, and Animations as JavaScript XML (JSX), maintaining a consistent code style.

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[7] ThreeJS Website

[8] React Three Fiber Repository

React Three Fiber also only converts JSX syntax into ThreeJS call, been more maintainable by not depending on the renderer version directly. This also implies no performance impact because when the application is built, everything becomes ThreeJS calls, relying only on the ThreeJS, CPU, and GPU performance to render the 3D scene.

4.6 Figma

Figma[9] is an online, collaborative, free to use, prototyping tool utilized to create wireframes, high-fidelity UI prototypes, and design systems. It allows designers to develop UI mocks fast and share with users to get user experience feedback to improve the application interface as it goes. Figma also generates Cascading Style Sheets (CSS) examples for developers to use as a guideline on the style guide implementation.

4.7 Blender (2.92)

Blender is a multi-platform (Windows, Linux, and MacOS) software for 3D manipulation developing with Python and OpenGL. The tool is open-source and allows the user to control 3D scenes and mashes with interactive tools. Besides 3D modeling, it provides tools to handle 3D animation, shaders, textures, video editing, import and export 3D files.

The suite is free to use and offers excellent compatibility with other CAD platforms, sharing OBJ, FBX, 3DS, STL, besides allowing plugins to extend its functionalities.

4.8 Fusion 360

Fusion 360 is a cloud-based Computer-Aided Engineering (CAE) software that handles the design and engineering of electronics and manufacturing models in a single platform. It also supports the creation and exporting of 3D printers out-of-the-box. The software is

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[9] Figma Application

proprietary been developed, maintained, and distributed by Autodesk. The software also offers a free version with limited features and an educational use version for students and professors with full feature access, only needing an institutional email.

4.9 GLTF (2.0)

The Graphics Language Transmission Format (GLTF) is an open standard that allows for efficient communication and loading of 3D scenes, modes, textures, and animations by engines and applications. The format reduces the size of assets using a compaction algorithm in the render runtime to unpack them. This technology enables the streaming of interactive and interoperable use of 3D content across systems.

GLTF can be used as GLB, a binary format of specification that may include assets compressed in. In the GLB structure, besides the traditional GLTF JavaScript Object Notation (JSON) structure that stores node hierarch, material textures (external references), and cameras. The GLB also includes geometry (vertices and indexes), animations' keyframes, and compressed material textures.

GLTF also enables material textures with metallic-roughness shading params (e.g., base color, metalness, roughness, emission, normal map, ambient occlusion) and optional specular-glossiness shading (e.g., diffuse, specular, glossiness). The format is also highly compatible, been supported by Blender, Unity, NVidia, Autodesk, ThreeJS, and many others.

4.10 Cloud Computing

Cloud computing describes an on-demand computer system that usually offers specialized data storage and computing power without the need for this system's user to have a local infrastructure. This system benefits many by reducing costs on high-quality computing infrastructure while improving customer's security and stability [54].

4.10.1 Google Cloud Storage

Google Cloud Services[10] is Google's cloud provider. One of their products is Google Cloud Storage, the high-performance object storage that handles binary data storage and streaming. This service offer compression algorithms that increase download and upload speeds, low latency connections due to its geo-redundant servers, and security provided by a professional infrastructure.

The storage service is also affordable for developers by providing a free account where 5 GB can be stored free with full access to all its features. The service is very transparent with its usage statistics, showing a chart with stored data occupied over time and how much is left. It also provides complete documentation on how to integrate many languages and frameworks with Google Cloud.

4.10.2 Heroku

Heroku[11] is a cloud application platform where developers can deploy, manage, and scale inside their system. It offers an application runtime dedicated for server-side configuration, orchestration, load-balancing, failovers, logging, security, among others. The solution provides many utilities for providing a server-side application with stability and security while collecting metrics on application usage by providing monitors of throughput, response time, memory, and others.

Data is also stored in Heroku by using its Heroku Data service. The main difference from Google Cloud Storage is that it runs an instance of a Postgres database, which only stores relational string-based data.

Postgres[12] is a relational database that uses Structured Query Language (SQL) to manage its stored data. The database is open-source with more than 30 years of development used in many mission-critical and high-demand use cases (e.g., Uber, Netflix, and others), making it one of the most reliable, robust, and optimal choices for relational data

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[10] Google Cloud Services

[11] Heroku Services

[12] Postgres Website

storage.

4.10.3 Vercel

Vercel[13] is a platform for providing cloud applications. Although its goal is similar to Heroku's, its service is focused on deploying React applications fast without losing performance. It supports developers "with a single platform for HTTPS-enabled, CDN-backed, production-grade sites, React developers can prototype, launch, and iterate faster than ever before."

Every deployment in Vercel is automatically cached across a Content Delivery Network (CDN) that allocates the front-end data to more than 29 countries, allowing websites to be accessed as fast as possible. Vercel cloud provider is also free, and most of its solutions are open-source.

4.11 Mobile Device

A Samsung Galaxy Tab A6 was used to run the mobile software. The tablet is configured with an Octa-core 1.6GHz Cortex-A53 processor, 2GB of RAM, 16GB of internal memory, 7300mAh battery, 802.11 b/g/n WiFi card, and a 10-inch screen. This device model offers a ARM Mali-T830 MP2 dedicated GPU chip featuring two clusters and supports OpenGL ES 3.2, OpenCL 1.2 and DirectX 11 (FL 9_3). The tablet is used in combination with a vertical stand that holds the tablet horizontally to facilitate its use.

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[13] Vercel Services

Chapter 5

Architecture, Development, and Implementation

This chapter presents the application architecture, development, and implementation stages. First, Section 5.1 describe the planning stages for the software. Next, Section 5.2 shows how the software were developed. Finally, the creation of the digital manuals is detailed explaining each steps needed in order to maintain a new manual (Section 5.3).

5.1 Software Engineering

Plan the software solution was the first step during this work development. To engineer software is needed to improve the understand of the issue the system aims to solve, ensuring the proposed solution corrects the problem. This project began by visiting the industrial facility to understand better how we can improve and the key personnel behind those processes. There the test bench and the quality control process were presented, enabling the elaboration of possible solutions. After many interactions with the stakeholders, the software requirements, use cases, and prototypes were created.

5.1.1 Requirements

Requirements are descriptions of features and functionalities that the software should provide in order to work as expected by the customer. The requirements assist in mapping the stakeholders' needs and guide the software implementation towards those needs. Requirements (Table 5.1) were gathered during visits to the plant and meetings with stakeholders to validate their necessities.

Separating the application features in Functional Requirements (FR) and Non-Functional Requirements (NFR) improves the visualization of the separation between business-oriented and system-oriented features. The separation improves the development experience by offering a clear view when selecting the technologies for the development. For example, the NFR06 (Table 5.1) presents the software need to be reliable, only achieved by test. Using this information, the developer may conclude that select a technology that is well integrated with a test framework is a priority.

Identification	Requirement
FR01	Identify operators' during the inspection process (Mobile)
FR02	Manage operators access (Server)
FR03	Create new manuals and manage available ones (Web)
FR04	Find a specific manual fast on changing a test bench (Mobile)
FR05	List available components and their test benches (Mobile)
FR06	List instructions for a specific inspection (Mobile)
FR07	Allow operator to perform a complete inspection (geometrical and visual) or a visual inspection (Mobile)
FR08	Allow operator to take pictures of visible damages on rejected instructions (Mobile)
FR09	Display images and 3D animations representing the test bench usage for the geometric instructions (Mobile)
FR10	Show conformity, frequency, and other details on each instruction (Mobile)
NFR01	The system should registry the inspection time and accountability
NFR02	The system should run in a low-end tablet
NFR03	The system should provide a friendly user interface
NFR04	The system should be fast to use (not creating bottlenecks in the process)
NFR05	The system should be reliable
NFR06	The system should be provided by a third-party infrastructure

Table 5.1: Functional and Non-Function Requirements.

5.1.2 Use Cases and Classes

The use case technique allows the gathering, modeling, and representation of system requirements. Each use case is a collection of operations that the system should perform on actors' interaction. In this work, use cases represent software systems-related specifications. The goal is to show a more abstract structure of the business logic, enabling a more global visualization of the system domains and their relationships (Figure 5.1).

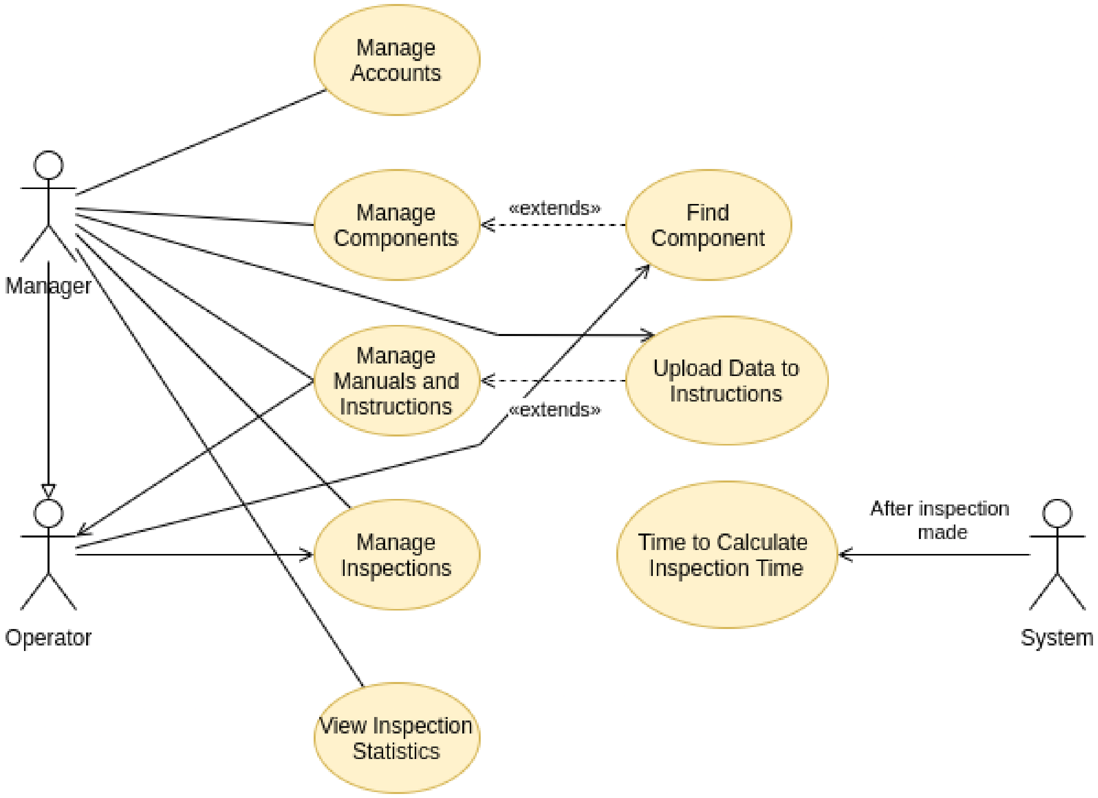


Figure 5.1: Use case diagram showing the relation between actors and use cases.

Identification	Use Cases
UC01	Manage accounts
UC02	Manage components
UC03	Find component
UC04	Manage manuals and instructions
UC05	Upload data to instructions
UC06	Manage inspections
UC07	Time to calculate Inspection time
UC08	View inspection statistics

Table 5.2: List of use cases with identification

The obtained use cases (Table 5.2) give a general view of the problem, but first they need to be further described as shown in the following list:

- **UC01**. The managers should create, read, modify, and delete accounts and their permissions of access;

- **UC02**. The manager should be able to create, read, modify, and delete entries for each component;
- **UC03**. Operators should be able to find component and their manuals by scanning a QRCODE present in each test bench;
- **UC04**. Managers should create, read, modify, and delete manuals and instructions for each component. The operator should be able to read these entries;
- **UC05**. Managers should upload data, e.g., images (png, jpg) or 3D files (glb), to each instruction and the component thumbnail;
- **UC06**. The managers should be able to create and read inspections. The operators can create inspections;
- **UC07**. The system calculates the average time of the inspection (total and for each instruction) when an inspection is made;
- **UC08**. The manager should visualize statistics about the inspections made for each component.

After the use cases were elaborated, a class diagram was created (Figure 5.2) using the use cases as guideline. Class diagrams model object-oriented systems used as a conceptual model of the application's structure and data, improving the system implementation details' visualization.

5.1.3 Prototypes

After the requirements and use cases were completed, the UI mockup was based on those to create a scenario and validated with users by simulation and prototyping. This strategy aims to improve the software cohesion with the stakeholders' expectations by showing more meaningful context to the application usage and structure.

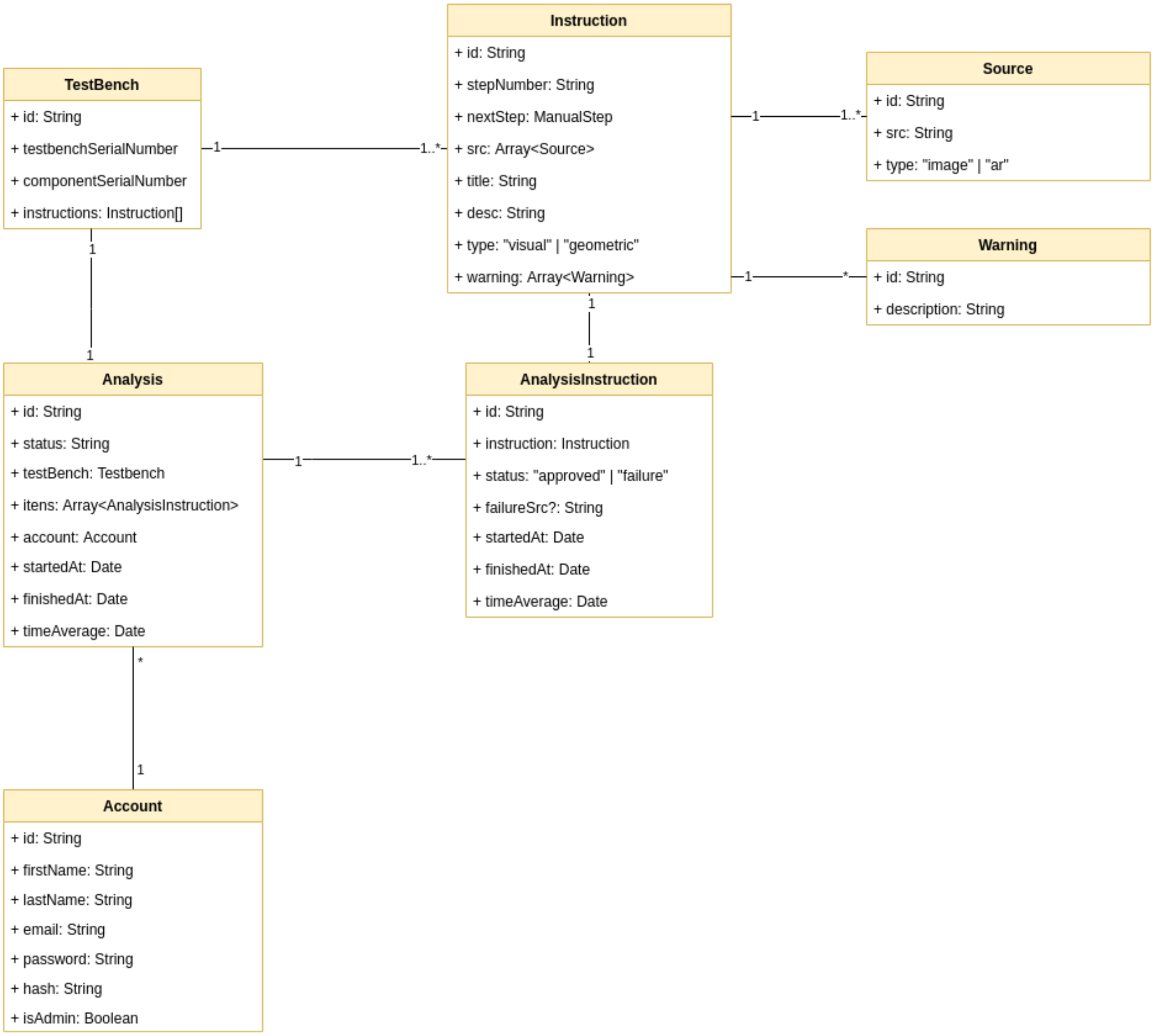
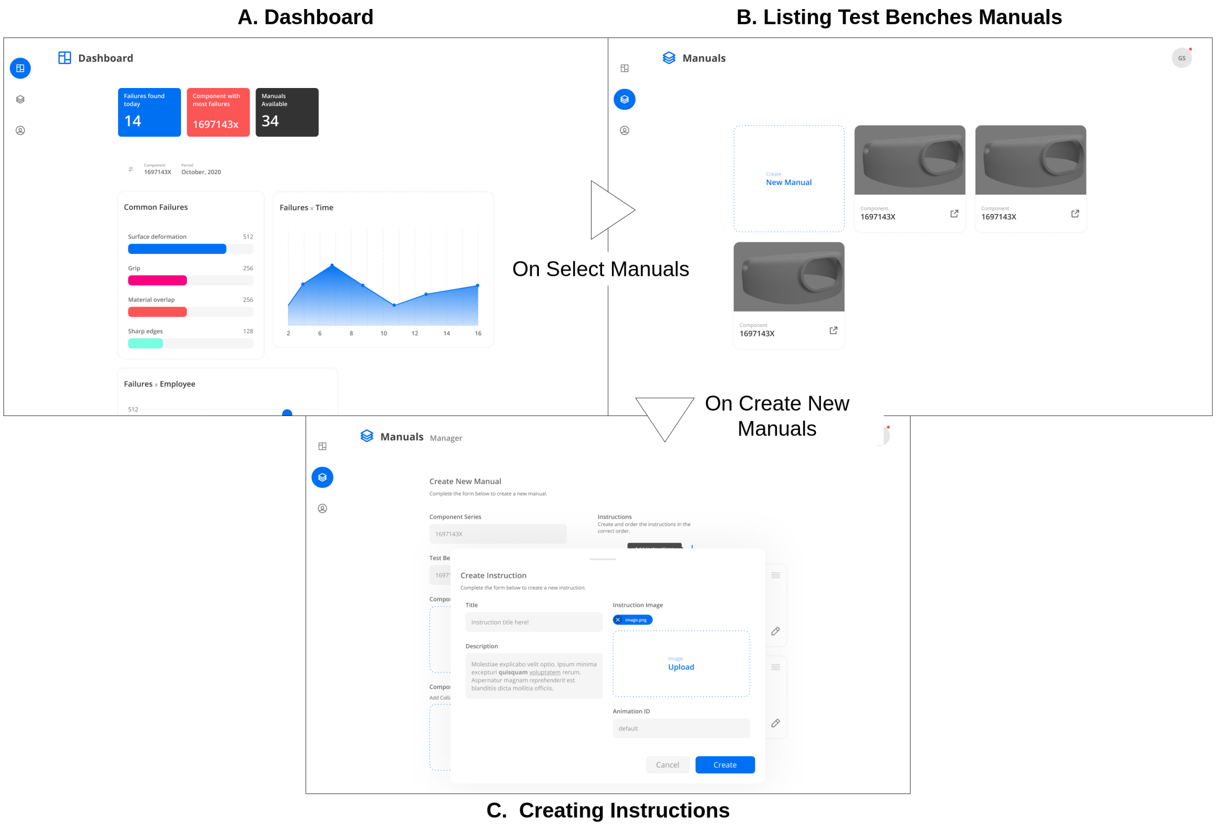


Figure 5.2: Class diagram showing the classes and their relationships to model structures and data for implementation.

The mockups were created using Figma and provided graphical illustrations and mimicked interactions for: The admin application (Figure 5.3), used by the managers to control content and review analysis data; The inspection application (Figure 5.4), used by operators to inspect components and provide analysis results.

The requirements, use cases, and prototypes were presented to the stakeholders to validate the concept, then improved based on their suggestions. With the final concept approved, the application began to be architectured and developed.


A. Dashboard

B. Listing Test Benches Manuals

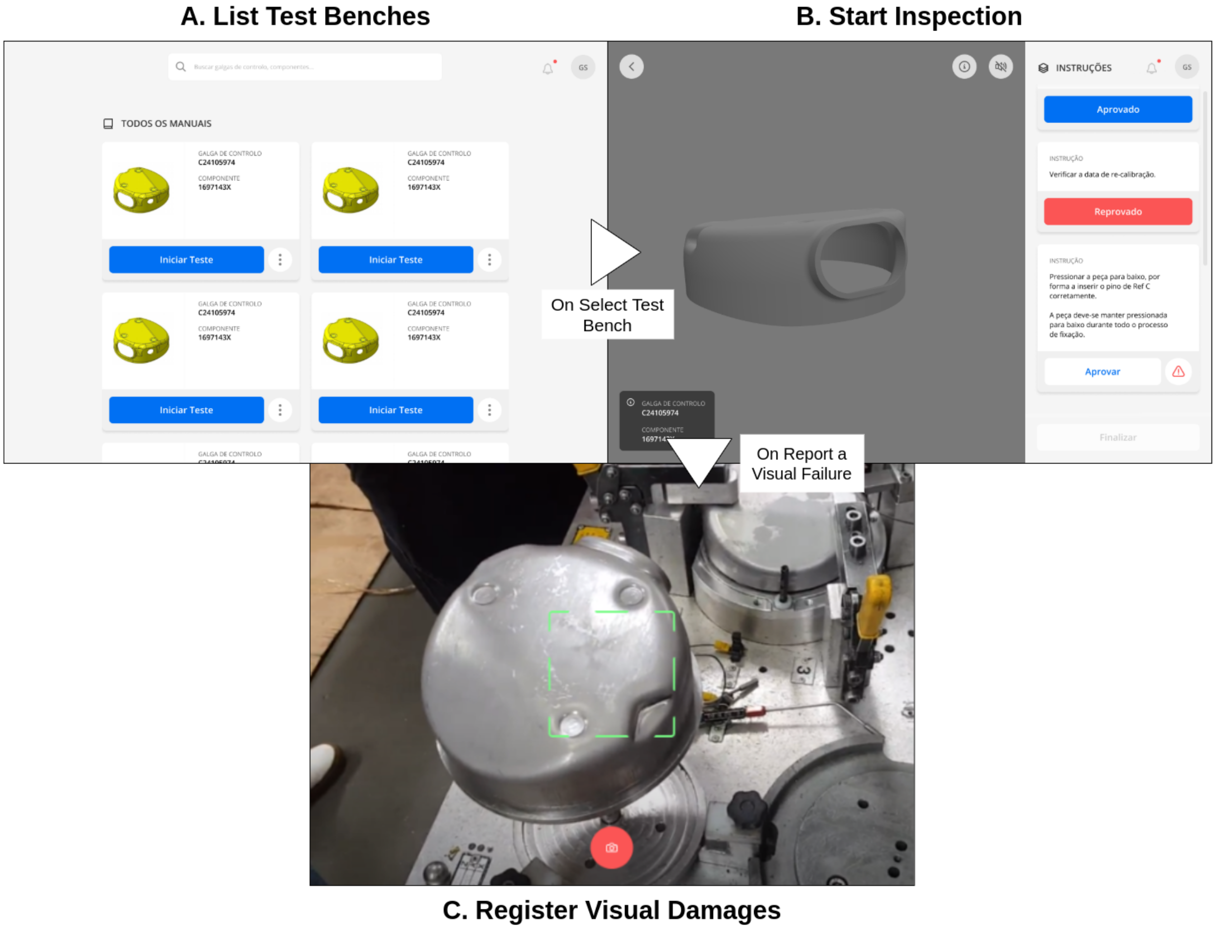
C. Creating Instructions

Figure 5.3: Screens of the admin application prototype. A. The main dashboard, B. Listing test bench manuals, and C. Form used to create the manuals' instruction.

5.1.4 Architecture

With a more accurate view of the application needs, the software architecture consisted of separating the software in specific domains, the client-side and the server-side. Where the client-side implemented the web application (Figure 5.5.B) and the mobile application (Figure 5.5.A), and the server-side performed the server application (Figure 5.5.C), which handles storage, security and provides business logic to the client-side. The client-side and server-side communicate through HTTP requests, allowing the connection of any authorized solution, e.g., Mobile Apps, Web Apps, and IoT applications.

By decoupling the client-side application responsibilities from the server-side increases the reusing of the back-end logic for many applications. This separation of responsibilities also improves the client-side, enabling the developer to use more suitable techniques to



A. List Test Benches

B. Start Inspection

On Select Test Bench

On Report a Visual Failure

C. Register Visual Damages

Buscar galgas de controlo, componentes...

TODOS OS MANUAIS

GALGA DE CONTROLO C24105974
COMPONENTE 1697143X

GALGA DE CONTROLO C24105974
COMPONENTE 1697143X

GALGA DE CONTROLO C24105974
COMPONENTE 1697143X

GALGA DE CONTROLO C24105974
COMPONENTE 1697143X

INSTRUÇÃO
Verificar a data de re-calibração.

INSTRUÇÃO
Pressionar a peça para baixo, por forma a inserir o pino de Ref C corretamente.

A peça deve-se manter pressionada para baixo durante todo o processo de fixação.

Figure 5.4: Inspection application prototype. The screens represent an inspection process. A. Main screen listing available test benches, B. Inspection process, and C. Registering visual damage.

provide the user with a better experience. One example of the technique applied to the client-side specific solutions was the stale while revalidate pattern (HTTP RFC 5861). This improves the server-side response time and automatically presents data in almost "real-time" by caching and revalidating it as the user interacts with the page. Another advantage of this patter is that the application now consumes the cache, decreasing to only one request made to the back-end, thus consuming less connection bandwidth.

The proposed solution relies on cloud services to deploy applications and store data. Many companies do not have IT personnel or infrastructure to support data security, high-quality storage, and information distribution. Thus the need for third-party computing

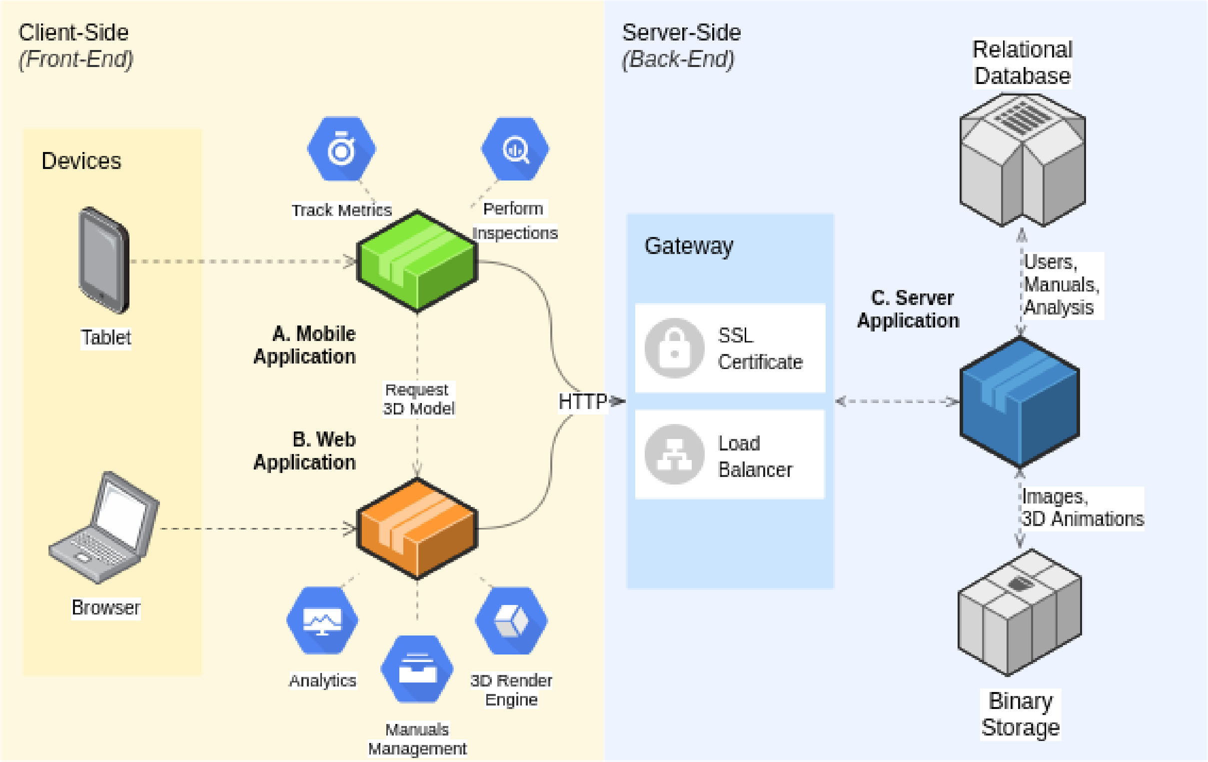


Figure 5.5: Software architecture created during this state.

infrastructure (e.g., Amazon AWS, Heroku, Google Cloud, Microsoft Azure) exists to distribute and manage application security, scale, storage, monitoring, among others. In the designed solution, the cloud system handles:

- Deployment automation;
- Testing pipelines automation;
- Security with Transport Layer Security (TLS) to cryptograph the communication between the client and server, which prevents attacks that aim to store information in the payload of transport operations (i.e., Man in the Middle threats);
- Storage relational data related to the inspection procedures and achieved results, test benches, and user accounts. This provides efficient storage with data recovery and security;

- Storage of binary data related to images and 3D models binary provides a high-quality connection with end-to-end compression of binary files.

The separation of databases to store relational and binary data is needed for each case, with the relational text database handling data for SQL queries from the server and the binary database (file storage) facilitating the access by the client-side system.

5.2 Software Development

The proposed architecture previously described was implemented in three main applications: Server, Web, and Mobile. Each of these software works together through the network to provide the required functionalities and support a reliable inspection process.

5.2.1 Server-Side

The server-side is responsible for handling the computational power, business logic, and persistence logic. These core components are available in cloud services and use the server as its brain to orchestrate the use of these features according to the demand.

Server

The server application was developed using Typescript, NodeJS, and ExpressJS, to create an HTTP server where end-points are structured as a RESTful API. That means the server provides HTTP routes that can interact with HTTP methods (e.g., POST, GET, PUT, DELETE). For example, to create an account, the system could request a "/accounts" route with a "POST" method to execute the account creation with the request payload information. This pattern allows creating a more semantic back-end, thus facilitating the client integration with the API.

The server application functionalities consist of persisting, processing, and transforming data from the client-side while transporting this data to other cloud instances (i.e., database). The business logic presented in the requirements and use cases is implemented in the server. This is because servers are more reliable and secure in handling data, providing this to consumers while abstracting implementation and logic details. For example, if an IoT would rely on data stored by this application instead of implementing connections to the same database, it would be simple to integrate with the API and decentralize the IoT-specific functionalities. The same work for a web and mobile application will focus on the user interaction and content presentation than business logic and implementation details.

Binary Storage

By implementing dependency injection and base itself on CLEAN architecture, the server was able to keep infrastructure logic separated from the business logic. A good practice that allows the system to be agnostic on which data provide its use. In the final implementation, the application was deployed to work with Google Cloud Storage due to their simple integration, benefits for research works, and transparency on service usage. The application also implemented integration with Azure Blob Storage.

Binary storage's primary usage is to store binary data, like 3D files and images. The Google Cloud Storage provided a georedundant server, compression algorithms, which increases the download/upload speeds during file transfer. In this work, render 3D files on a tablet is a crucial part. Problems that may occur on this data transmission may directly impact the UX during usage.

Relational Database

The application uses TypeORM to communicate with the database, like the binary storage, the database was decoupled from the application and considered an infrastructure layer that should be interchangeable whenever needed. This is only possible using dependency injection and Object Relational Mapper (ORM) to interact with the database as a repository interface and define its structure using migration (i.e., a database versioning system that transforms the database and its data to conform with the application models). In this application, Postgres was used by been a reliable, accessible, and open-source solution with cloud instances freely available for integration (i.e., Heroku Data). The application also provides out-of-the-box integration with MySQL, MariaDB, Postgres, CockroachDB, SQLite, Microsoft SQL Server, Oracle, and SAP Hana.

The principal usage for the relational database is to store relational data, represented by Figure 5.2. The database relates information of accounts, test benches, analysis, and sources related to the inspection. This data presents a relational structure; for example, analysis relates to accounts foreign key to identifying who performs the inspection. Also, the analysis is related to the test bench and component in which the inspection was performed to enable tracking of failures on each component.

5.2.2 Client-Side

In a distributed system, the client-side is the part of the software which is present in the user device, i.e., a browser displaying web content or a mobile application. In this work, the client-side web and mobile apps present the data and both can render 3D animations.

Web

The web application was developed using the ReactJS framework to create a Single-Page Application (SPA). To handle HTTP requests and responses, Axios was used with SWR to provide a cache invalidation strategy on HTTP GET responses. This approach allows the application to automatically request new data, ensuring the request is only sent once. Its response is shared globally without needing a global state manager to handle API data. To style the application, Styled Components was used to create JSX components with style contain in them. This technology with atomic design allowed the application to be structured, separating logic from presentation and reusing it as React Native components with little effort.

The web app is mainly responsible for providing quality control management with an intuitive UI that allows management of inspection manuals, visualization of results, and statistics. This empowers the personnel by offering a reliable and friendly tool where information can be available more quickly. For example, a newly created manual will be ready simultaneously for the operator to start its usage, not needing to assign the instructions to a test bench manually.

3D Render Engine

The 3D render engine was implemented with ThreeJS, React, and react-three-fiber. Although the render engine is decoupled, it was deployed with the web application instance, available through the "/render" route. The render engine works with WebGL and can be accessible by any browser or web view to show its content. An HTTP request should be sent to the render route with the folder and file path present in the URL to use the engine. The application will look for the specified path in the binary database, request the GLTF file, and render it on the client side.

The 3D render engine is accountable for rendering the 3D animations and handling user interactions. It allows users to use an orbital control tool to move around the animation object pivot, using one finger swipe gesture. It also enables two fingers scissors gesture to zoom on the 3D animation to improve the details' visibility.

Mobile

The mobile application is one of the central pieces of this work. Its primary objective is to guide operators through their tasks using images and 3D animations to improve their work. Another essential part of this system is to collect data on the whole inspection process, for example, the start and end time of each task, the status of the inspection, photos of visible damages, user accountability, among others. These data points are then sent through an HTTP request to the back-end to store and process it.

The mobile application is implemented with React Native to create a mobile application running on Android and IOS (although Android was the target during the development). Axios and SWR are also used to control HTTP calls and caching strategy to improve the application's network usage. The Styled Component package was also used to inherit components created for the web application, keeping a consistent style throughout the platform.

It also implements a web view component responsible for the 3D animation and interactions. It requests the web application on the render route with the instruction-specific file path. This implementation improved performance by using ThreeJS and WebGL.

5.2.3 Test

End-to-End (E2E) tests were done in the back-end to ensure conformity and stability with the requirements. The server application is the operation's brain, so it is logical to focus the tests on it. E2E tests were done on all the available routes and methods. These tests consist of sending an HTTP request to a route and seeing if the response confirmed the test case expected result. The whole data flow (e.g., middlewares, controllers, use cases, services, providers) and integration of the application with other cloud instances are tested using the E2E test.

The mobile applications were connected to Sentry, an online platform that integrates with the mobile application to analyze and aggregates crash, bug, and telemetry reports. These reports provided a broader view of problems that happened in the application, a quantitative analysis of how many problems happen, and to whom those problems happened.

5.2.4 Deployment

For the web and server repositories, the deployment process consisted of separating the branches in one protected master and each feature on a specific branch. In the server application exclusively, at each commit or merge made to any branch, GitHub Actions executed tests and if they passed, it allowed other pipelines to happen. The deployment pipeline happens on margin a feature branch into master. It consisted of integrating GitHub Actions and the cloud services (e.g., Heroku and Vercel) to make available the latest code to the production environment.

For the mobile application, this process was manual and happened by executing the deployment command. Then, Expo would automatically push the latest build to the OTA channel, where the client-installed application receives and updates the application on the go.

5.3 Process Digitization

After the application was fully implemented, the process of digitizing the analog gauge inspection process began by turning process and guides into a digital representation of the method. This process starts by gathering the necessary data from the test bench usage guide and operation control guide. Next, the data is modeled and optimized into 3D animations for each instruction. Finally, all the information is exported into the web application to provide a digital guide to the entire system.

5.3.1 Data Arrangement

Before starting the digitization process, for each test bench, it is needed to obtain the specific instruction manuals so images and pieces of information can be extracted from them. Understanding these manuals at this stage is very important to know how the instruction works to represent them during the animation process. Every test bench also provides a 3D model supplied by the test bench's manufacturer. This data is categorized divided into separated folders labeled with each test bench identification series.

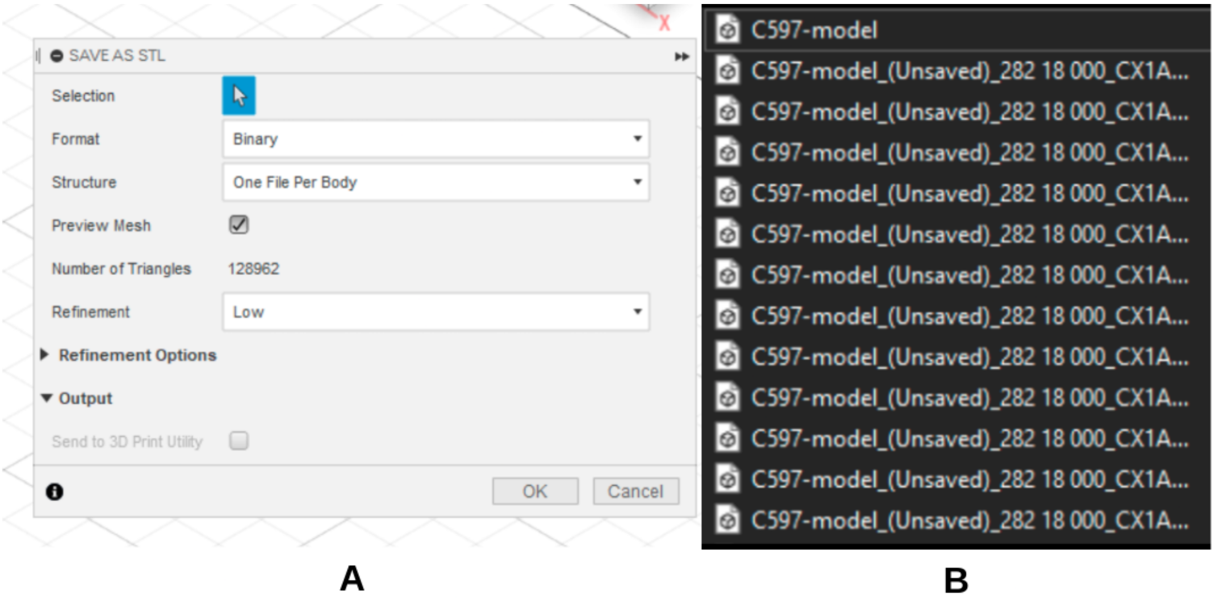
Next, all images present in each manual are extracted into a single image file, identified by the instruction it represents. Images representing test benches usage (Figure 5.6.A) will allow operators to choose between 3D animation or traditional images when executing their tasks. Images representing visible damages (Figure 5.6.B) will only be provided during the visual inspection, a use case that 3D models can not represent accurately.

Figure 5.6: Images illustrating: A. Test bench usage; B. Component damage.

5.3.2 Models

This stage consists of many processes needed in order to obtain 3D models for manual digitization. As a result of this pipeline, reliable 3D animations were obtained and provided to the web app.

Importing



Selection
Format: Binary
Structure: One File Per Body
Preview Mesh ☑
Number of Triangles: 128962
Refinement: Low
Send to 3D Print Utility ☐

C597-model
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
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C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...

Figure 5.7: A. Fusion 360 STL exporter utility; B. STL files generated by the "One File Per File" option.

Before importing the 3D model into Blender, the test bench 3D model needs to be transformed into a format adequate for Blender. The file provided in STEP format by the manufacturer needs to be converted into STL to be accessible. This conversion also needs to keep the mashes separated to allow a more precise edition of the model. To achieve this, Autodesk's Fusion 360 was used to import the STEP file, and by applying the structure option "One File Per File" (Figure 5.7.A) on the STL exporter, the model was exported in multiple STL files (Figure 5.7.B) for each mash.

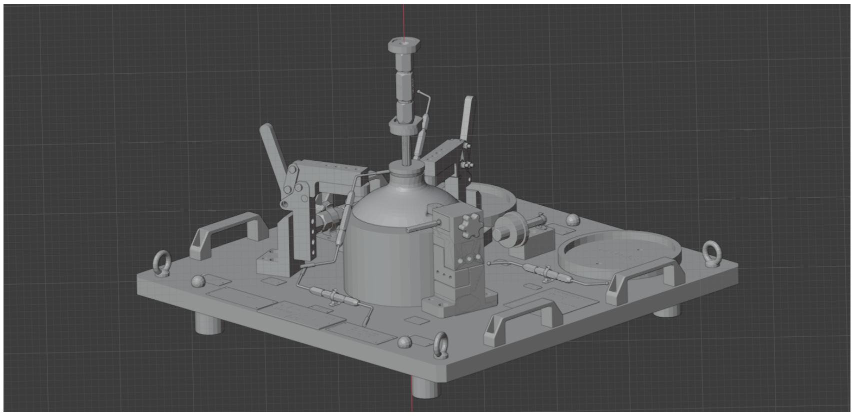


Figure 5.8: Test bench 3D model ready to be used by Blender.

Next, to import the files into Blender, the STL importer available in the files tab was used to import multiple STL files. Those files contain each mash global position and size, allowing them to be grouped into one collection and manipulated altogether without losing the original position and dimensions. The final result (Figure 5.8) has each mash grouped into specific collections representing tools, supports, components, and additional details. Those collections also were labeled according to the item identification defined by the analog manual.

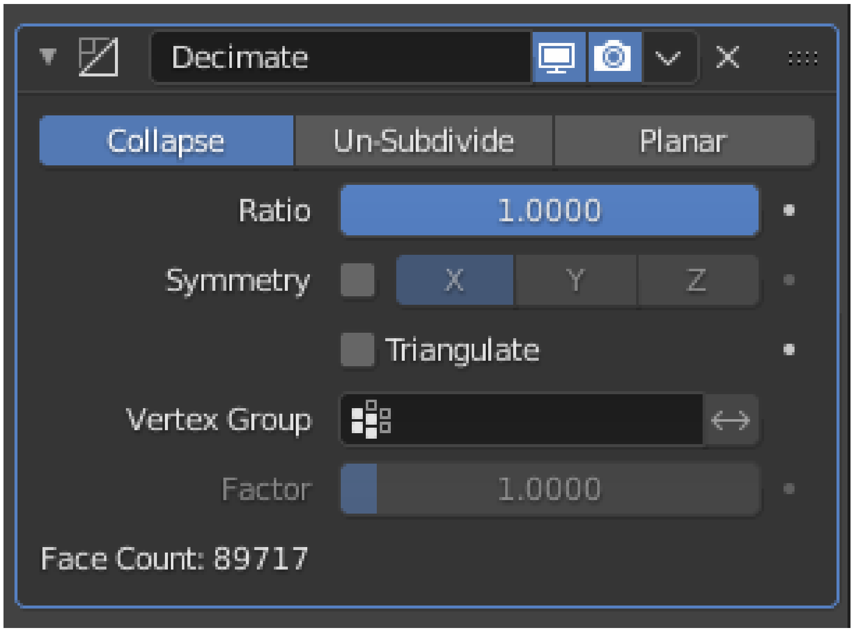
Optimization

Optimization is the process of removing unnecessary vertices and faces in order to decrease the file size and improve loading times. This process directly impacts the performance of the 3D rendering affecting the UX. The model's bad optimization means that the final

GLTF file will be rougher on loading and in low-end devices will run with lower FPS speeds.

Because of the CAD project's nature, the imported model is very detailed with millions of faces that may not be useful to the project. First, all meshes unused by any instruction were removed to lower the number of items presented by the model.

Next, unnecessary complex objects were remodeled with simpler meshes. This behavior is caused by the conversion process and makes simple objects, like cubes, that may only need six faces to have hundreds of faces to represent them. The final model is highly improved by removing the overly complex faces from simple objects without losing fidelity from the original sample.



Ratio 1.0000
Symmetry ☐ X Y Z
☐ Triangulate
Vertex Group
Factor 1.0000
Face Count: 89717

Figure 5.9: Blender's decimate modifies component.

Finally, on complex objects that may demand lots of time to reflector into simpler ones, the "decimate" modifier (Figure 5.9) was applied to reduce the number of faces presented in the mesh. The modifier can reduce a component with 89717 faces (Figure 5.10.A) to only 897 faces (Figure 5.10.B) with a ratio of 0.01%. However, this approach's main counterpoint is that the final quality is also reduced, thus needing to be used with moderation to not decrease the final piece's definition in an unusable state.

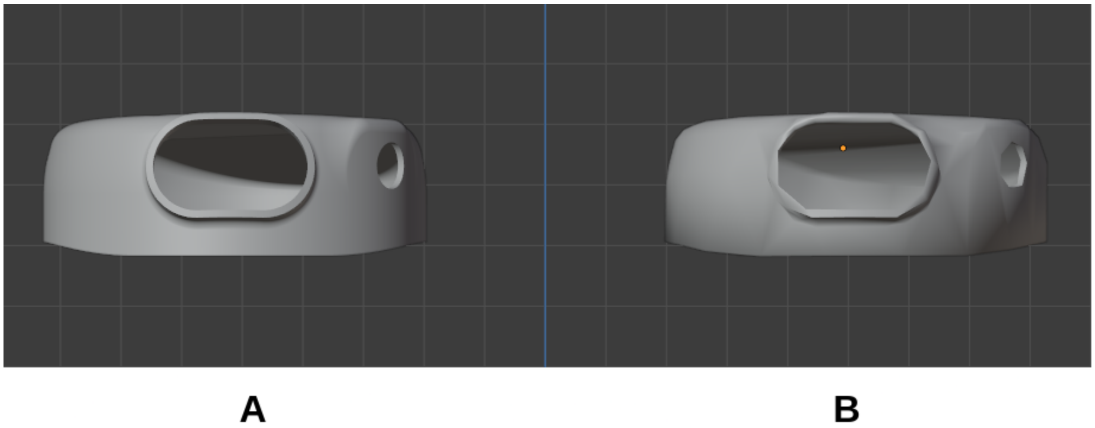


Figure 5.10: Visual comparison between mash before (A) and after (B) the decimate modifier been applied.

Texturing

Knowing that the target format for the file project is a GLTF file, some limitations are needed to be addressed to find a suitable Blender shader to work with the format. GLTF only allows metallic, roughness, specular, glossiness, base color, and texture image shading. Blender's "Principled BSDF" demonstrated reliability in exporting the created material to a GLTF binary. It was used during the texturing process to provide a more realistic look to the model.

During the texturing, the base color was used over the image-based texture to decrease the binary size produced, removing the need to export Base64 images encoded with the GLTF file. This choice was made in order to improve the 3D animation download speeds over the internet connection.

Animation

An animation exists for each instruction. Before starting animating, a copy of the optimized and textured Blender file should be created using the instruction number to identify it. The unnecessary meshes that did not present any context or importance to the instruction's process were removed to improve the file size further.

Animation is an essential part of promoting user-friendly access to inspection process information. To animate the application, the Bender Keyframe component (Figure 5.11) was used to create multiple states of the model's pieces (e.g., a clip open and a clip close) and interpolate those into an animated movement. These states were added until the whole keyframe illustrated the analog inspection process completely.

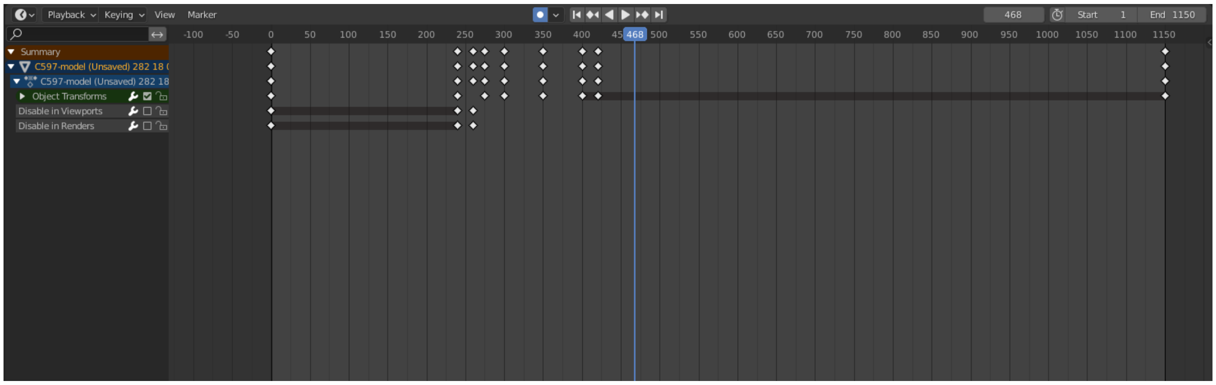


Figure 5.11: Bender's keyframe component

After the animation been completed, it was exported as a GLTF binary, which contained models, shaders, and keyframes ready to be used in a single file. They were limited to only animate meshes when exporting to the format. Finally, the final file was created, and the animation process repeated until all the instructions were done.

5.3.3 Manual Creation

With the guides' data categorized and the models created, the manual can be added to the web application to make it available to the operators. During this stage, the web application was opened in the "/manuals" route, and the "create manual" button was selected. A form was filled with the information regarding the test bench and component.

Next, each instruction is specified in a modal (i.e., floating window) form with the content gathered from the guides, images, and GLTF binary files. On completing the creation, the instructions were arranged in order of execution and then submitted to the server application to handle the file upload and data persistence. Finally, the data is available for the mobile applications to access the newly created test bench manual and ready to register inspection data.

During this chapter, the system was architected to suit the industry needs, then developed to achieve the expected outcome. With all these demanded parts implemented, the application is ready for the users to test. In the next chapter, the solution was introduced in the industrial environment, put to the test with real people, and their experience using the application was gathered.

Chapter 6

Testing and Evaluation

In this chapter, the software was deployed in the factory quality control process and tested with real people. The user experience using the application was collected with the System Usability Scale, and crash reports were collected and analyzed during all the application usage.

6.1 Results

This section describes the results obtained by the application development and usage in an industrial environment. The software was tested in the industrial environment for eight days, from 02/26/2021 to 03/09/2021. During this period, usability and stability data were collected to ensure system confidence. The results are principally positive, presenting an excellent opportunity for this work in improving quality control processes.

6.1.1 Deployment and Testing

To guarantee the application's stability, the server was deployed in a Cloud environment using the master branch as the production-ready source code. The back-end environment was fully accessible by the mobile device via wireless internet. The WiFi was provided by the industrial facility and accessible within all the factory areas.

To identify users, accounts were created for the operators and management personnel, each owning different permission levels to access data. To authenticate the account, the user uses his email and password to log in to the mobile and web system (according to the owned permission). This information allows the system to identify who is making the inspection.

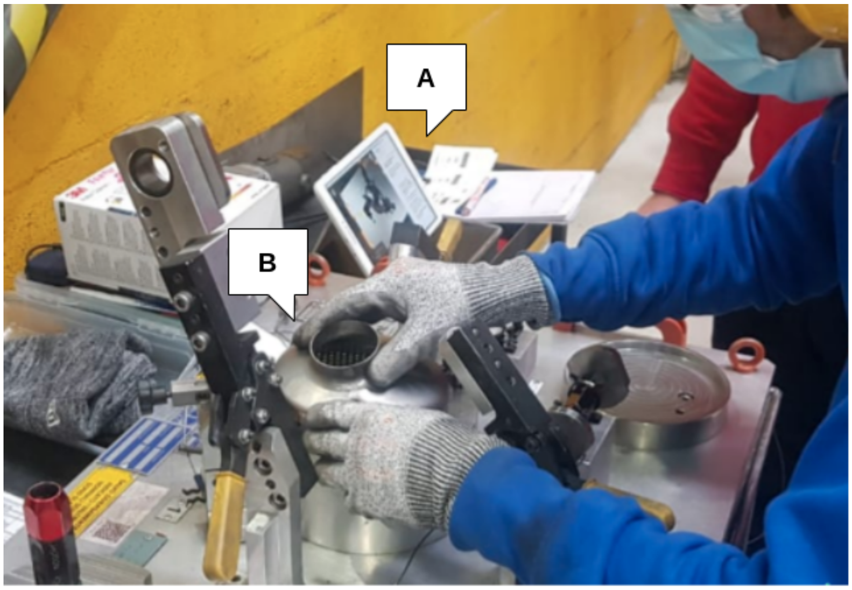
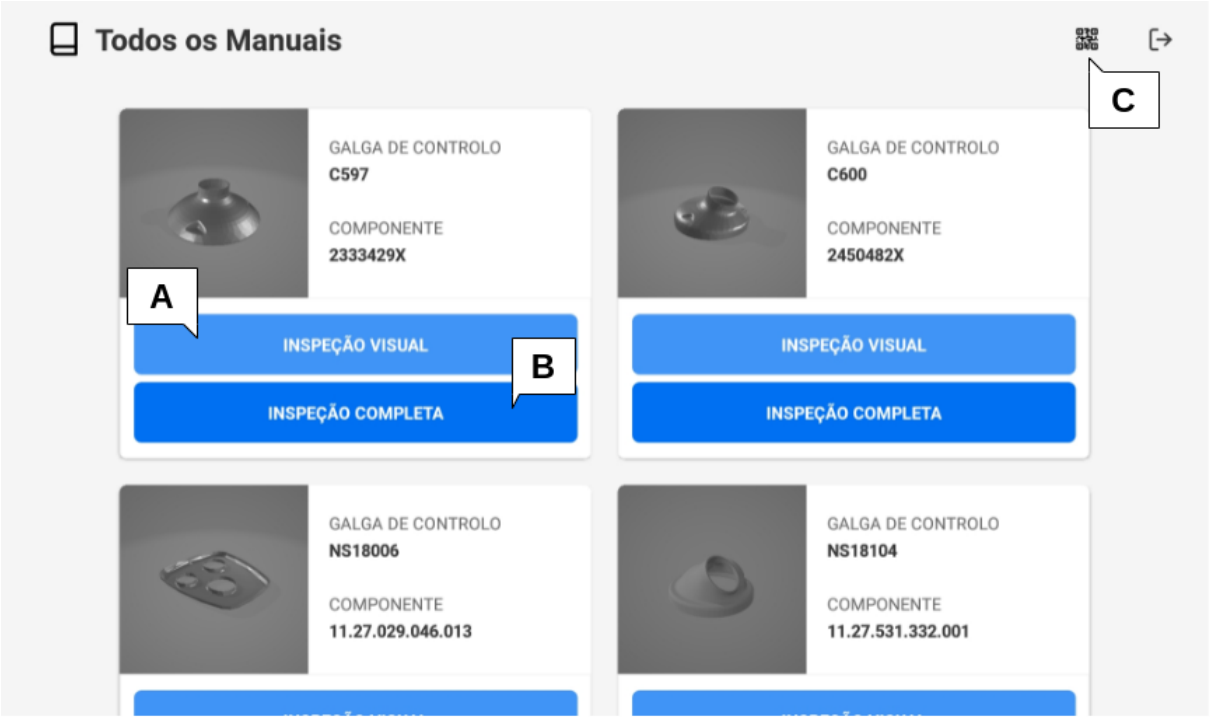


Figure 6.1: Mobile application been used in the production environment: A) The tablet running the mobile application, placed near the operator; B) The operator executing the instructions.

To utilize the software, the tablet device (Samsung Galaxy Tab A6) was positioned in a vertical stand near the test benches (Figure 6.1). This allowed the operator to easily observe and interact with the device without impacting the test bench's usage. Although the stand keeps the device securely in place, it also allows to easily remove the table to scan QR Codes or photograph visible damages.

Before starting the inspection, the operator can select the part model and inspection method (see Figure 6.2.a or 6.2.b) or scan a QR Code present in the test benches by selecting the QR Code button (Figure 6.2.c). This improves the overall user experience and speed of the process by allowing a specific manual to be quickly obtained compared with the analog process, which needs the manuals to be added into a visible place before


Todos os Manuais

GALGA DE CONTROLO
C597
COMPONENTE
2333429X

GALGA DE CONTROLO
C600
COMPONENTE
2450482X

GALGA DE CONTROLO
NS18006
COMPONENTE
11.27.029.046.013

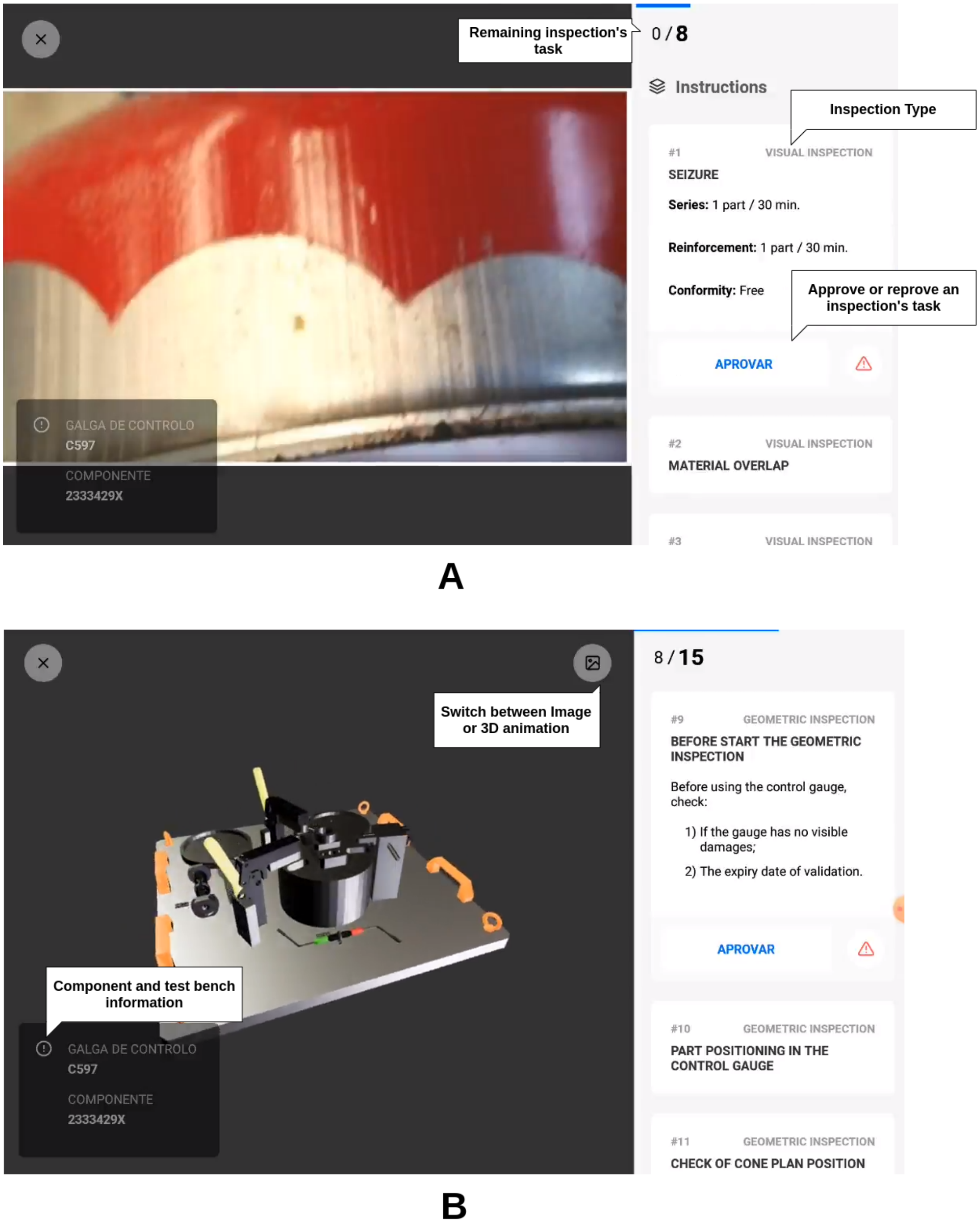
GALGA DE CONTROLO
NS18104
COMPONENTE
11.27.531.332.001

Figure 6.2: List of available test benches and components: A) Execute visual inspection; B) Execute visual and geometric inspection; C) Find the test bench's manual from a QR Code.

the test bench was used.

During the inspection, there are two types of instructions that can be visualized: I) a visual inspection that shows photos of visual unconformities that can be present in the piece (Figure 6.3.a), and II) geometric inspection that guides the operator through the inspection operation and test bench usage (Figure 6.3.b). These different instruction sets allow a faster inspection process I) to be executed with more frequency taking less time, allowing pictures to be registered and stored. A complete inspection task II) with lower frequencies and longer execution times will be carried out using more immersive instruction (offered by the 3D animation) to achieve a more friendly experience.

After the inspection, the server gathered the information provided by each analysis, and statistics were generated and presented to the operators. These statistics are accessible by quality control management to better understand the impact caused by the machines in each component production (e.g., most common failures, components with



#1 VISUAL INSPECTION

SEIZURE

Series: 1 part / 30 min.

Reinforcement: 1 part / 30 min.

Conformity: Free

#2 VISUAL INSPECTION

MATERIAL OVERLAP

#3 VISUAL INSPECTION

#9 GEOMETRIC INSPECTION

BEFORE START THE GEOMETRIC INSPECTION

Before using the control gauge, check:

1) If the gauge has no visible damages;
2) The expiry date of validation.

#10 GEOMETRIC INSPECTION

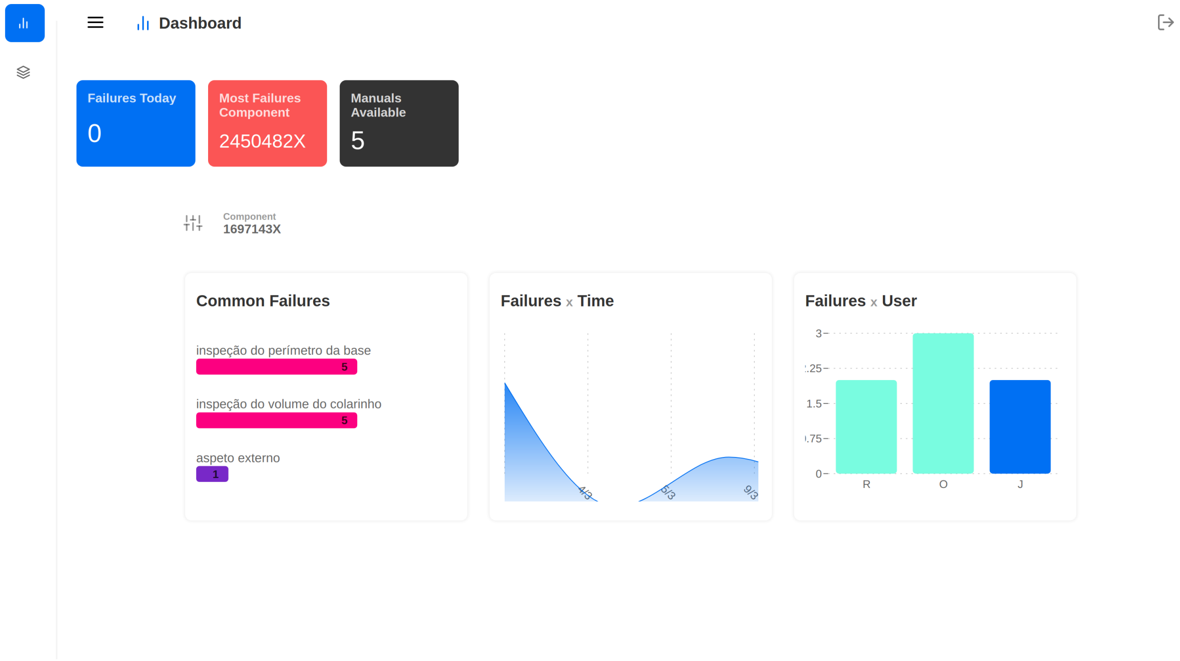
PART POSITIONING IN THE CONTROL GAUGE

#11 GEOMETRIC INSPECTION

CHECK OF CONE PLAN POSITION

Figure 6.3: Mobile application inspection screen showing: A) Visual inspection procedures; B) Geometric inspection procedures.

most damages, quantity of inspection per operators). The statistics and each inspection analysis can then be accessed by the web application (Figure 6.4) via the internet.



Failures Today 0

Most Failures Component 2450482X

Manuals Available 5

Component 1697143X

Figure 6.4: Web application home screen showing inspections statistics.

6.1.2 Usability Analysis

During the inspection process, the SUS evaluates the operators' overall experience during the mobile application usage and the general system integration. The survey demonstrates the solution fitness with a score between 0 and 100, and the objective is to show how suitable the solution is from the workers' perspective.

The SUS survey is a digital form that registers the operators' answers anonymously, duration time, and begins/end timestamps, the questions used in the survey were written in Portuguese and are available in Appendix A. At the end of each inspection activity, the survey pops up in the mobile app, requiring the user to answer their experience using the system and stores the data in a CSV file.

To test the application, two groups were created: a control group (I) and an operator group (II). For Group I, five people outside the factory within a varied range of knowledge in technology and no previous experience in quality control procedures were tested and used as the control group. Group II consisted of six people tested while working with the software to help them during factory quality control procedures. All of the six candidates were experienced with the inspection tasks and familiar with the industrial process.

Data Treatment

After one week of the application been used in the industry, the data was exported into Google Sheets and analyzed. The survey received twenty-six (26) responses in total (Table 6.1), with the answers varying from one to five (Likert scale) representing how much the tester agree with the statement. The answer are composed by five (5) from Group I and twenty-one (21) from Group II. The survey's submission timestamp was then compared to the inspection's submission timestamp associating each answer with the accountable email and selecting only the first response in order to solve the data duplicity.

Table 6.1: All survey entries

N.	Statement	Avg.	Var.
1	I think that I would like to use this product frequently.	4.68	0.73
2	I found the product unnecessarily complex.	1.36	0.24
3	I thought the product was easy to use.	4.84	0.14
4	I think that I would need the support of a technical person to be able to use this product.	2.00	0.83
5	I found the various functions in the product were well integrated.	4.56	0.26
6	I thought there was too much inconsistency in this product.	1.68	0.56
7	I imagine that most people would learn to use this product very quickly.	4.64	0.24
8	I found the product very awkward to use.	1.72	1.21
9	I felt very confident using the product.	4.52	1.09
10	I needed to learn a lot of things before I could get going with this product.	1.60	0.50

During the analysis of the Group II data, a discovery was made. Due to the mobile application keeping the user logged in, most operators would forget to sign out after using the software, sharing their accounts with others without knowing. To increase the data reliability, answers that were observed by the authors and the ones that included comments were considered trustworthy. Next, the remaining ones had the survey duration time compared to the control group time range in order to identify invalid answers. In the end, a total of eleven (11) data points were obtained (Table 6.2), five (5) from Group I and six (6) from Group II.

Table 6.2: Survey entries after data treatment

N.	Statement	Avg.	Var.
1	I think that I would like to use this product frequently.	4.36	1.45
2	I found the product unnecessarily complex.	1.27	0.22
3	I thought the product was easy to use.	4.91	0.09
4	I think that I would need the support of a technical person to be able to use this product.	1.64	0.45
5	I found the various functions in the product were well integrated.	4.64	0.25
6	I thought there was too much inconsistency in this product.	1.55	0.47
7	I imagine that most people would learn to use this product very quickly.	4.64	0.25
8	I found the product very awkward to use.	1.55	1.47
9	I felt very confident using the product.	4.09	2.09
10	I needed to learn a lot of things before I could get going with this product.	1.27	0.22

Statement Analysis

After cleaning the data obtained by the survey, individual statements can be analyzed to provide a complete picture of the users' perception while testing the application. To better understand each answers the variation of the responses (Table 6.2) and the variation per answers between groups (Figure 6.5) was used.

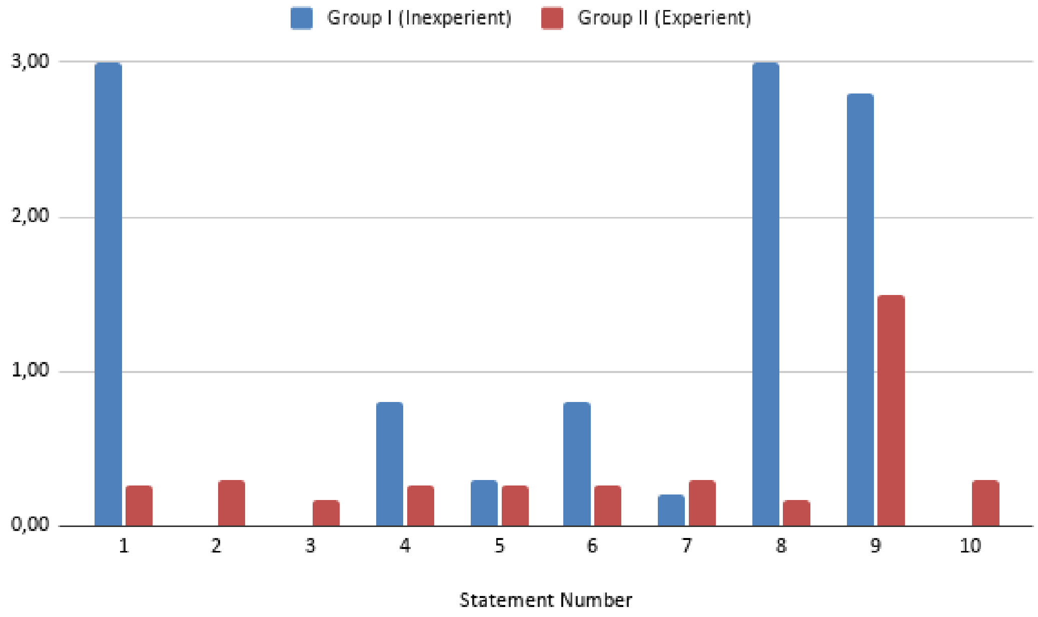


Figure 6.5: Results obtained comparing the response variation per group Group I inexperienced and Group II experienced.

The statements' answers were the score variation were beneath 1.00 was considered uniform across the groups indicating that most of the entries agree with the score obtained.

With variations above 1.00, a deeper analysis needs to be carried:

- **I think that I would like to use this product frequently.** The statement 1 answer was one of the higher variations (1.45), but when compared the variation between Group I (3.00) and Group II (0.73) answers the opinion of experienced operator is alike, strongly agreeing with the statement. While inexperienced subjects did not fully agree, which can be explained by they not having the full picture of the inspection process.
- **I found the product very awkward to use.** The statement results had a variation of 1.47, with Group I varying 3.00 and Group II 0.17. This difference between groups may also be related to the inexperience with the process, with some users from Group I reporting that they did not fully understood some of the processes the application was presenting.
- **I felt very confident using the product.** The statement results had a variation of 2.09, with Group I varying 2.80 and Group II 1,50. Both groups vary their answers a lot, some hypothesis can be discussed for this results. No previous training and minimal instructions were needed in order to obtain a raw experience of users interacting with the software, this may show that the software lacks helpers and tutorials to guide new users on using the app, helping they better understand the environment. The friction from moving from paper to tablet technology may also be a factor for this variation, when looking towards Group II.

By analyzing each statement and the variance of their responses a wider view of users type can be observed. Some aspects of the application related to the initial knowledge needed by the users to effective use the system. Previous training and a application tour for first time users, explaining application features and usage, could improve both inexperienced and experienced workers on handling the software.

The results also presented a uniform acceptance when stated its ease to use. Most users agreed that they would not need external help and would be easy to start working with the application. This positive results show that although improvements may be needed the user experience observed during test was consistent, simple, and accurate. Adding value to the inspection process by reducing the perceived knowledge gap and start time for new operator to use the system.

Score Analysis

The final score was calculated using the average value of each answer and then used to compute the SUS score following the algorithm:

- The values of odd-numbered questions were subtracted by one;
- The values of even-numbered questions were multiplied by minus one and then added by five;
- All the values were added and multiplied by 2.5, producing a value between 0 and 100 describing the system's final score.

First, the SUS score was calculated for the data before (Table 6.1), obtaining 87.20 points. Then, the data obtained by the treatment process (Table 6.2) was calculated and achieved an 88.40 score on the SUS survey. Finally, the SUS scores before and after the data treatment were compared, showing a standard deviation of 0.86, with Table 6.3 representing the deviation per answer.

Table 6.3: Standard deviation per statement before and after data treatment

N.	Avg. Before Treatment	Avg. After Treatment	σ
1	4.68	4.36	0.2263
2	1.36	1.27	0.0636
3	4.84	4.91	0.0495
4	2.00	1.64	0.2546
5	4.56	4.64	0.0566
6	1.68	1.55	0.0919
7	4.64	4.64	0.0000
8	1.72	1.55	0.1202
9	4.52	4.09	0.3041
10	1.60	1.27	0.2333

In the SUS scale, results classified above 70 are good products, with better products been over 80, and genuinely superior ones above 90 [52]. Considering the final score of

88.40, the developed software was perceived by the users as a product with very good usability. These results show that the users acknowledge that the software solution is simple to use, implements its functionalities well, and adds value during the execution of their inspection tasks. Also, the statement score that described the application as *"easy to use"* and *"easy to learn"* increased when presented to inexperienced users (Figure 6.6). This result may indicate that the application presents a possibility for increasing the learnability of newly inserted workers into the quality inspection task.

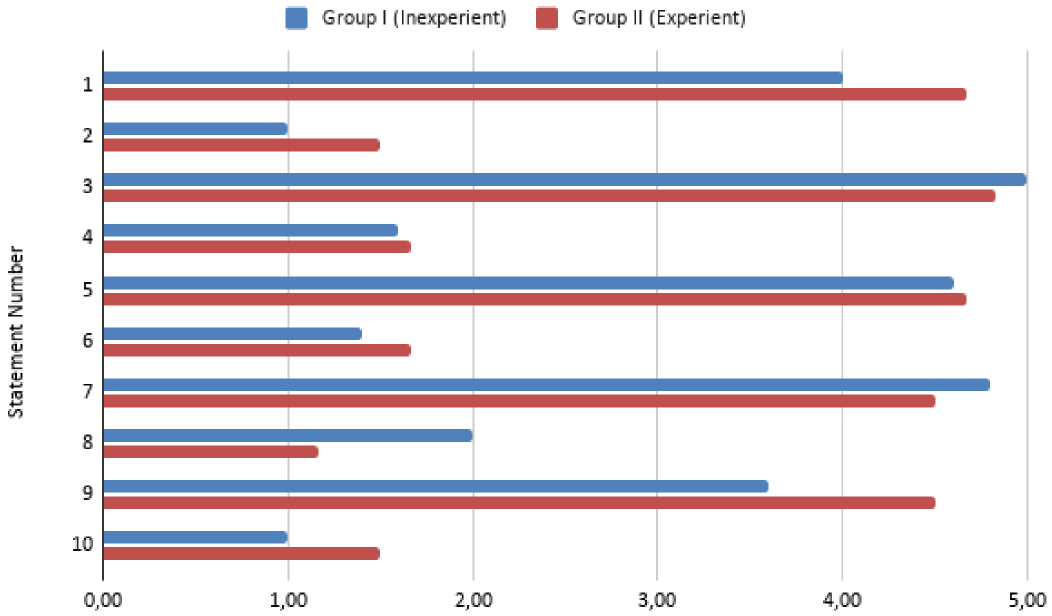


Figure 6.6: Results obtained comparing the average response from users inexperienced (Group I) and experienced (Group II).

Feedback from the company corroborates the results by showing the positive aspect of the system, reviewing the application as *"a great added value"* for the components inspection operation, being very well perceived by the quality control management and operators performing the tasks.

6.1.3 Stability Analysis

The developed system is a mission-critical system that needs to be reliable to not affect the industry quality control operations. To ensure the software stability, unit and e2e tests were written to ensure the system is stable in given conditions. During the application usage (02/26/2021 to 03/09/2021), metrics were collected to monitor unexpected errors and systems misbehaviors during the test in the production environment.

Sentry[1] was used to track the application's exceptions during the production use, registering the failures in a cloud service with errors description, location, the user affected, and interactions before the exception being raised. The error collection automatically sends through the network the error information alerting if any unexpected behavior occurs. After third-eight inspections made by the operators in a period of eight days, no errors were detected by the platform, and no failures in the software were reported by the users when asked.

The positive result on application stability shows that the application contributes with a solid foundation and offers opportunities for its usage in the production environment by being previously experimented with no errors in real-world test conditions.

6.2 Discussions

During tests in the production environment, one problem noticed was that users would forget to sign out after completing their work shift in the quality control inspection. Although the authentication problem could be solved by instructing operators on how to handle their accounts, perhaps it would be more reliable to automatically log out users after completing the inspection task, excluding the possibility of sharing accounts. To reduce the friction on starting the inspection tasks caused by the access depending on filling email and password, occurring on every new analysis. A RFC tags, Bar Code or QR Code could be attached to the worker's badge and required to be scanned to log in, quickly identifying the accountable without consuming much time to begin the inspection.

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[1] Sentry Web Site

Another flaw discovery made when analyzing the inspection times extracted from the database was that operators forgot to confirm the inspection reflecting on unreal analysis times, the time representing the beginning to the end of the complete inspection task, with most occurrences being on the last shift of the week (Friday). One inspection time had 260408989 milliseconds of duration (more than 72 hours), resulting in an inaccurate inspection time being register in the database. This issue only affects the general inspection time, with the particular time per task still reliable and not affected. To solve this issue, the general time calculation could be done by the sum of all the tasks' time registering it without depending on the user action to select the finish button.

Although flaws were encountered showing the system needs for improvement, one vital aspect for every industrial-grade software is training. Most of the defects found occurred from human errors caused by their inexperience while using the software and could be avoided with basic training prior to the software usage. Even when having software with superb usability, operators should be trained on how to operate the solution and be supported to guarantee the correct use of the system. The HMI works not as a replacement but as a companion to the usage instructions, working together by conducting the user through their tasks and aiding when technical knowledge gaps appear.

Furthermore, the overall benefits of the application were not harmed on the objective of digitizing the quality control inspection process. The application is still reliable in reporting inspection failures and times. Although the general time of the inspection is inaccurate, the times related to individual inspection tasks were always accurate. The data provided by the application is still being delivered to the management immediately in digital media. The application remains well perceived by experienced and inexperienced users as a "simple to use tool".

Chapter 7

Conclusion and Future Work

Quality control is a vital part of factories' production processes. Using inspection methods (visual and geometric) to verify the correctness of produced parts is an established practice in the sector. This work analyzed an industry that applied gauge inspection tools utilizing papers for manuals to guide operators through the inspection steps and paper spreadsheets to register the results of these inspection tasks. While cheap, this practice may not be adequate by creating misleading results to the quality control management while limiting the support provided to operators during the inspection. These problems open space for cost-effective technological solutions that can remove the reliability issues while using the operators in a HiL inspection process.

To solve the issues, this work developed a digital personnel assistant that supports the industry by offering guidance to operators during the execution of the inspection process. While in the background, the application collects data related to the performed tasks using the information to create a database of common visual damages and notifying the management with relevant statistics used by the quality control to identify production issues. The developed application supports a non-immersive VR with a Desktop VR experience using tablets. It allows users to visualize and interact with 3D scenes while performing real-world actions without supporting sensory output.

The final version of the solution was integrated into an industrial factory using cloud computing technologies to supply the plant with adequate infrastructure for the application. The software was tested in the production pipeline to ensure its stability and verify the workers' perception while handling the system. The results extracted from the testing stage were very positive, with no system failures happening during the test period and the overall user experience while using the system been considerably positive. It was also well noticed by industry leaders and quality control management been reviewed as *"a great added value"* for the components inspection operation.

The proposed software approaches contribute to time optimization created by removing unnecessary tasks related to the data collection and manual positioning with more automated ones are essential for factories looking forward to implementing digital transformation in the long term. The collected data can give more insights into migrating to an Industry 4.0 paradigm while being cost-effective in its implementation, only relying on tablet devices, cloud infrastructure, and internet access points.

Reviewing the work's objectives, the initial goal of developing a mobile and web application that empower operators with tools that improve the confiability of quality control inspection and enables their managers with means to visualize the performance of the inspection the process was succeeded. The developed systems was successfully applied into an industrial environment and was perceived by the industry staff as a advantage brought to the process. With all objectives completed a stable solution was surely created and embedded into the industry quality control process without changing drastically the process current been used by the industry with lower costs. Nevertheless, the system solved quality control bottlenecks mainly related with the use of paper to share information in a factory that moves itself towards a digital transformation, effectively achieving the proposed goals. Also, this work contributes with an article published in ISIE (International Symposium on Industrial Electronics). The symposium unites industry experts, researchers, and academics to share impressions and expertise surrounding new technologies associated with industrial electronics.

Future work will be dedicated to applying computer vision algorithms and artificial intelligence to help operators verify the correctness of visual and geometrical inspection.

Also, improvements could be made to ensure a more intelligent work set up using modern identification technologies to detect operators during their tasks. A long-term analysis of the system use at the industrial facility could also be carried out to identify if significant impact was made to production quality and speed.

Bibliography

[1] L. D. Xu, E. L. Xu, and L. Li, “Industry 4.0: State of the art and future trends,” *International Journal of Production Research*, vol. 56, no. 8, pp. 2941–2962, Mar. 2018. DOI: `10.1080/00207543.2018.1444806`. [Online]. Available: `https://doi.org/10.1080/00207543.2018.1444806`.

[2] J. Egger and T. Masood, “Augmented reality in support of intelligent manufacturing – a systematic literature review,” *Computers & Industrial Engineering*, vol. 140, p. 106 195, Feb. 2020. DOI: `10.1016/j.cie.2019.106195`. [Online]. Available: `https://doi.org/10.1016/j.cie.2019.106195`.

[3] L. Da Xu, W. He, and S. Li, “Internet of things in industries: A survey,” *IEEE Transactions on industrial informatics*, vol. 10, no. 4, pp. 2233–2243, 2014.

[4] A. Belhadi, K. Zkik, A. Cherrafi, S. M. Yusof, and S. E. fezazi, “Understanding big data analytics for manufacturing processes: Insights from literature review and multiple case studies,” *Computers & Industrial Engineering*, vol. 137, p. 106 099, Nov. 2019. DOI: `10.1016/j.cie.2019.106099`. [Online]. Available: `https://doi.org/10.1016/j.cie.2019.106099`.

[5] Y. Zhang, G. Zhang, Y. Liu, and D. Hu, “Research on services encapsulation and virtualization access model of machine for cloud manufacturing,” *Journal of Intelligent Manufacturing*, vol. 28, no. 5, pp. 1109–1123, Mar. 2015. DOI: `10.1007/s10845-015-1064-2`. [Online]. Available: `https://doi.org/10.1007/s10845-015-1064-2`.

[6] T. Masood and J. Egger, "Adopting augmented reality in the age of industrial digitalisation," *Computers in Industry*, vol. 115, p. 103 112, Feb. 2020. DOI: `10.1016/j.compind.2019.07.002`. [Online]. Available: `https://doi.org/10.1016/j.compind.2019.07.002`.

[7] D. Costa, F. Pires, N. Rodrigues, J. Barbosa, G. Igrejas, and P. Leitao, "Empowering humans in a cyber-physical production system: Human-in-the-loop perspective," in *2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS)*, IEEE, May 2019. DOI: `10.1109/icphys.2019.8780138`. [Online]. Available: `https://doi.org/10.1109/icphys.2019.8780138`.

[8] D. S. Nunes, P. Zhang, and J. S. Silva, "A survey on human-in-the-loop applications towards an internet of all," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 944–965, 2015. DOI: `10.1109/comst.2015.2398816`. [Online]. Available: `https://doi.org/10.1109/comst.2015.2398816`.

[9] G. D. Abowd, A. K. Dey, P. J. Brown, N. Davies, M. Smith, and P. Steggles, "Towards a better understanding of context and context-awareness," in *Handheld and Ubiquitous Computing*, Springer Berlin Heidelberg, 1999, pp. 304–307. DOI: `10.1007/3-540-48157-5_29`. [Online]. Available: `https://doi.org/10.1007/3-540-48157-5_29`.

[10] R. Davies, "Industry 4.0 digitalisation for productivity and growth," *European Parliamentary Research Service*, vol. 1, 2015.

[11] X. Yao, J. Zhou, Y. Lin, Y. Li, H. Yu, and Y. Liu, "Smart manufacturing based on cyber-physical systems and beyond," *Journal of Intelligent Manufacturing*, vol. 30, no. 8, pp. 2805–2817, Dec. 2017. DOI: `10.1007/s10845-017-1384-5`. [Online]. Available: `https://doi.org/10.1007/s10845-017-1384-5`.

[12] P. Milgram, H. Takemura, A. Utsumi, and F. Kishino, "Augmented reality: A class of displays on the reality-virtuality continuum," in *Telemanipulator and Telepresence Technologies*, H. Das, Ed., SPIE, Dec. 1995. DOI: `10.1117/12.197321`. [Online]. Available: `https://doi.org/10.1117/12.197321`.

[13] ACEA, "Acea economic and market report – full-year 2019," ACEA, May 2020. [Online]. Available: `https://www.acea.be/uploads/statistic_documents/Economic_and_Market_Report_full-year_2019.pdf`.

[14] ——, "Employment in the eu automotive industry," ACEA, 2020. [Online]. Available: `https://www.acea.be/statistics/article/employment`.

[15] ——, "Employmentshare of direct automotive employment in the eu, by country," ACEA, 2020. [Online]. Available: `https://www.acea.be/statistics/article/share-of-direct-automotive-employment-in-the-eu-by-country`.

[16] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, and M. Hoffmann, "Industry 4.0," *Business & Information Systems Engineering*, vol. 6, no. 4, pp. 239–242, Jun. 2014. DOI: `10.1007/s12599-014-0334-4`. [Online]. Available: `https://doi.org/10.1007/s12599-014-0334-4`.

[17] T. E. of Encyclopaedia Britannica, "Industrial revolution," in *Encyclopaedia Britannica*, Encyclopaedia Britannica, 2020. [Online]. Available: `https://www.britannica.com/event/Industrial-Revolution`.

[18] J. Rifkin, *The third industrial revolution : how lateral power is transforming energy, the economy, and the world*. New York: Palgrave Macmillan, 2011, ISBN: 978-0-230-11521-7.

[19] H. Kagermann, J. Helbig, A. Hellinger, and W. Wahlster, *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group*. Forschungsunion, 2013.

[20] M. Hermann, T. Pentek, and B. Otto, "Design principles for industrie 4.0 scenarios," in *2016 49th Hawaii International Conference on System Sciences (HICSS)*, IEEE, Jan. 2016. DOI: `10.1109/hicss.2016.488`. [Online]. Available: `https://doi.org/10.1109/hicss.2016.488`.

[21] P. Buxmann, T. Hess, and R. Ruggaber, "Internet of services," *Business & Information Systems Engineering*, vol. 1, no. 5, pp. 341–342, Sep. 2009. DOI: `10.1007/s12599-009-0066-z`. [Online]. Available: `https://doi.org/10.1007/s12599-009-0066-z`.

[22] W. de Paula Ferreira, F. Armellini, and L. A. D. Santa-Eulalia, "Simulation in industry 4.0: A state-of-the-art review," *Computers & Industrial Engineering*, vol. 149, p. 106 868, Nov. 2020. DOI: `10.1016/j.cie.2020.106868`. [Online]. Available: `https://doi.org/10.1016/j.cie.2020.106868`.

[23] A. Albers, B. Gladysz, T. Pinner, V. Butenko, and T. Stürmlinger, "Procedure for defining the system of objectives in the initial phase of an industry 4.0 project focusing on intelligent quality control systems," *Procedia CIRP*, vol. 52, pp. 262–267, 2016. DOI: `10.1016/j.procir.2016.07.067`. [Online]. Available: `https://doi.org/10.1016/j.procir.2016.07.067`.

[24] P. Kovac, I. Maňková, M. Gostimirović, M. Sekulić, and B. Savkovic, "A review of machining monitoring systems," *Journal of PRODUCTION ENGINEERING*, vol. 14, pp. 1–6, Jan. 2011.

[25] R. Teti, K. Jemielniak, G. O'Donnell, and D. Dornfeld, "Advanced monitoring of machining operations," *CIRP Annals*, vol. 59, no. 2, pp. 717–739, 2010. DOI: `10.1016/j.cirp.2010.05.010`. [Online]. Available: `https://doi.org/10.1016/j.cirp.2010.05.010`.

[26] E. Petritoli, F. Leccese, and G. S. Spagnolo, "In-line quality control in semiconductors production and availability for industry 4.0," in *2020 IEEE International Workshop on Metrology for Industry 4.0 IoT*, 2020, pp. 665–668. DOI: `10.1109/MetroInd4.0IoT48571.2020.9138296`.

[27] G. Cogorno, *Geometric dimensioning and tolerancing for mechanical design.* New York: McGraw-Hill, 2011, ISBN: 9780071772129.

[28] V. K. Pathak, A. K. Singh, M. Sivadasan, and N. K. Singh, "Framework for automated GD&t inspection using 3d scanner," *Journal of The Institution of Engineers (India): Series C*, vol. 99, no. 2, pp. 197–205, Aug. 2016. DOI: `10.1007/s40032-016-0337-7`. [Online]. Available: `https://doi.org/10.1007/s40032-016-0337-7`.

[29] J. Nee, *Fundamentals of tool design*. Dearborn, Mich: Society of Manufacturing Engineers, 2010, ISBN: 9780872638679.

[30] M.-W. Cho, H. Lee, G.-S. Yoon, and J. Choi, "A feature-based inspection planning system for coordinate measuring machines," *The International Journal of Advanced Manufacturing Technology*, vol. 26, no. 9-10, pp. 1078–1087, Aug. 2005. DOI: `10.1007/s00170-004-2077-8`. [Online]. Available: `https://doi.org/10.1007/s00170-004-2077-8`.

[31] L. Qi, S. Wang, Y. Zhang, Y. Sun, and X. Zhang, "Quality inspection guided laser processing of irregular shape objects by stereo vision measurement: Application in badminton shuttle manufacturing," *Optical Engineering*, vol. 54, no. 11, p. 113 101, Nov. 2015.

[32] M. D. Gregorio, G. Nota, M. Romano, M. Sebillo, and G. Vitiello, "Designing usable interfaces for the industry 4.0," in *Proceedings of the International Conference on Advanced Visual Interfaces*, ACM, Sep. 2020. DOI: `10.1145/3399715.3399861`. [Online]. Available: `https://doi.org/10.1145/3399715.3399861`.

[33] E. Lodgaard and S. Dransfeld, "Organizational aspects for successful integration of human-machine interaction in the industry 4.0 era," *Procedia CIRP*, vol. 88, pp. 218–222, 2020. DOI: `10.1016/j.procir.2020.05.039`. [Online]. Available: `https://doi.org/10.1016/j.procir.2020.05.039`.

[34] B. Hollifield, "A high performance hmi–better graphics for operations effectiveness," in *2012 Water/Wastewater and Automation Controls Symposium*, 2012.

[35] G. Lee, C. M. Eastman, T. Taunk, and C.-H. Ho, “Usability principles and best practices for the user interface design of complex 3d architectural design and engineering tools,” *International Journal of Human-Computer Studies*, vol. 68, no. 1-2, pp. 90–104, Jan. 2010. DOI: `10.1016/j.ijhcs.2009.10.001`. [Online]. Available: `https://doi.org/10.1016/j.ijhcs.2009.10.001`.

[36] W. Galitz, *The essential guide to user interface design : an introduction to GUI design principles and techniques*. Indianapolis, IN: Wiley Pub, 2007, ISBN: 978-0-470-05342-3.

[37] D. Fiorella, A. Sanna, and F. Lamberti, “Multi-touch user interface evaluation for 3d object manipulation on mobile devices,” *Journal on Multimodal User Interfaces*, vol. 4, no. 1, pp. 3–10, Dec. 2009. DOI: `10.1007/s12193-009-0034-4`. [Online]. Available: `https://doi.org/10.1007/s12193-009-0034-4`.

[38] G. Bishop and H. Fuchs, “Research directions in virtual environments,” *ACM SIGGRAPH Computer Graphics*, vol. 26, no. 3, pp. 153–177, Aug. 1992. DOI: `10.1145/142413.142416`. [Online]. Available: `https://doi.org/10.1145/142413.142416`.

[39] T. Mazuryk and M. Gervautz, “Virtual reality - history, applications, technology and future,” Dec. 1999.

[40] A. Valerio Netto, “Realidade virtual - definições, dispositivos e aplicações,” Mar. 2002.

[41] M. Slater, M. Usoh, and A. Steed, “Depth of presence in virtual environments,” *Presence*, vol. 3, pp. 130–144, Jan. 1994. DOI: `10.1162/pres.1994.3.2.130`.

[42] M. Saez, F. P. Maturana, K. Barton, and D. M. Tilbury, “Real-time manufacturing machine and system performance monitoring using internet of things,” *IEEE Transactions on Automation Science and Engineering*, vol. 15, no. 4, pp. 1735–1748, Oct. 2018. DOI: `10.1109/tase.2017.2784826`. [Online]. Available: `https://doi.org/10.1109/tase.2017.2784826`.

[43] M. Mabkhot, A. Al-Ahmari, B. Salah, and H. Alkhalefah, “Requirements of the smart factory system: A survey and perspective,” *Machines*, vol. 6, no. 2, p. 23, Jun. 2018. DOI: `10.3390/machines6020023`. [Online]. Available: `https://doi.org/10.3390/machines6020023`.

[44] A. Moreno, G. Velez, A. Ardanza, I. Barandiaran, Á. R. de Infante, and R. Chopitea, “Virtualisation process of a sheet metal punching machine within the industry 4.0 vision,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 11, no. 2, pp. 365–373, Jun. 2016. DOI: `10.1007/s12008-016-0319-2`. [Online]. Available: `https://doi.org/10.1007/s12008-016-0319-2`.

[45] L. Pérez, E. Diez, R. Usamentiaga, and D. F. Garcıa, “Industrial robot control and operator training using virtual reality interfaces,” *Computers in Industry*, vol. 109, pp. 114–120, Aug. 2019. DOI: `10.1016/j.compind.2019.05.001`. [Online]. Available: `https://doi.org/10.1016/j.compind.2019.05.001`.

[46] L. F. de Souza Cardoso, F. C. M. Q. Mariano, and E. R. Zorzal, “A survey of industrial augmented reality,” *Computers & Industrial Engineering*, vol. 139, p. 106 159, Jan. 2020. DOI: `10.1016/j.cie.2019.106159`. [Online]. Available: `https://doi.org/10.1016/j.cie.2019.106159`.

[47] A. Syberfeldt, M. Holm, O. Danielsson, L. Wang, and R. L. Brewster, “Support systems on the industrial shop-floors of the future – operators’ perspective on augmented reality,” *Procedia CIRP*, vol. 44, pp. 108–113, 2016. DOI: `10.1016/j.procir.2016.02.017`. [Online]. Available: `https://doi.org/10.1016/j.procir.2016.02.017`.

[48] S. C. Peres, T. Pham, and R. Phillips, “Validation of the system usability scale (SUS),” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 57, no. 1, pp. 192–196, Sep. 2013. DOI: `10.1177/1541931213571043`. [Online]. Available: `https://doi.org/10.1177/1541931213571043`.

[49] J. Rubin and D. Chisnell, *Handbook of usability testing: how to plan, design, and conduct effective tests*, 2nd ed. Indianapolis, IN: Wiley Pub, 2008, OCLC: ocn212204392, ISBN: 9780470185483.

[50] A. Assila, K. Oliveira, and H. Ezzedine, “Standardized usability questionnaires: Features and quality focus,” *Computer Science and Information Technology*, vol. 6, 2016.

[51] B. Shackel, “Usability – context, framework, definition, design and evaluation,” *Interacting with Computers*, vol. 21, no. 5-6, pp. 339–346, Dec. 2009. DOI: `10.1016/j.intcom.2009.04.007`. [Online]. Available: `https://doi.org/10.1016/j.intcom.2009.04.007`.

[52] A. Bangor, P. T. Kortum, and J. T. Miller, “An empirical evaluation of the system usability scale,” *International Journal of Human-Computer Interaction*, vol. 24, no. 6, pp. 574–594, Jul. 2008. DOI: `10.1080/10447310802205776`. [Online]. Available: `https://doi.org/10.1080/10447310802205776`.

[53] B. Eisenman, *Learning React Native : building mobile applications with JavaScript.* Sebastopol, CA: O’Reilly Media, 2015, ISBN: 978-1491929001.

[54] S. A. Bello, L. O. Oyedele, O. O. Akinade, M. Bilal, J. M. D. Delgado, L. A. Akanbi, A. O. Ajayi, and H. A. Owolabi, “Cloud computing in construction industry: Use cases, benefits and challenges,” *Automation in Construction*, vol. 122, p. 103 441, Feb. 2021. DOI: `10.1016/j.autcon.2020.103441`. [Online]. Available: `https://doi.org/10.1016/j.autcon.2020.103441`.

Appendix A

System Usability Scale Questionnaire (Portuguese)

Eu usaria a aplicação frequentemente *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

A aplicação é muito complexa *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

A aplicação é fácil de usar *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Eu precisaria de suporte técnico para poder utilizar a aplicação *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Várias funções da aplicação estavam muito bem integradas *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Havia muita inconsistência na aplicação *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

A maioria das pessoas aprenderia a usar a aplicação muito rapidamente *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Achei a aplicação bastante desconfortável de usar *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Senti-me muito seguro usando a aplicação *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Preciso aprender muitas coisas antes de poder usar a aplicação *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Comentários (opcional)

Appendix B

Project Original Proposal

INSTITUTO POLITÉCNICO DE BRAGANÇA
Escola Superior de Tecnologia e Gestão

Proposta de Dissertação

Mestrado em Sistemas de Informação

2020/21

Título: Desenvolvimento de assistente digital de suporte à execução de procedimentos de medição de controlo de peças

Orientador (IPB): Paulo Leitão

Coorientador (UTFPR): Jorge Aikes Junior, Pedro Luiz de Paula Filho

Aluno: Giuseppe Antonio Setem Davanzo

Contextualização:

No contexto da Indústria 4.0, a integração de operadores e outros humanos nos novos sistemas ciber-físicos assume crucial importância, uma vez que o humano é considerado como a peça mais flexível do sistema. Assim, é fundamental a implementação de sistemas que facilitem a integração dos humanos, utilizando tecnologias disruptivas como sejam novas interfaces homem-máquina, realidade virtual e aumentada, e assistentes pessoais inteligentes. Estes últimos são aplicações computacionais que suportam o operador na interação com máquinas e computadores durante a realização de tarefas ou serviços, utilizando comandos de voz, imagens e informação contextual para elaborar recomendações e ações a serem realizadas. Estas aplicações recorrem a diversas tecnologias TIC, nomeadamente de processamento de imagem, processamento de fala, e realidade virtual e aumentada, assim como a diversas tecnologias para a interação homem-máquina, nomeadamente HMD (Head-mounted devices), e.g., Microsoft Hololens, dispositivos portáveis, e.g., smartphones e tablets, projetores, e.g., monitores, e dispositivos de reconhecimento gestual, e.g., Leap Motion.

Este trabalho consiste num desafio real colocado pela empresa Catraport (https://www.p-cautomotive.com/en/group/catraport), em cooperação com o CeDRI - Centro de Investigação em Digitalização e Robótica Inteligente (http://www.cedri.ipb.pt/).

Objetivo:

O objetivo deste trabalho consiste no desenvolvimento de um assistente digital, baseado em tecnologias TIC, nomeadamente realidade virtual e visão artificial, para suportar a execução de procedimentos de medição de controlo de peças produzidas, alinhado com a Indústria 4.0.

A solução a ser desenvolvida visa a fácil integração de operadores em sistemas ciber-físicos, incluindo funcionalidades de apoio à realização de tarefas de medição de controlo de peças, que são personalizados e atualmente realizados através de suporte de lista de instruções impressas em papel. Atualmente a operação é realizada nas seguintes fases:

- O operador procura em stock o medidor apropriado para a peça a ser verificada.
- O operador coloca o medidor e as instruções em papel no trólei portátil e transporta-o para a linha.
- O operador coloca a peça a ser verificada no medidor e aplica a sequencia de ações indicada na lista de instruções em papel.

Pretende-se com esta proposta de trabalho melhorar a eficiência do controlo de produção através do desenvolvimento de uma solução digital que elimine as instruções em papel e as substitua por um sistema que guie passo-a-passo o operador usando um sistema de visão. O sistema deve também, dentro do possível verificar a execução correta das tarefas.

Pré-requisitos:

Para a realização deste projeto é interessante que o aluno tenha conhecimentos sólidos de programação e realidade virtual.

Cronograma de Atividades

Este trabalho compreende a execução das seguintes etapas:

Tarefa 1 - Estudo do sistema atual e análise dos requisitos (M1)

Tarefa 2 - Familiarização das plataformas para processamento de imagem e realidade virtual (M2-M3)

Tarefa 3 – Especificação do sistema de assistência digital (M4-M5)

Tarefa 4 – Desenvolvimento do sistema de guia passo a passo da execução da lista de instruções usando realidade virtual (M4-M7)

Tarefa 5 – Desenvolvimento do sistema de visão artificial (M8-M9)

Tarefa 6 - Testes e validação do protótipo (M9)

Tarefa 7 - Escrita da dissertação e defesa final do trabalho (M10-M11)

Infraestruturas e recursos necessários

Este trabalho será desenvolvido no laboratório de Automação, Controlo e Robótica (LCAR).

Dedication

I dedicate this work to my family and friends, especially to my parents Marcos Cesar Davanzo and Maria Cristina Setem Davanzo. Who always supported me and inspired me to continue challenging myself and persevering in my studies.

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Abstract

Industries quality control procedures are usually dependent on gauge inspection tools, and these tools are used to inspect visual and geometrical tolerance conformity. Operators are guided during an inspection by using paper tutorials that assist them in performing their tasks and registering the result of the performed analysis. This traditional method of registering information may be misleading, lowering the effectiveness of the quality control by providing inaccurate and error-prone inspection results. This work implements a system that uses emergent technologies (e.g., Human-Machine Interfaces, Virtual Reality, Distributed Systems, Cloud Computing, and Internet of Things (IoT)) to propose a cost-effective solution that supports operators and quality control managers in the realization and data collection of gauge inspection control procedures. The final system was deployed in an industrial production plant, with the delivered results showing its efficiency, robustness, and highly positive feedback from the operators and managers. The software may offer a quicker and efficient execution of analysis tasks, significantly decreasing the setup time required to change the inspected product reference.

Keywords: Cyber-Physical Systems, Quality Control, Inspection Systems, Industry 4.0, Virtual Reality.

Contents

List of Tables

List of Figures

Acronyms

ABMS Agent-Based Modeling and Simulation.

AGD American Gage Design.

AR Augmented Reality.

CAD Computer-Aided Design.

CAE Computer-Aided Engineering.

CDN Content Delivery Network.

CLI Command-Line Interface.

CMM Coordinate Measuring Machine.

CPPS Cyber-Physical Production System.

CPS Cyber-Physical System.

DOM Document Object Model.

DT Digital Twin.

E2E End-to-End.

ECMA European Computer Manufacturers Association.

ES6 ECMAScript 2015.

EU European Union.

FaaS Factory as a Service.

FR Functional Requirements.

GLTF Graphics Language Transmission Format.

HCI Human-Computer Interaction.

HiL Human-in-the-Loop.

HiLCPS Human-in-the-Loop Cyber-Physical System.

HMD Head Mounted Devices.

HMI Human-Machine Interface.

HTML HyperText Markup Language.

HTTP Hypertext Transfer Protocol.

ICT Information and Communications Technology.

IoS Internet of Services.

IoT Internet of Things.

IPA Intelligent Personal Assistant.

JS JavaScript.

JSON JavaScript Object Notation.

JSX JavaScript XML.

MTUI Multi-touch User Interfaces.

NFR Non-Functional Requirements.

NPM Node Package Manager.

ORM Object Relational Mapper.

OS Operational System.

OTA Over-The-Air.

PWA Progressive Web Apps.

SPA Single-Page Application.

SQL Structured Query Language.

SUS System Usability Scale.

TLS Transport Layer Security.

TS TypeScript.

UI User Interface.

UX User Experience.

VR Virtual Reality.

WoW Window on Word.

XML Extensible Markup Language.

process. The solution was applied in the quality control process facing the challenging of an industrial production line. The main objectives of this work are:

1. Develop a mobile application that will empower operators with tools for quality control;
2. Develop a web application for data visualization at production process inspection level;
3. Apply the developed solution in a industrial environment;
4. Identify advantages of the application use in a production environment.

The solution should also be reliable and cost-effective ready for use in a production environment without creating issues and bottlenecks in the process. The developed system seeks to improve the current state of many industries by digitizing the use of paper in the mission-critical quality assurance process.

1.3 Contributions

This work will produce several contributions to different communities, such as Industry 4.0 researchers, software engineers, HMI researchers, seeking to provide to the automotive industry a cost-effective way to move towards digital transformation.

For Industry 4.0 researchers, this project offers a real-world case for a distributed system that uses a Human-in-the-Loop (HiL) during quality control. For software engineers and HMI researchers, the work shows the development and use of a cloud computing system that interacts with operators and their managers through an HMI that uses 3D to better guide users in the factories process. For industries, this work offers an alternative for moving towards an Industry 4.0 era cost-effectively while gathering data to understand better processes and improvements that can be made to ensure quality.

1.4 Document Structure

This work will present its content in the following order. First, the technical knowledge and context necessary for understanding the terms and concepts used in work are presented in Chapter 2. Next, the case study and the problem analysis are demonstrated in Chapter 3 with a rough idea of how to approach problem-solving. In Chapter 4, materials and methods used during the work development are listed and detailed. Chapter 5 presents the architecture and implementation of the developed solution, demonstrating what technologies were used to create the final system. Finally, Chapter 6 analysis the results and open a discussion on positive and negative aspects found in this work. Chapter 7 wraps all the before mentioned topics to conclude the work and present a future direction for this project.

Chapter 2

Context and Technologies

In this chapter, the basis of our project is presented. Firstly, Industry 4.0 is contextualized demonstrating the history, techniques and components utilized in its implementation (Section 2.1). Next, quality control and gauge tools' usage on industrial components inspection are evaluated (Section 2.2). This chapter then describes Human-Machine Interface (HMI) guidelines and concepts applied to 3D and Multi-Touch displays (Section 2.3). Finally, we detail Virtual Reality (VR) (Section 2.4) and Usability Test instruments (Section 2.5).

2.1 Industry 4.0

The industry remains one of the most critical parts of the global economy. Provide material goods in a profoundly mechanized and automatized method is a driving force to the fourth industrial revolution. From the beginning of industrialization, technological leaps guided changes in the behavior of industries operation. These paradigm shifts now are entitled "industrial revolutions" [16].

In the period 1760 to 1830, the First Industrial Revolution was happening confined to Britain. Aware of their head start, the British banned the exportation of machinery, skilled workers, and manufacturing techniques. Although the British monopoly could not last forever, industrial methods were brought to continental Europe, transforming the economy from west to east. Those industries embodied the employment of steam-powered machines in the production of goods [17].

In the mid-nineteenth century and first half of the twentieth century, the Second Industrial Revolution occurred, the modern industry began to utilize many natural, and artificial resources not formerly used [17](e.g., lighter metals, new alloys, synthetic products like plastics), and the excessive usage of electricity in the production [16].

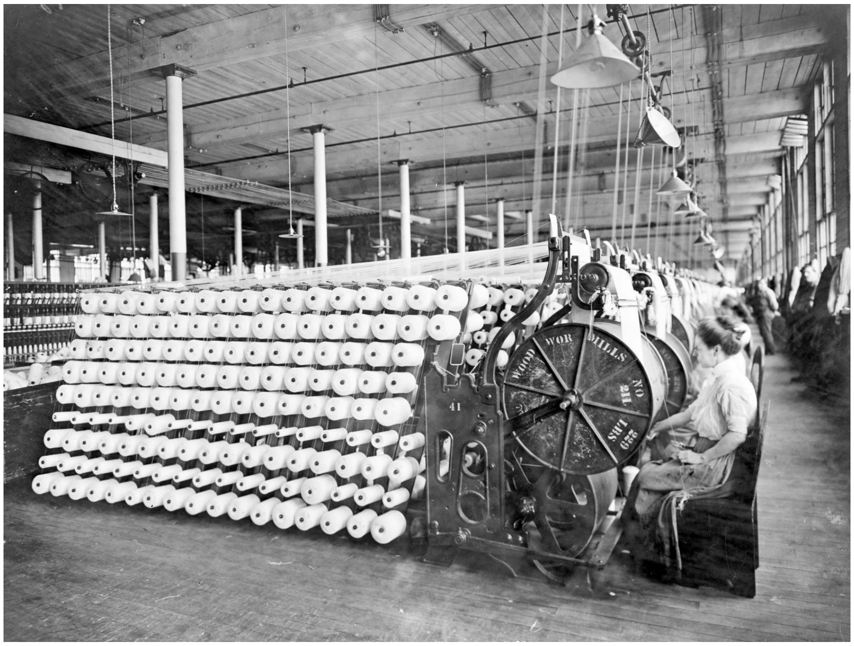


Figure 2.1: Industrial revolution factory workers. Boston, C. 1912. [17]

At the end of the twentieth century and the beginning of the twenty-first century, the Third Industrial Revolution had a meaningful impact as the First Industrial Revolution had in the nineteenth century and the Second Industrial Revolution in the twentieth century [18]. It fundamentally transforms every slant of the way we work and live. Great pillars of the Third Industrial Revolution are the shift to renewable energy, the buy and sell of energy on an interactive power grid, internet technology usage, and the widespread digitalization in industrial facilities [16].

The advances in digitalization within factories and the combination of internet technologies oriented to an intelligent factory appear to result in a new fundamental paradigm transformation in industrial production [16]. This future envisions a modular and efficient manufacturing system where dynamic business and engineering processes allow last-minute adjustments to display and deliver the capacity to react flexibly to disruptions and failures. They are powered by an end-to-end provider over the manufacturing process, facilitating optimized decision-making [19].

The expression Industry 4.0 was first used at the Hannover Fair in 2011 and has been noticed by many parts, from academics to government officials worldwide. It is not only a technological-related challenge to the relevant industries, but Industry 4.0 will also have far-reaching organizational implications, presenting a chance to generate new business and corporate models, facilitating more inclusive employee engagement [19].

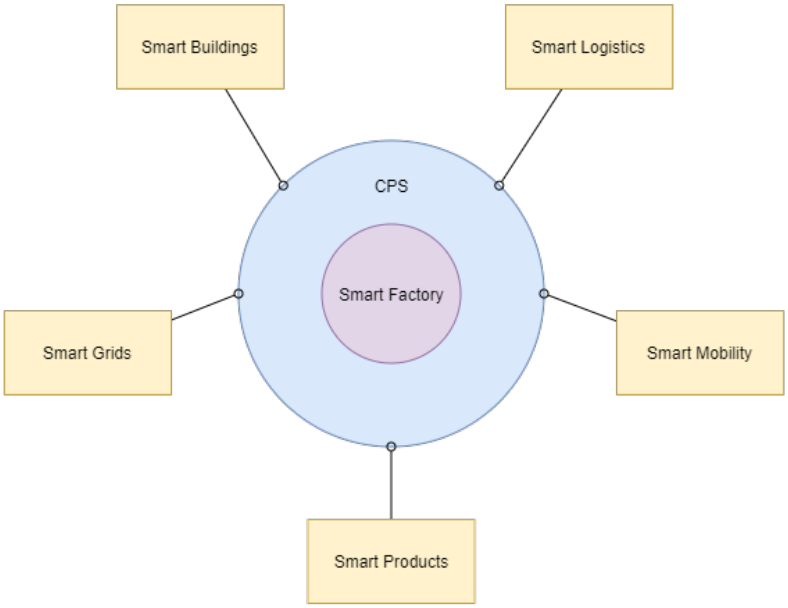


Figure 2.2: Smart factories as part of Internet of Things and Internet of Services. Adapted from [19].

2.1.1 Components

To enable this engaging environment while enabling an intelligent, networked world, Industry 4.0 relies on multiple components to implement smart factory plants. Thus, improving the capability to manage complexity, less inclined to errors, and more efficient manufacturing goods. By decentralizing the production logic in multiple components, Industry 4.0 products can comprehend the aspects of their manufacturing process and logistics (Figure 2.2), transforming the traditional value chains and business models [19]. Some of those components are [20][21]:

- **Cyber-Physical Systems (CPS)**. A CPS integrates the computational and physical process. They are embedded computers and networks liable to watch and manage the concrete process and provide feedback on consequences in a physical or computational process. This component relies on identification technologies (e.g., RFID tags), decentralized services for storage and analytics, and sensors compatible with networks;

- **Internet of Things (IoT)**. IoT allows "things" and "objects" (for example, RFID tags, sensors, smartphones) to interact with each other, cooperating with other smart components in a network to achieve a mutual purpose. IoT is a network where CPS collaborate to accomplish a specific objective;

- **Internet of Services (IoS)**. It allows vendors to offer services via the internet and combine it within the production chain. IoS allows a new way of dynamic variation of the distribution of individual value chain activities, supporting both functional and technical features;

- **Smart Factories**. It is a context-aware factory that assists people and machines in executing their tasks. Indicating that the system can consider contextual data like an object's position and status, performing their duties based on physical and digital information.

As described by Hermann, Pentek, and Otto [20] the intelligent factory "base on the definitions given for CPS and the IoT, assist people and machines in the execution of their tasks...". One project that implements such a system is the SMART FACE under the "Autonomics for Industrie 4.0" program initiated by the German Federal Ministry for Economic Affairs and Energy. The project supports using a modular assembly station that acknowledges the customer-specific configuration and can decide autonomously which working steps are needed, individually composing the necessary process through the IoS network.

2.1.2 Design Principles

Design principles support companies in identifying possible Industry 4.0 projects, which then can be implemented [20]. A straightforward approach is necessary for identifying variables and model an advance in the business implementation towards Industry 4.0. In essence, Industry 4.0 design principles are fundamental concepts that describe this phenomenon and promote its accomplishment [22][20][19]:

- **Interoperability**. The capacity of two or more systems to coexist, interact, and interoperate, for example, sharing resources. In companies that implement Industry 4.0, communication standards are a crucial factor for a successful implementation. Enabling vertical integration with different company systems at a different hierarchical level (e.g., physical, software, a business process). Also, horizontal integration consists of inter-company integration of IT systems, both within and across an organization;

- **Virtualization**. It monitors CPS physical process by associating sensor data with a virtual plat virtual representation, allowing for real-world events visualization in a digital form. Virtualization is essentially associated with information transparency and enabling technologies such as CPS, VR, AR, and Digital Twin (DT);

- **Decentralization**. It implies that one system network is not centrally managed.

Embedded systems should allow CPS to choose their process based on an identification key provided by the product to the machine before performing its tasks, shifting the paradigm from the central planning and controlling;

- **Real-Time Capability**. It enables real-time data-driven decision-making supported by gathering data and analysis in real-time events. Applying this principle, the plant can permanently track and analyze its components and react to this by making smarter data-diving decisions;
- **Service Orientation**. Provides organization to focus on selling services instead of products, known as Factory as a Service (FaaS). By identifying product-specific processes that compose customer-specific requirements into a final product;
- **Modularity**. A modular system should adjust to changes in its requirements by supplanting or extending individual modules. Modularity applies to many stages of the production cycle, enabling mass customization, flexibility, and fast manufacturing.

Implementing these patterns, advancements within factories, and the combination of internet technologies oriented to an intelligent factory appears adjusting industries into the 4.0 paradigm. It may maximize the advantages of its production capacity while improving the volume and quality of its service.

2.2 Quality Control

The objective of an independent evaluation of product and process quality as a fundamental element of quality control is an accomplishment that can only be achieved with monitoring measurement technologies [23]. As Albers, Gladysz, Pinner, *et al.* [23] paper quotes from Kovac, Maňková, Gostimirović, *et al.* [24], it is impossible to monitor these manufacturing processes' conditions directly. This is why measurable indicators have to be identified and implemented to conclude the quality state so that industries can have quantitative measures of the production quality, comprehending the process issues present in the plant to improve the product quality.

As mentioned by Teti, Jemielniak, O'Donnell, *et al.* [25] and quoted by Albers, Gladysz, Pinner, *et al.* [23]. The gains of intelligent quality control systems using sensors and indicators haven't succeeded in practice yet. The principal cause is the inevitable regulations that need to be applied to sensors on specific applications and the proper techniques to create suitable indicators.

To maintain quality, Petritoli, Leccese, and Spagnolo [26] paper proposes that "through an accurate analysis of the production processes and an appropriate flow of post-product test data, it is possible to correct the quality drift of the product during the production itself without waiting for the lot to run out".

To have a uniform quality assurance system is essential to start with the preparation of development down through the put in service. It is necessary to reduce potential problems from the production process. Consequently, checkpoints need to be established to prevent an item considered feasible to induce failure from reaching the next process step [26].

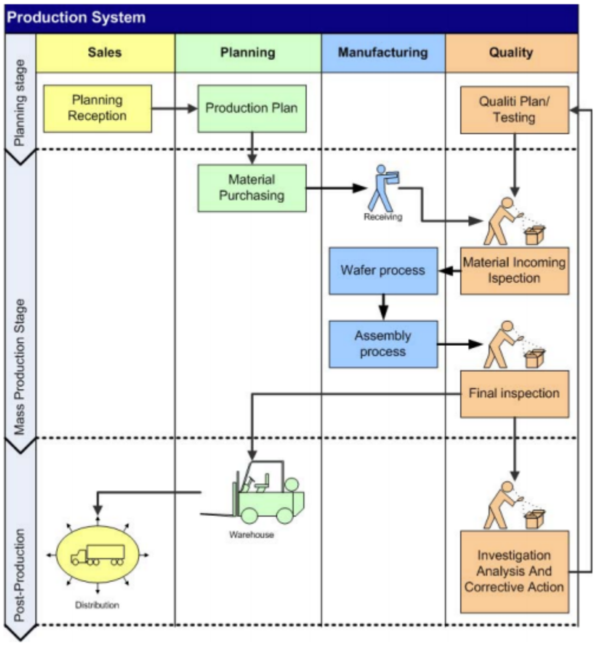


Figure 2.3: Production stages of a semiconductors production process. The figure shows the production stages and their relationship with the quality control stages [26].

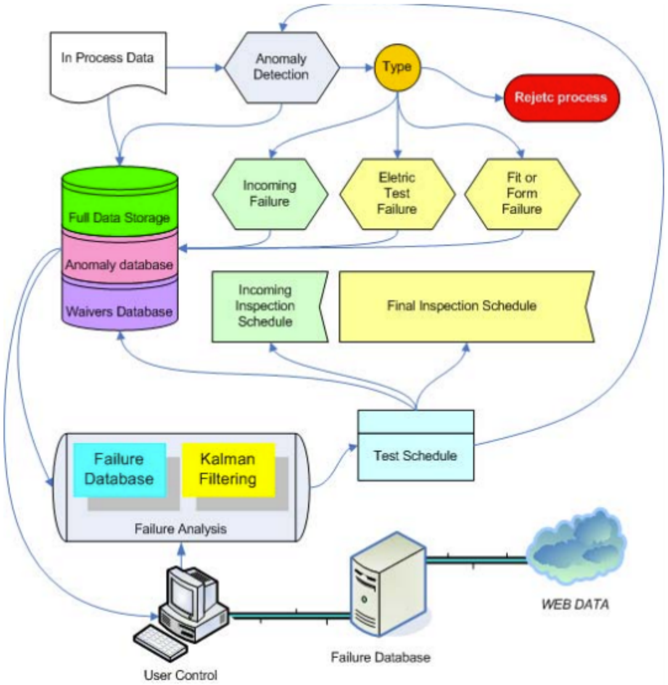


Figure 2.4: Quality processes in production systems [26].

One example of the application of quality control automation in Industry 4.0 is the Petritoli, Leccese, and Spagnolo [26] paper. The author applies quality control systems in a semiconductors production process (Figure 2.3) to correct the product's quality during the production itself. The author implements an online quality control system based on the process data coming from multiple stages of the production process in which the components are tested.

The data flow, represented by Figure 2.4, processes the data when it enters into the general database then sent to the Anomaly Detection layer, which detects nonconformities and classifies them. The failed component is marked by test failure (Incoming, Electric Test, or Fit/Form) and stored in the Anomaly Database, used during later Failure Analysis. By analyzing the production and quality processes, the author was able to test a reasonable number of electronic components leading to a significant increase in operational availability, thus reducing extraordinary maintenance interventions [26].

2.2.1 Geometric Inspection

Quality control inspection methods aim to evaluate products by creating metrics and measurements to monitor the process quality. This process is essential to identify the product defects and calibrate the machines' disposal along the production line. These traditional inspection processes (e.g., geometric inspection techniques) present some problems, primarily the loss of time and occurrence of errors when the inspection procedure is unknown and the manual collection of data related to detected defects.

Conventional tolerancing methods have been in use since the middle of the 1800s to ensure conformity in produced goods. Complex components are formed by several characteristics (e.g., planar, cylindrical, spherical, etc.). The machining process during the fabrication of all these features may impact the entire construction's overall accuracy. To guarantee that dependent pears will work together after the parts go through the production process. Techniques like Geometric Dimensioning and Tolerancing (GD&T) and Coordinate Dimensioning and Tolerancing (CD&T) are used to provide quantitative and qualitative measures for the quality of the pieces [27][28].

2.2.2 Types of Geometric Inspection

GD&T and CD&T are practiced to ensure quality in an industrial environment by examining manufacturing components with gauges. When the design of a component is used as a guide for its manufacturing process, the designer defines the piece limits of size, shape, and composition with dimensions, specifications, and tolerances present for every specification in the workpiece's drawing project [27][29].

Coordinate Dimensioning and Tolerancing (CD&T)

Since the middle of the nineteenth century, the industry has been using the plus or minus tolerancing system for tolerancing drawings. CD&T uses the plus or minus tolerancing system to represent the tolerance found in the piece [27]. In Figure 2.5, an example of the CD&T is shown to demonstrate the metric usage. Note that the dimension may be located anywhere within the gray rectangle [29].

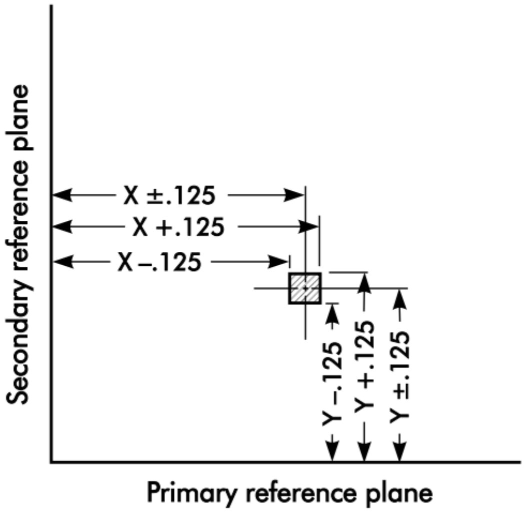


Figure 2.5: Example of CD&T applied into a object [29].

When handing cylindrical shapes, like a hole, for example, the center of the hole's tolerance can be determined by the difference of the X and Y coordinate tolerance measurements. After calculating the dimensions shift, the difference can be visualized in the intersection of the 45 degrees diagonal line to calculate the cylindrical tolerance (Figure 2.6)[29].

This method creates rectangular tolerance zones that are not precise when handling cylindrical objects or holes in a piece, differing in values when two measurements are applied. Another limitation of the CD&T is not representing size variation of shapes. For example, if the hole increases in size, it has more location tolerance, but there is no way to specify additional tolerances with the plus or minus tolerancing system [27].

Geometric Dimensioning and Tolerancing (GD&T)

GD&T is a representative language. It is utilized to define the size, shape, form, orientation, and location of features. When verifying the tolerance of complex objects, the features brought by the GD&T allow the identification of straightness, flatness, circularity, and cylindricity that can be incorporated into the piece in the form of errors [27][28].

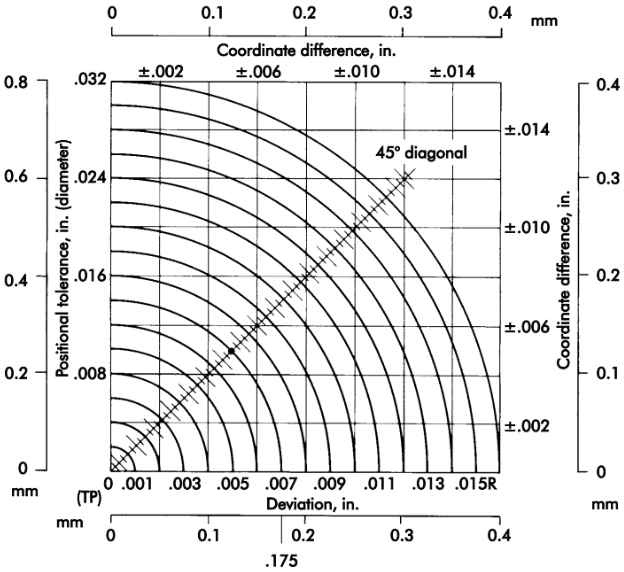


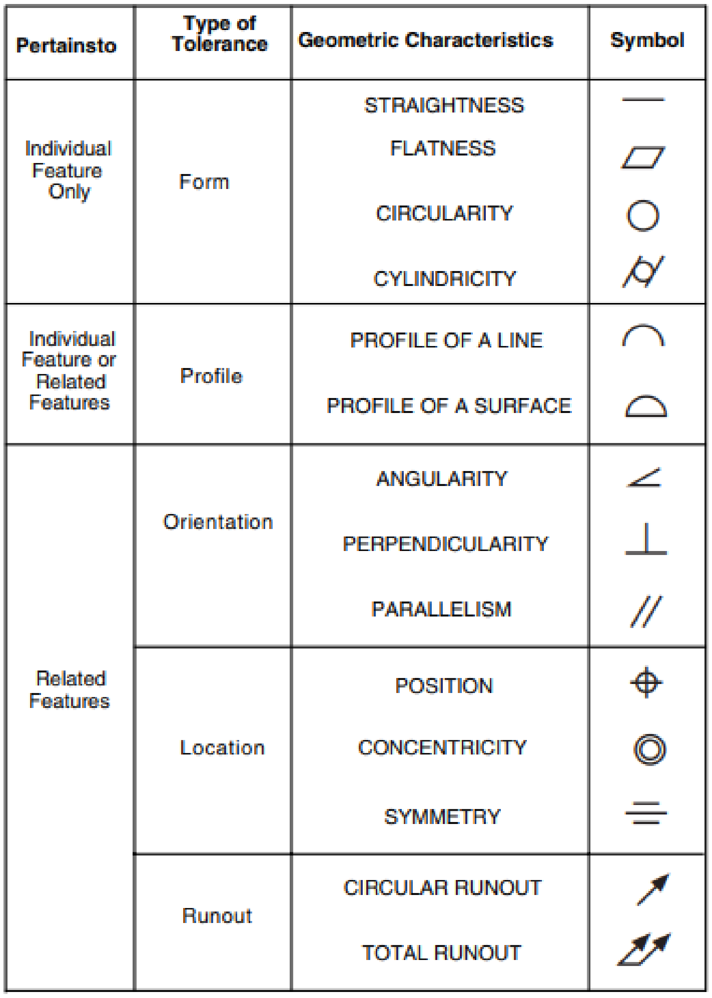
Figure 2.6: Guideline to calculate cylindrical tolerance [29].

To represent the object's characteristics more effectively, GD&T defines a series of symbols, terms, and rules to clarify a piece's conformities. Figure 2.7 demonstrates the symbolic language characters used to describe the tolerance type (e.g., form, profile, orientation, runout, and location). In Figure 2.8 feature control frame is illustrated, showing the meaning of each of its components. GD&T uses uppercase letters to identify the "faces" of the piece geometry (also know as datum), instructing the manufacturer by representing datums in order of presence and importance [27].

When compared to the CD&T, GD&T shows a more descriptive approach to dimension and tolerancing representation, allowing industries to have more context during complex components examination. Thus, impacting directly the quality of the final product produced by factories.

2.2.3 Concepts of Geometric Inspection

To understand the guidelines provided by CD&T or GD&T, it is necessary first to understand the methods and needs they try to solve.



Pertainsto	Type of Tolerance	Geometric Characteristics	Symbol
Individual Feature Only	Form	STRAIGHTNESS	⏤
		FLATNESS	▱
		CIRCULARITY	○
		CYLINDRICITY	⌭
Individual Feature or Related Features	Profile	PROFILE OF A LINE	⌒
		PROFILE OF A SURFACE	⌓
Related Features	Orientation	ANGULARITY	∠
		PERPENDICULARITY	⊥
		PARALLELISM	//
	Location	POSITION	⌖
		CONCENTRICITY	◎
		SYMMETRY	⌯
	Runout	CIRCULAR RUNOUT	↗
		TOTAL RUNOUT	⌰

Figure 2.7: GD&T symbols, tolerance types and their characteristics [27].

Tolerance

Tolerance implies the full measure in which a dimension could range from a specified size. It is not feasible in an industrial process to produce many components with precisely the same dimensions. Thus, working with tolerances is needed [29].

When verifying a part's tolerances, the designer delimits each feature's characteristics and their relationships with other of the piece features. They are acknowledging that two workpieces, distances, or quantities can not be exactly alike. Therefore, the designer specifies an ideal condition and calculates a degree of error that a component diversion can be tolerated [27][29].

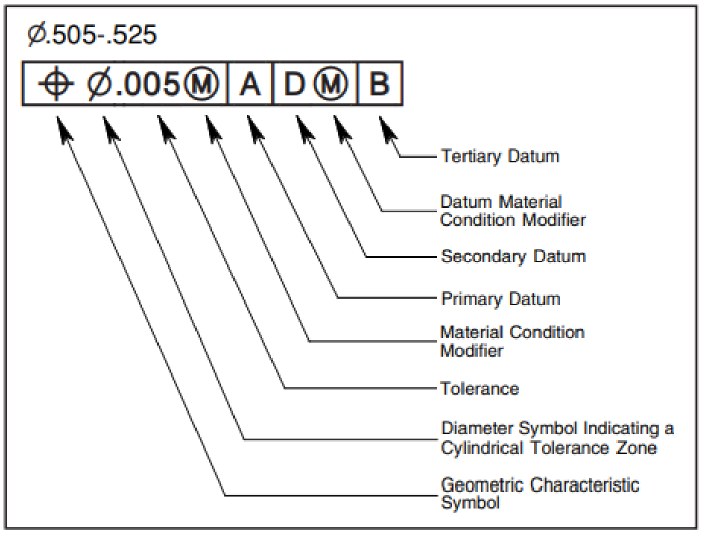


Figure 2.8: The feature control frame with description labels [27].

Gauging Principles

Gauge tolerance is usually planned based on component tolerance amount. For some gauges, the 10% rule is typically applied to limit the measure of gauge tolerance. Consequently, with the nonexistence of a specified gauge tolerance threshold, the maker will use 10% of the component tolerance as the gauge tolerance amount for a working gauge [29].

Next, the direction in which the allowance is should be determined. Two basic systems exist, bilateral and unilateral, but variations are commonly used, based on the product and facilities. When choosing an allowance system, the objective aims to reach the economical production of 100% usable parts as possible, accept suitable components and reject bad ones [29].

- **The bilateral system** (Figure 2.9.a) has the gauge tolerance zone divided into high and low limits of work tolerance. The gauge tolerance zones, in this case, are half plus and half minus concerning the high or low limit of the work tolerance zone;
- **The unilateral system** (Figure 2.9.b) has a work tolerance zone that includes the gauge tolerance area. This causes the work tolerance to be smaller by the sum of

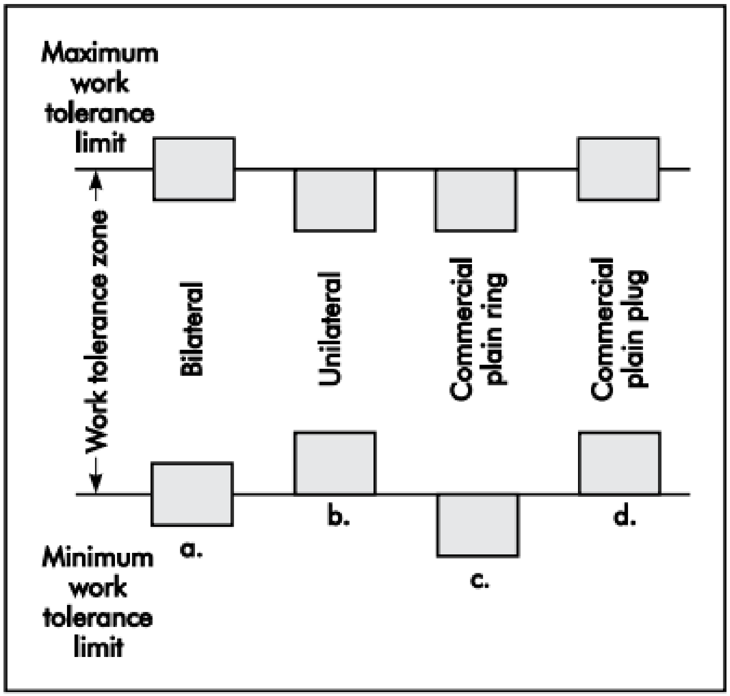


Figure 2.9: Different systems of gauge tolerance allocation [29].

the gauge tolerance, but guarantees that all parts passed by such a gauge will be inside the work tolerance zone despite the quantity of the gauge size variation;

- **The commercial plain ring** (Figure 2.9 c) and d) are commercial variation of the two basic systems. The product and the facilities should determine modifications.

Industries broadly use gauging to identify unwanted tolerances in the manufactured pieces. Although some standardized systems exist (Figure 2.9), the gauge may vary according to the product need in order to guarantee the final piece's best quality.

Gauging Wear

As Nee [29] demonstrates in his book, no gauges are perfect. If an ideal gauge existed in the real world, it would be imperfect after just one examining operation. The gauge wear amount during only one analysis operation is hard to measure, but several analysis operations' total wear can affect the measurement's precision. A gauge can fade past usefulness, so some allowance should be built into tolerance value. All gauge tools have an expiration date and should continually be verified previous to each inspection.

Gauging Materials

The materials utilized to make gauge tools may vary according to the production which it runs. Medium production usually uses hardened alloy steel to the wear surface of gauges. In higher demanding production, chromium-plated are typically used instead. When a gauge needs to have a higher degree of accuracy in long and wear excessive use, tungsten-carbide contacts often are used on gauges. The worn gauges surfaces can be ground down, chrome-plated, reground, lapped to size, and put back into service [29].

2.2.4 Tools for Geometric Inspection

Tools are needed to inspect the geometric dimensions and tolerances of a manufactured piece. Although the final tooling will always depend on the workpiece necessities, those pieces' testing methods may vary from traditional gauge tools to computerized automated systems.

Gauge tools

A gauge tool is typically built with two parts. One part is described as a "go" end. This end should allow clearance throwing the gauge tolerance zone. And another end is called "no-go," which should be more significant than the tolerance threshold. Many types of gauge tools exist to test many aspects of machined component conformity, e.g., custom commercial gauge (Figure 2.10.a), screw pitch gauge (Figure 2.10.b), plug gauge (Figure 2.10.c), ring gauge (Figure 2.10.d), among others [29].

Most gauges are standardized by norms, like American Gage Design (AGD). Although an exclusive gauge may be designed to inspect a particular component, AGD serves as a guideline for the tooling design [29]. For example, AGD standards generalize three types of plug gauge:

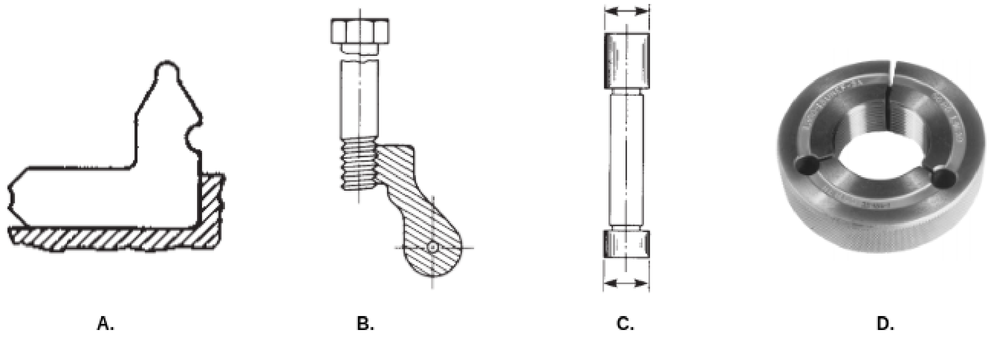


Figure 2.10: Types of gauge tools used by industries. Adapted from [29].

- **Single-end plug gauge**. This type of gauge consists of two separated gauge parts (a "go" and "no-go"), with each one of them having its handle (Figure 2.11.a);
- **Double-end plug gauge**. his is a single handle gauge tool with one gauge member (a "go" and "no-go") on each end (Figure 2.11.b);
- **Progressive gauge**. A single handle gauge with both parts (a "go" and "no-go") mounted on the same end. Both inspection ends are put together with the "go" part mounted in the front of the "no-go" end (Figure 2.11.c);

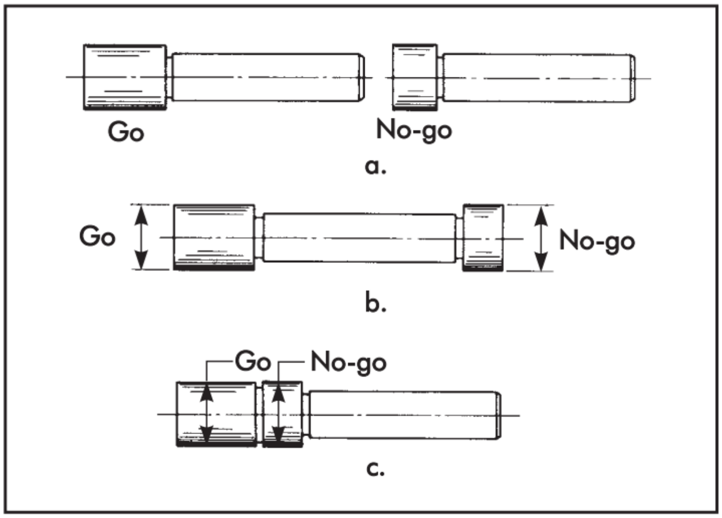


Figure 2.11: AGD cylindrical plug gages used to inspect the diameter of holes [29].

The usage of traditional gauge tools is a straightforward and manual process, depending on human operators to use the gauge tool and test it correctly. Standards help the design in developing gauges for testing manufactured pieces.

Coordinate Measuring Machine (CMM)

The Coordinate Measuring Machine (CMM) is an automated tool utilized by industries as a critical component of manufactured components inspection. CMMs enable Computer-Aided Inspection to increase accuracy and precision, emphasizing modern manufacturing qualities. CMMs are equipped with a touch probe that extracts high accurate data from surfaces which can then be compared with CAD files, utilizing the features information as metrics for the inspection [30].

Although extensively used in industry, To integrate CMMs in the industrial quality inspection process, the elaboration of an inspection planning strategy is needed to produce an optimum inspection strategy achieving more accurate and faster inspection results. CMMs deliver high accuracy with a slow measurement speed causing bottlenecks in the industry productivity. CMMs also highly depend on experienced operators to plan an effective strategy, which may be problematic and complex. The execution of the planning task will directly impact the inspection's measuring time, cost, and errors [30][28]

3D Scanner

In [28] paper, a 3D scanner to automatically check the geometric tolerance of parts is proposed. The author used the 3D scanner device to compare the scanned model with the tolerance specified by the components' tolerances, usually provided by a CAD file. The difference found when comparing with the specified tolerance is accepted or rejected according to the piece conformity with the guideline, generating a report with all the discoveries in the end. Although the author defines this approach as reliable and reproducible, the use of this technique depends a lot on highly experienced workers and excellent planning to perform the analysis correctly. The solution also isn't affordable and has been implemented in a controlled environment.

Cameras

In [31] paper, the authors approach the quality control of a badminton shuttle manufacturer by developing a solution that analysis the geometrical features of the feather used by the shuttles, identifying inconformities during the laser cut process. The solution uses multiple cameras to detect and measure unconformities in irregular-shaped objects and compares it with a 3D model of its real-world counterpart before the laser cutting operation. The laboratory prototype built presents a possibility for reduction of the time and power on handling faulty materials. However, implementing these automatic systems is not the proper solution for all processes since they usually require a high investment and/or present a high implementation complexity is dependent on the inspection process. In this sense, traditional quality control systems may face difficulty using automatic tools on the production line.

Although very promising, most of the state of the art solutions using emergent technologies remain highly experimental and mainly tested in a laboratory environment with only specific parts being used and not considering the industrial requirements. Another disadvantage for the before-mentioned approaches is their high implementation prices, a problem for small and medium-sized companies that aim to make the transitioning to use more digital geometry inspection methods.

2.3 Human-Machine Interfaces

Human-Machine Interface (HMI) can be described as the process by which humans interact with machines, implying in any machine or device used to perform or support individuals in their tasks [32]. An effective HMI solution is one that handles machine operations efficiently by humans without potential errors [33]. As Hollifield [34] states and Gregorio, Nota, Romano, *et al.* [32] quotes, in an industrial context, a satisfactory HMI should provide an operator means to identify and intercede effectively and quickly on irregularities within a process before they turn into a real emergency.

HMI is widely adopted by Industry 4.0. It can help industrial factories decrease the number of emergencies and accidents by providing operators with a macro view of their surroundings and rapidly reacting to situations. Powered by data and supported by assistance systems, humans can benefit when using the HMI for decision-making. The human-machine interface reduces the complexity of the process and makes them more manageable for users [32][33].

2.3.1 Principles and Guidelines

User interaction is a progressive field where new technology has always been employed to facilitate human-machine communication. Guidelines and best practices exist to support designers in building great HMI, presenting recommendations that may benefit the achievement of a good HMI design [35][36].

General principles are those that deal with common User Interface (UI) principles. This principle can be applied in most systems that rely on a UI to interact with a user. Some of those principles are [35][36]:

- **Consistency**. This is defined as the uniformity of system semantics across similar situations. This can be a consistent template, interaction method, term, and/or operation that is commonly used throughout the whole system;
- **Visibility**. Delivering important information prominent and easily detectable to the user. Users should quickly find tools and/or important information for their task;
- **Feedback**. The system should always give feedback to user's actions. For example, when a user interacts with a button visual feedback should be presented;
- **Recoverability**. Systems should provide users with options that enable them to recognize and recover from errors.

Although general principles can be applied to many systems, when handling 3D modeling and visualization, another set of regulations is suggested to be utilized. These principles are used by software, such as Computer-Aided Design (CAD), to better interact with the 3D spaces in 2D software [35]. Some of those 3D specific guidelines are:

- **Maximization of Workspace**. Interfaces should provide maximum screen space for modeling and viewing 3D models;
- **Graphical Richness**. Usage of graphical information, such as images and animation, enhance user comprehension when not over-utilized;
- **Direct Manipulation**. The HMI may provide the user with a direct operation to manipulate an object or scene within the 3D space. One example is the usage of the pinch gesture to apply zoom in a 3D dimension.

By applying the General and 3D specific principles, the software achieves more excellent usability and integration of its features. But when developing HMI is also needed to think about the user's support that will interact with the UI. For these, best practices show how to handle user support [35][36]:

- **Familiarity**. Take into consideration the users' experience in the real world and with other software when interacting with a new system. Maintain conformity with operating system conventions, 3D modeling system conventions, or similarities with the users' work;
- **Customizability**. Support users to modify the interface or operation of the system based on their preference;
- **Assistance**. Provide the user explicit assistance with tutorials and implicitly, by giver the user clues in which direction to follow;
- **Minimalist design**. The HMI should keep the user interface design simple, minimizing redundancy, and eliminating information that may confuse the user;
- **Context recognition**. The system should identify the context of the user and automatically modify the interface and/or operation to the one that best suits the user.

A more usable UI will be achieved by following the guidelines and improving the software's final UX. Empowering users, the HMI will reduce complexity and makes the cognitive load caused by complex information more manageable by the user.

2.3.2 Multi-touch User Interfaces (MTUI)

Multi-touch User Interfaces (MTUI) enables the user with more intuitive interactions than the keyboard and mouse inputs would provide. One example of the usage of this paradigm would be a photo gallery that uses the finger's "swipe gesture" on the display surface to browse the collection [37].

Many use cases may require the human-machine interfaces to provide visualization and interaction of 3D objects in touch-sensitive devices. The Fiorella, Sanna, and Lamberti [37] paper evaluates multi-touch interaction methods seeking an effective approach to this problem. The MTUI presented by the author results in the usage of the following gestures to interact with the 3D environment:

- **Picking gesture** is used to select an object (Figure 2.12.a);
- **Pinch gesture** enables the user to modify the scale of the object (Figure 2.12.b);
- **Two-finger gesture** allows translating the object (Figure 2.12.c).

These multi-touch interactions, when compared to traditional button-based user interfaces, received more positive feedbacks. The paper author concludes that most of the experiment subjects find the handheld device suitable for 3D graphics application [37]. Proving that is possible to translate 3D computer graphics applications to the 3D mobile application, by using MTUI instead of mouse input for dragging, rotating, and zooming [37].

2.3.3 HMI concepts applied to Industry 4.0

Industry 4.0 demands smart factories with all process equipped with support to interconnected data. Machines and industrial equipment will mature to more autonomous and

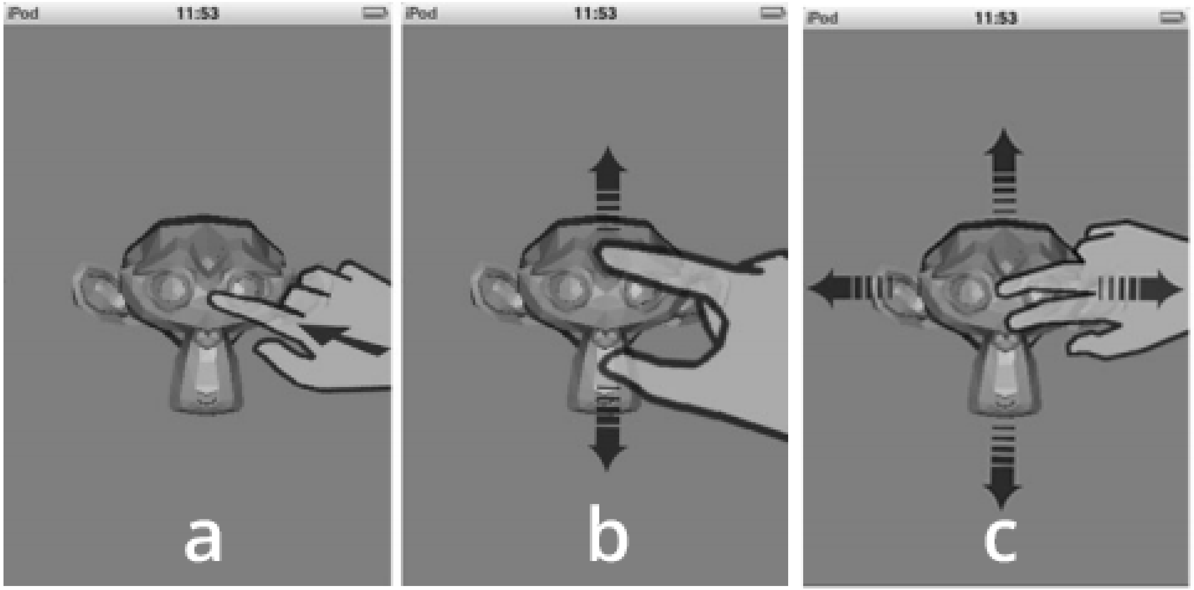


Figure 2.12: The designed Multi-touch User Interfaces: Picking gesture (A); Pinch gesture (B); Two-finger gesture (C) [37].

self-organizing, making one complex manufacturing process more manageable [33]. A key component for the reduction of complexity is the Human-Machine Interface, which can be integrated with industry-related data to provide humans with tools that can aid digital decision making [33].

The development of industrial-grade HMI will always depend on organizational specifics [33]. The collection of experiences, skills, familiarity, and motives that make operators handle job-related duties and challenges requires the process to adequate two important aspects:

- The technical competence that enables successful user-friendly HMI innovations [33];
- The worker competence to operate in a highly autonomous and interconnected environment [33].

According to Lodgaard and Dransfeld [33], the success of an HMI integration into Industry 4.0 will differ for each manufacturing company. Identify the maturity level of those companies is crucial to managing the integration in those digital transformations.

Useful and user-friendly HMI requires the development of approaches based on a company maturity level.

2.4 Virtual Reality (VR)

As cited by Bishop and Fuchs [38] and quoted by Mazuryk and Gervautz [39], Virtual Reality (VR) can be defined as “Real-time interactive graphics with three-dimensional models, combined with a display technology that gives the user the immersion in the model world and direct manipulation.” - i. e., an advanced UI that enables the user to navigate and interact in a three-dimensional environment.

Virtual Reality portrays to the user an experience characterized by the coexistence of immersion, interaction, and involvement [40]. An immersive VR experience may provide a person with a virtual environment with the feeling and experience of being in the actual environment. This can be achieved by the usage of display gear (i.e. output devices) and devices that introduce other senses to the virtual environment (i.e. input devices) [40].

2.4.1 Immersion

Immersion is the feeling of being part of the environment. There are two types of VR visualization, the immersive and the not-immersive [40].

The immersive VR experience can be achieved by the usage of display gear and/or devices that introduces other senses to the virtual environment. Although vision is our main sense when working with VR, another stimulus like sounds and touch response can be used to better the user perception of the digital environment [40].

In another way, the non-immersive VR usually utilizes monitors to visualize the 3D scene. If compared to immersive solutions, the main positive point of the non-immersive technology is the affordable cost and straightforward usage. Although the advantages of non-immersive VR are clear, immersive VR is the tendency of most future Virtual Reality applications because of the immersive capacities brought by the technology and extensive research been used in the field [40].

2.4.2 Levels of Immersion

As Slater, Usoh, and Steed [41] explains and Mazuryk and Gervautz [39] quotes, the Virtual Reality system is responsible for delivering sensory feedback to the user. The quality of the experience immersion will be determined by the feeling of presence in the virtual environment. In a perfect world, a VR experience will always be high-resolution, high-quality, and consistent on the displays, with the information being stimulated to all user's senses. However, in reality, the VR immersion does not always fill the given requirements and will be classified by the level of immersion that the solution provides to the user.

- **Desktop VR**. Also known as Window on Word (WoW) systems, the Desktop VR is the simplest type of VR application. It uses a conventional monitor to display the virtual world, without supporting sensory output;

- **Fish Tank VR**. These systems are an evolution of the Desktop VR with support to head tracking, which improves the user immersion. The display technology is still provided by conventional monitors and does not support sensory output;

- **Immersive Systems**. It is the more immersive system, placing the user in an immersive computer-generated world. This paradigm uses HMD, stereoscopic view, audio, haptic, and sensory to enhance the user experience.

2.4.3 Virtual Reality in The Industry 4.0

There are several simulation-based approaches available in literature being employed in the context of Industry 4.0, e.g. VR, AR, Agent-Based Modeling and Simulation (ABMS), Digital Twin (DT), and others [22]. As Hermann, Pentek, and Otto [20] mentioned and Paula Ferreira, Armellini, and Santa-Eulalia [22] quote, although there is no consensus on the definition of Industry 4.0, some of its core technological components and design principles can be identified and used to support the implementation of Industry 4.0 scenarios in companies, like, real-time capability and virtualization.

Real-time capabilities, i.e. real-time data collection, analysis, and support to data-driven decision making, will transform work content, work processes, and the working environment, connecting people, objects, and systems [19]. In [42], an approach for modeling and assessing the performance of manufacturing systems is proposed, using a virtual model to increase the performance of the real system. The proposed framework combines modeling of hybrid systems with plant floor data extracted using IoT to solve some of the synchronization and performance challenges faced on digitally representing a real industry. This can be achieved by monitoring machine and system-level variables with synchronous operation between the real and virtual environments, supporting manages on the floor plant with their decision making.

Virtualization, as quoted from Paula Ferreira, Armellini, and Santa-Eulalia [22], is the virtual replication of a physical system by linking sensor and actuators' data with a digitized factory model [20]. A virtual system is effective for issues such as training and conducting the workforce while performing manual processes, diagnosing, and predicting faults, and guiding maintenance tasks to fix failures [43]. Moreno, Velez, Ardanza, *et al.* [44] paper shows a study case on the virtualization process of a metal punching machine. The article exemplifies the application of virtualization with Digital Twin, addressing the creation of a DT of a material removal machine so that it can be used within a simulator to collect valuable information without wasting resources. The digital representation uses an Extensible Markup Language (XML) file to arrange the 3D model representation with data provided by Ethernet/IP (TCP/UDP connections) from the real machine. The simulator may warn the user about potential risks by comparing the program trajectories and their linear speeds with the trap's location and state.

Virtual Reality (VR) is a powerful tool when combined with real-time data and virtualization, enabling a more immersive interaction in manufacturing, increasing a user's perception and interaction with the real world, supporting different activities such as training, assembly, and maintenance [22]. Pérez, Diez, Usamentiaga, *et al.* [45] demonstrate an integrated human-robot interface using commercial gaming technologies and real robotics hardware and software to create a VR-controlled robot, in an immersive interactive environment where the operator can be trained. The innovation of the proposed approach is that it combines training, simulation, and control in a safe and non-expensive integrated application. Results show that the immersive experience succeeds in increment the efficiency of the simulation processes with a cost-effective solution, although the Head Mounted Devices (HMD) might cause sickness during intensive use, as shown by the author which finds out that 88.33% of the user's felt sick during the experiment.

A 2020 survey about industrial augmented reality studies realized by Souza Cardoso, Mariano, and Zorzal [46] reveals a notable use of AR technology by many general mechanical industries, generally producer of small components for other companies, largely in the automotive segment. The most meaningful use of AR in the examined period was by HMD and the primary benefit was the reduction of performance time, accompanied by improvement in quality and increase in learning, circumstances that contribute to costs reduction. From every one of the subjects examined only 5% were implemented in a production environment, offering a great area for research of disruptive solutions.

In [47], the author introduces a discussion on the use of AR in industrial shop-floors, for the experiment were built four prototypes adopting different display technologies, next tested in an industrial company workforce, and finally, the pros and cons of each approach were compared. The prototypes were:

1. Video-based glasses, an Oculus Rift [1] mounted with two cameras that stream video into the screen. This solution provides a hand-free solution, but was heavy to wear and had the operator's vision completely digitalized which can be to risk in an industrial environment;

2. Optical Glass, a C-Wear glasses connected to an Android-based device as computing unity with the augmented reality implementation. As result, a hand-free tool with non-obstrusive visualization of the real-world was offered, but as a counterpoint, image updating at head moves sometimes lag, the solution difficult to use the glasses

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[1] Oculus Rift Website

if already wearing ordinary glasses, and the weight of the optical glasses started to be perceived after some time;

3. Video-based tablet, a hand-held tablet that uses the device camera in combination with an augmented reality software. Its pros were a high familiarity perceived by the operator, while the cons were that the solution either occupies the operator's hands or, if placed in a stand, obstruct the operator's field of view, another problem was that in case of an object comes in the way of the camera the virtual objects disappear;

4. Spatial projector implements augmented reality by disconnecting the display from the user and integrating it into the environment. This method achieved a hand-free solution without affecting the operator's sight and without carrying additional weight. Although it depends on hardware permanently installed in the working environment and sometimes the information can become invisible if something came in the way of the projection.

As result, most of the participants believed that the prototypes were easy to understand and use. Another positive aspect revealed by the study was that most participants perceived increased efficiency with AR. However, the complexity of the task must be high enough for the operator to sense that it is deserving of using the augmented reality system.

2.5 Usability Test

A usability test is a process used both during and after the development of a product. It aims to test the prototype through an interactive process with constant user feedback. The usability test depends on consistent communication between usability specialists, product designers, and consumers [48]. As shown by Rubin and Chisnell [49], this might require constant task-based prototype testing, research, interviews, and survey to achieve a more relevant analysis.

2.5.1 Instruments and Measures

Peres, Pham, and Phillips [48] state that is developing questionnaires require many aspects to consider to create good instruments. Their paper describes several steps to take for quality control of a survey before its administration. Some useful guidelines like the length of the questionnaire, the qualitative item analysis, expert review, and pilot test are an excellent way to assert the survey quality. In their study, Peres, Pham, and Phillips [48] used the following instruments to measure the effectiveness of their survey:

- **Convergent Validity**. Describes the relationship between two different measures that aim to capture the same construct. This instrument consists of ten items, on which usability is rated on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree);
- **Divergent Validity**. Divergent validity refers to items that should not be related. That is, measures should not conceptually relate to the items. As a result, divergent estimates expect a low correlation between items;
- **Criterion-related Validity**. This instrument is a relationship between a measure in question and an external objective measure, i. e., a performance measure. When comparing to an objective performance measure, Peres, Pham, and Phillips [48] studies show that a medium-size correlation is expected;
- **Reliability**. The reliability measure describes the internal consistency of a survey by analyzing how the items of a questionnaire related to each other;
- **Sensitivity**. This topic refers to which differences can be detected by an instrument when an independent variable, for example, usability, is manipulated. By grouping means of the high-usability conditions with the low-usability conditions, the sensitivity can be assessed;
- **Respondent Workload**. The workload put to the subject of the test can be asserted by using a single-item scale such as "It was exhausting for me to respond

to the questions.", representing the participant fatigue during the survey;

- **Respondent Motivation**. A test subject's motivation may be analyzed by adding items that may show interest and pleasure using words that indicate fun, joy, and/or interest while completing the questionnaire;

- **Questionnaire Completion Time**. Online surveys can be used to record the completion time of each item.

2.5.2 System Usability Scale (SUS)

When working with Human-Computer Interaction (HCI), it is common sense to use usability evaluation tools to address the recommended solution's quality. Assila, Oliveira, and Ezzedine [50] describes usability evaluation as a well-defined and well-studied subject utilized to make systems easy to use and learn. Shackel [51] states and Assila, Oliveira, and Ezzedine [50]. quotes that "usability is the capability to be used by humans easily and effectively and associated with five criteria, i.e., effectiveness, learnability, retention, error, and attitude".

Although there are plenty of distinct great options to usability test (Table 2.1) [52], Assila, Oliveira, and Ezzedine [50] review on HCI literature found out that most of the studies on usability are focused on comparing one or more survey systems with the System Usability Scale (SUS), investigating the correlation between them. The general usage of SUS occurs by the fact that it is utilized as an industry standard for a usability test, performing a more quick and general usability assessment.

Survey name	*Number of questions*	*Availability*	*Interface measured*	*Reliability*
After Scenario Questionnaire (ASQ)	3	Non-proprietary	Any	0.93
Computer System Usability Questionnaire (CSUQ)	19	Non-proprietary	Computer based	0.95
Poststudy System Usability Questionnaire (PSSUQ)	19	Non-proprietary	Computer based	0.96
Software Usability Measurement Inventory (SUMI)	50	Proprietary	Software	0.89
System Usability Scale (SUS)	10	Non-proprietary	Any	0.85
Web Site Analysis and Measurement Inventory (WAMMI)	20	Proprietary	Web based	0.96

Table 2.1: Summary of available usability surveys (adapted from [3]).

Chapter 3

Case Study and Problem Analysis

The study considered in this work is related to gauge tools to perform the quality control of parts produced in a steel cold stamping factory plant. In such a process, the operator uses a pre-configured testing bench, as illustrated in Figure 3.1, to inspect the geometry compliance of a particular produced part. These testing benches provide gauge tools for the component-specific inspection, guides (for instructions and component conformity specifications), and expiration dates for the tools' effectiveness for each component series.

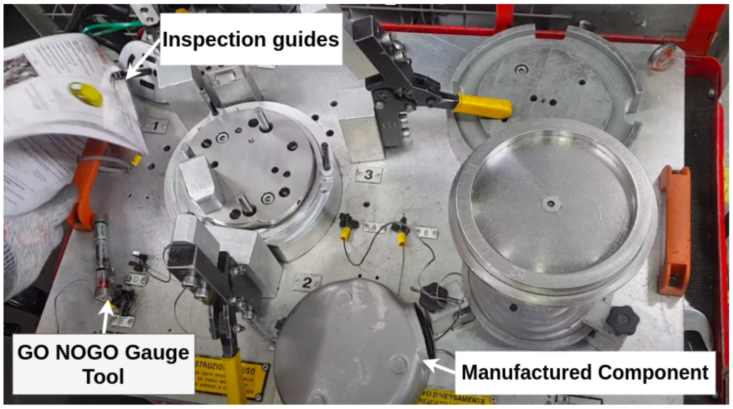


Figure 3.1: Test bench used by operators during the inspection process.

3.1 Quality Control

Quality control inspections are usually carried out many times in a day with the intent to test as many components as possible minimizing production failure. The specified interval between each analysis may be defined by quality control management, and at each interval, a partial or complete inspection may be executed.

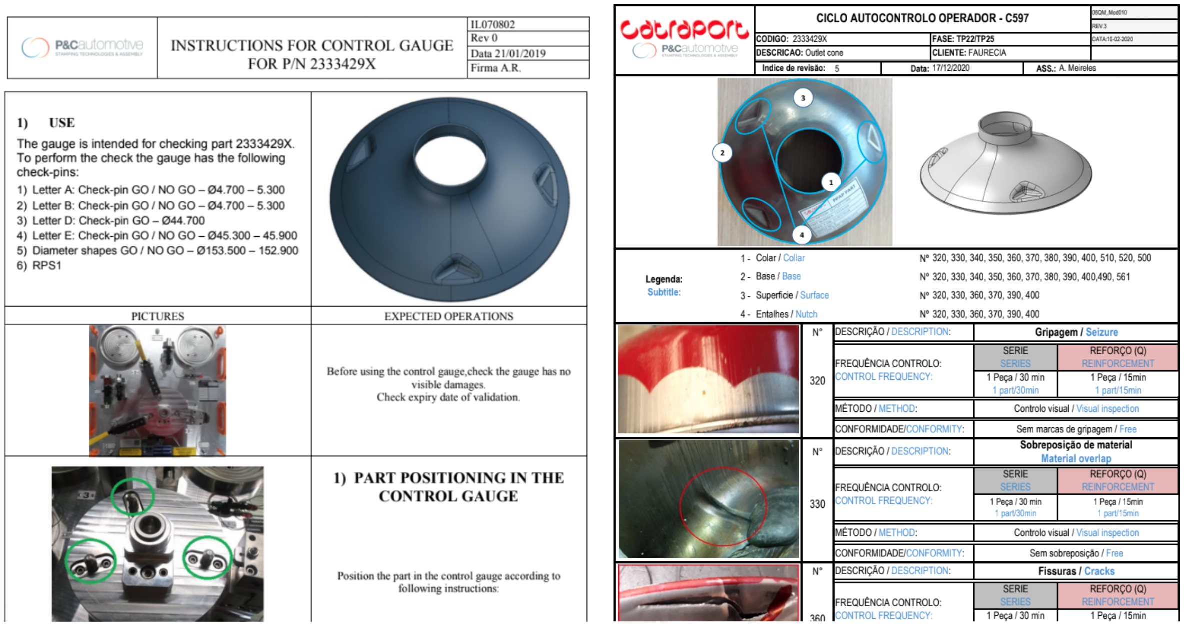
In our study case, these inspections can be divided into two categories visual and geometrical. Visual inspection frequencies are more often and faster to be executed, increasing the number of inspections to detect visible damage present in the produced piece.

The geometrical inspection is often less frequent and happens after a visual inspection. This technique utilizes "go" and "no-go" gauges to inspect the components' geometric conformity, a common among factories. This process involves executing a step-by-step analysis to inspect a component with tools that may or may not enter the tolerance specified.

For both analysis methods, guidance through the visual and geometrical inspection process is provided to the operators via tutorial papers. The test bench usage guide (Figure 3.2.a) provides step-by-step information on how to use the test bench during the inspection, the operation control guide (Figure 3.2.b) shows common failures, tolerances, and inspection methods used during the inspection.

Once the operator finishes the inspection, the results are recorded in the paper spreadsheet. It offers insights into the non-conformities found during the inspection. The recorded information is sent to quality control management, which will use the data to register metrics and better understand the production problems.

The main problem with this approach is the execution time and the number of errors that can exist due to the operators' difficulties in memorizing and executing the entire inspection sequence for the different part references correctly. This difficulty can become more evident in changing part reference, especially when the operator starts the inspection procedure and requires time to adjust the inspection routine.



P&Cautomotive	INSTRUCTIONS FOR CONTROL GAUGE FOR P/N 2333429X	IL070802 Rev 0 Data 21/01/2019 Firma A.R.

1) USE

The gauge is intended for checking part 2333429X. To perform the check the gauge has the following check-pins:

1) Letter A: Check-pin GO / NO GO – Ø4.700 – 5.300
2) Letter B: Check-pin GO / NO GO – Ø4.700 – 5.300
3) Letter D: Check-pin GO – Ø44.700
4) Letter E: Check-pin GO / NO GO – Ø45.300 – 45.900
5) Diameter shapes GO / NO GO – Ø153.500 – 152.900
6) RPS1

PICTURES	EXPECTED OPERATIONS
	Before using the control gauge,check the gauge has no visible damages. Check expiry date of validation.
	1) PART POSITIONING IN THE CONTROL GAUGE Position the part in the control gauge according to following instructions:

A.

Catraport P&Cautomotive	CICLO AUTOCONTROLO OPERADOR - C597		06QM_Mod010 REV.3
	CODIGO: 2333429X	**FASE:** TP22/TP25	DATA:10-02-2020
	DESCRICAO: Outlet cone	**CLIENTE:** FAURECIA	
	Indice de revisão: 5	**Data:** 17/12/2020	**ASS.:** A. Meireles

Legenda:
Subtitle:

1 - Colar / Collar	Nº 320, 330, 340, 350, 360, 370, 380, 390, 400, 510, 520, 500
2 - Base / Base	Nº 320, 330, 340, 350, 360, 370, 380, 390, 400,490, 561
3 - Superficie / Surface	Nº 320, 330, 360, 370, 390, 400
4 - Entalhes / Nutch	Nº 320, 330, 360, 370, 390, 400

Nº			
320	DESCRIÇÃO / DESCRIPTION:	**Gripagem / Seizure**	
	FREQUÊNCIA CONTROLO: CONTROL FREQUENCY:	SERIE SERIES	REFORÇO (Q) REINFORCEMENT
		1 Peça / 30 min 1 part/30min	1 Peça / 15min 1 part/15min
	MÉTODO / METHOD:	Controlo visual / Visual inspection	
	CONFORMIDADE/CONFORMITY:	Sem marcas de gripagem / Free	
330	DESCRIÇÃO / DESCRIPTION:	**Sobreposição de material** **Material overlap**	
	FREQUÊNCIA CONTROLO: CONTROL FREQUENCY:	SERIE SERIES	REFORÇO (Q) REINFORCEMENT
		1 Peça / 30 min 1 part/30min	1 Peça / 15min 1 part/15min
	MÉTODO / METHOD:	Controlo visual / Visual inspection	
	CONFORMIDADE/CONFORMITY:	Sem sobreposição / Free	
360	DESCRIÇÃO / DESCRIPTION:	**Fissuras / Cracks**	
	FREQUÊNCIA CONTROLO: CONTROL FREQUENCY:	SERIE SERIES	REFORÇO (Q) REINFORCEMENT
		1 Peça / 30 min	1 Peça / 15min

B.

Figure 3.2: Guides used by operators during the inspection: Test bench usage guide (A); Operation control guide (B)

The traditional method also creates a loss of time when converting the inspection report into digital support. Changing the test bench reference also implies changing all the paper guides used, creating a more time-consuming task. Additionally, using a paper spreadsheet to record data can be misleading once the data recorded may be wrong or incomplete, needing the future treatment to register more efficiently in a digital means, creating an additional loss of time to the operators writing the report.

3.2 Solution Requirements

The presence of Information and Communications Technology (ICT) and IPA, as the proposed work, are increasing in the industry. To digitize this inspection process, this works contributes to improve the inspection speed and the operator's perceived comfort by using a 3D environment to enhance the inspection process learnability, easing the operator's workload. Furthermore, using reliable storage to store and collect analysis data digitally from the beginning of the user interaction is essential to enable an automatical reporting functionality, without depending on operators to specify failures, besides including the photos of visual non-conformities (Figure 3.3).

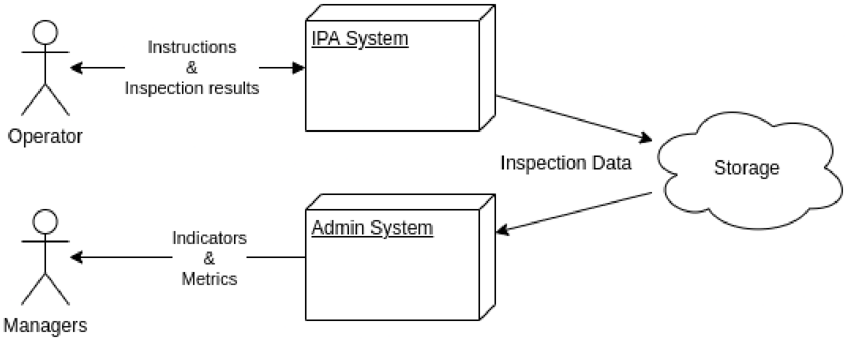


Figure 3.3: Diagram illustrating proposed system. It connects operators inspection results to managers while empowering operators with enhanced instruction data.

The collected data should be accessed in real-time by externals systems, e.g., management personnel that can visualize and analyze the results using proper metrics and better understand-conformities, contributing to identify earlier failure trends and proceed with machine calibration. As the result of the solution implementation is expected that the system improves the inspection quality control by offering: A more friendly HMI enabling operators to easily understand their tasks; Registering inspection information's more reliable; Reduce the inspection time by eliminating the data collection process; And improving quality control times by removing the need to change paper guides for every test bench replacement.

3.3 Development Strategy

To begin the software developed in this work is necessary to define the application's required functionalities. Thus, gathering the industry requirements and use cases is needed to understand the industrial process better. Therefore, the software engineering concept of iteratively creating use cases and prototypes is necessary to establish a common ground with the stakeholder. The methods described below are represented by Figure 3.4.

First, a visit to the industrial facility was made to understand better the quality control process and the key personnel behind those processes. All the crucial details were registered with notes, photos, and videos. Next, the content of those entries was analyzed to create a report explaining the factory inspection process. This report was used to contextualize all the project participants and create an environment prosperous for ideas. During an online meeting, brainstorm was carried out with the project participants'. Finally, ideas were collected, elaborated, and then proposed as possible solutions to the stakeholders.

With the possible solutions presented to the stakeholder, the process understanding was again refined, and the viability of each idea was discussed to find a more effective solution. After the meeting, notes took from the discussion were molded into functional and non-functional requirements using a spreadsheet to register it. Next, the requirements were transformed into use cases, and a diagram was drawn to represent them. Finally, screen prototypes were created with Figma using the use cases as guidelines.

The meetings with the industry personnel were frequent and happened during many stages of the development of this work. After each new iteration (e.g., brainstorm, requirements gathering, prototyping, and development), the project direction was validated with the industry responsible to ensure the work conforms with their needs. During this process, the understanding of the business logic was improved, and the communication of each of the project parts (e.g., developer, advisor, industry personnel) became more evident.

As defined by the prototypes and use cases, the implementation began by using those as guidelines to develop the solution with NodeJs, React, and React Native. Next, tests were executed with Jest to identify application failures before shipping to production. Finally, the application was deployed to the cloud using GitHub Actions to make continuous deployment on Vercel, Heroku, and Google Cloud, enabling secure external access to the software. During the whole application development and eventual bug fixes, this process was repeated, fully automated to create a fast and reliable release pipeline.

Digitization happened when the software requirements needed to create the manual were implemented. The process consists of using Fusion 360 and Blender to import, export, optimize, texture, and animate the final object to render in the mobile application. The final GLTF model is exported with the manual content into the web application to create a digital copy of the analog guide. This process is repeated until all the requested manuals are made and their content fully digitized.

After development and content creation, the application was presented to a control test group, and their answers were registered in an online SUS form. This group did not work in the factory and presents a diversified range of knowledge about software usage and industrial quality control. Next, the application was introduced in the industrial environment, integrated with the quality control process by fixing the tablet near a test bench. Moreover, managers were instructed on how to handle the application and apply the tests to the operators. During the production environment experiments, the online form registered their answers and related them with the email used during the device authentication.

Finally, the user test results were collected as a CSV file, imported to a spreadsheet, and analyzed to understand the user's perception better while handling the software and how this affected their work. Also, bug statistics were collected in order to check the application stability during production usage.

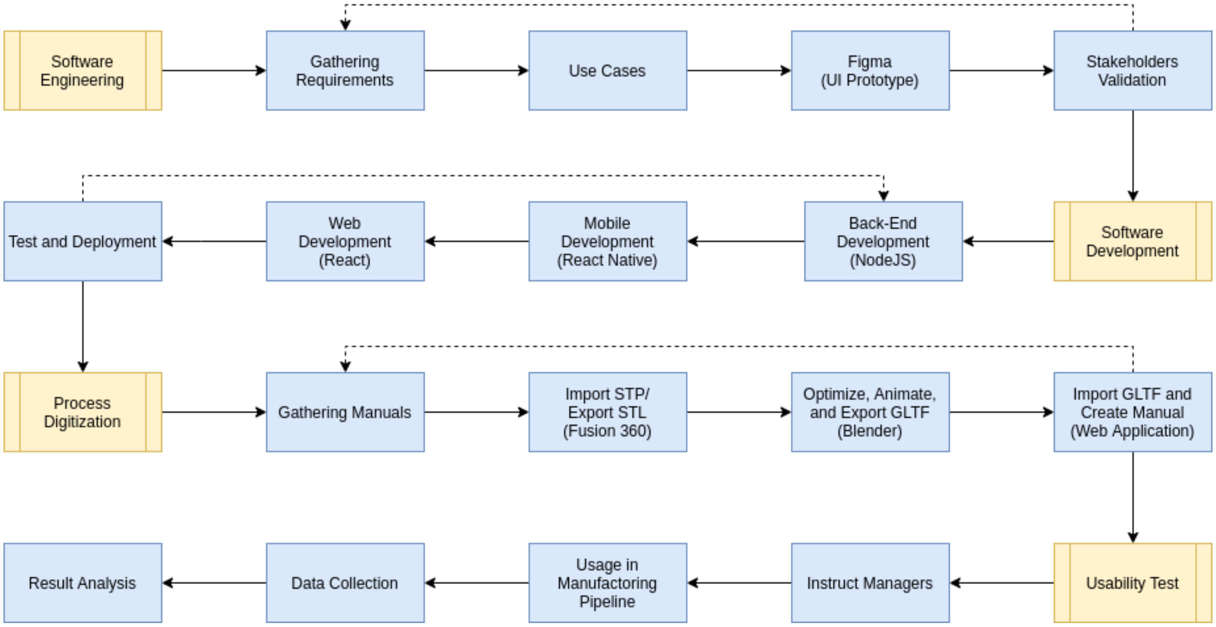


Figure 3.4: Diagram illustrating the strategy used during this work development.

Chapter 4

Technologies And Software Description

This chapter aims to present and explain the technologies utilized in this work and describe the reason for their usage during this project's application development. Technologies presented in Sections 4.1, 4.2, and 4.6 were used before and during all the applications development. The Sections 4.3 to 4.5 were used in both web and mobile apps. To create the digitized guides Sections 4.7 to 4.9 were applied. Finally, to deploy the application into production and provide infrastructure were utilized technologies described in 4.10 and 4.11. In the next chapter more details will be given in how these tools are used to solve the problem.

4.1 NodeJS (14.15.5)

NodeJS[1] is a JavaScript (JS) runtime built on top of Chrome's V8 JS engine. It was developed to enable JS to be executed in computers by a Command-Line Interface (CLI), allowing JS applications to be used as executables. Although more common concurrency models use the available Operational System (OS) threads to execute parallel computing, NodeJS employs an asynchronous event-driven strategy using a single thread in a

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[1] NodeJS Website

non-blocking event loop. This design allows creating network-based applications more efficiently than traditional thread-based alternatives, free from dead-lock and I/O blocks, using the event loop's ability to perform JavaScript callback functions after completing other work.

4.1.1 Node Package Manager (NPM)

Another advantage of NodeJS is the Node Package Manager (NPM)[2], which eases the import and configuration of libraries and frameworks for the runtime and makes the development process even more straightforward by improving the developer experience. NPM is also one of the package repositories with more contributions, with more than 1500000 modules available for development usage in the NPM public registry. The available packages vary from application-specific uses like ExpressJS, enabling NodeJS to receive Hypertext Transfer Protocol (HTTP) calls, and development-specific like Babel and ESLint, providing developers with better tooling for the task.

4.1.2 JavaScript (JS)

JS is a lightweight, interpreted, or just-in-time compiled programming language with multi-paradigm (e.g., object-orientation, imperative, and functional) and dynamic types. JS was first submitted to the European Computer Manufacturers Association (ECMA) to be used as a standard to implement scripting across multiple browser vendors. In the current NodeJS version, not all modern JS features are enabled by default (e.g., import/export, async/await, object deconstruction), only supporting the ECMAScript 2015 (ES6) specification.

4.1.3 TypeScript (TS)

Transpile languages into JavaScript is a common practice in the JS ecosystem. It uses a more developer-friendly language to increase productivity without losing compatibility

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[2] NPM Website

with older standards achieving a greater user-base. During the application development, Babel (version 7.12.1) was imported via NPM to allow TypeScript (TS) (version 4.0.2) to be used during the application construction to improve development further. TS extends the latest JS version by adding a strong type system, validating the JS ahead of time (i.e., providing errors and fixes before the code be executed). During the application execution, Babel transpile and optimizes the TS files into ES6 standards and then runs it in the NodeJS runtime.

4.2 Jest (26.6.3)

Jest[3] is a JS testing framework. Its usage aims to grant correctness to code features, describing test cases for each use case, thus improving the service's reliability. The tests executed by Jest are decoupled from the business logic and run in a parallelized manner by performing in a separate runtime process. Jest is an open-source tool-agnostic technology that integrates with Babel, TS, Node, React, Angular, Vue, and others.

4.3 React (16.11.0 - 17.0.1)

React[4] is a JS framework for developing web apps, Progressive Web Apps (PWA), mobile apps, and desktop apps. React is based on business logic componentization and declarative views, allowing for a predictable and straightforward UI implementation. Another advantage produced by the React framework is its multi-platform capability, allowing the reusability of code and knowledge in many target platforms (e.g., Android, IOS, MacOS, Windows, Linux, Web Browsers). React was used for both mobile (version 16.11.0) and web (17.0.1) development. The main difference from those targes is the additional React Native package only present in the mobile version.

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[3] Jest Website

[4] React Website

4.3.1 React Dom (16.11.0 - 17.0.1)

React uses React DOM to bind the Document Object Model (DOM) global methods into React and render JS elements on the screen. The DOM is accountable for connecting web pages to scripts by representing a document's structures (i.e., HTML) in memory. This allows JS to manipulate the document in a logical tree, where the script language can control this tree structure, style, and content.

The DOM provided by the browser usually suffers from performance issues when handling many manipulations at once. This happens because of the re-rendering of the UI that occurs to the manipulated element and its children. This step is computationally expensive, and excessive writes to the DOM have a significant impact on performance. React DOM solves this problem by creating an immutable Virtual DOM, which computes the necessary changes using an in-memory version of the DOM with a Diff algorithm and re-renders the minimal amount required to display the UI change (Figure 4.1).

4.3.2 React Native (Expo SDK 38.0.2) & Expo (38.0.8)

React Native[5] is used exclusively in mobile development. It allows the creation of native apps for Android and IOS using React. It combines both React and Javascript to build business logic and interface components reusable for any platform. Expo[6] is a set of tools and services built around React Native to improve developer experience on developing, building, deploying, and simulating Android and IOS applications.

Expo offers advantages from traditional React Native boilerplates by providing:

- **Multi-Platform Build.** Expo provides services to build the final application in the cloud. It allows developers to deploy for Android and IOS without having an XCode or Android Studio in their development environment;
- **Over-The-Air (OTA) Updates.** It provides OTA channels by default to developers deploying updates to the application. Whenever client device connects to the

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[5] React Native Website

[6] Expo Website

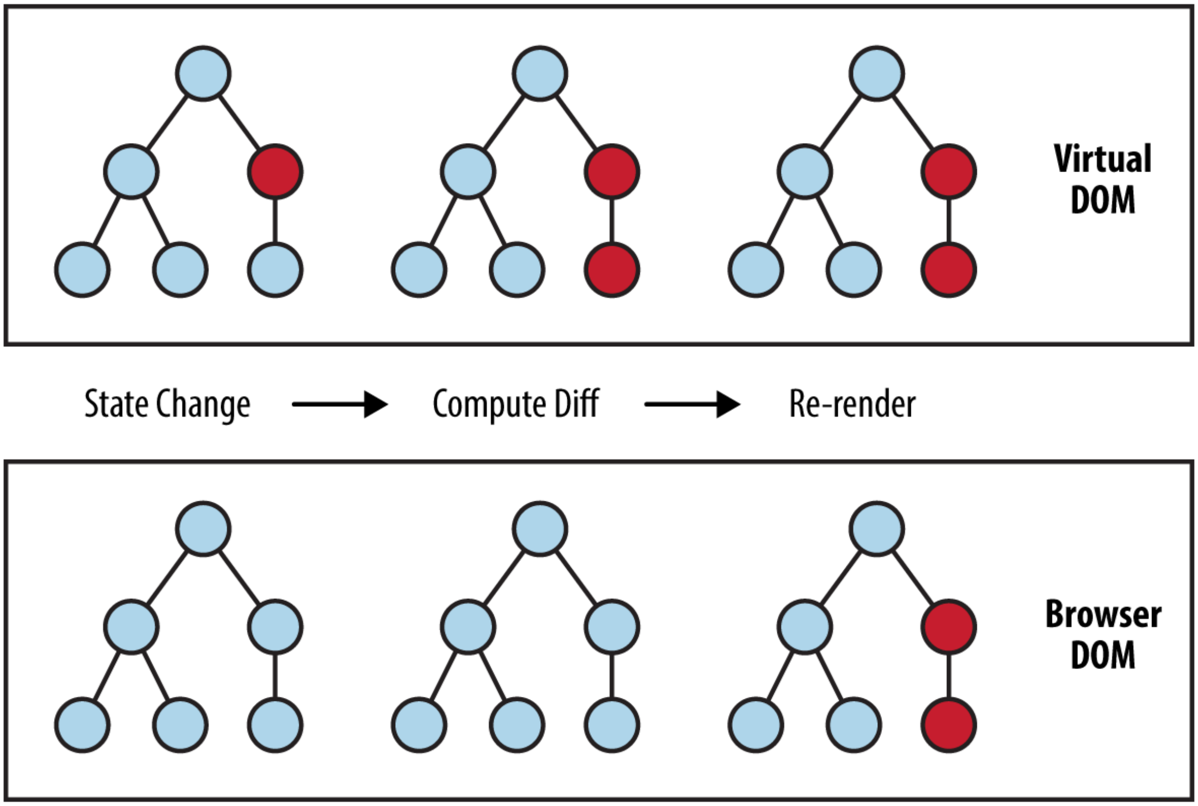

Figure 4.1: Virtual DOM Performing calculations compared to Browser DOM [53].

network, available updates are checked, downloaded, and installed;

- **Application Sharing.** Expo provides a development client that can be downloaded on any device, enabling testers to access the application anywhere during the development. It facilitates the sharing of the application, increasing feedbacks on the application's functionalities and implementation.

These advantages make Expo tooling an excellent option when working with React Native by increasing the developer's productivity.

4.4 ThreeJS (0.123.0)

ThreeJS[7] is an open-source, cross-platform, general-purpose 3D library. The project was created aiming to help web developers to work with 3D on the Web. The current stable version includes a WebGL renderer, but WebGPU, SVG, CSS3D, and OpenGL (Expo Three) bindings are also available to be used with the platform.

ThreeJS is developed with JavaScript and distributed via NPM, enabling any JS project to access and extend its functionalities easily. Some of the functionalities brought by the ThreeJS package are:

- THREE object abstraction around the traditional WebGL calls;
- Import and Export 3D files and textures (e. g., GLTF, COLLADA, OBJ, among others);
- Orbit Controls for manipulating the camera around the orbit target;
- Animation rendering, mixing and importing;

By offering many abstractions from the traditional WebGL, ThreeJS improves the developer productivity by including utilities for working with 3D. The library's counterpoint is the procedural coding style when handling the 3D scene, which difficulties its integration with more declarative frameworks, like React.

4.5 React Three Fiber (5.3.10)

React Three Fiber[8] abstracts the ThreeJS by simplifying the code when working with React and React Native. It implements a 3D scene with declarative and reusable components that allow the React framework to address 3D Objects, Light, Cameras, and Animations as JavaScript XML (JSX), maintaining a consistent code style.

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[7] ThreeJS Website

[8] React Three Fiber Repository

React Three Fiber also only converts JSX syntax into ThreeJS call, been more maintainable by not depending on the renderer version directly. This also implies no performance impact because when the application is built, everything becomes ThreeJS calls, relying only on the ThreeJS, CPU, and GPU performance to render the 3D scene.

4.6 Figma

Figma[9] is an online, collaborative, free to use, prototyping tool utilized to create wireframes, high-fidelity UI prototypes, and design systems. It allows designers to develop UI mocks fast and share with users to get user experience feedback to improve the application interface as it goes. Figma also generates Cascading Style Sheets (CSS) examples for developers to use as a guideline on the style guide implementation.

4.7 Blender (2.92)

Blender is a multi-platform (Windows, Linux, and MacOS) software for 3D manipulation developing with Python and OpenGL. The tool is open-source and allows the user to control 3D scenes and mashes with interactive tools. Besides 3D modeling, it provides tools to handle 3D animation, shaders, textures, video editing, import and export 3D files.

The suite is free to use and offers excellent compatibility with other CAD platforms, sharing OBJ, FBX, 3DS, STL, besides allowing plugins to extend its functionalities.

4.8 Fusion 360

Fusion 360 is a cloud-based Computer-Aided Engineering (CAE) software that handles the design and engineering of electronics and manufacturing models in a single platform. It also supports the creation and exporting of 3D printers out-of-the-box. The software is

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[9] Figma Application

proprietary been developed, maintained, and distributed by Autodesk. The software also offers a free version with limited features and an educational use version for students and professors with full feature access, only needing an institutional email.

4.9 GLTF (2.0)

The Graphics Language Transmission Format (GLTF) is an open standard that allows for efficient communication and loading of 3D scenes, modes, textures, and animations by engines and applications. The format reduces the size of assets using a compaction algorithm in the render runtime to unpack them. This technology enables the streaming of interactive and interoperable use of 3D content across systems.

GLTF can be used as GLB, a binary format of specification that may include assets compressed in. In the GLB structure, besides the traditional GLTF JavaScript Object Notation (JSON) structure that stores node hierarch, material textures (external references), and cameras. The GLB also includes geometry (vertices and indexes), animations' keyframes, and compressed material textures.

GLTF also enables material textures with metallic-roughness shading params (e.g., base color, metalness, roughness, emission, normal map, ambient occlusion) and optional specular-glossiness shading (e.g., diffuse, specular, glossiness). The format is also highly compatible, been supported by Blender, Unity, NVidia, Autodesk, ThreeJS, and many others.

4.10 Cloud Computing

Cloud computing describes an on-demand computer system that usually offers specialized data storage and computing power without the need for this system's user to have a local infrastructure. This system benefits many by reducing costs on high-quality computing infrastructure while improving customer's security and stability [54].

4.10.1 Google Cloud Storage

Google Cloud Services[10] is Google's cloud provider. One of their products is Google Cloud Storage, the high-performance object storage that handles binary data storage and streaming. This service offer compression algorithms that increase download and upload speeds, low latency connections due to its geo-redundant servers, and security provided by a professional infrastructure.

The storage service is also affordable for developers by providing a free account where 5 GB can be stored free with full access to all its features. The service is very transparent with its usage statistics, showing a chart with stored data occupied over time and how much is left. It also provides complete documentation on how to integrate many languages and frameworks with Google Cloud.

4.10.2 Heroku

Heroku[11] is a cloud application platform where developers can deploy, manage, and scale inside their system. It offers an application runtime dedicated for server-side configuration, orchestration, load-balancing, failovers, logging, security, among others. The solution provides many utilities for providing a server-side application with stability and security while collecting metrics on application usage by providing monitors of throughput, response time, memory, and others.

Data is also stored in Heroku by using its Heroku Data service. The main difference from Google Cloud Storage is that it runs an instance of a Postgres database, which only stores relational string-based data.

Postgres[12] is a relational database that uses Structured Query Language (SQL) to manage its stored data. The database is open-source with more than 30 years of development used in many mission-critical and high-demand use cases (e.g., Uber, Netflix, and others), making it one of the most reliable, robust, and optimal choices for relational data

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[10] Google Cloud Services

[11] Heroku Services

[12] Postgres Website

storage.

4.10.3 Vercel

Vercel[13] is a platform for providing cloud applications. Although its goal is similar to Heroku's, its service is focused on deploying React applications fast without losing performance. It supports developers "with a single platform for HTTPS-enabled, CDN-backed, production-grade sites, React developers can prototype, launch, and iterate faster than ever before."

Every deployment in Vercel is automatically cached across a Content Delivery Network (CDN) that allocates the front-end data to more than 29 countries, allowing websites to be accessed as fast as possible. Vercel cloud provider is also free, and most of its solutions are open-source.

4.11 Mobile Device

A Samsung Galaxy Tab A6 was used to run the mobile software. The tablet is configured with an Octa-core 1.6GHz Cortex-A53 processor, 2GB of RAM, 16GB of internal memory, 7300mAh battery, 802.11 b/g/n WiFi card, and a 10-inch screen. This device model offers a ARM Mali-T830 MP2 dedicated GPU chip featuring two clusters and supports OpenGL ES 3.2, OpenCL 1.2 and DirectX 11 (FL 9_3). The tablet is used in combination with a vertical stand that holds the tablet horizontally to facilitate its use.

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[13] Vercel Services

Chapter 5

Architecture, Development, and Implementation

This chapter presents the application architecture, development, and implementation stages. First, Section 5.1 describe the planning stages for the software. Next, Section 5.2 shows how the software were developed. Finally, the creation of the digital manuals is detailed explaining each steps needed in order to maintain a new manual (Section 5.3).

5.1 Software Engineering

Plan the software solution was the first step during this work development. To engineer software is needed to improve the understand of the issue the system aims to solve, ensuring the proposed solution corrects the problem. This project began by visiting the industrial facility to understand better how we can improve and the key personnel behind those processes. There the test bench and the quality control process were presented, enabling the elaboration of possible solutions. After many interactions with the stakeholders, the software requirements, use cases, and prototypes were created.

5.1.1 Requirements

Requirements are descriptions of features and functionalities that the software should provide in order to work as expected by the customer. The requirements assist in mapping the stakeholders' needs and guide the software implementation towards those needs. Requirements (Table 5.1) were gathered during visits to the plant and meetings with stakeholders to validate their necessities.

Separating the application features in Functional Requirements (FR) and Non-Functional Requirements (NFR) improves the visualization of the separation between business-oriented and system-oriented features. The separation improves the development experience by offering a clear view when selecting the technologies for the development. For example, the NFR06 (Table 5.1) presents the software need to be reliable, only achieved by test. Using this information, the developer may conclude that select a technology that is well integrated with a test framework is a priority.

Identification	Requirement
FR01	Identify operators' during the inspection process (Mobile)
FR02	Manage operators access (Server)
FR03	Create new manuals and manage available ones (Web)
FR04	Find a specific manual fast on changing a test bench (Mobile)
FR05	List available components and their test benches (Mobile)
FR06	List instructions for a specific inspection (Mobile)
FR07	Allow operator to perform a complete inspection (geometrical and visual) or a visual inspection (Mobile)
FR08	Allow operator to take pictures of visible damages on rejected instructions (Mobile)
FR09	Display images and 3D animations representing the test bench usage for the geometric instructions (Mobile)
FR10	Show conformity, frequency, and other details on each instruction (Mobile)
NFR01	The system should registry the inspection time and accountability
NFR02	The system should run in a low-end tablet
NFR03	The system should provide a friendly user interface
NFR04	The system should be fast to use (not creating bottlenecks in the process)
NFR05	The system should be reliable
NFR06	The system should be provided by a third-party infrastructure

Table 5.1: Functional and Non-Function Requirements.

5.1.2 Use Cases and Classes

The use case technique allows the gathering, modeling, and representation of system requirements. Each use case is a collection of operations that the system should perform on actors' interaction. In this work, use cases represent software systems-related specifications. The goal is to show a more abstract structure of the business logic, enabling a more global visualization of the system domains and their relationships (Figure 5.1).

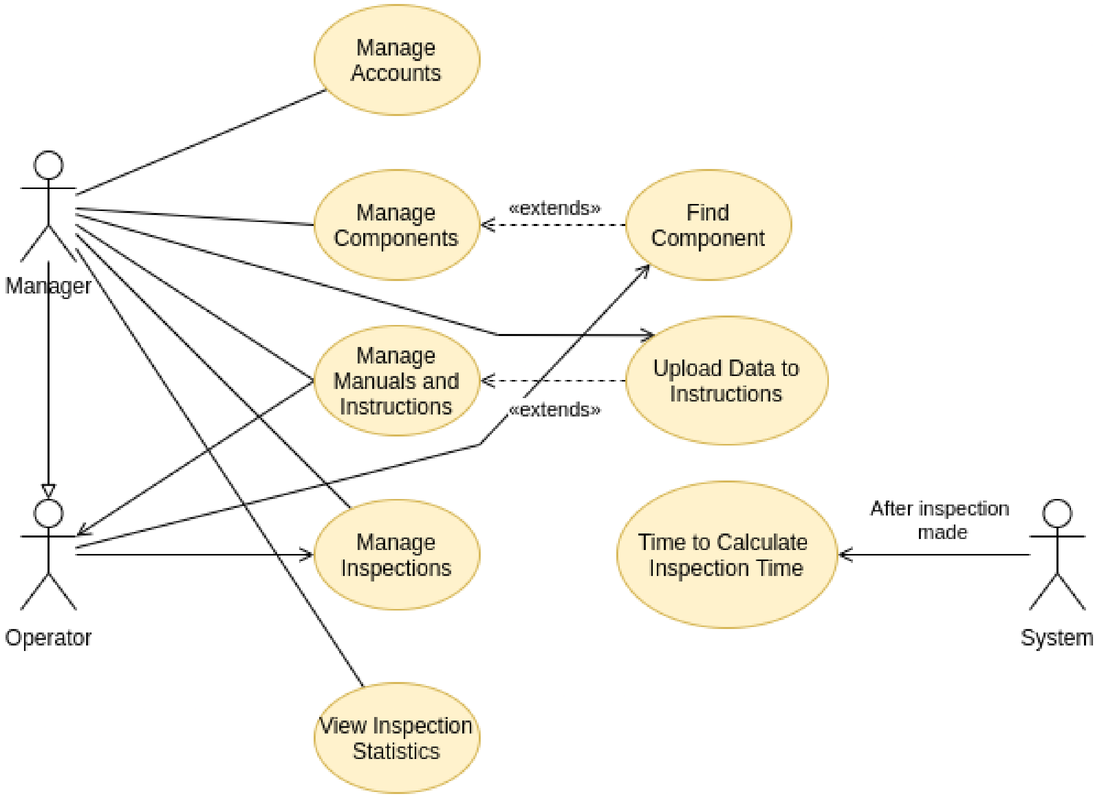


Figure 5.1: Use case diagram showing the relation between actors and use cases.

Identification	Use Cases
UC01	Manage accounts
UC02	Manage components
UC03	Find component
UC04	Manage manuals and instructions
UC05	Upload data to instructions
UC06	Manage inspections
UC07	Time to calculate Inspection time
UC08	View inspection statistics

Table 5.2: List of use cases with identification

The obtained use cases (Table 5.2) give a general view of the problem, but first they need to be further described as shown in the following list:

- **UC01**. The managers should create, read, modify, and delete accounts and their permissions of access;

- **UC02**. The manager should be able to create, read, modify, and delete entries for each component;
- **UC03**. Operators should be able to find component and their manuals by scanning a QRCODE present in each test bench;
- **UC04**. Managers should create, read, modify, and delete manuals and instructions for each component. The operator should be able to read these entries;
- **UC05**. Managers should upload data, e.g., images (png, jpg) or 3D files (glb), to each instruction and the component thumbnail;
- **UC06**. The managers should be able to create and read inspections. The operators can create inspections;
- **UC07**. The system calculates the average time of the inspection (total and for each instruction) when an inspection is made;
- **UC08**. The manager should visualize statistics about the inspections made for each component.

After the use cases were elaborated, a class diagram was created (Figure 5.2) using the use cases as guideline. Class diagrams model object-oriented systems used as a conceptual model of the application's structure and data, improving the system implementation details' visualization.

5.1.3 Prototypes

After the requirements and use cases were completed, the UI mockup was based on those to create a scenario and validated with users by simulation and prototyping. This strategy aims to improve the software cohesion with the stakeholders' expectations by showing more meaningful context to the application usage and structure.

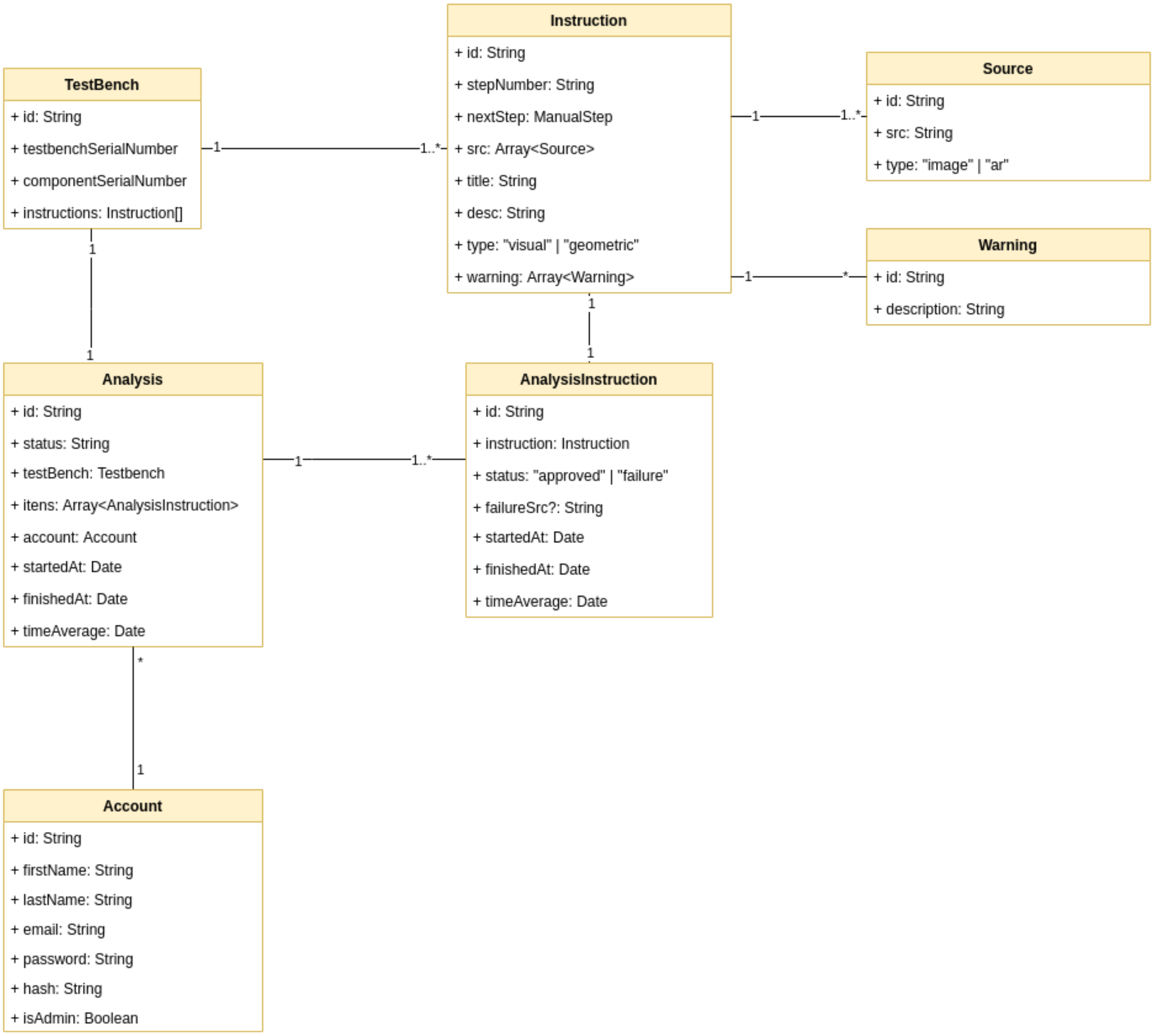
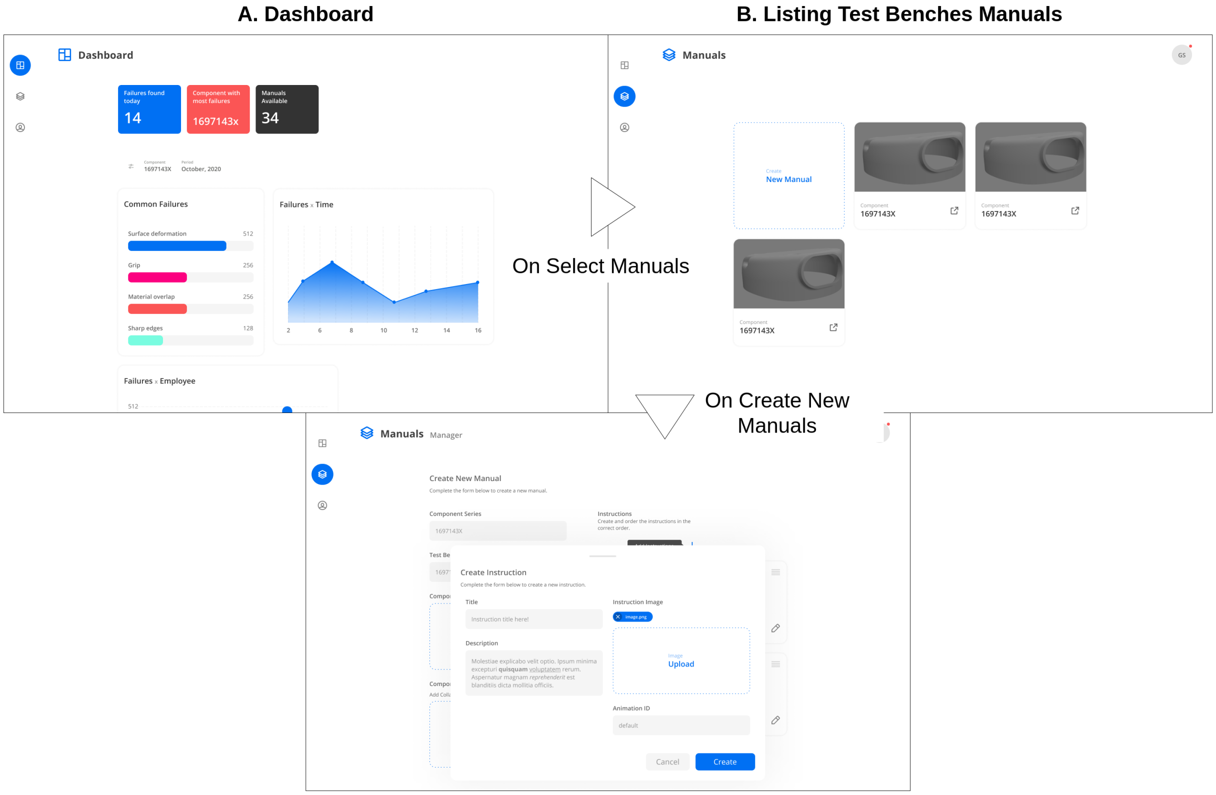


Figure 5.2: Class diagram showing the classes and their relationships to model structures and data for implementation.

The mockups were created using Figma and provided graphical illustrations and mimicked interactions for: The admin application (Figure 5.3), used by the managers to control content and review analysis data; The inspection application (Figure 5.4), used by operators to inspect components and provide analysis results.

The requirements, use cases, and prototypes were presented to the stakeholders to validate the concept, then improved based on their suggestions. With the final concept approved, the application began to be architectured and developed.



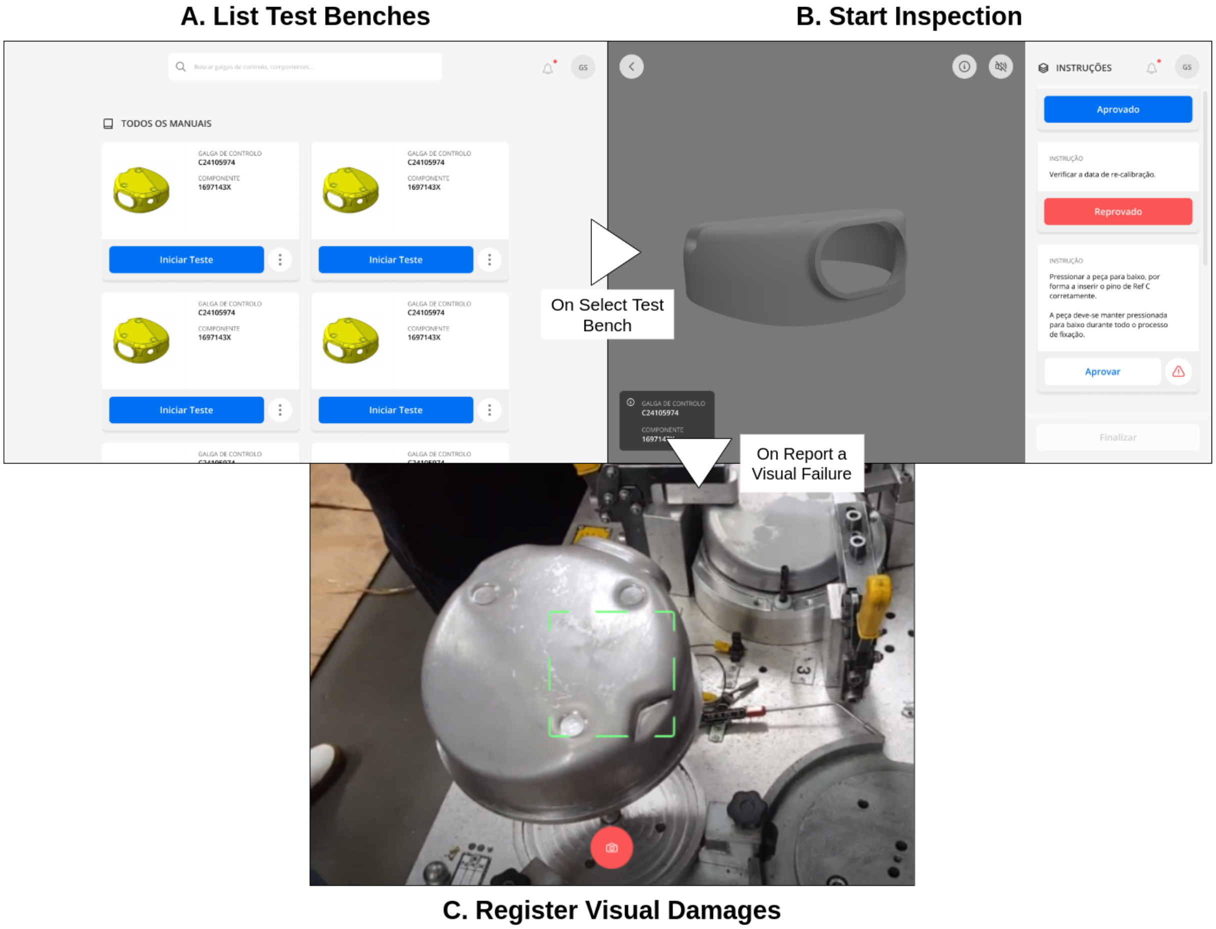
C. Creating Instructions

Figure 5.3: Screens of the admin application prototype. A. The main dashboard, B. Listing test bench manuals, and C. Form used to create the manuals' instruction.

5.1.4 Architecture

With a more accurate view of the application needs, the software architecture consisted of separating the software in specific domains, the client-side and the server-side. Where the client-side implemented the web application (Figure 5.5.B) and the mobile application (Figure 5.5.A), and the server-side performed the server application (Figure 5.5.C), which handles storage, security and provides business logic to the client-side. The client-side and server-side communicate through HTTP requests, allowing the connection of any authorized solution, e.g., Mobile Apps, Web Apps, and IoT applications.

By decoupling the client-side application responsibilities from the server-side increases the reusing of the back-end logic for many applications. This separation of responsibilities also improves the client-side, enabling the developer to use more suitable techniques to



GALGA DE CONTROLO C24105974
COMPONENTE 1697143X

INSTRUÇÃO
Verificar a data de re-calibração.

INSTRUÇÃO
Pressionar a peça para baixo, por forma a inserir o pino de Ref C corretamente.

A peça deve-se manter pressionada para baixo durante todo o processo de fixação.

Figure 5.4: Inspection application prototype. The screens represent an inspection process. A. Main screen listing available test benches, B. Inspection process, and C. Registering visual damage.

provide the user with a better experience. One example of the technique applied to the client-side specific solutions was the stale while revalidate pattern (HTTP RFC 5861). This improves the server-side response time and automatically presents data in almost "real-time" by caching and revalidating it as the user interacts with the page. Another advantage of this patter is that the application now consumes the cache, decreasing to only one request made to the back-end, thus consuming less connection bandwidth.

The proposed solution relies on cloud services to deploy applications and store data. Many companies do not have IT personnel or infrastructure to support data security, high-quality storage, and information distribution. Thus the need for third-party computing

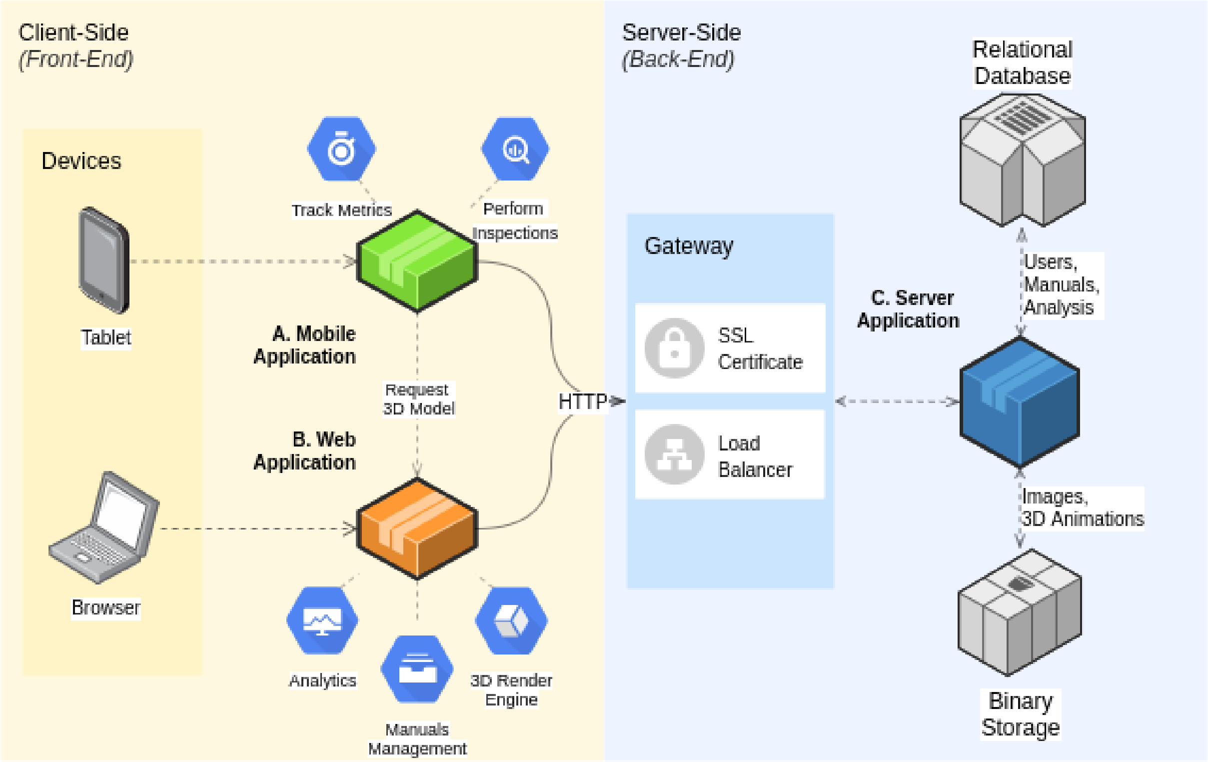


Figure 5.5: Software architecture created during this state.

infrastructure (e.g., Amazon AWS, Heroku, Google Cloud, Microsoft Azure) exists to distribute and manage application security, scale, storage, monitoring, among others. In the designed solution, the cloud system handles:

- Deployment automation;
- Testing pipelines automation;
- Security with Transport Layer Security (TLS) to cryptograph the communication between the client and server, which prevents attacks that aim to store information in the payload of transport operations (i.e., Man in the Middle threats);
- Storage relational data related to the inspection procedures and achieved results, test benches, and user accounts. This provides efficient storage with data recovery and security;

- Storage of binary data related to images and 3D models binary provides a high-quality connection with end-to-end compression of binary files.

The separation of databases to store relational and binary data is needed for each case, with the relational text database handling data for SQL queries from the server and the binary database (file storage) facilitating the access by the client-side system.

5.2 Software Development

The proposed architecture previously described was implemented in three main applications: Server, Web, and Mobile. Each of these software works together through the network to provide the required functionalities and support a reliable inspection process.

5.2.1 Server-Side

The server-side is responsible for handling the computational power, business logic, and persistence logic. These core components are available in cloud services and use the server as its brain to orchestrate the use of these features according to the demand.

Server

The server application was developed using Typescript, NodeJS, and ExpressJS, to create an HTTP server where end-points are structured as a RESTful API. That means the server provides HTTP routes that can interact with HTTP methods (e.g., POST, GET, PUT, DELETE). For example, to create an account, the system could request a "/accounts" route with a "POST" method to execute the account creation with the request payload information. This pattern allows creating a more semantic back-end, thus facilitating the client integration with the API.

The server application functionalities consist of persisting, processing, and transforming data from the client-side while transporting this data to other cloud instances (i.e., database). The business logic presented in the requirements and use cases is implemented in the server. This is because servers are more reliable and secure in handling data, providing this to consumers while abstracting implementation and logic details. For example, if an IoT would rely on data stored by this application instead of implementing connections to the same database, it would be simple to integrate with the API and decentralize the IoT-specific functionalities. The same work for a web and mobile application will focus on the user interaction and content presentation than business logic and implementation details.

Binary Storage

By implementing dependency injection and base itself on CLEAN architecture, the server was able to keep infrastructure logic separated from the business logic. A good practice that allows the system to be agnostic on which data provide its use. In the final implementation, the application was deployed to work with Google Cloud Storage due to their simple integration, benefits for research works, and transparency on service usage. The application also implemented integration with Azure Blob Storage.

Binary storage's primary usage is to store binary data, like 3D files and images. The Google Cloud Storage provided a georedundant server, compression algorithms, which increases the download/upload speeds during file transfer. In this work, render 3D files on a tablet is a crucial part. Problems that may occur on this data transmission may directly impact the UX during usage.

Relational Database

The application uses TypeORM to communicate with the database, like the binary storage, the database was decoupled from the application and considered an infrastructure layer that should be interchangeable whenever needed. This is only possible using dependency injection and Object Relational Mapper (ORM) to interact with the database as a repository interface and define its structure using migration (i.e., a database versioning system that transforms the database and its data to conform with the application models). In this application, Postgres was used by been a reliable, accessible, and open-source solution with cloud instances freely available for integration (i.e., Heroku Data). The application also provides out-of-the-box integration with MySQL, MariaDB, Postgres, CockroachDB, SQLite, Microsoft SQL Server, Oracle, and SAP Hana.

The principal usage for the relational database is to store relational data, represented by Figure 5.2. The database relates information of accounts, test benches, analysis, and sources related to the inspection. This data presents a relational structure; for example, analysis relates to accounts foreign key to identifying who performs the inspection. Also, the analysis is related to the test bench and component in which the inspection was performed to enable tracking of failures on each component.

5.2.2 Client-Side

In a distributed system, the client-side is the part of the software which is present in the user device, i.e., a browser displaying web content or a mobile application. In this work, the client-side web and mobile apps present the data and both can render 3D animations.

Web

The web application was developed using the ReactJS framework to create a Single-Page Application (SPA). To handle HTTP requests and responses, Axios was used with SWR to provide a cache invalidation strategy on HTTP GET responses. This approach allows the application to automatically request new data, ensuring the request is only sent once. Its response is shared globally without needing a global state manager to handle API data. To style the application, Styled Components was used to create JSX components with style contain in them. This technology with atomic design allowed the application to be structured, separating logic from presentation and reusing it as React Native components with little effort.

The web app is mainly responsible for providing quality control management with an intuitive UI that allows management of inspection manuals, visualization of results, and statistics. This empowers the personnel by offering a reliable and friendly tool where information can be available more quickly. For example, a newly created manual will be ready simultaneously for the operator to start its usage, not needing to assign the instructions to a test bench manually.

3D Render Engine

The 3D render engine was implemented with ThreeJS, React, and react-three-fiber. Although the render engine is decoupled, it was deployed with the web application instance, available through the "/render" route. The render engine works with WebGL and can be accessible by any browser or web view to show its content. An HTTP request should be sent to the render route with the folder and file path present in the URL to use the engine. The application will look for the specified path in the binary database, request the GLTF file, and render it on the client side.

The 3D render engine is accountable for rendering the 3D animations and handling user interactions. It allows users to use an orbital control tool to move around the animation object pivot, using one finger swipe gesture. It also enables two fingers scissors gesture to zoom on the 3D animation to improve the details' visibility.

Mobile

The mobile application is one of the central pieces of this work. Its primary objective is to guide operators through their tasks using images and 3D animations to improve their work. Another essential part of this system is to collect data on the whole inspection process, for example, the start and end time of each task, the status of the inspection, photos of visible damages, user accountability, among others. These data points are then sent through an HTTP request to the back-end to store and process it.

The mobile application is implemented with React Native to create a mobile application running on Android and IOS (although Android was the target during the development). Axios and SWR are also used to control HTTP calls and caching strategy to improve the application's network usage. The Styled Component package was also used to inherit components created for the web application, keeping a consistent style throughout the platform.

It also implements a web view component responsible for the 3D animation and interactions. It requests the web application on the render route with the instruction-specific file path. This implementation improved performance by using ThreeJS and WebGL.

5.2.3 Test

End-to-End (E2E) tests were done in the back-end to ensure conformity and stability with the requirements. The server application is the operation's brain, so it is logical to focus the tests on it. E2E tests were done on all the available routes and methods. These tests consist of sending an HTTP request to a route and seeing if the response confirmed the test case expected result. The whole data flow (e.g., middlewares, controllers, use cases, services, providers) and integration of the application with other cloud instances are tested using the E2E test.

The mobile applications were connected to Sentry, an online platform that integrates with the mobile application to analyze and aggregates crash, bug, and telemetry reports. These reports provided a broader view of problems that happened in the application, a quantitative analysis of how many problems happen, and to whom those problems happened.

5.2.4 Deployment

For the web and server repositories, the deployment process consisted of separating the branches in one protected master and each feature on a specific branch. In the server application exclusively, at each commit or merge made to any branch, GitHub Actions executed tests and if they passed, it allowed other pipelines to happen. The deployment pipeline happens on margin a feature branch into master. It consisted of integrating GitHub Actions and the cloud services (e.g., Heroku and Vercel) to make available the latest code to the production environment.

For the mobile application, this process was manual and happened by executing the deployment command. Then, Expo would automatically push the latest build to the OTA channel, where the client-installed application receives and updates the application on the go.

5.3 Process Digitization

After the application was fully implemented, the process of digitizing the analog gauge inspection process began by turning process and guides into a digital representation of the method. This process starts by gathering the necessary data from the test bench usage guide and operation control guide. Next, the data is modeled and optimized into 3D animations for each instruction. Finally, all the information is exported into the web application to provide a digital guide to the entire system.

5.3.1 Data Arrangement

Before starting the digitization process, for each test bench, it is needed to obtain the specific instruction manuals so images and pieces of information can be extracted from them. Understanding these manuals at this stage is very important to know how the instruction works to represent them during the animation process. Every test bench also provides a 3D model supplied by the test bench's manufacturer. This data is categorized divided into separated folders labeled with each test bench identification series.

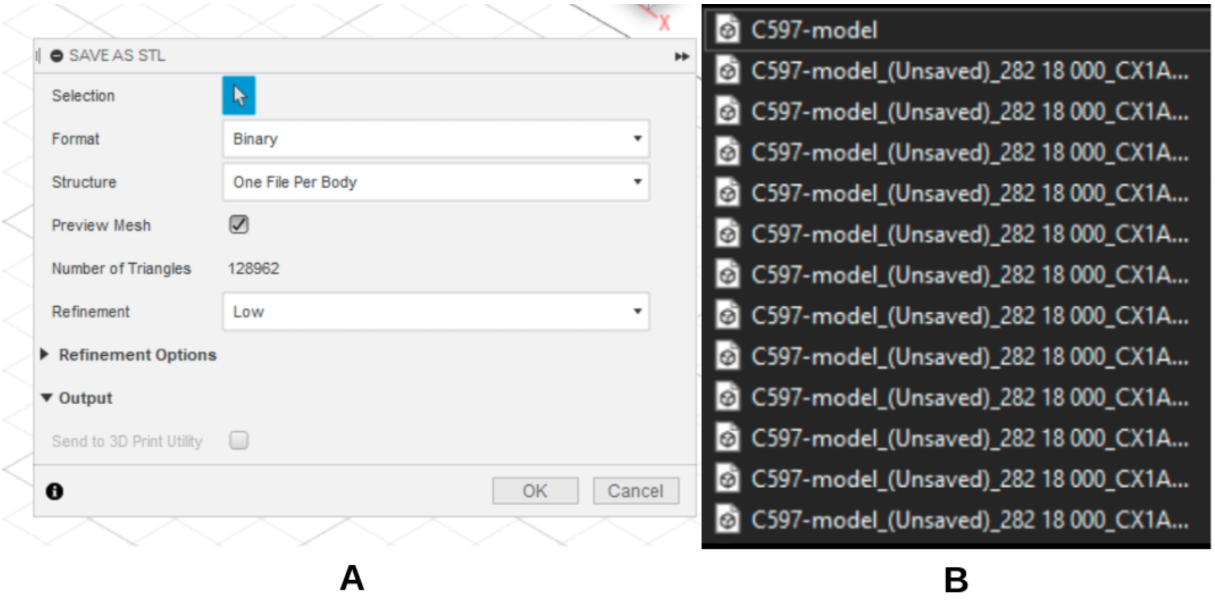
Next, all images present in each manual are extracted into a single image file, identified by the instruction it represents. Images representing test benches usage (Figure 5.6.A) will allow operators to choose between 3D animation or traditional images when executing their tasks. Images representing visible damages (Figure 5.6.B) will only be provided during the visual inspection, a use case that 3D models can not represent accurately.

Figure 5.6: Images illustrating: A. Test bench usage; B. Component damage.

5.3.2 Models

This stage consists of many processes needed in order to obtain 3D models for manual digitization. As a result of this pipeline, reliable 3D animations were obtained and provided to the web app.

Importing


SAVE AS STL

Selection

Format: Binary

Structure: One File Per Body

Preview Mesh ☑

Number of Triangles: 128962

Refinement: Low

Refinement Options

Output

Send to 3D Print Utility ☐

C597-model
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...
C597-model_(Unsaved)_282 18 000_CX1A...

Figure 5.7: A. Fusion 360 STL exporter utility; B. STL files generated by the "One File Per File" option.

Before importing the 3D model into Blender, the test bench 3D model needs to be transformed into a format adequate for Blender. The file provided in STEP format by the manufacturer needs to be converted into STL to be accessible. This conversion also needs to keep the mashes separated to allow a more precise edition of the model. To achieve this, Autodesk's Fusion 360 was used to import the STEP file, and by applying the structure option "One File Per File" (Figure 5.7.A) on the STL exporter, the model was exported in multiple STL files (Figure 5.7.B) for each mash.

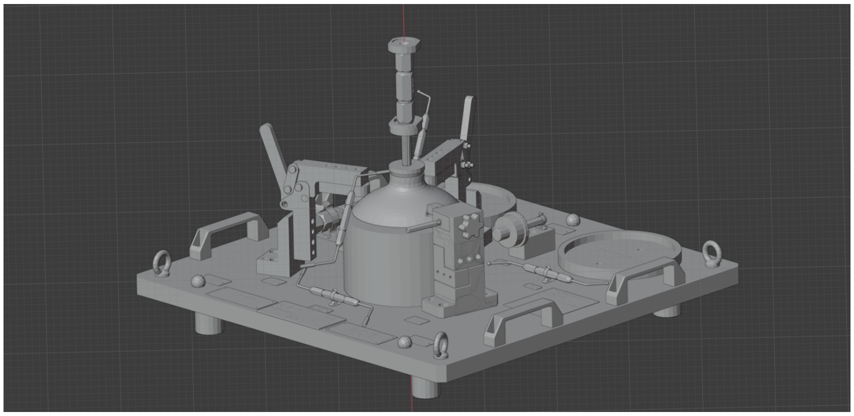


Figure 5.8: Test bench 3D model ready to be used by Blender.

Next, to import the files into Blender, the STL importer available in the files tab was used to import multiple STL files. Those files contain each mash global position and size, allowing them to be grouped into one collection and manipulated altogether without losing the original position and dimensions. The final result (Figure 5.8) has each mash grouped into specific collections representing tools, supports, components, and additional details. Those collections also were labeled according to the item identification defined by the analog manual.

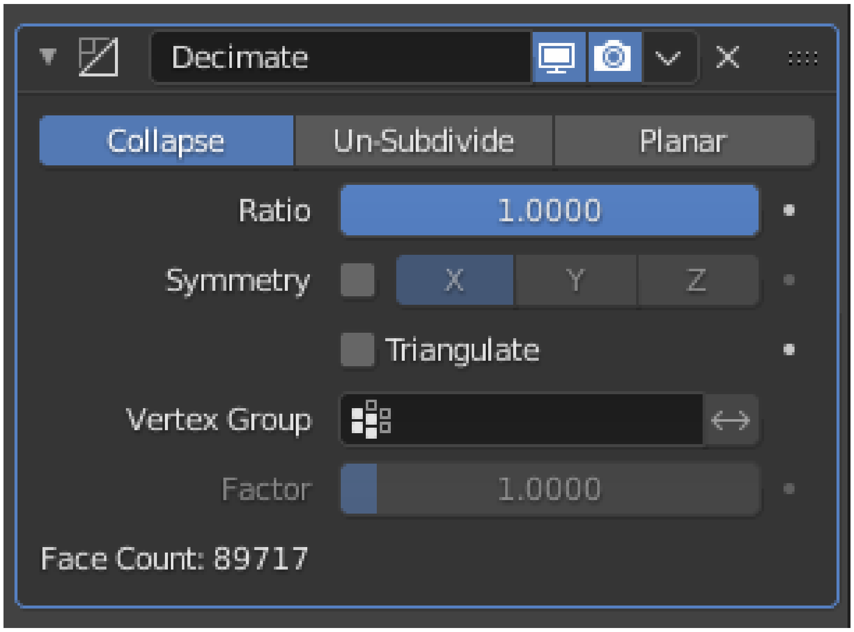
Optimization

Optimization is the process of removing unnecessary vertices and faces in order to decrease the file size and improve loading times. This process directly impacts the performance of the 3D rendering affecting the UX. The model's bad optimization means that the final

GLTF file will be rougher on loading and in low-end devices will run with lower FPS speeds.

Because of the CAD project's nature, the imported model is very detailed with millions of faces that may not be useful to the project. First, all meshes unused by any instruction were removed to lower the number of items presented by the model.

Next, unnecessary complex objects were remodeled with simpler meshes. This behavior is caused by the conversion process and makes simple objects, like cubes, that may only need six faces to have hundreds of faces to represent them. The final model is highly improved by removing the overly complex faces from simple objects without losing fidelity from the original sample.



Ratio 1.0000

Symmetry ☐ X Y Z

☐ Triangulate

Vertex Group

Factor 1.0000

Face Count: 89717

Figure 5.9: Blender's decimate modifies component.

Finally, on complex objects that may demand lots of time to reflector into simpler ones, the "decimate" modifier (Figure 5.9) was applied to reduce the number of faces presented in the mesh. The modifier can reduce a component with 89717 faces (Figure 5.10.A) to only 897 faces (Figure 5.10.B) with a ratio of 0.01%. However, this approach's main counterpoint is that the final quality is also reduced, thus needing to be used with moderation to not decrease the final piece's definition in an unusable state.

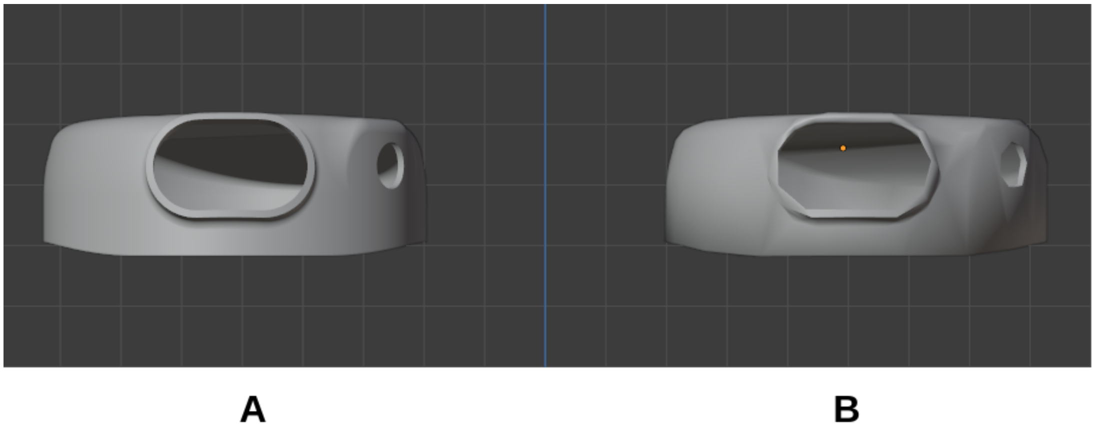


Figure 5.10: Visual comparison between mash before (A) and after (B) the decimate modifier been applied.

Texturing

Knowing that the target format for the file project is a GLTF file, some limitations are needed to be addressed to find a suitable Blender shader to work with the format. GLTF only allows metallic, roughness, specular, glossiness, base color, and texture image shading. Blender's "Principled BSDF" demonstrated reliability in exporting the created material to a GLTF binary. It was used during the texturing process to provide a more realistic look to the model.

During the texturing, the base color was used over the image-based texture to decrease the binary size produced, removing the need to export Base64 images encoded with the GLTF file. This choice was made in order to improve the 3D animation download speeds over the internet connection.

Animation

An animation exists for each instruction. Before starting animating, a copy of the optimized and textured Blender file should be created using the instruction number to identify it. The unnecessary meshes that did not present any context or importance to the instruction's process were removed to improve the file size further.

Animation is an essential part of promoting user-friendly access to inspection process information. To animate the application, the Bender Keyframe component (Figure 5.11) was used to create multiple states of the model's pieces (e.g., a clip open and a clip close) and interpolate those into an animated movement. These states were added until the whole keyframe illustrated the analog inspection process completely.

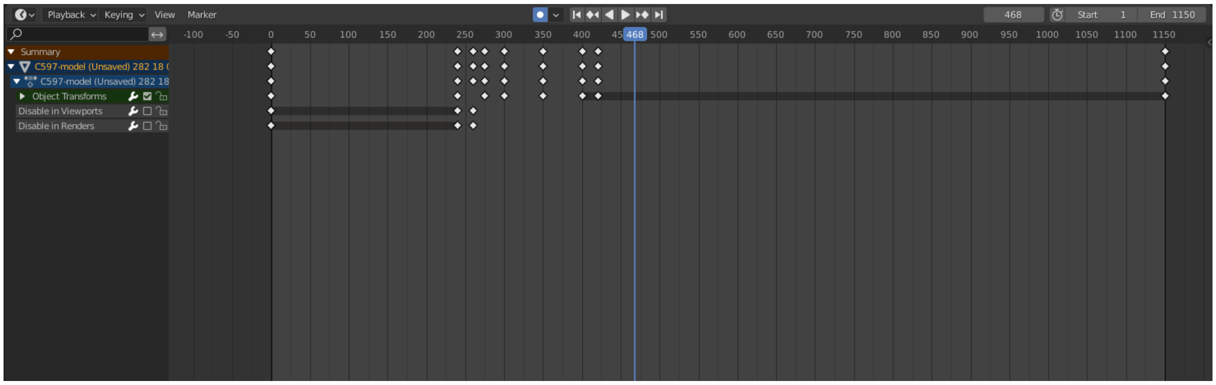


Figure 5.11: Bender's keyframe component

After the animation been completed, it was exported as a GLTF binary, which contained models, shaders, and keyframes ready to be used in a single file. They were limited to only animate meshes when exporting to the format. Finally, the final file was created, and the animation process repeated until all the instructions were done.

5.3.3 Manual Creation

With the guides' data categorized and the models created, the manual can be added to the web application to make it available to the operators. During this stage, the web application was opened in the "/manuals" route, and the "create manual" button was selected. A form was filled with the information regarding the test bench and component.

Next, each instruction is specified in a modal (i.e., floating window) form with the content gathered from the guides, images, and GLTF binary files. On completing the creation, the instructions were arranged in order of execution and then submitted to the server application to handle the file upload and data persistence. Finally, the data is available for the mobile applications to access the newly created test bench manual and ready to register inspection data.

During this chapter, the system was architected to suit the industry needs, then developed to achieve the expected outcome. With all these demanded parts implemented, the application is ready for the users to test. In the next chapter, the solution was introduced in the industrial environment, put to the test with real people, and their experience using the application was gathered.

Chapter 6

Testing and Evaluation

In this chapter, the software was deployed in the factory quality control process and tested with real people. The user experience using the application was collected with the System Usability Scale, and crash reports were collected and analyzed during all the application usage.

6.1 Results

This section describes the results obtained by the application development and usage in an industrial environment. The software was tested in the industrial environment for eight days, from 02/26/2021 to 03/09/2021. During this period, usability and stability data were collected to ensure system confidence. The results are principally positive, presenting an excellent opportunity for this work in improving quality control processes.

6.1.1 Deployment and Testing

To guarantee the application's stability, the server was deployed in a Cloud environment using the master branch as the production-ready source code. The back-end environment was fully accessible by the mobile device via wireless internet. The WiFi was provided by the industrial facility and accessible within all the factory areas.

To identify users, accounts were created for the operators and management personnel, each owning different permission levels to access data. To authenticate the account, the user uses his email and password to log in to the mobile and web system (according to the owned permission). This information allows the system to identify who is making the inspection.

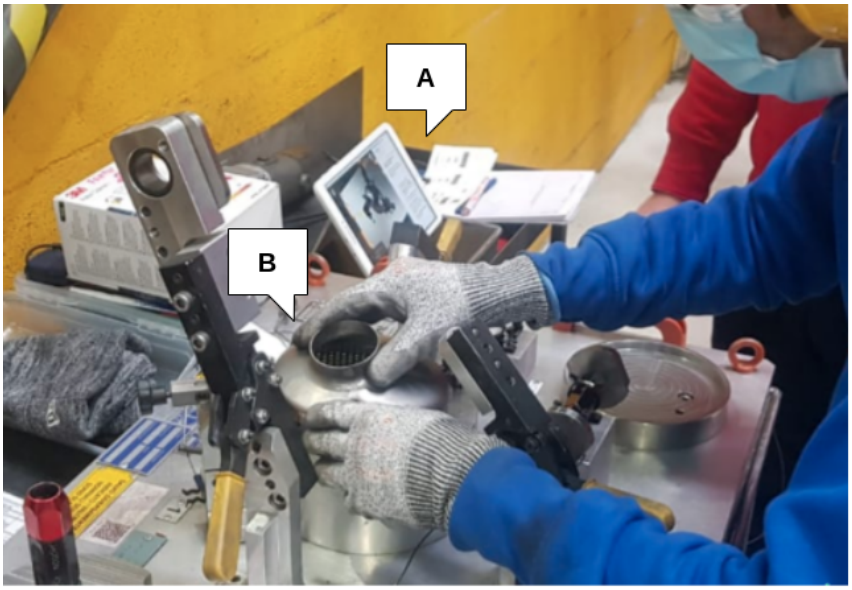
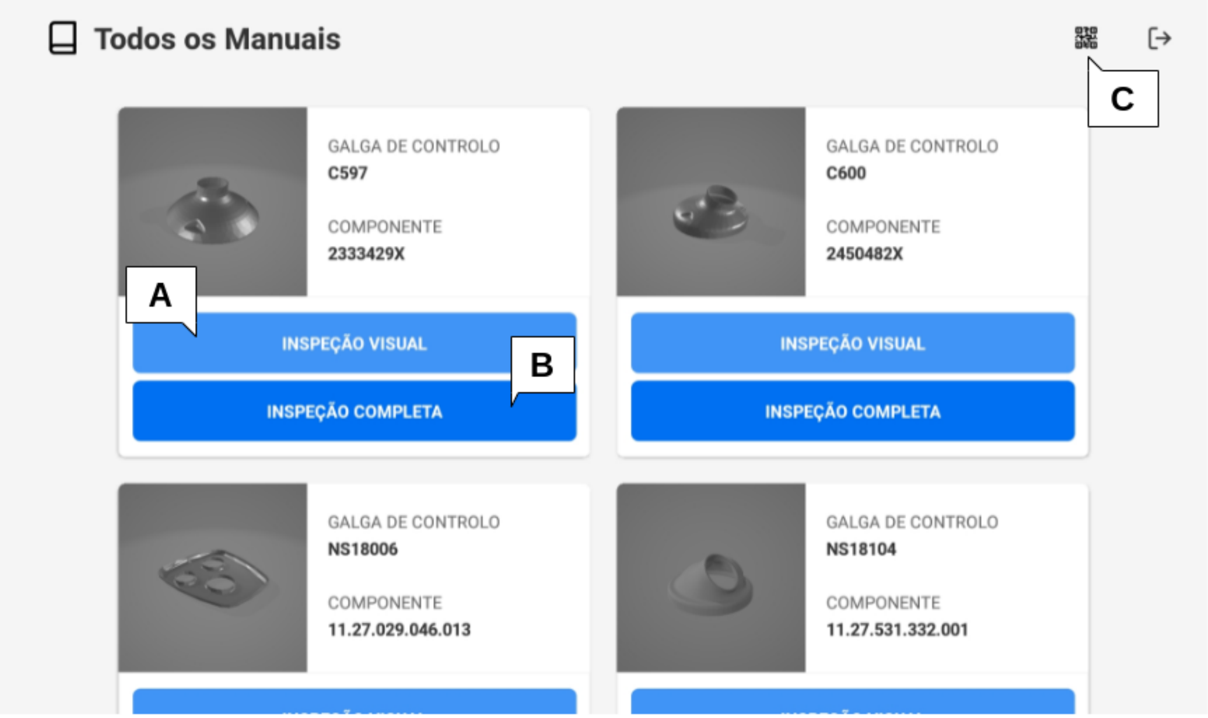


Figure 6.1: Mobile application been used in the production environment: A) The tablet running the mobile application, placed near the operator; B) The operator executing the instructions.

To utilize the software, the tablet device (Samsung Galaxy Tab A6) was positioned in a vertical stand near the test benches (Figure 6.1). This allowed the operator to easily observe and interact with the device without impacting the test bench's usage. Although the stand keeps the device securely in place, it also allows to easily remove the table to scan QR Codes or photograph visible damages.

Before starting the inspection, the operator can select the part model and inspection method (see Figure 6.2.a or 6.2.b) or scan a QR Code present in the test benches by selecting the QR Code button (Figure 6.2.c). This improves the overall user experience and speed of the process by allowing a specific manual to be quickly obtained compared with the analog process, which needs the manuals to be added into a visible place before



Todos os Manuais

GALGA DE CONTROLO
C597
COMPONENTE
2333429X

GALGA DE CONTROLO
C600
COMPONENTE
2450482X

GALGA DE CONTROLO
NS18006
COMPONENTE
11.27.029.046.013

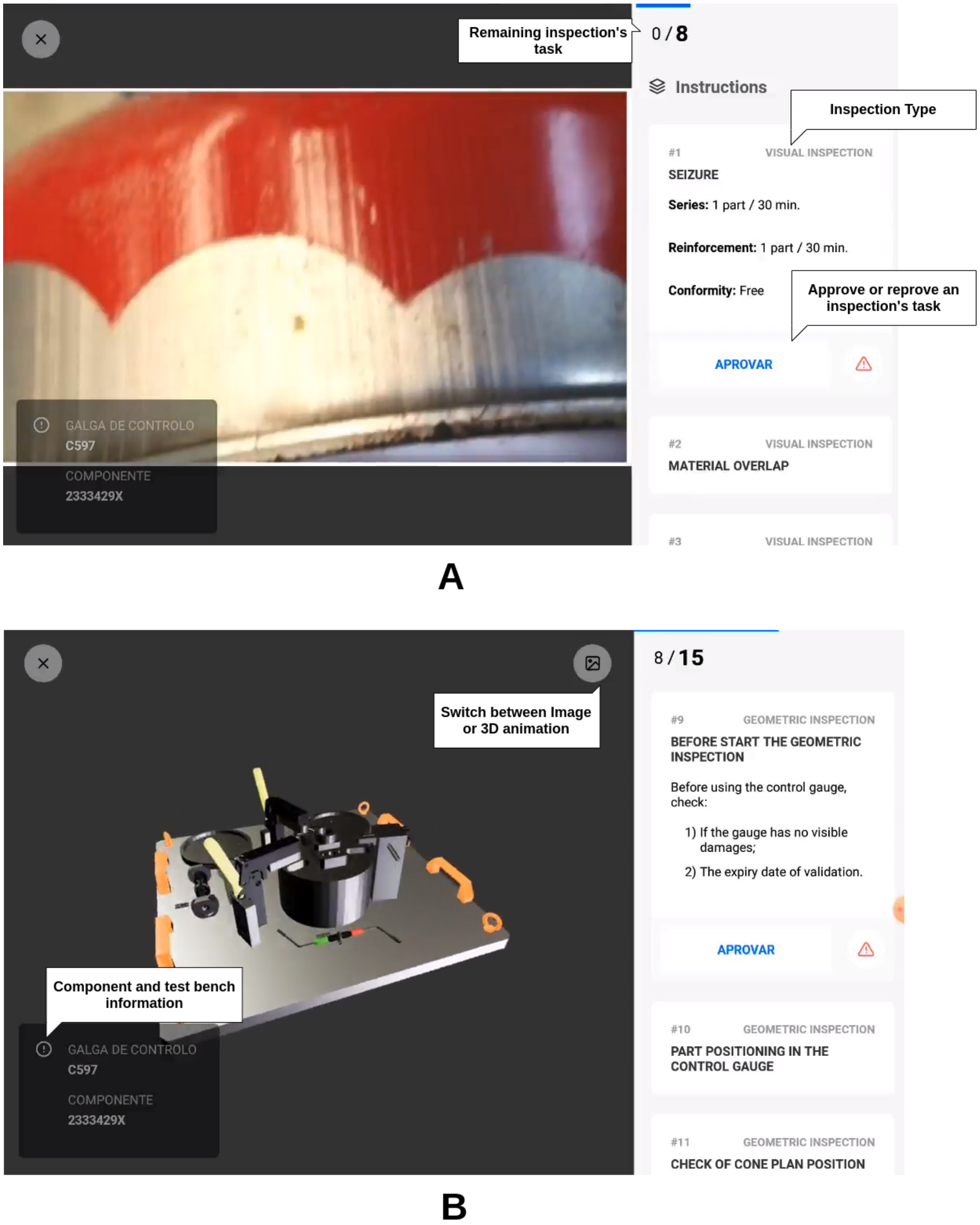
GALGA DE CONTROLO
NS18104
COMPONENTE
11.27.531.332.001

Figure 6.2: List of available test benches and components: A) Execute visual inspection; B) Execute visual and geometric inspection; C) Find the test bench's manual from a QR Code.

the test bench was used.

During the inspection, there are two types of instructions that can be visualized: I) a visual inspection that shows photos of visual unconformities that can be present in the piece (Figure 6.3.a), and II) geometric inspection that guides the operator through the inspection operation and test bench usage (Figure 6.3.b). These different instruction sets allow a faster inspection process I) to be executed with more frequency taking less time, allowing pictures to be registered and stored. A complete inspection task II) with lower frequencies and longer execution times will be carried out using more immersive instruction (offered by the 3D animation) to achieve a more friendly experience.

After the inspection, the server gathered the information provided by each analysis, and statistics were generated and presented to the operators. These statistics are accessible by quality control management to better understand the impact caused by the machines in each component production (e.g., most common failures, components with



0 / 8

#1 VISUAL INSPECTION

SEIZURE

Series: 1 part / 30 min.

Reinforcement: 1 part / 30 min.

Conformity: Free

#2 VISUAL INSPECTION

MATERIAL OVERLAP

#3 VISUAL INSPECTION

GALGA DE CONTROLO
C597

COMPONENTE
2333429X

8 / 15

#9 GEOMETRIC INSPECTION

BEFORE START THE GEOMETRIC INSPECTION

Before using the control gauge, check:

1) If the gauge has no visible damages;

2) The expiry date of validation.

#10 GEOMETRIC INSPECTION

PART POSITIONING IN THE CONTROL GAUGE

#11 GEOMETRIC INSPECTION

CHECK OF CONE PLAN POSITION

GALGA DE CONTROLO
C597

COMPONENTE
2333429X

Figure 6.3: Mobile application inspection screen showing: A) Visual inspection procedures; B) Geometric inspection procedures.

most damages, quantity of inspection per operators). The statistics and each inspection analysis can then be accessed by the web application (Figure 6.4) via the internet.

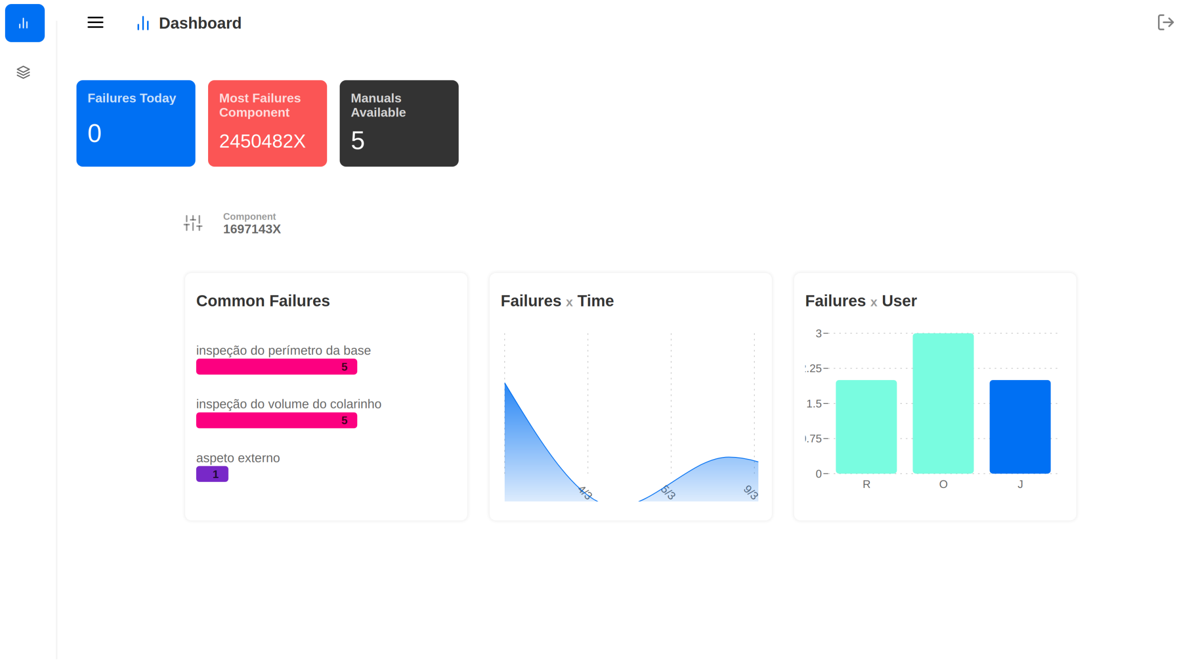


Figure 6.4: Web application home screen showing inspections statistics.

6.1.2 Usability Analysis

During the inspection process, the SUS evaluates the operators' overall experience during the mobile application usage and the general system integration. The survey demonstrates the solution fitness with a score between 0 and 100, and the objective is to show how suitable the solution is from the workers' perspective.

The SUS survey is a digital form that registers the operators' answers anonymously, duration time, and begins/end timestamps, the questions used in the survey were written in Portuguese and are available in Appendix A. At the end of each inspection activity, the survey pops up in the mobile app, requiring the user to answer their experience using the system and stores the data in a CSV file.

To test the application, two groups were created: a control group (I) and an operator group (II). For Group I, five people outside the factory within a varied range of knowledge in technology and no previous experience in quality control procedures were tested and used as the control group. Group II consisted of six people tested while working with the software to help them during factory quality control procedures. All of the six candidates were experienced with the inspection tasks and familiar with the industrial process.

Data Treatment

After one week of the application been used in the industry, the data was exported into Google Sheets and analyzed. The survey received twenty-six (26) responses in total (Table 6.1), with the answers varying from one to five (Likert scale) representing how much the tester agree with the statement. The answer are composed by five (5) from Group I and twenty-one (21) from Group II. The survey's submission timestamp was then compared to the inspection's submission timestamp associating each answer with the accountable email and selecting only the first response in order to solve the data duplicity.

Table 6.1: All survey entries

N.	Statement	Avg.	Var.
1	I think that I would like to use this product frequently.	4.68	0.73
2	I found the product unnecessarily complex.	1.36	0.24
3	I thought the product was easy to use.	4.84	0.14
4	I think that I would need the support of a technical person to be able to use this product.	2.00	0.83
5	I found the various functions in the product were well integrated.	4.56	0.26
6	I thought there was too much inconsistency in this product.	1.68	0.56
7	I imagine that most people would learn to use this product very quickly.	4.64	0.24
8	I found the product very awkward to use.	1.72	1.21
9	I felt very confident using the product.	4.52	1.09
10	I needed to learn a lot of things before I could get going with this product.	1.60	0.50

During the analysis of the Group II data, a discovery was made. Due to the mobile application keeping the user logged in, most operators would forget to sign out after using the software, sharing their accounts with others without knowing. To increase the data reliability, answers that were observed by the authors and the ones that included comments were considered trustworthy. Next, the remaining ones had the survey duration time compared to the control group time range in order to identify invalid answers. In the end, a total of eleven (11) data points were obtained (Table 6.2), five (5) from Group I and six (6) from Group II.

Table 6.2: Survey entries after data treatment

N.	Statement	Avg.	Var.
1	I think that I would like to use this product frequently.	4.36	1.45
2	I found the product unnecessarily complex.	1.27	0.22
3	I thought the product was easy to use.	4.91	0.09
4	I think that I would need the support of a technical person to be able to use this product.	1.64	0.45
5	I found the various functions in the product were well integrated.	4.64	0.25
6	I thought there was too much inconsistency in this product.	1.55	0.47
7	I imagine that most people would learn to use this product very quickly.	4.64	0.25
8	I found the product very awkward to use.	1.55	1.47
9	I felt very confident using the product.	4.09	2.09
10	I needed to learn a lot of things before I could get going with this product.	1.27	0.22

Statement Analysis

After cleaning the data obtained by the survey, individual statements can be analyzed to provide a complete picture of the users' perception while testing the application. To better understand each answers the variation of the responses (Table 6.2) and the variation per answers between groups (Figure 6.5) was used.

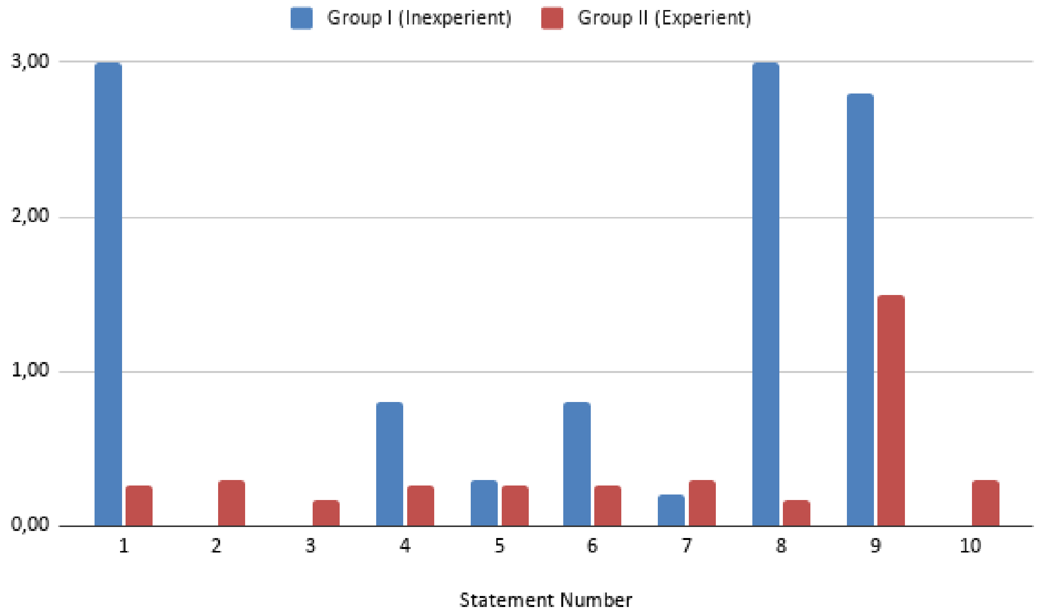


Figure 6.5: Results obtained comparing the response variation per group Group I inexperienced and Group II experienced.

The statements' answers were the score variation were beneath 1.00 was considered uniform across the groups indicating that most of the entries agree with the score obtained.

With variations above 1.00, a deeper analysis needs to be carried:

- **I think that I would like to use this product frequently.** The statement 1 answer was one of the higher variations (1.45), but when compared the variation between Group I (3.00) and Group II (0.73) answers the opinion of experienced operator is alike, strongly agreeing with the statement. While inexperienced subjects did not fully agree, which can be explained by they not having the full picture of the inspection process.
- **I found the product very awkward to use.** The statement results had a variation of 1.47, with Group I varying 3.00 and Group II 0.17. This difference between groups may also be related to the inexperience with the process, with some users from Group I reporting that they did not fully understood some of the processes the application was presenting.
- **I felt very confident using the product.** The statement results had a variation of 2.09, with Group I varying 2.80 and Group II 1,50. Both groups vary their answers a lot, some hypothesis can be discussed for this results. No previous training and minimal instructions were needed in order to obtain a raw experience of users interacting with the software, this may show that the software lacks helpers and tutorials to guide new users on using the app, helping they better understand the environment. The friction from moving from paper to tablet technology may also be a factor for this variation, when looking towards Group II.

By analyzing each statement and the variance of their responses a wider view of users type can be observed. Some aspects of the application related to the initial knowledge needed by the users to effective use the system. Previous training and a application tour for first time users, explaining application features and usage, could improve both inexperienced and experienced workers on handling the software.

The results also presented a uniform acceptance when stated its ease to use. Most users agreed that they would not need external help and would be easy to start working with the application. This positive results show that although improvements may be needed the user experience observed during test was consistent, simple, and accurate. Adding value to the inspection process by reducing the perceived knowledge gap and start time for new operator to use the system.

Score Analysis

The final score was calculated using the average value of each answer and then used to compute the SUS score following the algorithm:

- The values of odd-numbered questions were subtracted by one;
- The values of even-numbered questions were multiplied by minus one and then added by five;
- All the values were added and multiplied by 2.5, producing a value between 0 and 100 describing the system's final score.

First, the SUS score was calculated for the data before (Table 6.1), obtaining 87.20 points. Then, the data obtained by the treatment process (Table 6.2) was calculated and achieved an 88.40 score on the SUS survey. Finally, the SUS scores before and after the data treatment were compared, showing a standard deviation of 0.86, with Table 6.3 representing the deviation per answer.

Table 6.3: Standard deviation per statement before and after data treatment

N.	Avg. Before Treatment	Avg. After Treatment	σ
1	4.68	4.36	0.2263
2	1.36	1.27	0.0636
3	4.84	4.91	0.0495
4	2.00	1.64	0.2546
5	4.56	4.64	0.0566
6	1.68	1.55	0.0919
7	4.64	4.64	0.0000
8	1.72	1.55	0.1202
9	4.52	4.09	0.3041
10	1.60	1.27	0.2333

In the SUS scale, results classified above 70 are good products, with better products been over 80, and genuinely superior ones above 90 [52]. Considering the final score of

88.40, the developed software was perceived by the users as a product with very good usability. These results show that the users acknowledge that the software solution is simple to use, implements its functionalities well, and adds value during the execution of their inspection tasks. Also, the statement score that described the application as *"easy to use"* and *"easy to learn"* increased when presented to inexperienced users (Figure 6.6). This result may indicate that the application presents a possibility for increasing the learnability of newly inserted workers into the quality inspection task.

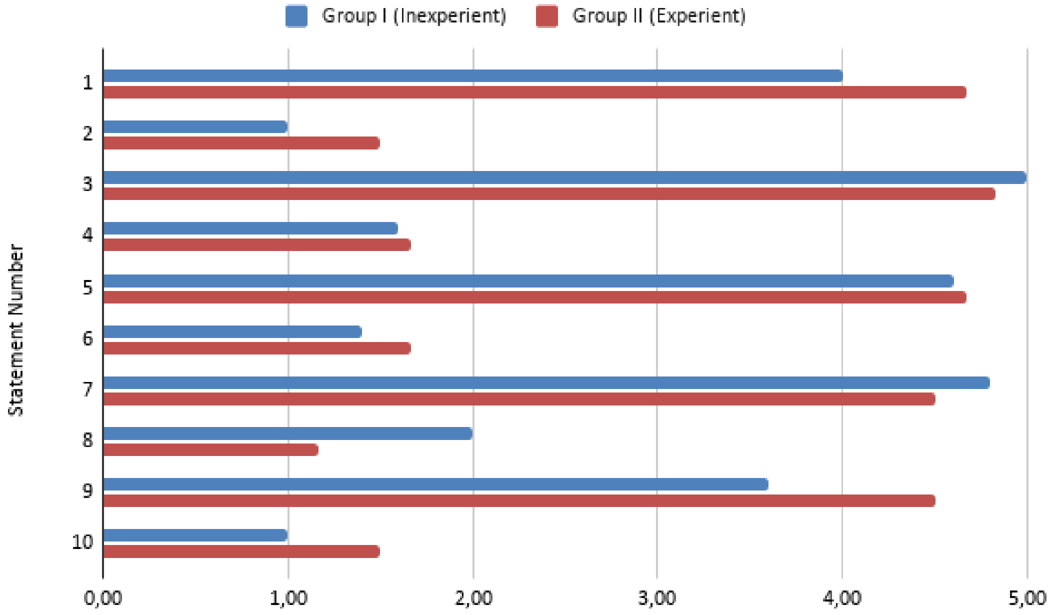


Figure 6.6: Results obtained comparing the average response from users inexperienced (Group I) and experienced (Group II).

Feedback from the company corroborates the results by showing the positive aspect of the system, reviewing the application as *"a great added value"* for the components inspection operation, being very well perceived by the quality control management and operators performing the tasks.

6.1.3 Stability Analysis

The developed system is a mission-critical system that needs to be reliable to not affect the industry quality control operations. To ensure the software stability, unit and e2e tests were written to ensure the system is stable in given conditions. During the application usage (02/26/2021 to 03/09/2021), metrics were collected to monitor unexpected errors and systems misbehaviors during the test in the production environment.

Sentry[1] was used to track the application's exceptions during the production use, registering the failures in a cloud service with errors description, location, the user affected, and interactions before the exception being raised. The error collection automatically sends through the network the error information alerting if any unexpected behavior occurs. After third-eight inspections made by the operators in a period of eight days, no errors were detected by the platform, and no failures in the software were reported by the users when asked.

The positive result on application stability shows that the application contributes with a solid foundation and offers opportunities for its usage in the production environment by being previously experimented with no errors in real-world test conditions.

6.2 Discussions

During tests in the production environment, one problem noticed was that users would forget to sign out after completing their work shift in the quality control inspection. Although the authentication problem could be solved by instructing operators on how to handle their accounts, perhaps it would be more reliable to automatically log out users after completing the inspection task, excluding the possibility of sharing accounts. To reduce the friction on starting the inspection tasks caused by the access depending on filling email and password, occurring on every new analysis. A RFC tags, Bar Code or QR Code could be attached to the worker's badge and required to be scanned to log in, quickly identifying the accountable without consuming much time to begin the inspection.

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[1] Sentry Web Site

Another flaw discovery made when analyzing the inspection times extracted from the database was that operators forgot to confirm the inspection reflecting on unreal analysis times, the time representing the beginning to the end of the complete inspection task, with most occurrences being on the last shift of the week (Friday). One inspection time had 260408989 milliseconds of duration (more than 72 hours), resulting in an inaccurate inspection time being register in the database. This issue only affects the general inspection time, with the particular time per task still reliable and not affected. To solve this issue, the general time calculation could be done by the sum of all the tasks' time registering it without depending on the user action to select the finish button.

Although flaws were encountered showing the system needs for improvement, one vital aspect for every industrial-grade software is training. Most of the defects found occurred from human errors caused by their inexperience while using the software and could be avoided with basic training prior to the software usage. Even when having software with superb usability, operators should be trained on how to operate the solution and be supported to guarantee the correct use of the system. The HMI works not as a replacement but as a companion to the usage instructions, working together by conducting the user through their tasks and aiding when technical knowledge gaps appear.

Furthermore, the overall benefits of the application were not harmed on the objective of digitizing the quality control inspection process. The application is still reliable in reporting inspection failures and times. Although the general time of the inspection is inaccurate, the times related to individual inspection tasks were always accurate. The data provided by the application is still being delivered to the management immediately in digital media. The application remains well perceived by experienced and inexperienced users as a "simple to use tool".

Chapter 7

Conclusion and Future Work

Quality control is a vital part of factories' production processes. Using inspection methods (visual and geometric) to verify the correctness of produced parts is an established practice in the sector. This work analyzed an industry that applied gauge inspection tools utilizing papers for manuals to guide operators through the inspection steps and paper spreadsheets to register the results of these inspection tasks. While cheap, this practice may not be adequate by creating misleading results to the quality control management while limiting the support provided to operators during the inspection. These problems open space for cost-effective technological solutions that can remove the reliability issues while using the operators in a HiL inspection process.

To solve the issues, this work developed a digital personnel assistant that supports the industry by offering guidance to operators during the execution of the inspection process. While in the background, the application collects data related to the performed tasks using the information to create a database of common visual damages and notifying the management with relevant statistics used by the quality control to identify production issues. The developed application supports a non-immersive VR with a Desktop VR experience using tablets. It allows users to visualize and interact with 3D scenes while performing real-world actions without supporting sensory output.

The final version of the solution was integrated into an industrial factory using cloud computing technologies to supply the plant with adequate infrastructure for the application. The software was tested in the production pipeline to ensure its stability and verify the workers' perception while handling the system. The results extracted from the testing stage were very positive, with no system failures happening during the test period and the overall user experience while using the system been considerably positive. It was also well noticed by industry leaders and quality control management been reviewed as *"a great added value"* for the components inspection operation.

The proposed software approaches contribute to time optimization created by removing unnecessary tasks related to the data collection and manual positioning with more automated ones are essential for factories looking forward to implementing digital transformation in the long term. The collected data can give more insights into migrating to an Industry 4.0 paradigm while being cost-effective in its implementation, only relying on tablet devices, cloud infrastructure, and internet access points.

Reviewing the work's objectives, the initial goal of developing a mobile and web application that empower operators with tools that improve the confiability of quality control inspection and enables their managers with means to visualize the performance of the inspection the process was succeeded. The developed systems was successfully applied into an industrial environment and was perceived by the industry staff as a advantage brought to the process. With all objectives completed a stable solution was surely created and embedded into the industry quality control process without changing drastically the process current been used by the industry with lower costs. Nevertheless, the system solved quality control bottlenecks mainly related with the use of paper to share information in a factory that moves itself towards a digital transformation, effectively achieving the proposed goals. Also, this work contributes with an article published in ISIE (International Symposium on Industrial Electronics). The symposium unites industry experts, researchers, and academics to share impressions and expertise surrounding new technologies associated with industrial electronics.

Future work will be dedicated to applying computer vision algorithms and artificial intelligence to help operators verify the correctness of visual and geometrical inspection.

Also, improvements could be made to ensure a more intelligent work set up using modern identification technologies to detect operators during their tasks. A long-term analysis of the system use at the industrial facility could also be carried out to identify if significant impact was made to production quality and speed.

Bibliography

[1] L. D. Xu, E. L. Xu, and L. Li, “Industry 4.0: State of the art and future trends,” *International Journal of Production Research*, vol. 56, no. 8, pp. 2941–2962, Mar. 2018. DOI: `10.1080/00207543.2018.1444806`. [Online]. Available: `https://doi.org/10.1080/00207543.2018.1444806`.

[2] J. Egger and T. Masood, “Augmented reality in support of intelligent manufacturing – a systematic literature review,” *Computers & Industrial Engineering*, vol. 140, p. 106 195, Feb. 2020. DOI: `10.1016/j.cie.2019.106195`. [Online]. Available: `https://doi.org/10.1016/j.cie.2019.106195`.

[3] L. Da Xu, W. He, and S. Li, “Internet of things in industries: A survey,” *IEEE Transactions on industrial informatics*, vol. 10, no. 4, pp. 2233–2243, 2014.

[4] A. Belhadi, K. Zkik, A. Cherrafi, S. M. Yusof, and S. E. fezazi, “Understanding big data analytics for manufacturing processes: Insights from literature review and multiple case studies,” *Computers & Industrial Engineering*, vol. 137, p. 106 099, Nov. 2019. DOI: `10.1016/j.cie.2019.106099`. [Online]. Available: `https://doi.org/10.1016/j.cie.2019.106099`.

[5] Y. Zhang, G. Zhang, Y. Liu, and D. Hu, “Research on services encapsulation and virtualization access model of machine for cloud manufacturing,” *Journal of Intelligent Manufacturing*, vol. 28, no. 5, pp. 1109–1123, Mar. 2015. DOI: `10.1007/s10845-015-1064-2`. [Online]. Available: `https://doi.org/10.1007/s10845-015-1064-2`.

[6] T. Masood and J. Egger, “Adopting augmented reality in the age of industrial digitalisation,” *Computers in Industry*, vol. 115, p. 103 112, Feb. 2020. DOI: `10.1016/j.compind.2019.07.002`. [Online]. Available: `https://doi.org/10.1016/j.compind.2019.07.002`.

[7] D. Costa, F. Pires, N. Rodrigues, J. Barbosa, G. Igrejas, and P. Leitao, “Empowering humans in a cyber-physical production system: Human-in-the-loop perspective,” in *2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS)*, IEEE, May 2019. DOI: `10.1109/icphys.2019.8780138`. [Online]. Available: `https://doi.org/10.1109/icphys.2019.8780138`.

[8] D. S. Nunes, P. Zhang, and J. S. Silva, “A survey on human-in-the-loop applications towards an internet of all,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 944–965, 2015. DOI: `10.1109/comst.2015.2398816`. [Online]. Available: `https://doi.org/10.1109/comst.2015.2398816`.

[9] G. D. Abowd, A. K. Dey, P. J. Brown, N. Davies, M. Smith, and P. Steggles, “Towards a better understanding of context and context-awareness,” in *Handheld and Ubiquitous Computing*, Springer Berlin Heidelberg, 1999, pp. 304–307. DOI: `10.1007/3-540-48157-5_29`. [Online]. Available: `https://doi.org/10.1007/3-540-48157-5_29`.

[10] R. Davies, “Industry 4.0 digitalisation for productivity and growth,” *European Parliamentary Research Service*, vol. 1, 2015.

[11] X. Yao, J. Zhou, Y. Lin, Y. Li, H. Yu, and Y. Liu, “Smart manufacturing based on cyber-physical systems and beyond,” *Journal of Intelligent Manufacturing*, vol. 30, no. 8, pp. 2805–2817, Dec. 2017. DOI: `10.1007/s10845-017-1384-5`. [Online]. Available: `https://doi.org/10.1007/s10845-017-1384-5`.

[12] P. Milgram, H. Takemura, A. Utsumi, and F. Kishino, “Augmented reality: A class of displays on the reality-virtuality continuum,” in *Telemanipulator and Telepresence Technologies*, H. Das, Ed., SPIE, Dec. 1995. DOI: `10.1117/12.197321`. [Online]. Available: `https://doi.org/10.1117/12.197321`.

[13] ACEA, "Acea economic and market report – full-year 2019," ACEA, May 2020. [Online]. Available: `https://www.acea.be/uploads/statistic_documents/Economic_and_Market_Report_full-year_2019.pdf`.

[14] ——, "Employment in the eu automotive industry," ACEA, 2020. [Online]. Available: `https://www.acea.be/statistics/article/employment`.

[15] ——, "Employmentshare of direct automotive employment in the eu, by country," ACEA, 2020. [Online]. Available: `https://www.acea.be/statistics/article/share-of-direct-automotive-employment-in-the-eu-by-country`.

[16] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, and M. Hoffmann, "Industry 4.0," *Business & Information Systems Engineering*, vol. 6, no. 4, pp. 239–242, Jun. 2014. DOI: `10.1007/s12599-014-0334-4`. [Online]. Available: `https://doi.org/10.1007/s12599-014-0334-4`.

[17] T. E. of Encyclopaedia Britannica, "Industrial revolution," in *Encyclopaedia Britannica*, Encyclopaedia Britannica, 2020. [Online]. Available: `https://www.britannica.com/event/Industrial-Revolution`.

[18] J. Rifkin, *The third industrial revolution : how lateral power is transforming energy, the economy, and the world*. New York: Palgrave Macmillan, 2011, ISBN: 978-0-230-11521-7.

[19] H. Kagermann, J. Helbig, A. Hellinger, and W. Wahlster, *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group*. Forschungsunion, 2013.

[20] M. Hermann, T. Pentek, and B. Otto, "Design principles for industrie 4.0 scenarios," in *2016 49th Hawaii International Conference on System Sciences (HICSS)*, IEEE, Jan. 2016. DOI: `10.1109/hicss.2016.488`. [Online]. Available: `https://doi.org/10.1109/hicss.2016.488`.

[21] P. Buxmann, T. Hess, and R. Ruggaber, "Internet of services," *Business & Information Systems Engineering*, vol. 1, no. 5, pp. 341–342, Sep. 2009. DOI: `10.1007/s12599-009-0066-z`. [Online]. Available: `https://doi.org/10.1007/s12599-009-0066-z`.

[22] W. de Paula Ferreira, F. Armellini, and L. A. D. Santa-Eulalia, "Simulation in industry 4.0: A state-of-the-art review," *Computers & Industrial Engineering*, vol. 149, p. 106 868, Nov. 2020. DOI: `10.1016/j.cie.2020.106868`. [Online]. Available: `https://doi.org/10.1016/j.cie.2020.106868`.

[23] A. Albers, B. Gladysz, T. Pinner, V. Butenko, and T. Stürmlinger, "Procedure for defining the system of objectives in the initial phase of an industry 4.0 project focusing on intelligent quality control systems," *Procedia CIRP*, vol. 52, pp. 262–267, 2016. DOI: `10.1016/j.procir.2016.07.067`. [Online]. Available: `https://doi.org/10.1016/j.procir.2016.07.067`.

[24] P. Kovac, I. Maňková, M. Gostimirović, M. Sekulić, and B. Savkovic, "A review of machining monitoring systems," *Journal of PRODUCTION ENGINEERING*, vol. 14, pp. 1–6, Jan. 2011.

[25] R. Teti, K. Jemielniak, G. O'Donnell, and D. Dornfeld, "Advanced monitoring of machining operations," *CIRP Annals*, vol. 59, no. 2, pp. 717–739, 2010. DOI: `10.1016/j.cirp.2010.05.010`. [Online]. Available: `https://doi.org/10.1016/j.cirp.2010.05.010`.

[26] E. Petritoli, F. Leccese, and G. S. Spagnolo, "In-line quality control in semiconductors production and availability for industry 4.0," in *2020 IEEE International Workshop on Metrology for Industry 4.0 IoT*, 2020, pp. 665–668. DOI: `10.1109/MetroInd4.0IoT48571.2020.9138296`.

[27] G. Cogorno, *Geometric dimensioning and tolerancing for mechanical design.* New York: McGraw-Hill, 2011, ISBN: 9780071772129.

[28] V. K. Pathak, A. K. Singh, M. Sivadasan, and N. K. Singh, "Framework for automated GD&t inspection using 3d scanner," *Journal of The Institution of Engineers (India): Series C*, vol. 99, no. 2, pp. 197–205, Aug. 2016. DOI: `10.1007/s40032-016-0337-7`. [Online]. Available: `https://doi.org/10.1007/s40032-016-0337-7`.

[29] J. Nee, *Fundamentals of tool design*. Dearborn, Mich: Society of Manufacturing Engineers, 2010, ISBN: 9780872638679.

[30] M.-W. Cho, H. Lee, G.-S. Yoon, and J. Choi, "A feature-based inspection planning system for coordinate measuring machines," *The International Journal of Advanced Manufacturing Technology*, vol. 26, no. 9-10, pp. 1078–1087, Aug. 2005. DOI: `10.1007/s00170-004-2077-8`. [Online]. Available: `https://doi.org/10.1007/s00170-004-2077-8`.

[31] L. Qi, S. Wang, Y. Zhang, Y. Sun, and X. Zhang, "Quality inspection guided laser processing of irregular shape objects by stereo vision measurement: Application in badminton shuttle manufacturing," *Optical Engineering*, vol. 54, no. 11, p. 113 101, Nov. 2015.

[32] M. D. Gregorio, G. Nota, M. Romano, M. Sebillo, and G. Vitiello, "Designing usable interfaces for the industry 4.0," in *Proceedings of the International Conference on Advanced Visual Interfaces*, ACM, Sep. 2020. DOI: `10.1145/3399715.3399861`. [Online]. Available: `https://doi.org/10.1145/3399715.3399861`.

[33] E. Lodgaard and S. Dransfeld, "Organizational aspects for successful integration of human-machine interaction in the industry 4.0 era," *Procedia CIRP*, vol. 88, pp. 218–222, 2020. DOI: `10.1016/j.procir.2020.05.039`. [Online]. Available: `https://doi.org/10.1016/j.procir.2020.05.039`.

[34] B. Hollifield, "A high performance hmi–better graphics for operations effectiveness," in *2012 Water/Wastewater and Automation Controls Symposium*, 2012.

[35] G. Lee, C. M. Eastman, T. Taunk, and C.-H. Ho, "Usability principles and best practices for the user interface design of complex 3d architectural design and engineering tools," *International Journal of Human-Computer Studies*, vol. 68, no. 1-2, pp. 90–104, Jan. 2010. DOI: `10.1016/j.ijhcs.2009.10.001`. [Online]. Available: `https://doi.org/10.1016/j.ijhcs.2009.10.001`.

[36] W. Galitz, *The essential guide to user interface design : an introduction to GUI design principles and techniques*. Indianapolis, IN: Wiley Pub, 2007, ISBN: 978-0-470-05342-3.

[37] D. Fiorella, A. Sanna, and F. Lamberti, "Multi-touch user interface evaluation for 3d object manipulation on mobile devices," *Journal on Multimodal User Interfaces*, vol. 4, no. 1, pp. 3–10, Dec. 2009. DOI: `10.1007/s12193-009-0034-4`. [Online]. Available: `https://doi.org/10.1007/s12193-009-0034-4`.

[38] G. Bishop and H. Fuchs, "Research directions in virtual environments," *ACM SIGGRAPH Computer Graphics*, vol. 26, no. 3, pp. 153–177, Aug. 1992. DOI: `10.1145/142413.142416`. [Online]. Available: `https://doi.org/10.1145/142413.142416`.

[39] T. Mazuryk and M. Gervautz, "Virtual reality - history, applications, technology and future," Dec. 1999.

[40] A. Valerio Netto, "Realidade virtual - definições, dispositivos e aplicações," Mar. 2002.

[41] M. Slater, M. Usoh, and A. Steed, "Depth of presence in virtual environments," *Presence*, vol. 3, pp. 130–144, Jan. 1994. DOI: `10.1162/pres.1994.3.2.130`.

[42] M. Saez, F. P. Maturana, K. Barton, and D. M. Tilbury, "Real-time manufacturing machine and system performance monitoring using internet of things," *IEEE Transactions on Automation Science and Engineering*, vol. 15, no. 4, pp. 1735–1748, Oct. 2018. DOI: `10.1109/tase.2017.2784826`. [Online]. Available: `https://doi.org/10.1109/tase.2017.2784826`.

[43] M. Mabkhot, A. Al-Ahmari, B. Salah, and H. Alkhalefah, “Requirements of the smart factory system: A survey and perspective,” *Machines*, vol. 6, no. 2, p. 23, Jun. 2018. DOI: `10.3390/machines6020023`. [Online]. Available: `https://doi.org/10.3390/machines6020023`.

[44] A. Moreno, G. Velez, A. Ardanza, I. Barandiaran, Á. R. de Infante, and R. Chopitea, “Virtualisation process of a sheet metal punching machine within the industry 4.0 vision,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 11, no. 2, pp. 365–373, Jun. 2016. DOI: `10.1007/s12008-016-0319-2`. [Online]. Available: `https://doi.org/10.1007/s12008-016-0319-2`.

[45] L. Pérez, E. Diez, R. Usamentiaga, and D. F. Garcıa, “Industrial robot control and operator training using virtual reality interfaces,” *Computers in Industry*, vol. 109, pp. 114–120, Aug. 2019. DOI: `10.1016/j.compind.2019.05.001`. [Online]. Available: `https://doi.org/10.1016/j.compind.2019.05.001`.

[46] L. F. de Souza Cardoso, F. C. M. Q. Mariano, and E. R. Zorzal, “A survey of industrial augmented reality,” *Computers & Industrial Engineering*, vol. 139, p. 106 159, Jan. 2020. DOI: `10.1016/j.cie.2019.106159`. [Online]. Available: `https://doi.org/10.1016/j.cie.2019.106159`.

[47] A. Syberfeldt, M. Holm, O. Danielsson, L. Wang, and R. L. Brewster, “Support systems on the industrial shop-floors of the future – operators’ perspective on augmented reality,” *Procedia CIRP*, vol. 44, pp. 108–113, 2016. DOI: `10.1016/j.procir.2016.02.017`. [Online]. Available: `https://doi.org/10.1016/j.procir.2016.02.017`.

[48] S. C. Peres, T. Pham, and R. Phillips, “Validation of the system usability scale (SUS),” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 57, no. 1, pp. 192–196, Sep. 2013. DOI: `10.1177/1541931213571043`. [Online]. Available: `https://doi.org/10.1177/1541931213571043`.

[49] J. Rubin and D. Chisnell, *Handbook of usability testing: how to plan, design, and conduct effective tests*, 2nd ed. Indianapolis, IN: Wiley Pub, 2008, OCLC: ocn212204392, ISBN: 9780470185483.

[50] A. Assila, K. Oliveira, and H. Ezzedine, "Standardized usability questionnaires: Features and quality focus," *Computer Science and Information Technology*, vol. 6, 2016.

[51] B. Shackel, "Usability – context, framework, definition, design and evaluation," *Interacting with Computers*, vol. 21, no. 5-6, pp. 339–346, Dec. 2009. DOI: `10.1016/j.intcom.2009.04.007`. [Online]. Available: `https://doi.org/10.1016/j.intcom.2009.04.007`.

[52] A. Bangor, P. T. Kortum, and J. T. Miller, "An empirical evaluation of the system usability scale," *International Journal of Human-Computer Interaction*, vol. 24, no. 6, pp. 574–594, Jul. 2008. DOI: `10.1080/10447310802205776`. [Online]. Available: `https://doi.org/10.1080/10447310802205776`.

[53] B. Eisenman, *Learning React Native : building mobile applications with JavaScript.* Sebastopol, CA: O'Reilly Media, 2015, ISBN: 978-1491929001.

[54] S. A. Bello, L. O. Oyedele, O. O. Akinade, M. Bilal, J. M. D. Delgado, L. A. Akanbi, A. O. Ajayi, and H. A. Owolabi, "Cloud computing in construction industry: Use cases, benefits and challenges," *Automation in Construction*, vol. 122, p. 103 441, Feb. 2021. DOI: `10.1016/j.autcon.2020.103441`. [Online]. Available: `https://doi.org/10.1016/j.autcon.2020.103441`.

Appendix A

System Usability Scale Questionnaire (Portuguese)

Eu usaria a aplicação frequentemente *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

A aplicação é muito complexa *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

A aplicação é fácil de usar *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Eu precisaria de suporte técnico para poder utilizar a aplicação *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Várias funções da aplicação estavam muito bem integradas *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Havia muita inconsistência na aplicação *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

A maioria das pessoas aprenderia a usar a aplicação muito rapidamente *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Achei a aplicação bastante desconfortável de usar *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Senti-me muito seguro usando a aplicação *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Preciso aprender muitas coisas antes de poder usar a aplicação *

	1	2	3	4	5	
Discordo fortemente	○	○	○	○	○	Concordo plenamente

Comentários (opcional)

Appendix B

Project Original Proposal

INSTITUTO POLITÉCNICO DE BRAGANÇA
Escola Superior de Tecnologia e Gestão

Proposta de Dissertação

Mestrado em Sistemas de Informação

2020/21

Título: Desenvolvimento de assistente digital de suporte à execução de procedimentos de medição de controlo de peças

Orientador (IPB): Paulo Leitão

Coorientador (UTFPR): Jorge Aikes Junior, Pedro Luiz de Paula Filho

Aluno: Giuseppe Antonio Setem Davanzo

Contextualização:

No contexto da Indústria 4.0, a integração de operadores e outros humanos nos novos sistemas ciber-físicos assume crucial importância, uma vez que o humano é considerado como a peça mais flexível do sistema. Assim, é fundamental a implementação de sistemas que facilitem a integração dos humanos, utilizando tecnologias disruptivas como sejam novas interfaces homem-máquina, realidade virtual e aumentada, e assistentes pessoais inteligentes. Estes últimos são aplicações computacionais que suportam o operador na interação com máquinas e computadores durante a realização de tarefas ou serviços, utilizando comandos de voz, imagens e informação contextual para elaborar recomendações e ações a serem realizadas. Estas aplicações recorrem a diversas tecnologias TIC, nomeadamente de processamento de imagem, processamento de fala, e realidade virtual e aumentada, assim como a diversas tecnologias para a interação homem-máquina, nomeadamente HMD (Head-mounted devices), e.g., Microsoft Hololens, dispositivos portáveis, e.g., smartphones e tablets, projetores, e.g., monitores, e dispositivos de reconhecimento gestual, e.g., Leap Motion.

Este trabalho consiste num desafio real colocado pela empresa Catraport (https://www.p-cautomotive.com/en/group/catraport), em cooperação com o CeDRI - Centro de Investigação em Digitalização e Robótica Inteligente (http://www.cedri.ipb.pt/).

Objetivo:

O objetivo deste trabalho consiste no desenvolvimento de um assistente digital, baseado em tecnologias TIC, nomeadamente realidade virtual e visão artificial, para suportar a execução de procedimentos de medição de controlo de peças produzidas, alinhado com a Indústria 4.0.

A solução a ser desenvolvida visa a fácil integração de operadores em sistemas ciber-físicos, incluindo funcionalidades de apoio à realização de tarefas de medição de controlo de peças, que são personalizados e atualmente realizados através de suporte de lista de instruções impressas em papel. Atualmente a operação é realizada nas seguintes fases:

- O operador procura em stock o medidor apropriado para a peça a ser verificada.
- O operador coloca o medidor e as instruções em papel no trólei portátil e transporta-o para a linha.
- O operador coloca a peça a ser verificada no medidor e aplica a sequencia de ações indicada na lista de instruções em papel.

Pretende-se com esta proposta de trabalho melhorar a eficiência do controlo de produção através do desenvolvimento de uma solução digital que elimine as instruções em papel e as substitua por um sistema que guie passo-a-passo o operador usando um sistema de visão. O sistema deve também, dentro do possível verificar a execução correta das tarefas.

Pré-requisitos:

Para a realização deste projeto é interessante que o aluno tenha conhecimentos sólidos de programação e realidade virtual.

Cronograma de Atividades

Este trabalho compreende a execução das seguintes etapas:

Tarefa 1 - Estudo do sistema atual e análise dos requisitos (M1)

Tarefa 2 - Familiarização das plataformas para processamento de imagem e realidade virtual (M2-M3)

Tarefa 3 – Especificação do sistema de assistência digital (M4-M5)

Tarefa 4 – Desenvolvimento do sistema de guia passo a passo da execução da lista de instruções usando realidade virtual (M4-M7)

Tarefa 5 – Desenvolvimento do sistema de visão artificial (M8-M9)

Tarefa 6 - Testes e validação do protótipo (M9)

Tarefa 7 - Escrita da dissertação e defesa final do trabalho (M10-M11)

Infraestruturas e recursos necessários

Este trabalho será desenvolvido no laboratório de Automação, Controlo e Robótica (LCAR).