UNIVERSITA' POLITECNICA DELLE MARCHE

UNIVERSITA' DEGLI STUDI DI URBINO CARLO BO

FACULTY OF ENGINEERING

Master's Degree course: **Green Industrial Engineering**

SVILUPPO E VALIDAZIONE DI UN SISTEMA DI ISPEZIONE LASER NON-A CONTATTO PER IL CONTROLLO DIMENSIONALE E QUALITATIVO IN AMBITO INDUSTRIALE: CALIBRAZIONE, COMPENSAZIONE VOLUMETRICA E ANALISI DELLE PRESTAZIONI DI MISURA.

DEVELOPMENT AND VALIDATION OF A NON-CONTACT LASER INSPECTION SYSTEM FOR DIMENSIONAL CONTROL IN INDUSTRIAL APPLICATIONS: CALIBRATION, VOLUMETRIC COMPENSATION AND MEASUREMENT PERFORMANCE ANALYSIS.

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A.Y. 2025/2026

"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."

— Lord Kelvin

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my academic supervisor, **Professor Nicola Paone**, for his invaluable guidance, continuous support, and insightful feedback throughout the development of this thesis.

I would also like to extend my sincere appreciation to my company supervisor, **Dr. Matteo Bezziccheri**, for his professionalism, technical knowledge, and support during my internship at Benelli Armi. His support, encouragement, and professional advice were sincerely appreciated throughout this experience.

A special thanks goes to the entire team at **Benelli Armi** for their collaboration, availability, and for providing a stimulating and professional working environment throughout the internship experience.

Finally, I would like to express my sincere gratitude to my family, especially my siblings, for their continuous support, encouragement, patience, and trust throughout my academic journey. Their presence and motivation have always been a valuable source of strength.

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1 INTRODUCTION

Due to strict safety regulations, tight dimensional tolerances, and high aesthetic standards, the weapons business represents a particularly difficult sector in the context of contemporary production, where product quality, process repeatability, and digital traceability are increasingly crucial. Because even little variations can affect shooting accuracy, mechanical dependability, and perceived product quality, shotgun barrel manufacture necessitates exact control over geometric alignment, functional features, and regulatory marks.

Inspection tasks in industrial production settings have always depended on skilled operators' manual visual judgment. Visual inspection has intrinsic constraints linked to subjectivity, operator tiredness, and decreased measurement traceability, notwithstanding its practical effectiveness. The need to convert qualitative inspection methods into objective, data-driven processes backed by automated measuring technology is increasing as production systems move toward Industry 4.0 paradigms.

Benelli has created the Be-Line project, a non-contact laser inspection system intended to automate shotgun barrel measurements using optical triangulation and three-dimensional reconstruction methods, in order to overcome these difficulties. In addition to providing digital reporting and traceability throughout the manufacturing workflow, the system facilitates the capture of extensive geometric data, enabling the assessment of important performance indicators pertaining to sight-line alignment, linearity, and planarity. The method seeks to increase consistency, decrease operator variability, and facilitate early non-conformity identification by substituting quantitative indications for simply visual judgement.

The implementation of such an automated inspection solution necessitates a thorough examination of acceptance criteria, system design, and measurement reliability. Specifically, different barrel designs exhibit diverse surface properties and geometric references, necessitating strong data processing algorithms and adaptive collection settings to maintain stable measurement circumstances. Thus, assessing the Be-Line measuring bench from both a metrological and an

industrial standpoint is a key component of our effort.

The performance evaluation of the Be-Line inspection system and the determination of objective acceptability tolerances for shotgun barrel alignment are the main topics of this thesis. Comparative measurements between the Be-Line system and a Coordinate Measuring Machine (CMM), which serves as a reference metrological tool to assess measurement uncertainty and precision, are one of the experimental activities. The study also seeks to convert operators' visual sensitivity into quantifiable thresholds that can differentiate between acceptable and unacceptable components through statistical analysis of production data.

Beyond the technical analysis, the thesis examines the wider ramifications of switching from manual inspection to automated optical measurement, emphasizing the advantages in terms of process standardization, digital traceability, and repeatability in an industrial setting.

The structure of the thesis is as follows. The state of the art is presented in Chapter 2, which also introduces weapon types, shotgun barrel structural components, and the KPIs used to characterize sight-line conformance. The Be-Line system, comprising the hardware and software design of the measuring bench and the triangulation-based sensing method, is explained in Chapter 3. The experimental validation procedures and performance assessment of the measuring system through calibration and comparison with CMM data are presented in Chapter 4. The determination of acceptability limits obtained from statistical analysis of production measures is the main topic of Chapter 5. Chapter 6 concludes with a summary of the key findings and a discussion of possible future developments.

The thesis supports the development of objective, repeatable, and digitally traceable quality control procedures by advancing the use of automated non-contact inspection technologies in high-precision manufacturing through this methodical approach.

2 STATE OF THE ART

Quality control is a key component of industrial manufacturing that guarantees customer satisfaction, functional dependability, and product conformance. Inspection techniques have gradually evolved over the past few decades due to the growing complexity of products, tighter regulations, and higher consumer expectations. Automated, non-contact inspection technologies that offer greater repeatability, objectivity, and data traceability are progressively supplementing—or even replacing—traditional quality control methods that rely on manual inspection and contact-based measurement devices.

One very important application area for dimensional and qualitative inspection systems is the guns industry. Tight dimensional tolerances, strict safety requirements, and high aesthetic criteria must all be met at the same time for firearm components. The barrel is the most important of these parts as it has a direct impact on ballistic performance, mechanical integrity, shooting accuracy, and overall weapon dependability. Even little geometric errors or misalignments can affect how well a product works or result in its rejection.

In this situation, inspection procedures need to take into account surface integrity, geometric consistency, functional feature alignment, and dimensional correctness. In the past, a lot of these inspections—particularly those pertaining to surface cleanliness, sight-line alignment, and barrel straightness—have mostly depended on manual visual examination carried out by skilled operators. These inspection techniques are intrinsically constrained by subjectivity, operator tiredness, shift unpredictability, and challenges in guaranteeing complete measurement traceability, even if human knowledge is still vital.

The creation of automated inspection systems that can carry out non-contact, high-resolution, repeatable measurements in industrial settings has been made possible by recent developments in optical metrology, machine vision, and laser-based measuring technologies. These systems are especially well-suited for inline or near-line inspection, where quick feedback and impartial decision-making are crucial to lowering production costs related to scrap, rework, and non-quality.

This chapter's goal is to provide the most recent developments in non-contact optical inspection technology for shotgun barrels. The chapter describes the essential performance indicators used to assess sight-line alignment, examines the structural and functional components of a shotgun barrel, and presents the major weapon categories pertinent to the industrial setting. In addition, it examines the benefits and drawbacks of conventional visual inspection techniques and talks about how automated optical inspection techniques are replacing manual inspection in contemporary production settings.

2.1 Firearm Categories

Based on its intended usage, loading method, and operating mechanism, firearms may be divided into several groups. This categorization has important ramifications for component geometry, assembly procedures, and quality control techniques in addition to being functional from the standpoint of production and inspection. Barrel design, reference characteristics, and inspection requirements are subject to different restrictions depending on the kind of firearm.

For the purposes of the present work, four primary firearm categories can be identified:

- **Semi-automatic firearms**
- **Pump-action firearms**
- **Over-and-under firearms**
- **Carbine firearms**

Despite the fact that all of these groups have similar functional principles, their mechanical structures result in various alignment reference systems and barrel configurations. As a result, inspection techniques need to be tailored to the unique features of every category.

2.1.1 Semi-Automatic Firearms

An operating mechanism that automatically cycles the action after each shot, ejecting the used cartridge and inserting a fresh one from the magazine, is what distinguishes semi-automatic rifles. In order to guarantee dependable cycling and constant ballistic performance, this mechanism

usually depends on gas-operated or inertia-driven systems, which place stringent constraints on barrel shape and alignment.[1]

Semi-automatic barrels frequently include a barrel extension (culatta) that connects directly to the weapon receiver for inspection purposes. This extension is an essential point of reference for sight-line alignment and mechanical assembly. Shooting accuracy might be adversely affected by changes in point-of-impact caused by any misalignment between the sight line and the barrel extension.

Moreover, semi-automatic barrels are frequently manufactured in large quantities, which makes them especially well-suited for automated inspection systems. Consistency, speed, and reproducibility are crucial in these production settings, and manual inspection becomes more ineffective and challenging to standardize across many operators and production shifts.

Figure 2-1: Semiautomatic [13]

2.1.2 Pump-Action Firearms

A manually actuated sliding fore-end is used in pump-action weapons to cycle the action. The user performs the pumping action, which introduces various mechanical limitations and reference geometries inside the barrel assembly, in contrast to semi-automatic systems.[2]

The codetta, a reference feature used for alignment in pump-action barrels, may be situated in an intermediate position rather than at the terminal end of the barrel extension. Determining reference systems for geometric and dimensional examination becomes more difficult as a result of this design.

Pump-action barrels are a more difficult scenario from a metrological standpoint than semi-automatic barrels. Accurate and repeatable measurement might become more difficult due to the displacement of the reference feature and the related fixture restrictions, which can increase susceptibility to positioning mistakes. Pump-action barrels are therefore a very useful test case for confirming the functionality and resilience of non-contact laser inspection systems.

Figure 2-2: Pump action [14]

2.1.3 Over-and-under firearms

The existence of two barrels placed vertically, creating a connected system in which both barrels must meet stringent alignment and convergence criteria, is what distinguishes over-and-under weapons. This weapon category is included here for completeness even though it is not the main topic of the current thesis.[3]

Additional geometric limitations, such as relative parallelism, angular alignment, and symmetry between the two barrels, are usually included in the examination of over-and-under barrels. These specifications highlight the potential benefits of three-dimensional measuring devices that can record all geometric data in a single inspection cycle.

Figure 2-3: Over and Under Firearms [15]

2.1.4 Carbines

Carbines are a more general class of weapons that can have various sighting arrangements and rifled barrels. Carbines frequently include qualitative characteristics and regulatory marks in addition to physical and geometric criteria that need to be confirmed for compliance.

Carbines are not specifically discussed in this thesis's experimental activity, but their inclusion emphasizes how adaptable contemporary inspection methods used in the guns business must be.[4]

Figure 2-4: Carbine [16]

2.1.5 Firearm Categories Examined in This Thesis

Experimental validation and performance analysis are restricted to semi-automatic and pump-action weapons in the context of this thesis. This choice takes into account each configuration's unique inspection difficulties as well as their applicability in the industrial production setting. In order to evaluate various barrel geometries, reference configurations, and alignment requirements under actual industrial conditions, the study focuses on the shift from conventional visual inspection methods to inspection approaches based on three-dimensional scanning technologies.

2.2 Main Elements of a Shotgun Barrel

One of the most important parts of a weapon is the rifle barrel, which directly affects accuracy, ballistic performance, structural integrity, and overall product quality. From the standpoint of manufacture and inspection, the barrel is an assemblage of many components, each with distinct functional responsibilities, geometric limitations, and reference qualities, rather than a single,

homogenous component. Determining suitable inspection tactics and accurately interpreting measurement findings from automated inspection systems require a thorough grasp of these components.

The barrel extension, barrel tube, and sight line are the three primary parts of a barrel assembly in industrial manufacturing. These elements can be joined in different ways to produce different geometric configurations, depending on the weapon class and design decisions. Inspection issues with alignment, straightness, flatness, and positional correctness are unique to each design.[5][6]

In order to ensure correct mechanical connection and functional alignment, the barrel extension serves as the interface between the barrel and the gun body. Culatta and fodero are the two primary forms of barrel extensions used in shotgun production. The selection of reference items used during dimensional inspection is greatly influenced by the decision between these two categories.

In culatta, as showing in *Figure 2-5*, the barrel connection is manufactured as a solid mechanical unit incorporating a reference element known as codetta (as showing in Figure 2-6). The codetta serves as a geometric reference for line-of-sight alignment and is a crucial reference point during inspections. Its position relative to the barrel axis must be precisely controlled, as any deviation, however slight, can result in the barrel being misaligned with the aiming system. Metrologically, the codetta is essential for determining the measurement coordinate system.

Figure 2-5: Exploded View of Barrel Assembly Highlighting the Culatta Reference Geometry [17]

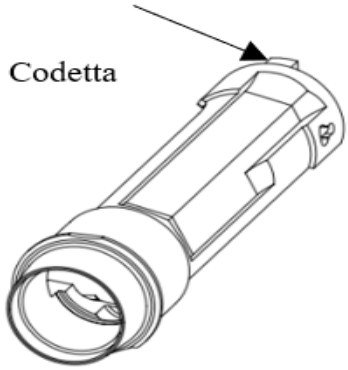

Figure 2-6: Barrel Extension with Codetta Reference Feature

In contrast, the fodero, integrates the line-of-sight directly into the barrel connection itself, as showing in Figure 2-7.

Figure 2-7: Geometric Layout of the Fodero Barrel Assembly [18]

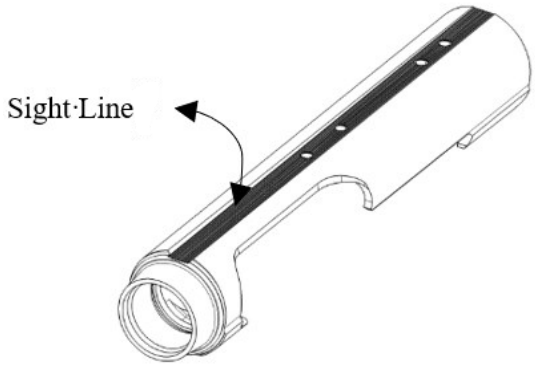

Figure 2-8: Sleeve Configuration with Integrated Sight Line

The main structural component of a rifle barrel that controls the projectile's trajectory is the barrel tube. In order to guarantee straightness, consistent wall thickness, and surface quality, it is usually produced using forming, drilling, and finishing techniques. Inspection-wise, the barrel tube needs to be assessed for both geometric consistency along its length and dimensional correctness [7].

Figure 2-9: Structural Geometry of the Barrel Tube [19]

The barrel tube may have a sight line that is either directly welded to the tube or fastened via intermediary components like spacers or support blocks, depending on the design solution used. These design decisions provide new possible sources of geometric variation and have a major influence on inspection needs.

One common design involves using a carbon fiber rib attached to the barrel tube via a series of spacers, often referred to as a "tasselli", as showing in Figure 2-10. In this design, the spacers define the rib's relative position to the barrel axis. Therefore, inspections must verify the straightness of the rib along its longitudinal axis and the flatness of its surface relative to the reference plane.

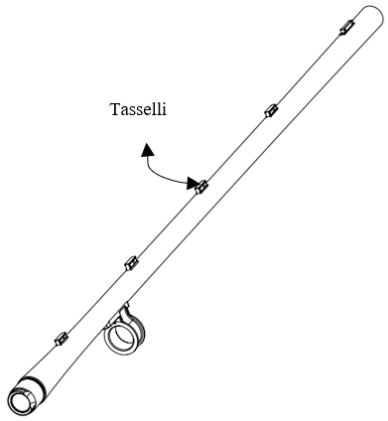

Figure 2-10: Barrel Tube with Carbon-Fiber Rib Mounted on Spacers

A welded rib is an alternative solution, where the line of sight is permanently attached to the pipe via welding, as showing Figure 2-11. While this method reduces the number of assembly components, it introduces potential distortions due to thermal effects during welding.

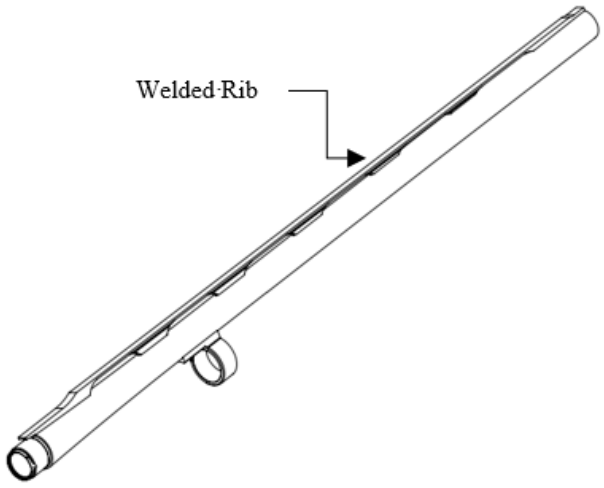

Figure 2-11: Barrel Tube with Welded Rib Configuration

There are several conceivable pipe designs when the barrel extension (culatta or fodero) and the line-of-sight integration technique (splits or welds) are combined. These configurations fall into four major groups, each of which has unique inspection issues and distinct reference features. For industrial use, an inspection system must be able to properly manage each of these setups.

A special case that deserves particular attention is that of pump-action shotgun barrel extensions, where the reference point of the codetta is not located at the end of the barrel, but rather in a middle area of the breech, as showing in *Figure 2-12*. This geometric peculiarity complicates the definition of the measurement coordinate system and increases sensitivity to fixturing errors during inspection. As a result, pump-action barrels represent a more demanding case for dimensional verification and provide a stringent test for the robustness of automated inspection systems.

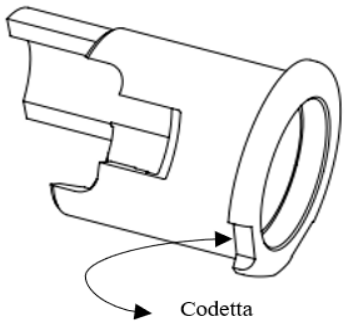

Figure 2-12: Codetta Reference Feature in the Pump-Action Barrel Extension

From a metrological standpoint, the barrel assembly may be viewed as a series of linked geometric elements, where variations at each interface may spread and compound, ultimately impacting the sight line's alignment. This idea is especially pertinent for assessing an inspection system's overall measurement performance since it emphasizes the necessity of thorough three-dimensional analysis as opposed to discrete point measurements.

Therefore, identifying relevant key performance indicators, choosing suitable reference characteristics, and creating trustworthy measurement techniques all depend on an understanding of the structural makeup and functional significance of each barrel piece. This knowledge serves as the foundation for the analysis that follows, in which the effectiveness of a non-contact laser inspection system is experimentally verified and the sight line alignment is assessed using certain dimensions and geometric indicators.

Four distinct configurations are conceivable when these elements are combined.

The pump-action breech is a specific example of a breech in which the reference element, the codetta, is situated in a different area of the breech rather than at the terminal end.

2.3 Coordinate system of a shotgun

In order to ensure consistency in geometric analysis and dimensional evaluation, the geometry of the shotgun barrel is described using a Cartesian reference coordinate system, as illustrated in Figure 2-13. The adoption of a standardized reference frame allows positional deviations, alignment errors, and geometric tolerances to be expressed in a clear and repeatable manner throughout the inspection process.

The main reference direction of the system is the barrel's longitudinal axis. This axis serves as the foundation for alignment evaluation since it depicts the primary geometric direction along which the majority of functional elements are produced. It is possible to describe lateral and vertical deviations from the nominal geometry because the transversal axes are specified orthogonally to the longitudinal direction.

In this framework, lateral displacement is usually represented by the X-axis, the barrel's longitudinal orientation by the Y-axis, and vertical variations by the Z-axis. Geometric measurements may be interpreted consistently thanks to the defining of these axes, regardless of the particular inspection technique used. It is feasible to compare findings across various measurement contexts and preserve traceability between design intent and inspection outcomes by referring all dimensional assessments to a single coordinate system [8].

The coordinate system presented in this section serves as the geometric basis for the study of alignment-related indicators discussed in the sections that follow, where sight-line conformance and overall barrel geometry are quantified using deviations along certain axes.

The axes are defined according to the Cartesian reference system described in the Figure 2-13.

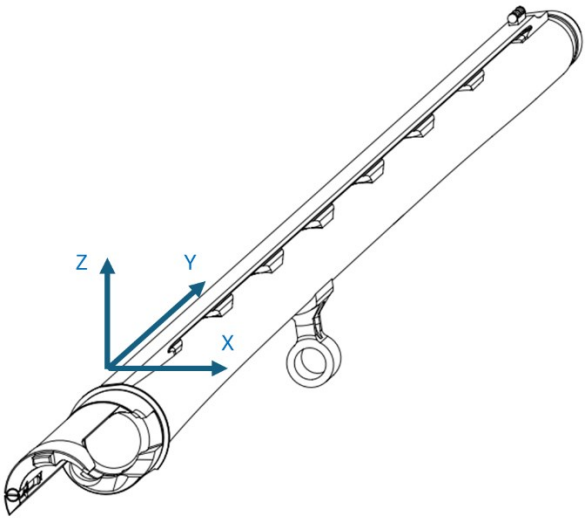

Figure 2-13: Cartesian Reference Coordinate System Defined for Barrel Geometry

2.4 Shotgun barrel: Key Performance Indicators

The assessment of shotgun barrel quality in contemporary industrial metrology is increasingly dependent on quantifiable, objective criteria as opposed to subjective visual examination. These characteristics, also known as Key Performance Indicators (KPIs), convert geometric and functional requirements into numerical values that can be reliably assessed in a standard measuring framework. By converting qualitative production expectations into quantitative criteria, KPIs make it possible to evaluate component conformance in a repeatable and verifiable manner [9].

Adopting KPIs is especially important when inspecting shotgun barrel assemblies since even little geometric variations can affect how well a product functions and is perceived. Manufacturers may increase repeatability across production batches and inspection settings, eliminate variability related to human interpretation, and create uniform acceptance norms by specifying quantitative indicators. By offering a standard numerical reference for assessing geometric aspects, KPIs also make it easier to compare various measuring techniques from a metrological standpoint.

The KPIs taken into consideration in this work fall into three primary areas when it comes to

shotgun barrel inspection:

i. Sight line alignment indicators, which explain the geometric and positional relationships between structural components in charge of assembly consistency and aim accuracy.
ii. Legal inscription indicators, which confirm that obligatory marks placed to the barrel surface in compliance with regulations are present and readable.
iii. Indicators of aesthetic defects, which are connected to surface quality elements like dents or scratches that might affect how the product appears even when dimensional conformance is met.

These KPI categories offer an organized framework for assessing barrel quality's functional and aesthetic components. Each group is further explained in the sections that follow, which concentrate on sight line geometry (Section 2.4.1), required inscriptions (Section 2.4.2), and aesthetic surface flaws (Section 2.4.3).

2.4.1 The sight line

One of a shotgun barrel's most important geometric and functional features is the sight line, which has a direct impact on aim accuracy and the end product's perceived quality. Mechanically speaking, the sight line is the geometric alignment along the barrel's longitudinal axis that is specified by the rib assembly and its supporting elements. To guarantee both functional performance during shooting and visual consistency from a manufacturing perspective, it is crucial to keep this alignment within defined bounds.

The assessment of sight line compliance in conventional production settings has frequently depended on visual inspection carried out by skilled operators. This method adds subjectivity and unpredictability even if it enables quick qualitative evaluation, particularly when variations are tiny or dispersed across long geometries. Because of this, as discussed in Section 2.4, contemporary industrial metrology uses objective, measurable Key Performance Indicators (KPIs) to define sight line compliance [9].

The KPIs that describe the conformity of the sight line are typically associated with three main

geometric aspects:

• **Positioning error between the barrel extension reference and the sight line**, which represents the deviation within structural reference elements along the assembly. This indicator shows how accurately the sight line is positioned in relation to the specified reference coordinate system and offers a direct measurement of alignment accuracy.

• **Planarity error along the vertical (Z) direction**, which characterizes the sight line surface's capacity to maintain alignment with an ideal reference plane. Planarity variations can be caused by mechanical forces imposed during manufacture, heat influences, or welding procedures. Visual appeal and geometric coherence can be impacted by even minor departures from planarity.

• **Linearity error along the longitudinal (X) direction**, which characterizes the extent to which the sight line follows an ideal straight trajectory along the barrel length. Aiming perception and overall alignment quality may be impacted by linearity variations, which can be caused by small structural bending or cumulative positioning mistakes of supporting pieces.

From a metrological perspective, these indicators are assessed using the Cartesian reference system presented in Section 2.3, in which lateral and vertical deviations are described by transversal axes and the longitudinal axis establishes the principal reference direction. The inspection process becomes more repeatable and traceable when sight line conformance is expressed by quantifiable KPIs. This lessens reliance on subjective visual judgment and allows for consistent comparison across various measuring techniques.

Therefore, the use of KPI-based evaluation marks a significant advancement in shotgun barrel inspection, turning a customarily qualitative evaluation into a quantified and organized framework that may assist statistical analysis and industrial quality control.

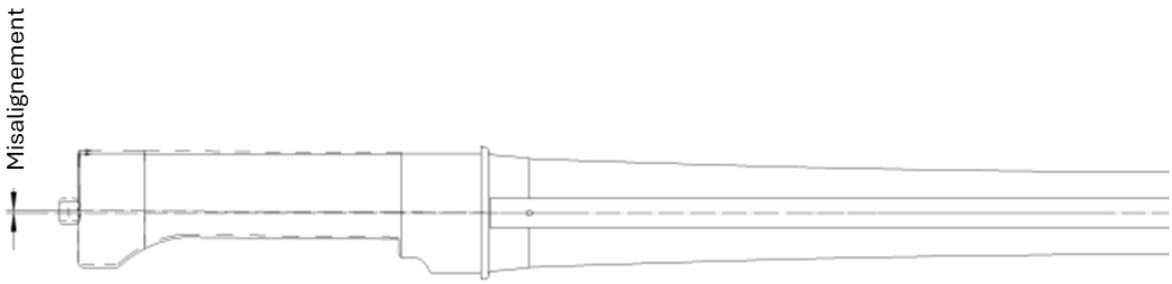

Figure 2-14: Conceptual Representation of Geometric Misalignment

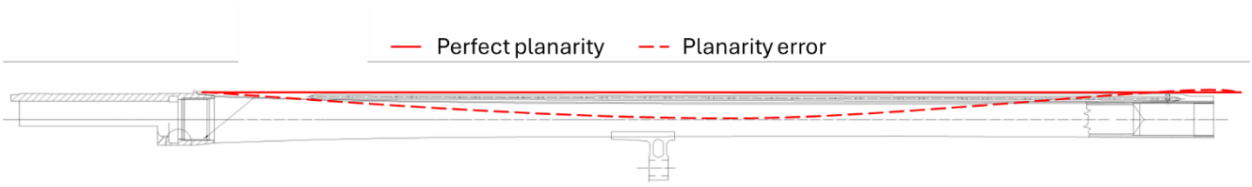

Figure 2-15: Comparison Between Ideal Planarity and Measured Planarity Deviation

Figure 2-16:. Comparison Between Ideal Linearity and Measured Linearity Deviation

2.4.2 Mandatory Legal Markings

Shotgun barrels must adhere to regulations that require permanent identification marks to be affixed to the outside surface in addition to geometric alignment. These inscriptions, which are sometimes referred to as scritta di legge in Italian industrial language, contain crucial details such chamber parameters, caliber designation, manufacturer identity, and proof or regulatory markings. Throughout the firearm's lifespan, their existence guarantees secure identification, regulatory compliance, and product traceability.

The Implementing Directive (EU) 2024/325, which amends Implementing Directive 2019/68, establishes revised technical standards on the labeling of guns and critical components at the European regulatory level. The guideline outlines uniform technical requirements intended to

provide consistent traceability throughout the EU and strengthen defenses against identification mark removal or change. The minimum depth of engraved marks, which must reach at least 0.08 mm (80 μm) to provide adequate visibility, durability, and resistance to wear or manipulation, is one of the important technical factors introduced [10].

From a production perspective, applying legal marks to metallic surfaces like the barrel, breech, or receiver components is a regulated procedure that involves engraving, stamping, or laser marking. Even after surface finishing procedures or extended usage, the marks will still be easily legible thanks to the specified minimum depth. For metallic components, where surface treatments or exposure to the environment may otherwise impair readability, this criterion is especially important.

Establishing consistent technical standards that facilitate accurate weapon identification and traceability throughout the manufacturing, distribution, and use stages is the aim of these regulatory guidelines. The European framework attempts to improve product authenticity and lower risks related to illicit modification or trafficking by imposing minimum marking depth and standardized inscription content.

The verification of required legal marks prioritizes regulatory compliance over dimensional accuracy, in contrast to the geometric KPIs discussed in the preceding sections. The evaluation of inscriptions guarantees that the barrel complies with legal criteria of identification, documentation, and certification, whereas geometric examination assesses alignment and structural compliance. These elements work together to provide a thorough assessment of shotgun barrel quality that incorporates functional, legal, and traceability factors.

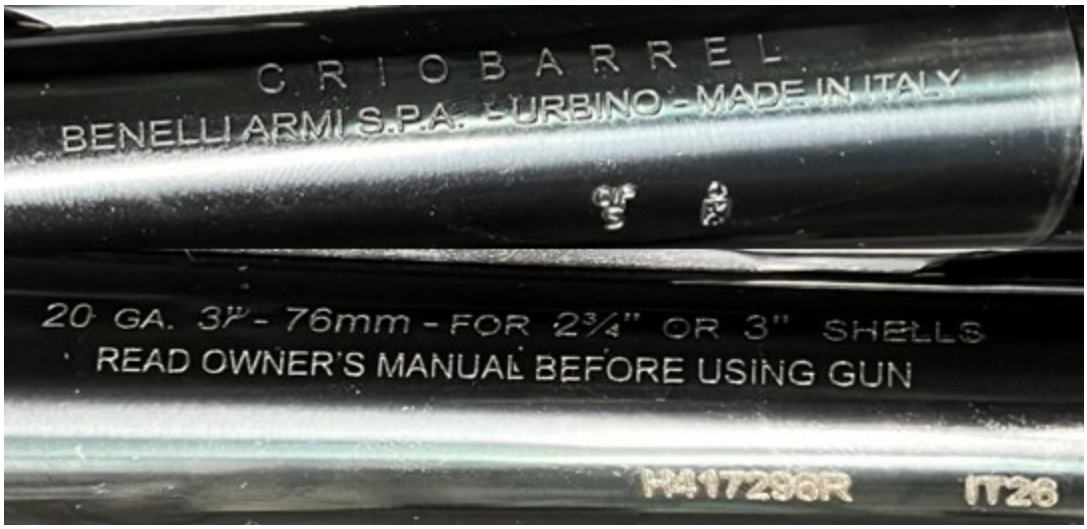

Figure 2-17: Legal Identification and Caliber Markings on Shotgun Barrels

2.4.3 Aesthetic Defects (Scratches and Dents)

In addition to geometric alignment and regulatory markings, the external surface condition of a shotgun barrel represents a relevant aspect of overall product evaluation. Even when dimensional parameters comply with nominal specifications, aesthetic imperfections such as scratches (graffi) and dents (ammaccature) may negatively influence the perceived quality of the firearm. For this reason, surface inspection constitutes an important complementary activity within the broader quality control process.

Aesthetic defects may originate from several stages of the manufacturing and handling workflow, including machining operations, transport between production stations, coating processes, or manual handling during assembly. These imperfections typically affect only localized regions of the external surface and do not necessarily compromise structural integrity or functional performance. Nevertheless, because firearms are high-value products where visual appearance contributes significantly to customer perception, the detection of such defects remains a critical requirement during inspection. Examples of surface imperfections typically evaluated during quality control are illustrated in Figure 2-18.

Figure 2-18: Example of Aesthetic Surface Scratches on the Barrel [20]

Dimensional verification and aesthetic evaluation are very different from an industrial inspection standpoint. While coordinate measurements and numerical parameters can be used to quantify geometric conformity, optical surface evaluation methods or visual inspection are frequently used to identify dents and scratches. Therefore, to make sure that both functional and aesthetic requirements are met, traditional inspection methods integrate operator-based visual inspections with objective dimensions measurements [11].

It is now possible to analyze surface texture using three-dimensional data collecting and image processing techniques thanks to recent advancements in optical metrology. The integration of geometric measurement with visual quality evaluation is still being investigated, despite the fact that automated identification of aesthetic faults is still a difficult task due to changes in surface polish, lighting circumstances, and coating qualities. Many industrial inspection procedures currently use a hybrid method that combines human experience with numerical evaluation to produce a trustworthy product quality assessment.

Before moving on to next phases of manufacturing, the inspection process makes sure that every barrel satisfies both engineering criteria and visual standards by differentiating between functional geometry and aesthetic appeal. The intricate nature of quality control in the production of firearms, where performance, compliance, and perceived workmanship must all be taken into account concurrently, is reflected in this dual viewpoint [12].

2.5 Visual inspection and analysis

One of the earliest and most popular approaches to industrial quality control is visual inspection. Its basic idea is based on the assessment of component conformance by direct sight, either with the unaided eye or via optical tools such camera-based systems, magnifiers, or microscopes. Visual inspection is still a crucial stage in many manufacturing industries for finding surface flaws, inconsistent assemblies, or geometric irregularities that might not be readily apparent using only dimensional measurements.

Because functional, safety, and aesthetic criteria coexist in the weapons business, visual inspection plays a particularly important role. Shotgun barrels are one example of a component that must meet tight geometric tolerances while yet looking excellent. Even little flaws, like as dents, scratches, or evident piece misalignment, can have an impact on the product's perceived quality and must be carefully considered throughout manufacture.

Visual inspection tasks have historically been carried out by skilled workers who gain the capacity to identify deviations by practice and frequent exposure to reference standards. To evaluate attributes including straightness, surface consistency, and overall assembly quality, these operators depend on tactile feedback, visual comparison, and lighting conditions. Because of the flexibility and adaptability that human skill offers, inspectors can assess complicated or varied geometries that could be difficult to express using only numerical characteristics.

However, manual visual assessment has a number of intrinsic drawbacks despite its adaptability. Variability across inspection shifts, environmental factors, operator subjectivity, and weariness all have an impact on the assessment process. Furthermore, depending solely on human judgment to maintain consistent inspection results becomes more difficult when industrial settings change toward larger production numbers and stricter quality criteria.

For these reasons, more objective and repeatable methods are being used in current industrial procedures to supplement conventional eye assessment. Manufacturers may lower variability, enhance traceability, and support consistent acceptance standards by integrating quantitative

measuring methods, digital imaging, and data-driven analysis. However, visual inspection is still an important supplementary step, especially when it comes to issues of final product verification and aesthetic assessment.

2.5.1 Advantages and Limitations of Visual Inspection

Visual inspection has been used in industrial quality control for a long time because of its many benefits. Its adaptability is one of its main advantages: human operators may concurrently assess a component's surface polish, color uniformity, geometric consistency, and overall aesthetic appeal. Inspectors can identify complicated or irregular faults that may be challenging to specify using only numerical criteria because to this holistic awareness.

Adaptability is another significant benefit. Skilled operators can adjust their assessment approach based on contextual data, such as manufacturing variances, identified critical zones, or production history. Visual inspection is especially useful in low-volume manufacturing, prototype assessment, or scenarios where inspection requirements change over time because of its adaptability.

Despite these advantages, visual examination has a number of inherent drawbacks. Subjectivity is the biggest drawback: the operator's expertise, eye acuity, and interpretation of acceptance criteria all affect the inspection results. Variations in production shifts and among inspectors might lead to inconsistent decision-making and worse overall repeatability.

Another issue is operator tiredness, particularly in high-throughput industrial settings where repeated operations must be completed continually. Extended visual evaluation may result in less focus and diminished capacity to identify flaws, raising the possibility of both erroneous component acceptance and needless rejection.

The absence of quantitative data is another significant disadvantage of simply visual assessment. Inspection findings are frequently presented as binary judgments, such as "acceptable" or "non-conforming," without including numerical information indicating the extent or direction of deviations. The lack of quantifiable data makes it more difficult to do statistical process analysis, track long-term trends, or create objective performance indicators.

Additionally, traceability becomes more difficult when human observation is the main method of inspection. The lack of comprehensive measurement records makes it challenging to reconstruct inspection circumstances or defend actions in hindsight, even though inspection results may be recorded. This restriction emphasizes the necessity of additional inspection techniques in highly regulated businesses where repeatability and quality documentation are crucial.

In an effort to maintain human knowledge while enhancing objectivity, reproducibility, and data availability, contemporary industrial settings are increasingly combining visual inspection with more organized measuring techniques. Modern inspection techniques aim to strike a balance between qualitative assessment and quantifiable indications that enable constant quality control, rather than doing away with the job of operators.

2.5.2 Current Inspection Workflow at Benelli

The Benelli production environment now employs an AS-IS workflow for inspection, with manual visual inspection carried out in the last stages of the manufacturing process serving as the primary basis for quality control operations. The inspection stage is located downstream in the manufacturing chain, following the completion of barrel assembly and marking processes, as shown in Figure 2-19.

The AS-IS configuration starts with the barrel assembly phase ("Assemblaggio Canna"), which is followed by the weapon assembly and required marking ("Assemblaggio Fucile + Marcatura"). Before going through any thorough inspection, the component already has a substantial production value. After that, the barrel goes through a series of intermediate processing stages before arriving at the "Controllo in bianco" visual inspection stage.

Operators typically use direct observation to check the barrel during this inspection step, evaluating sight line alignment, surface quality, and overall assembly conformance. Instead than using objective numerical metrics, the evaluation mostly depends on operator expertise and qualitative judgment. This method has been successful in the past, but it restricts the traceability of inspection data and creates operator variability.

A The AS-IS workflow's late placement of quality control in the manufacturing chain is a crucial feature. Since corrective actions or supplier returns take place after significant processing has already been finished, the identification of non-conforming components at this point may result in non-quality (N.C.) expenses, as shown in Figure 2-19. Production efficiency may be impacted by this downstream detection, which also raises operational risk.

The barrel moves on to the last packing stage, known as "Confezionamento," after being approved at the visual inspection stage. Therefore, acceptance judgments are mostly relied on visual knowledge rather than automated measuring tools, reflecting a conventional inspection paradigm centered on human evaluation in the AS-IS workflow.

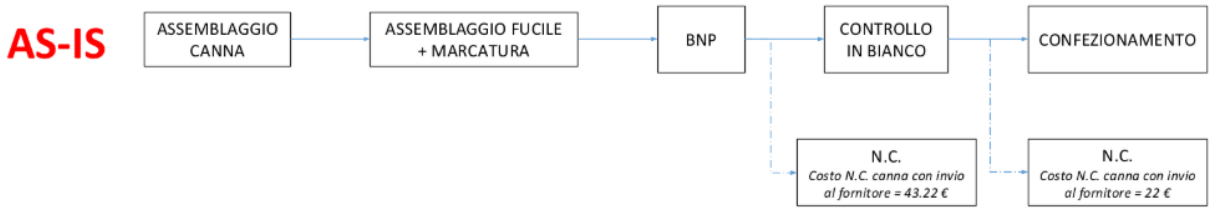

Figure 2-19: AS-IS Process Flow of Barrel Assembly and Quality Inspection

3 3D SCANNING SYSTEM

The 3D scanning system, referred to as Be-Line in Benelli, is a laser-based, non-contact three-dimensional scanning technology designed for automated shotgun barrel inspection in an industrial production setting. The system's architecture reduces reliance on operator subjectivity and manual inspection while supporting objective and repeatable evaluation of crucial geometric metrics. The measuring bench allows for the reliable capture of high-density surface data directly along the barrel's longitudinal axis by combining optical sensing with controlled mechanical motion.

The Be-Line system reconstructs a digital three-dimensional image of the component's outside surface, in contrast to conventional inspection methods that mainly rely on visual evaluation or contact-based measuring tools. As the measuring unit executes a controlled vertical translation, optical sensors collect consecutive barrel portions throughout the scanning operation. A single

point cloud is created by combining the collected data, and this point cloud serves as the geometric reference for all further analytic stages.

The measuring bench combines a number of subsystems, such as motion control, camera units, laser triangulation sensors, mechanical positioning components, and specialized data processing software. This connection allows the system to automatically extract important geometric indications that are used to assess the barrel assembly's conformance. The spatial connection between structural reference pieces, including the codetta and the tasselli, which serve as crucial criteria for alignment verification, is given special consideration.

The acquisition method not only evaluates geometry but also gathers visual data from specific areas of the barrel surface. This allows for the verification of required marks and facilitates digital traceability of components that have been examined. Each inspection cycle can yield objective, repeatable data that can be stored for quality documentation reasons thanks to the combination of automated reporting and three-dimensional measurement.

The optical sensing system's working principle, the measuring bench's hardware and software design, and the procedure for processing the collected data are all covered in depth in the sections that follow.

3.1 Triangulation-based sensing system

One of the most used non-contact measuring methods in industrial metrology for obtaining precise geometric data is optical triangulation. The basic geometric relationship between a light source, a seen surface, and a light-receiving sensor forms the basis of the concept. The distance between the sensor and the target surface may be ascertained without making physical contact by examining the location of reflected light on a detector.

A focused beam is projected toward the examined item by a semiconductor laser via a transmitting lens, as shown in Figure 3-1. When a laser beam hits a surface, it is reflected and picked up by a receiving lens. This lens then focuses the reflected signal onto a light-receiving component such a linear CCD or CMOS sensor. The distance between the sensor and the measured surface affects

the location of the reflected spot on the receiving element. This displacement is transformed into an exact spatial coordinate via geometric triangulation.

The stable baseline between the laser emitter and the optical receiver is necessary for the measuring principle. The detected position on the sensor array shifts when the surface approaches or moves away from the sensor due to variations in the angle of the reflected beam. The system transforms the optical data into quantitative distance information by using calibration parameters that are generated from the sensor geometry. Detailed surface profiles may be reconstructed by repeating this method throughout a scanning route.

For industrial inspection applications, triangulation-based sensing provides a number of benefits. High acquisition speed, precise spatial resolution, and the capacity to measure intricate geometries without mechanical touch are all made possible by the technique. Furthermore, optical triangulation is well suited for applications needing accurate geometric analysis since it is especially good at identifying minute deviations on structured surfaces.

Despite these benefits, the method is susceptible to surface characteristics such coating type, reflectance, and roughness. Surface finish variations might affect reflected light intensity and distribution, necessitating careful adjustment of acquisition parameters including exposure duration and optical setup. Because of this, triangulation systems are usually designed based on the predicted measurement circumstances and the properties of the material being investigated.

The general working principle of laser triangulation is depicted in Figure 3-1, which highlights the interaction between the semiconductor laser, transmitting optics, receiving lens, and light-receiving element used to determine the position of the measured surface.

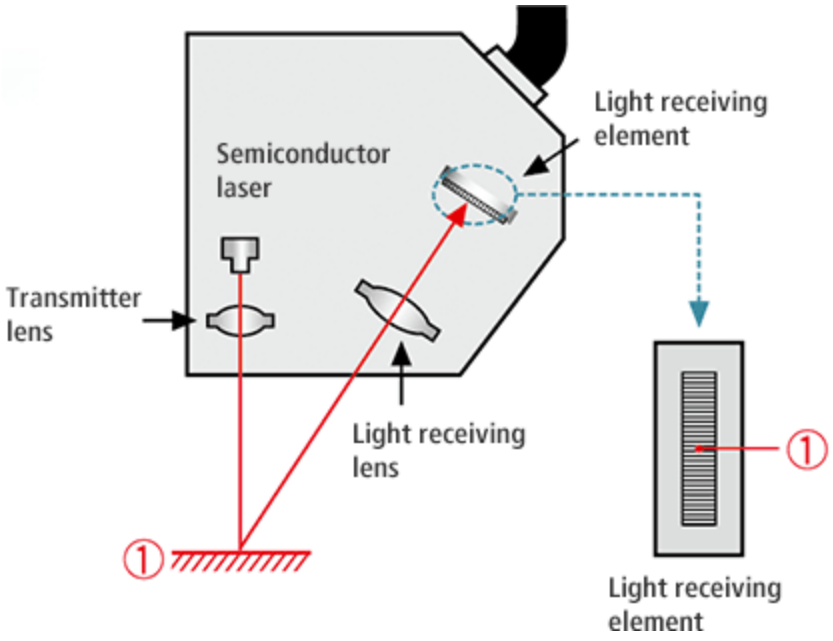

Figure 3-1: Schematic Representation of Laser Triangulation Geometry

3.2 Measurement bench architecture

In an industrial production setting, the Be-Line system is used as an integrated non-contact measuring bench for automated shotgun barrel assembly inspection. The design reduces reliance on human inspection processes while providing repeatable and traceable measurements by integrating mechanical positioning, optical sensing, data processing, and user interface on a single platform.

The measuring bench has been designed to offer a stable and regulated acquisition environment from a structural perspective. To guarantee measurement reproducibility and reduce the impact of outside disturbances like vibrations or changes in operator handling, mechanical stiffness, regulated motion, and uniform barrel alignment are crucial. Thus, robustness and alignment stability are given top priority in the bench's design, enabling the scanning procedure to be carried out under uniform geometric circumstances.

In order to guarantee consistent placement in relation to the system reference frame, the barrel is fixed on a special fixture. With this arrangement, the measuring procedure can follow a

predetermined scanning trajectory along the component's longitudinal axis. The technology guarantees that the obtained data is similar across many measurement cycles and production batches by keeping the optical sensors and the examined surface in a fixed relative orientation.

The architecture of the Be-Line bench can be conceptually divided into two main subsystems:

• a **hardware subsystem**, responsible for mechanical support, optical acquisition, sensor positioning, and signal generation;

• a **software subsystem**, responsible for data acquisition, data processing, KPI extraction, visualization of results, and automatic report generation.

The system may function as a single measuring platform while retaining configuration and future upgrade flexibility because to the separation of hardware and software components. While the software converts the collected data into quantifiable indicators for quality assessment, the hardware supplies the physical infrastructure needed for data collecting.

The hardware architecture and software framework that collectively comprise the Be-Line measuring bench's operating process are thoroughly explained in the next subsections.

3.2.1 Hardware architecture

In order to provide mechanical stability, consistent placement, and dependable acquisition conditions during non-contact examination of shotgun barrels, the Be-Line measuring bench's hardware architecture was created. The system combines mechanical, optical, and structural elements into a single measuring platform that can recreate the sight-line configuration and barrel geometry in an industrial setting.

All motion and sensor components are supported by a robust mechanical frame that makes up the core structure. This frame ensures consistent geometric reconstruction by offering the rigidity needed to reduce vibrations and positioning variations during scanning. Additionally, the structural arrangement keeps the optical sensors and the barrel's reference axis precisely aligned, which is crucial for preserving measurement precision during the acquisition process.

A specialized fixturing system made comprised of an upper constraint element and a bottom support is used to place the barrel inside the machine. This arrangement permits effective loading and unloading processes while guaranteeing stable placement during scanning. By keeping the barrel oriented consistently with respect to the machine coordinate system, the fixture minimizes the variability caused by manual manipulation.

Finding a system that could provide the lowest measurement uncertainty while preserving a large enough measurement field to reconstruct the barrel's whole geometry was how the optical sensor was chosen. Wenglor MLSL131 laser triangulation sensors were used for this. The working field simulation displays the effective measurement volume that may be achieved on a standard barrel layout, as shown in Figure 3-2. As seen in Figure 3-3, the sight-line geometry may be reconstructed with better coverage and less occlusion effects by using two laser sensors symmetrically positioned at around ±60° relative to the barrel axis.

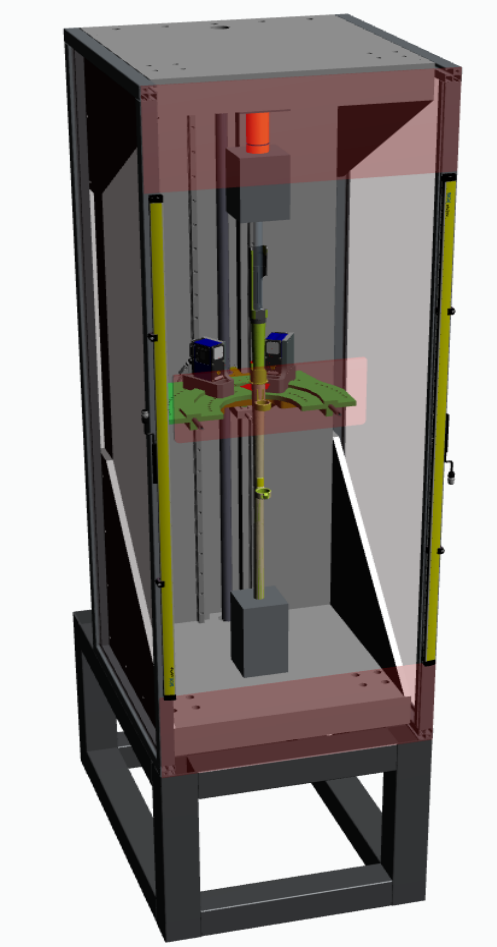

Figure 3-2: Dual Laser Triangulation Sensor Setup for Automated Barrel Inspection

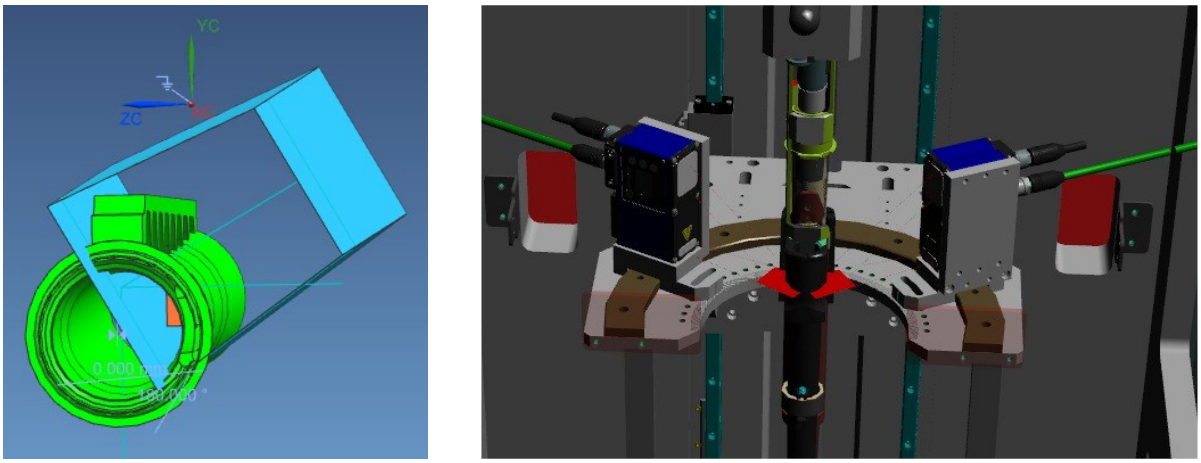

Figure 3-3: Dual Laser Triangulation Sensor Configuration and Measurement Field Simulation

A motorized carriage that travels vertically along precise linear guides holds the laser-camera modules. The carriage is placed at the barrel's top extremity at the start of each measurement cycle. In order to continuously collect surface profiles along the longitudinal axis, the carriage descends at a regulated and steady pace throughout acquisition. The acquisition phase concludes when the lower limit is reached, and the carriage returns to its starting position, readying the system for the subsequent inspection cycle.

A protective enclosure encloses the whole measuring bench to guarantee stable acquisition circumstances. By protecting the optical sensors from outside light sources and environmental disruptions, this enclosure ensures constant lighting conditions and lowers measurement variability between scans.

3.2.2 Software architecture

The measuring bench's software architecture is in charge of handling the data gathered, organizing the acquisition process, and obtaining the numerical indicators needed for dimensional evaluation. Its main function is to provide consistency and reproducibility throughout the measurement cycle by coordinating sensor collection, mechanical motion, and data processing.

The program loads the proper acquisition settings based on the chosen barrel configuration at the beginning of each inspection. The scanning range, exposure conditions, and motion settings necessary to guarantee steady data capture are some of these factors. The software maintains exact synchronization with the vertical movement of the sensor carriage while continually recording surface profiles taken by the laser-camera units during the scanning phase.

Following the scan, a rototranslation and merging process is used to the data obtained from the two optical sensors to produce a single unified three-dimensional point cloud, as shown in Figure 3-4. All geometric characteristics may be represented inside a single reference coordinate system thanks to this reconstruction stage, which makes it possible to consistently assess the positional connections between the barrel assembly's functional components.

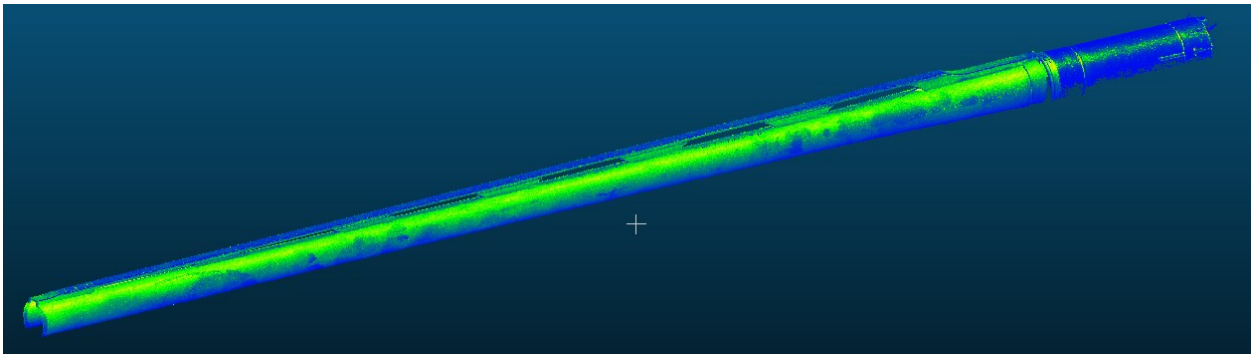

Figure 3-4: Cloud Compare Visualization of the Reconstructed Barrel Point Cloud

Dedicated processing methods calculate quantitative indicators utilized during inspection and extract certain geometric characteristics from the rebuilt point cloud. These contain additional geometric KPIs including linearity and planarity of the sight line, as well as positional deviation between reference pieces (Dis. tasselli – codetta [mm]). Concurrently, image-based analysis procedures assess whether mandatory barrel inscriptions are present and how deep they are, offering supplementary indicators of regulatory compliance Figure 3-5.

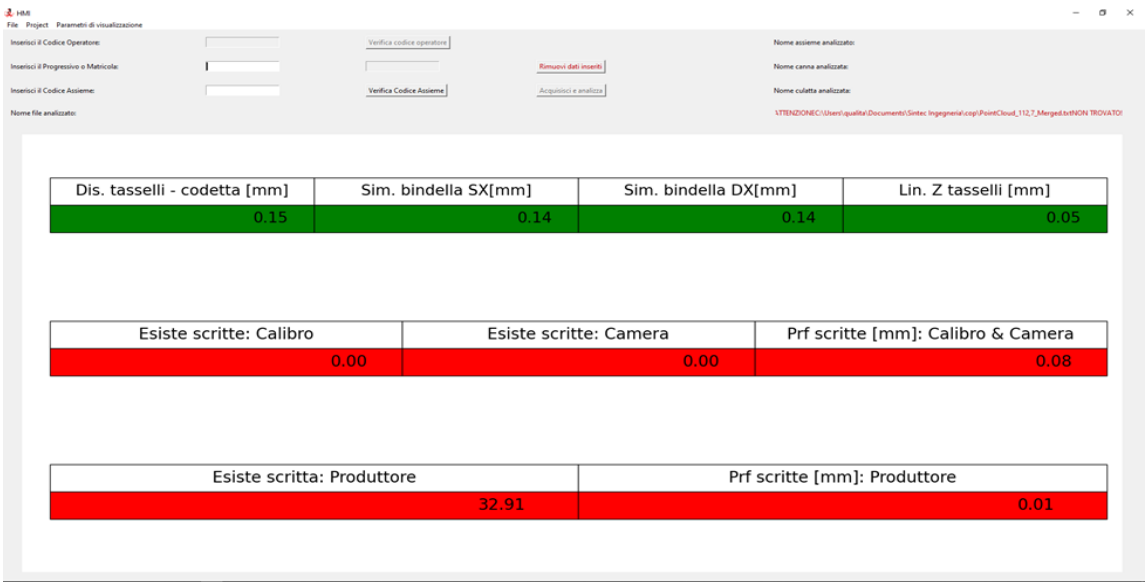

Figure 3-5: Automated KPI Evaluation and Barrel Inscription Analysis Interface

The software environment facilitates the study of surface areas with required inscriptions in addition to geometric assessment. Dedicated processing procedures assess the geometric

properties of the predicted marks and confirm their existence using the same collected data. Within the inspection procedure, all computed indicators and identification data are subsequently arranged and ready for reporting and visualization.

A specific graphical user interface that summarizes the primary geometric indications taken from the three-dimensional reconstruction is used to convey the processed findings to the operator. A structured representation of the computed parameters, including indicators for tasselli placement, rib alignment, and the confirmation of required inscriptions, is offered via the interface. The primary numerical reference utilized during manufacturing to assess the positional connection between structural elements connected to the sight line configuration is represented by the parameter Dis. tasselli – codetta [mm]. The program ensures uniformity between inspection cycles and enables quick interpretation of measurement findings by presenting the data in a consistent digital format.

The software design has an enhanced administrative interface that offers expanded diagnostic and analytical capabilities in addition to the basic operator interface that shows the major inspection indicators. As seen in Figure 3-6, this administrative view provides a more thorough depiction of the processed data, including a graphical representation of the misalignment between structural elements and the barrel assembly. Additionally, the interface offers specific visualizations pertaining to the sight line's linearity and planarity faults (Figure 3-7), enabling a more thorough evaluation of geometric deviations beyond the primary KPI indications. In order to confirm the presence and legibility of the markings, the administrative part also contains extracted photos of the barrel inscriptions that were found (Figure 3-8). This dual-level interface structure gives engineers and quality staff sophisticated analytical tools for process improvement, troubleshooting, and validation while allowing operators to concentrate on critical production indicators.

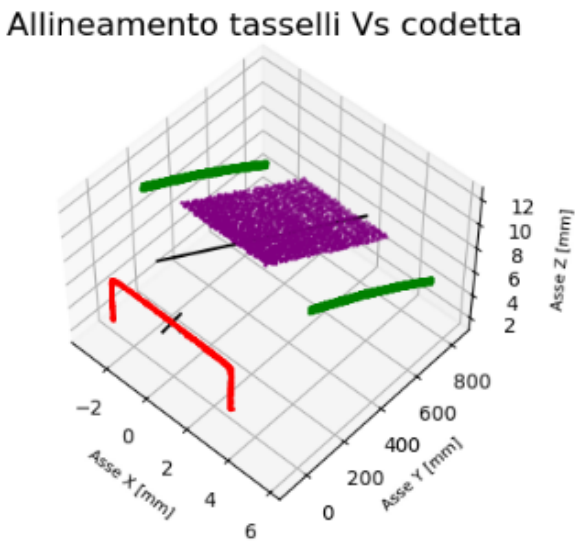

Figure 3-6: 3D Misalignment Analysis in Administrative Inspection Interface

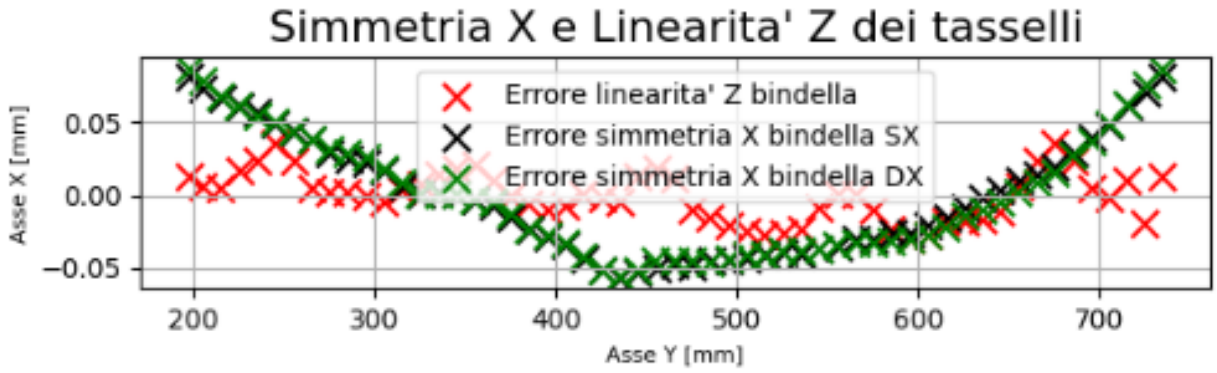

Figure 3-7: Administrative Interface Visualization of Sight Line Linearity and Planarity Errors

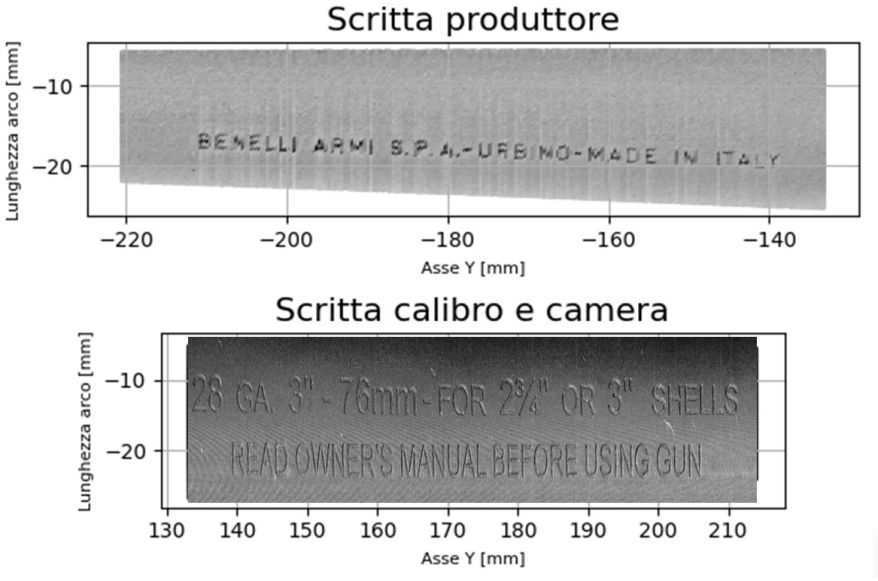

Figure 3-8: Administrative View of Detected Legal Markings

3.3 Measurement procedure by 3D Scanning System

The Be-Line system's measurement workflow is built on a systematic sequence that combines geometric analysis, point cloud reconstruction, acquisition parameter selection, and KPI extraction. The process is intended to be repeatable and flexible enough to accommodate various barrel assemblies and surface conditions.

A specific acquisition recipe is started at the start of every inspection cycle based on the kind of barrel assembly, which is determined by the matching barrel code. The primary acquisition parameters, such as the start and end locations of the scan, which change according on the component's shape, and the exposure duration, which is modified based on the barrel's surface finish, are defined by the chosen recipe. The spatial sampling step utilized during acquisition is constant despite these adjustable settings, guaranteeing consistent point density throughout measurements.

Following the scanning stage, a rototranslation method is used to align the data obtained by the two optical sensors inside a shared reference system. After that, the aligned datasets are combined

to create a single, cohesive point cloud that represents the barrel's scanned area. All following processing procedures are based on this combined geometry.

After that, the rebuilt point cloud moves on to the processing phase, where different analytical techniques are used depending on the kind of barrel assembly under examination. The implemented algorithms take into account various configurations of components, such as sheath-barrel assemblies with rib configurations, breech-barrel assemblies with trigger guard elements, and breech-barrel assemblies with rib structures. For each configuration to accurately identify reference geometries and functional pieces, certain feature extraction techniques are needed.

The first step in processing rib and bridge assemblies is to remove the rib's top plane from the point cloud. The lateral planes on the left and right sides are found by applying cutting sections to this plane. A reference line that describes the rib axis is created by interpolating between these lateral planes and the top plane. To guarantee correct alignment between the measurement frame and the component's physical shape, the barrel reference coordinate system is then rotated with respect to this rib axis.

Further geometric analysis is done for the breech and sheath components. A mean plane is computed by extracting the lateral planes related to the tang or sight line area. A representative mean line is then produced by interpolating this plane with the top plane of the tang or sight line. The centroid of the breech tang or sheath sight line is calculated to identify its ultimate location, giving a reference feature for further KPI measurement.

A number of KPIs are computed to assess the barrel assembly's conformance based on the retrieved geometric areas. These indications include the flatness error of the rib or bridge plane, the linearity error of the lateral rib planes, and the misalignment of the sight line, which is represented as the positional deviation of the breech tang centroid or sheath sight line. When combined, these metrics offer a numerical characterization of structural consistency and alignment quality.

The processing procedure retrieves characteristics linked to the verification of required legal inscriptions in addition to geometric indications. In order to project the inscription onto a flattened surface produced from design data, this process subtracts the obtained point cloud from the

nominal reference geometry in the area containing the lettering. The presence and engraving depth of the markings are then confirmed using depth analysis and optical character recognition (OCR) techniques, guaranteeing regulatory compliance.

All computed indications are shown in the graphical user interface at the conclusion of the processing sequence, giving operators a structured summary of the inspection findings and facilitating quick interpretation of measurement data.

3.4 Typical exposure time concerning the type surface

The exposure duration of the optical sensors in the Be-Line 3D scanning system is a crucial acquisition parameter that needs to be modified in accordance with the barrel's surface finishing. To guarantee a thorough and accurate reconstruction of the geometry, various coatings and treatments require particular exposure settings since laser triangulation is extremely sensitive to reflectivity and roughness.

The ideal exposure time is first established through an iterative validation procedure when a new barrel type or surface condition is introduced. An estimated exposure value is used for a preliminary scan, and Cloud Compare is used to assess the generated point cloud. In this assessment stage, the operator confirms the existence of acquisition flaws such gaps or holes (Figure 3-10) or spikes (Figure 3-9), which usually signify an improper balance between reflected signal strength and sensor saturation. If such artifacts are found, the scanning procedure is repeated and the exposure value is changed until a stable and continuous point cloud is formed (as shown in Figure 3-11).

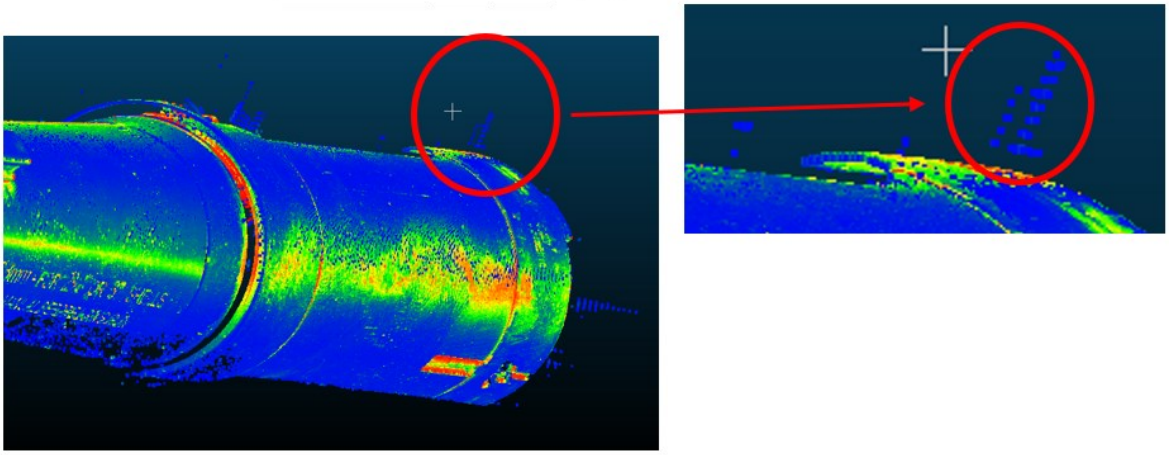

Figure 3-9: Spike Artifacts in Point Cloud Data Due to Improper Exposure Calibration

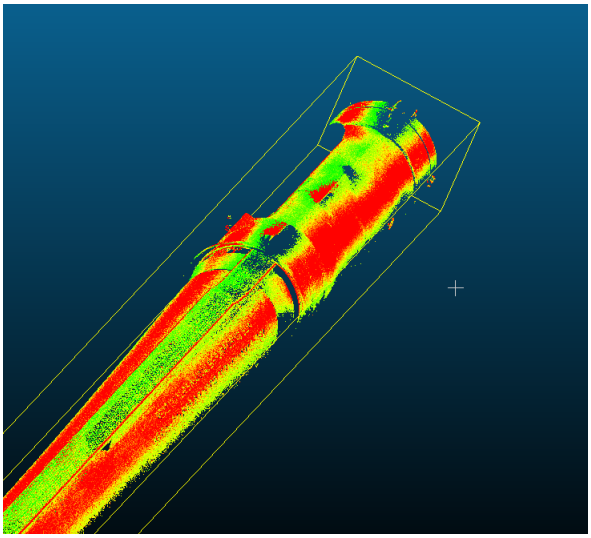

Figure 3-10: Acquisition Holes Detected During Exposure Calibration Phase

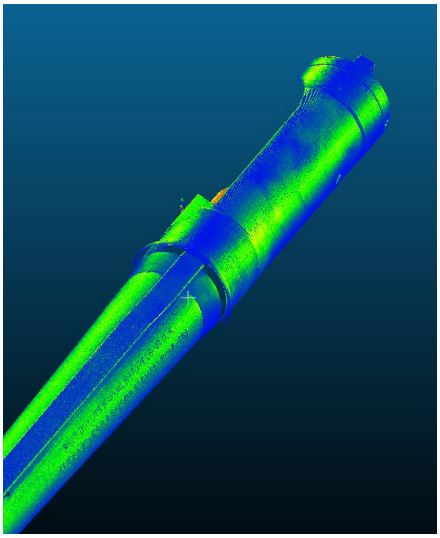

Figure 3-11: Validated Point Cloud Quality Following Exposure Calibration

The parameter is verified and saved in the Be-Line software environment when the proper exposure setting has been found. The acquisition recipe linked to the particular barrel surface type includes the verified exposure time. Because the program automatically retrieves the previously verified parameters, further measurements of barrels with the same finishing do not require human

modification. This process enables a uniform inspection workflow, minimizes operator reliance, and guarantees consistency in data collecting.

In general, defining and validating exposure duration is a crucial step in ensuring the 3D reconstruction process is of high quality. The Be-Line system delivers consistent and dependable acquisition performance across a variety of surface treatments by integrating recipe-based parameter storage with empirical analysis in Cloud Compare.

It is now feasible to forecast the ideal exposure time based on both the surface's aesthetic qualities and past acquisition data gathered for comparable finishes through repeated measurements and data analysis. This experience-based enhancement enhances measurement reproducibility across various manufacturing batches and drastically cuts setup time.

The usual exposure periods for a number of surface types used in manufacturing, such as glossy finishes, matte burnished surfaces, camouflage coatings, and Cerakote treatments, are compiled in Table 1. These numbers stand for reference settings that are obtained from both cumulative operating experience and experimental data. The goal of adjusting exposure duration is to maximize the quality of the obtained point cloud, reduce optical noise, and enhance surface reconstruction fidelity rather than changing the measurement process itself.

Surface Type	**Exposure time[µs]**
Assieme canna-componente: BEST Glossy	3500
Assieme canna-componente: Best Matte	2000
Assieme canna-componente: Glossy burnished	2000
Canna: Matte Glossy burnished Componente: Nichelato	2000
Canna: Matte burnished Componente: Nichelato	900
Assieme canna-componente: Matte burnished	500
Canna: Camouflage Componente: Matte burnished	500

Assieme canna-componente: Cerakote	500

Table 1: Typical Exposure Times for Different Surface Types

3.5 Measurement report

The Be-Line system automatically creates a digital inspection report linked to the scanned barrel at the conclusion of every measurement cycle. After the acquisition and processing stages are finished, the report is generated automatically and made instantly accessible, guaranteeing a continuous and verifiable inspection workflow. Figure 3-12 is an example of an automatically created report with recorded data arranged in a defined, structured way.

Important identifying details, such as the operator code, assembly code, progressive measurement number, and the date and time of inspection, are included in every report. These components provide complete traceability in the manufacturing environment by creating a direct connection between the physical component processed on the measuring bench and its matching digital record. Each inspection event may be uniquely recorded and retrieved when needed thanks to the automated link between identifying data and measurement findings.

The parameter **Dis. tasselli-codetta [mm]**, which is the main indication used during manufacturing to assess geometric conformance, is one of the numerical values obtained from dimensional analysis that are included in the report. The report summarizes additional inspection indicators that were taken from the three-dimensional reconstruction, such as linearity and planarity errors related to the sight line and the confirmation of the existence and depth of required inscriptions, in addition to this crucial positional parameter. Operators and quality engineers may quickly and thoroughly review the results of the inspection thanks to the display of these measurement values in a standardized manner.

The barrel is deemed compliant and moves on to the last stage of the production process when the measured value meets the predetermined acceptance criteria. At this point, before the manufacturing process is finished, operators do an extra check to validate the component's overall quality. This method contributes to a strong and dependable inspection strategy by fusing human

experience with computerized quantitative evaluation.

Retrospective examination of production data, internal auditing, and quality documentation are all supported by the automatic creation and archiving of measurement reports, like the example in Figure 3-12. Each report facilitates traceability and long-term monitoring of factory performance by acting as a permanent digital record of the inspection carried out on a particular barrel at a particular moment.

The measuring system creates an organized framework for non-contact dimensional inspection by combining automated acquisition, numerical analysis, and digital reporting. This improves process transparency, documentation, and repeatability in shotgun barrel manufacturing.

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Codice Operatore:	Codice Assieme:	Codice Progressivo	Codice Matricola	Nome F:
C0211600_1	PY_VAR11	PY_VAR12	2026 - 01 - 19 08:55:13	0.01
C0211600_2	PY_VAR35	PY_VAR36	2026 - 01 - 19 09:02:23	0.24
C0211600_3	PY_VAR11	PY_VAR12	2026 - 01 - 19 09:08:01	-0.04
C0211600_4	PY_VAR35	PY_VAR36	2026 - 01 - 19 09:13:40	0.22
C0211600_5	PY_VAR59	PY_VAR60	2026 - 01 - 19 09:19:35	0.16
C0211600_6	PY_VAR83	PY_VAR84	2026 - 01 - 19 09:28:15	0.01
C0211600_7	PY_VAR107	PY_VAR108	2026 - 01 - 19 09:34:41	-0.07
C0211600_8	PY_VAR131	PY_VAR132	2026 - 01 - 19 09:40:00	0.01
C0211600_9	PY_VAR155	PY_VAR156	2026 - 01 - 19 09:44:29	0.32
C0211600_10	PY_VAR179	PY_VAR180	2026 - 01 - 19 09:49:17	-0.09
C0211600_11	PY_VAR203	PY_VAR204	2026 - 01 - 19 09:53:42	0.32
C0211600_12	PY_VAR227	PY_VAR228	2026 - 01 - 19 09:58:28	-0.04
C0211600_13	PY_VAR251	PY_VAR252	2026 - 01 - 19 10:03:05	0.30
C0211600_14	PY_VAR275	PY_VAR276	2026 - 01 - 19 10:25:11	0.15
C0211600_15	PY_VAR299	PY_VAR300	2026 - 01 - 19 10:29:05	0.05
C0211600_16	PY_VAR323	PY_VAR324	2026 - 01 - 19 10:33:51	-0.04
C0211600_17	PY_VAR347	PY_VAR348	2026 - 01 - 19 10:38:11	0.28
C0211600_20	PY_VAR419	PY_VAR420	2026 - 01 - 19 10:51:19	0.11
C0211600_21	PY_VAR443	PY_VAR444	2026 - 01 - 19 10:55:42	-0.16
C0211600_22	PY_VAR467	PY_VAR468	2026 - 01 - 19 11:00:40	0.13
C0211600_23	PY_VAR491	PY_VAR492	2026 - 01 - 19 11:04:53	0.10
C0211600_24	PY_VAR515	PY_VAR516	2026 - 01 - 19 11:08:42	-0.01
C0211600_25	PY_VAR539	PY_VAR540	2026 - 01 - 19 11:12:38	0.35
C0211600_18	PY_VAR563	PY_VAR564	2026 - 01 - 19 11:41:31	-1.69
C0211600_19	PY_VAR587	PY_VAR588	2026 - 01 - 19 11:46:18	1.44

Figure 3-12: Measurement Data Report Generated by the Be-Line

3.6 Inspection Workflow to Be Implemented at Benelli

The inspection process and how it interacts with the current assembly and quality control stages must be well defined in order to integrate the automated inspection bench into the production

environment. The suggested "TO-BE" workflow is shown in Figure 3-13, which also highlights the measurement bench's place in the entire production sequence and the anticipated gains in defect management and process efficiency.

The inspection bench is placed just after the barrel assembly stage (assemblaggio canna) in the suggested layout. The workflow makes it possible to quickly identify non-conforming components before they go on to later processes like marking, final assembly, or packing by using dimensional verification at this early stage. In contrast to conventional inspection methods, which frequently carried out verification tasks later in the process, this upstream posture signifies a strategic change.

T Before further value-adding activities are performed, any deviations pertaining to sight-line alignment and structural location can be identified through the use of the measuring bench. Early detection of non-conforming barrels lowers the possibility of rework or scrap at downstream stations, where remedial efforts would result in increased operating costs, as shown in Figure 3-13. In particular, preventing defective components from reaching marking, white inspection (controllo in bianco), and packaging stages contributes to minimizing non-conformity costs and improving production flow continuity.

From an operational standpoint, the automated inspection stage functions as a manufacturing chain decision gate. While non-conforming parts can be routed toward remedial measures without compromising the effectiveness of succeeding operations, barrels that meet the acceptance requirements go into assembly and packing. This methodical process combines traceable measurement data with early detection to offer a more comprehensive quality assurance approach.

Additionally, by lowering dependence on subjective visual judgment at intermediate phases of manufacturing, the automated inspection bench helps standardize processes. A progressive shift to a more data-driven quality control system is supported by the workflow shown in Figure 3-13, which shows how digital inspection findings may be incorporated into the current production structure without interfering with established activities.

By adding an objective verification step at a crucial stage in the process, lowering downstream non-conformity costs, and enhancing the overall consistency of shotgun barrel manufacture at

Benelli, the suggested "TO-BE" inspection workflow improves production efficiency overall.

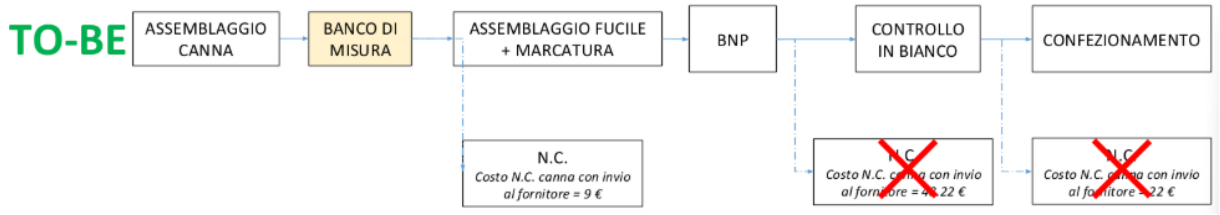

Figure 3-13 :TO-BE Process Flow of Barrel Assembly and Integrated Measurement Inspection

4 MEASUREMENT BENCH VALIDATION

A crucial stage in guaranteeing that the produced data are dependable, reproducible, and appropriate for industrial decision-making is the validation of a measuring system. Validation is essential in automated non-contact inspection settings because measurement results have a direct impact on product acceptability, manufacturing efficiency, and perceptions of overall quality.

In order to supplement and partially replace conventional verification methods, the Be-Line measuring bench has been created as a non-contact shotgun barrel inspection option. Therefore, it is vital to show that the system delivers measurements that are in line with Benelli's quality criteria and compatible with established metrological references prior to its integration into the production workflow.

Verifying the Be-Line system's capacity to precisely measure the crucial geometric parameters utilized for barrel assessment is the aim of the validation procedure. The accuracy of numerical findings obtained from the three-dimensional scanning process, the consistency of measurements over several acquisition cycles, and the system's resilience under various barrel designs and surface conditions are all given special consideration.

Comparing measurements made with the Be-Line system to reference measurements made with a Coordinate Measuring Machine (CMM) is a key component of the validation process. CMMs are frequently regarded as high-accuracy reference devices in industrial metrology because of their

traceability and well-characterized measurement uncertainty. Because of this, the Be-Line inspection bench's performance and dependability are evaluated using CMM data as a standard.

Through the analysis of several samples and several measurement cycles, the validation technique also mimics realistic manufacturing circumstances. This method makes it possible to assess measurement accuracy as well as consistency and repeatability, which are crucial features for an inspection system meant to be integrated into an industrial process.

The validation procedure looks at the system's capacity to enable trustworthy production decisions in addition to dimensional agreement. The measurement uncertainty related to the Be-Line bench must be kept low enough to prevent misleading classifications because barrel approval is dependent on numerical comparison with predetermined tolerance limits, especially for components placed close to acceptance thresholds.

The technological basis for using the Be-Line system as a production inspection tool is provided by the validation activities' outcomes. Additionally, they help define operating limitations, comprehend system behavior, and pinpoint possible development areas. For these reasons, a key element of the current thesis is measurement bench validation, which connects the system's technological description to its real-world industrial application.

The experimental activities conducted during the validation phase, including as sample analysis, measurement techniques, comparison assessments, calibration tasks, and performance evaluation, are described in the sections that follow.

4.1 Analysis samples

The evaluation of pump-action barrel assemblies is the main focus of the experimental validation described in this study, with special emphasis paid to the geometric alignment connected to the sight line reference characteristics. This phase's goal is to confirm that, when used on actual production components, the Be-Line inspection bench can produce measurement results that are compatible with reference metrological equipment.

A dataset made up of about 25 pump-action barrel samples was chosen from the manufacturing environment to guarantee a representative assessment. The validation can reflect genuine industrial settings rather than ideal laboratory circumstances since the selected samples cover a variety of geometric variables and natural process variability. In accordance with internal validation procedures, the number of examined samples was determined, offering a statistically significant foundation for evaluating system behavior and comparing measurement results.

A dual-measurement approach was used to each sample. In order to get the geometric indicators needed during manufacturing, the barrels were first examined using the non-contact scanning technology, with a focus on the positional parameter related to pump-action alignment. A Coordinate Measuring Machine (CMM), which is a reference metrological system because of its high precision and traceable measurement uncertainty, was then used to measure the identical samples. The basis for assessing the inspection bench's dependability is the comparison between these two datasets.

The chosen samples show whole barrel assemblies set up for pump-action mechanisms, where structural element alignment is crucial to functional performance. Pump-action assemblies are especially useful for verifying the inspection system's capacity to identify positional deviations as, in contrast to other barrel layouts, they necessitate particular attention to the relative placement of components engaged in mechanical motion.

The validation method attempts to ascertain if the inspection bench yields consistent findings across numerous acquisitions and whether the detected deviations continue to be compatible with production requirements by analyzing about 25 samples. Along with supporting the assessment of measurement uncertainty covered in the next sections, the gathered data also makes it possible to identify any systematic differences across measuring methods.

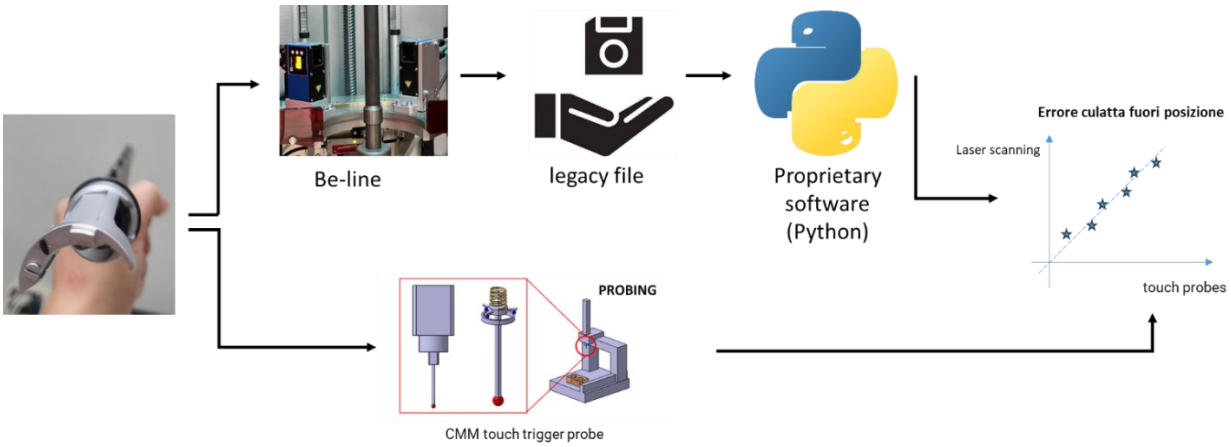

Figure 4-1: Comparison Workflow Between Laser Scanning and CMM Probing for Pump Action Validation

The objective is to validate the Be-Line measurement system for pump-action alignment measurements. While for the semi-automatics, the qualification had already been completed before my internship.

4.2 Measurement procedure by CMM

Figure 4-2: CMM Measurement Setup for Be-Line Alignment Verification

Two distinct inspection systems were used to develop a systematic measuring method in order to certify the Be-Line measurement bench: the Be-Line laser scanning system and a Coordinate Measuring Machine (CMM), which was used as a reference instrument. Results from contact-based and non-contact-based methods may be directly compared by using a dual-measurement methodology.

The positional connection between the bindella and the finta codetta, which is the primary alignment characteristic being studied, is the main focus of the CMM measuring technique, which was designed to offer a very precise reference for alignment verification.

The barrel was firmly fixed on the CMM fixture prior to measurement in order to guarantee mechanical stability and consistent placement during the probing procedure. Every effort was

made to prevent the introduction of residual stresses or deformations that could affect the measurement result.

The initial stage in the CMM process is to define the bindella's upper plane. In order to determine the orientation of the measurement coordinate system, this plane serves as the main geometric reference. Since all future measurements are stated in relation to this reference, precise identification of this plane is crucial.

Ten discrete measurement points were obtained on the left side of the bindella using a touch-trigger probing method once the plane was defined. To capture any variations and guarantee representative sampling of the feature, these sites were dispersed along the longitudinal direction.

Using the same distribution method, a second set of ten measurement sites was then obtained on the bindella's right side. The acquisition of data on both sides offers a solid foundation for determining the bindella axis and enables the assessment of symmetry.

The Cartesian coordinate system was oriented with relation to the bindella axis based on the measured bindella geometry. This phase minimizes the impact of setup-related misalignments by ensuring that positional deviations are assessed in a consistent and physically relevant reference frame.

After establishing the coordinate system, discrete probing was used to measure the codetta's midpoint. The secondary reference feature for alignment verification with respect to the bindella is represented by this point.

The notional finta codetta location, as specified by the design requirements, was then converted from the measured codetta midpoint. The observed geometry and the notional reference configuration may be directly compared thanks to this translation.

Lastly, the difference between the translated measured position and the nominal reference was used to calculate the finta codetta's positional error. The reference measurement that is utilized to compare the outcomes of the Be-Line system is this value.

4.3 Comparative analysis: CMM vs. Be-Line

The goal of the comparison validation phase is to assess how well measurements taken using a Coordinate Measuring Machine (CMM), the reference metrological system, and those taken from the Be-Line inspection bench are consistent. A crucial functional characteristic in the examination of pump-action barrel assemblies is the positional alignment related to the sight-line reference features.

About twenty-five pump-action barrel samples were chosen from the manufacturing environment to guarantee a realistic assessment of the measurement performance. Because the chosen dataset has realistic assembly settings and genuine process variability, the validation can represent real-world industrial situations rather than perfect lab setups. Because both technologies were used to test each sample, the non-contact optical measurements and the reference contact-based measurements could be directly compared.

The connection between the CMM values and the Be-Line findings is displayed under unacceptable circumstances in Figure 4-3, which presents the first comparison between the two measurement datasets. A weak linear connection between the systems during this phase is shown by the dispersion of the measurement points and the comparatively low coefficient of determination ($R2 = 0.2564$). The significant dispersion indicates the existence of external disturbances impacting the measurement stability rather than an inherent restriction of the sensing device itself, even though a general positive trend is evident.

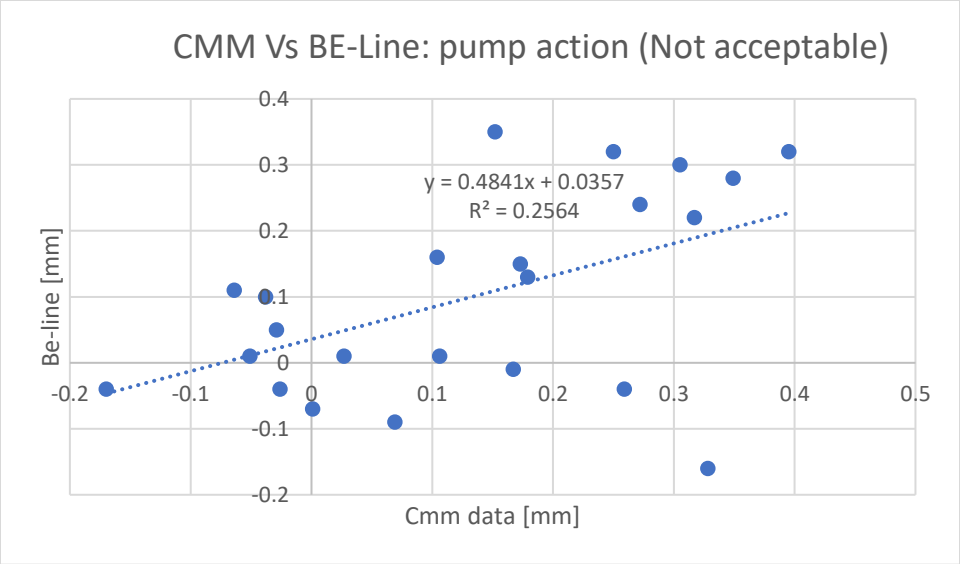

Figure 4-3: CMM vs. Be-Line Correlation for Pump Action (Non-Acceptable Conditions)

In order to find possible causes of systematic error, a thorough mechanical examination of the measuring bench was carried out after this observation. A fixture-related problem that affected the barrel's positional stability during scanning was found during the inquiry. The mechanical component indicated by the arrow in Figure 4-4 was not correctly fastened, causing the barrel to move slightly during acquisition. Variations in the reference alignment brought forth by this instability resulted in inconsistent measurement outcomes and a decreased correlation with the reference CMM readings.

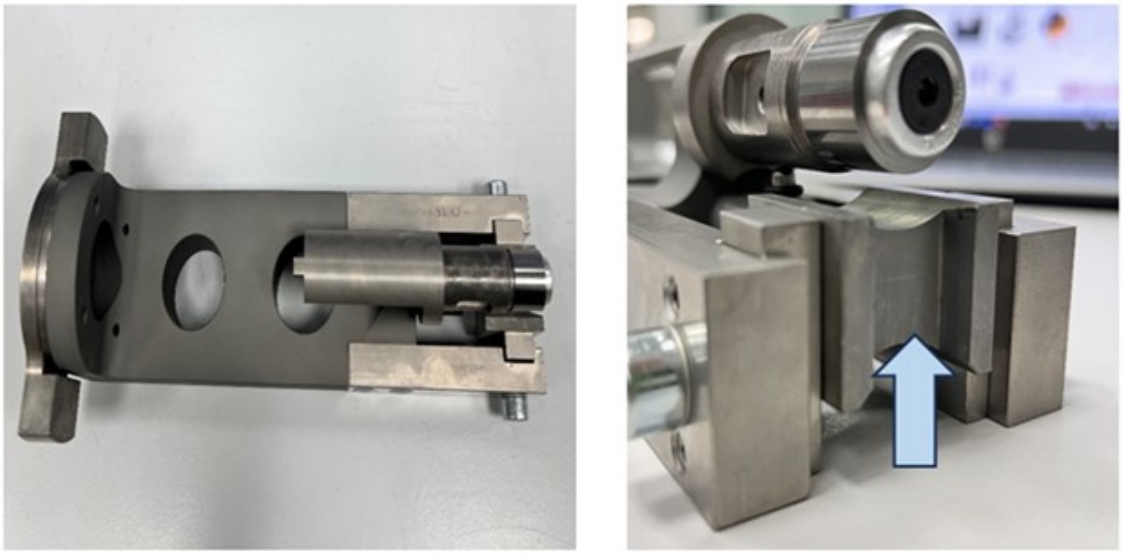

Figure 4-4: Identified Fixture Issue in the Be-Line Barrel Measurement Instrument

The validation process was repeated with the same set of samples after the fixture configuration was adjusted and the barrel's mechanical restriction was ensured. A notable improvement in correlation is shown in Figure 4-5, which displays the revised comparison. Strong agreement between the Be-Line measurements and the CMM reference values is demonstrated by the regression analysis's significantly higher coefficient of determination ($R^2 = 0.8609$). The decrease in data dispersion indicates that mechanical instability, not limits of the optical measuring technique, was the source of the disparities seen during the first phase.

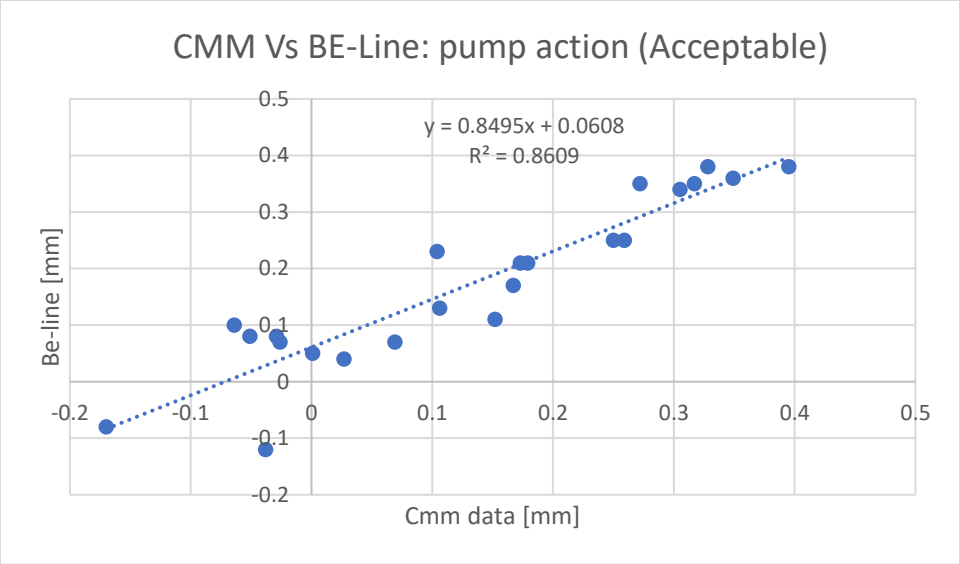

Figure 4-5: Be-Line Correlation for Pump Action (Acceptable Conditions)

The significance of mechanical resilience in automated inspection systems is shown by this comparative examination. The stability of the fixturing system and the repeatability of the positioning circumstances determine the total measurement reliability, even when the sensor technology offers high-resolution data. The Be-Line bench's appropriateness for production inspection of pump-action barrel assemblies was supported by its constant performance in line with the reference metrological system after the mechanical problem was fixed.

4.4 Calibration bar

A specific calibration exercise was part of the measurement bench validation process, which evaluated the optical triangulation system's intrinsic geometric reliability without reference to actual barrel assemblies. In order to assess the linearity of the acquisition process, the consistency of sensor motion, and the lack of systematic distortions during scanning, a reference artifact with validated geometry and high dimensional stability was needed.

As seen in Figure 4-6, a silicon-carbide (Si-SiC) parallel rule was chosen as a calibration artifact. Because of its exceptional stiffness-to-weight ratio, great wear resistance, and low thermal expansion coefficient, silicon carbide is frequently used in high-precision metrology. Si-SiC

structures are especially well-suited for optical measuring systems based on laser triangulation because they offer better dimensional stability and less vulnerability to environmental changes when compared to conventional granite references.

Art.	Cod.	Size mm LxWxH	Class	□ // µm	KG
RS	0770	750 x 54 x 114	00	3.5	7.1
RS	0750	750 x 54 x 114	000	1.8	7.1
RS	0771	1000 x 54 x 114	00	4.0	9.5
RS	0751	1000 x 54 x 114	000	2.0	9.5
RS	0772	1500 x 54 x 154	00	5.0	18
RS	0752	1500 x 54 x 154	000	2.5	18
RS	0773	2000 x 74 x 154	00	6.0	26
RS	0753	2000 x 74 x 154	000	3.0	26

SI-SIC SILICON CARBIDE MAIN PROPERTIES		
Bulk density	Kg/dm^3	3.1
Apparent porosity	Vol%	0.0
Tensile strength	MPa	340
Young Modulus	GPa	340
Length expansion coeff.	$K^{-1}*10^{-6}$	4.5

Figure 4-6: Silicon Carbide (Si-SiC) Parallel Rule Used as Test Sample

Two parallel, precisely ground sides made in accordance with strict metrological criteria define the calibration bar. The verification of translational correctness and geometric consistency during scanning is made possible by the existence of certified flat surfaces. The artifact's eligibility as a reference sample for assessing sensor performance under controlled settings is confirmed by the material qualities and dimensions parameters listed in the manufacturer's datasheet.

Following delivery, the usual fixturing arrangement was used to firmly attach the calibration sample inside the measurement bench, as shown in Figure 4-7. In order to credit any detected discrepancies to the measuring equipment rather than external alignment issues, special emphasis was paid to ensure proper positioning and mechanical stability throughout acquisition. In order to achieve a dense and uniform point distribution while preserving stable signal quality, a sampling step of 0.02 mm and an exposure period of 500 µs were used for the scanning procedure.

Figure 4-7: Sample Mounted in the Be-Line 3D Scanning System During Measurement

Cloud Compare software was then used to analyze and show the collected dataset. The sample's reconstructed three-dimensional geometry is shown in Figure 4-8, where steady acquisition conditions are confirmed throughout the scanning trajectory by the uniform distribution of the point cloud. Planar regression techniques were used to extract and separately fit the two planar faces of the calibration bar from this dataset. The resulting fitted planes and their spatial distribution are displayed in Figure 4-9, where the rebuilt surfaces demonstrate constant orientation and great geometric coherence.

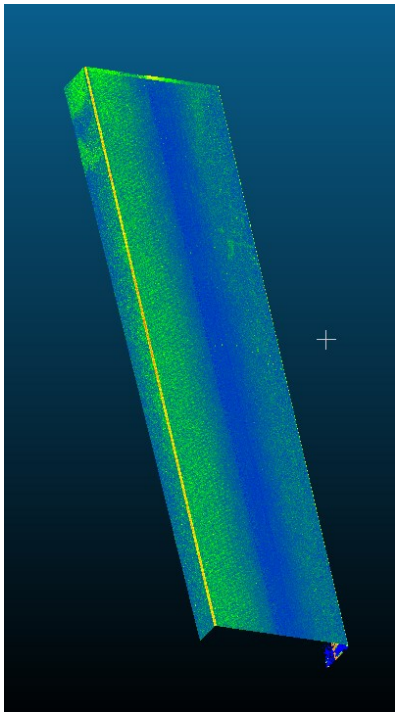

Figure 4-8: Point Cloud of the Sample Visualized in Cloud Compare

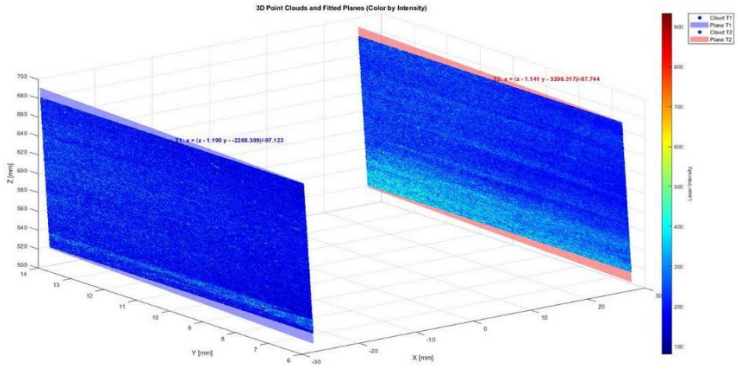

Figure 4-9: Two Parallel Planar Faces Extracted from the Point Cloud with Fitted Planes

The distance between the two fitted planes was measured throughout the whole surface in order to characterize the measurement performance. Figure 4-10 displays the statistical distribution of the point-to-plane offsets as a symmetrical, narrow histogram. The detected deviations stay within a maximum range of around 0.016 mm, suggesting steady acquisition behavior and verifying that the reference surfaces' predicted parallelism is maintained during the scanning operation.

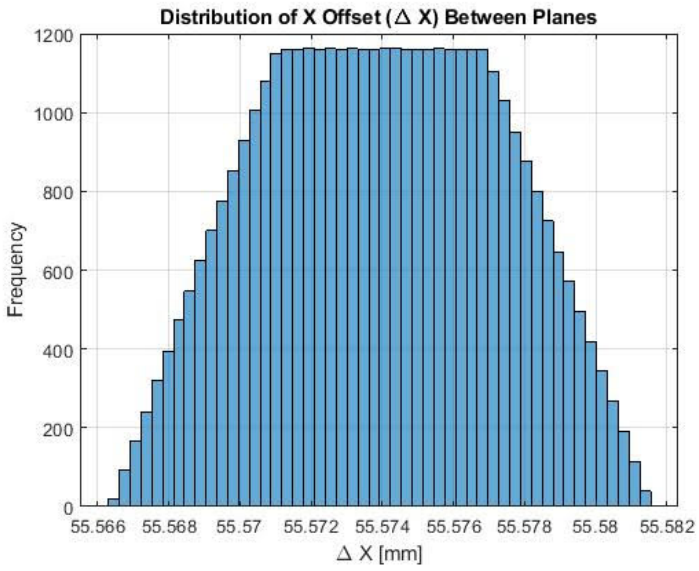

Figure 4-10: Histogram of Point-to-Point Distances Between the Two Parallel Faces

The histogram's lack of irregular clusters or isolated spikes indicates that there are no notable mechanical disturbances and the sensor motion along the vertical axis is smooth. These findings offer experimental proof that the optical triangulation technology consistently maintains angular stability and linearity during the acquisition procedure.

These findings suggest that the Si-SiC calibration bar may be regarded as a trustworthy reference artifact for confirming the measurement bench's functionality. The calibration activity supports the system's viability for non-contact dimensional inspection in industrial applications by demonstrating that it can reproduce flat geometries with high consistency under stable mechanical circumstances and appropriate acquisition parameters.

4.5 Performance of the Be-line

The Be-Line inspection system's performance was assessed after calibration operations using the Si-SiC reference artifact and comparative validation with Coordinate Measuring Machine (CMM) data. This phase's goal was to evaluate measurement accuracy, robustness, repeatability, and industrial application under practical operating circumstances.

After the mechanical fixturing problem was fixed, the comparison with CMM measurements showed significant agreement in terms of precision. The enhanced correlation demonstrated that, provided the mechanical setup is appropriately stable, the triangulation-based acquisition procedure consistently replicates dimensional trends related to pump-action alignment without adding systematic measurement bias.

Repeatability is one of the system's main advantages. The automated non-contact acquisition method guarantees constant measurement conditions over several scans and reduces operator influence. The lack of probing engagement, in contrast to contact-based approaches, lowers handling or positioning variability and supports consistent inspection processes in production settings.

The significance of mechanical stability was also emphasized by the validation activities. Rather of being a sensor technology restriction, the first unacceptable correlation found during pump-action testing was linked to a fixture constraint problem. Following adjustment, the correlation significantly improved, confirming the system's sensitivity to mechanical disturbances and demonstrating the measurement chain's resilience.

Additional proof of steady sensor motion and geometric consistency was obtained by calibration utilizing the Si-SiC parallel rule. The optical triangulation method's dependability was validated by the little dispersion seen in plane-to-plane variations, which verified proper linearity and angular alignment along the scanning axis.

From an operational perspective, the system improves traceability and supports data-driven quality control by facilitating the quick gathering of dense three-dimensional data through automated processing and digital report production. Overall, the findings show that the inspection system satisfies the performance requirements required for dependable application in shotgun barrel inspection and supports the definition of acceptability criteria presented in the following chapter by achieving a balanced combination of accuracy, repeatability, and efficiency.

4.5.1 Measurement uncertainty

In order to determine the metrological dependability of the Be-Line inspection system in relation to the reference Coordinate Measuring Machine (CMM), measurement uncertainty was evaluated. The positional misalignment parameter Dis. tasselli – codetta [mm], which serves as the primary quantitative reference for acceptance judgments made during inspection, was the only alignment Key Performance Indicator (KPI) taken into account while doing the uncertainty calculation.

The uncertainty analysis concentrates on the dispersion between Be-Line measurements and CMM reference values related to this single alignment KPI, as opposed to being produced from several geometric indicators. This method guarantees direct consistency between the industrial decision criterion used during production and the uncertainty assessment.

The uncertainty assessment stays focused on the misalignment measurement itself, enabling a consistent comparison between semi-automatic and pump-action assemblies without redefining the metrological framework, even though different barrel configurations may introduce variations in geometric reference conditions.

4.5.1.1 Semi-automatic configuration

An actual, physically defined codetta that is directly connected to the bindella reference geometry serves as the foundation for the alignment measurement in the semi-automatic setup. The measurement coordinate system may be clearly and unambiguously defined thanks to this physical reference, which greatly lowers the uncertainty associated with geometric reconstruction and reference extrapolation.

The relationship between Be-Line readings and CMM reference measurements for semi-automatic barrels is displayed in Figure 4-11. Excellent agreement between the two measuring techniques is demonstrated by the scatter plot, which shows a strong linear connection with a regression slope around unity and a coefficient of determination of $R^2 = 0.9817$. This outcome shows that when a genuine codetta reference is provided, the Be-Line system can properly replicate dimensional trends detected by the CMM.

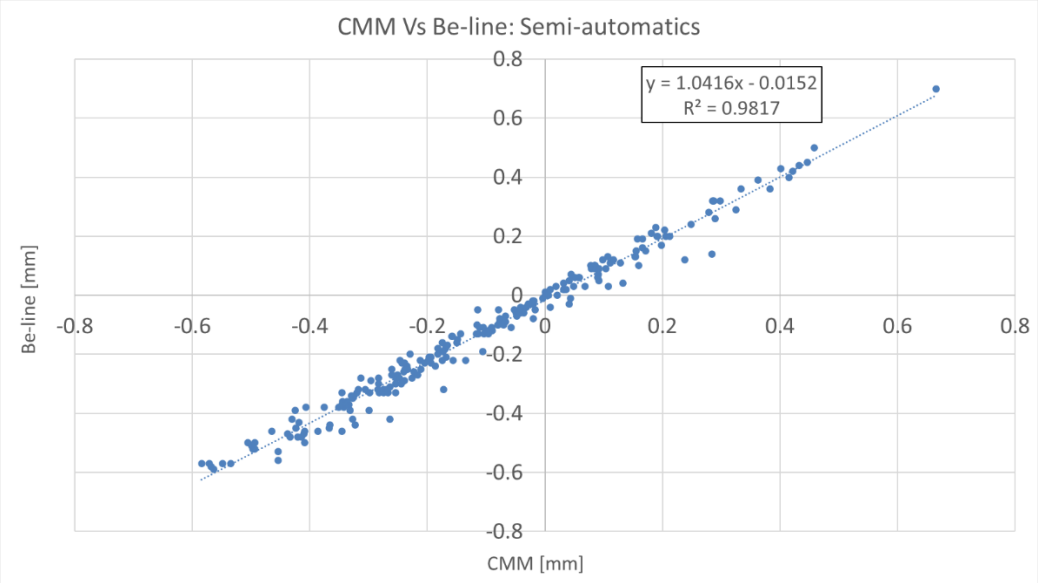

Figure 4-11: Correlation Between CMM Reference Measurements and Be-Line Data in Semi-Automatic configuration

T The process capacity analysis in Figure 4-12 displays the statistical distribution of the measurement discrepancies between Be-Line and CMM. The absence of systematic bias is confirmed by the histogram, which shows a roughly Gaussian distribution centered on the nominal goal value. Table 2 summarizes the results of the analysis of 217 samples, which yielded a total standard deviation of around 0.034–0.035 mm.

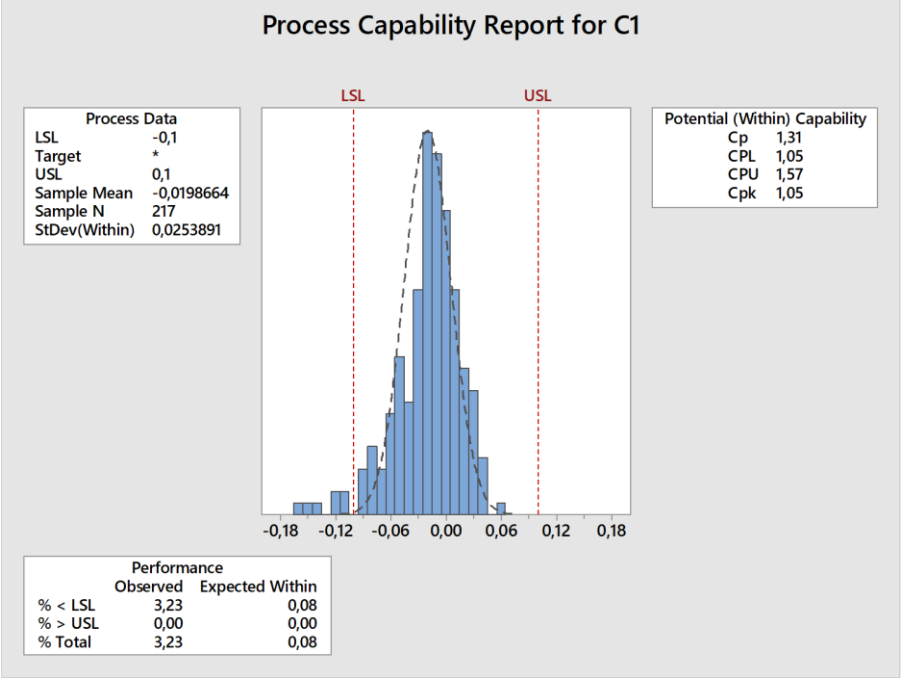

Figure 4-12: Process Capability Analysis of Measurement Differences (C1) Relative to Specification Limits

TOTAL STANDARD DEVIATION [mm]	0.034
NUMBER OF SAMPLES ANALYZED	217

Table 2: Summary of Experimental Dataset and Total Standard Deviation

Based on this distribution, the expanded uncertainty evaluated at a **95% confidence level** is:

$$U(95\%) = \pm 0.068 \text{ mm}$$

4.5.1.2 Pump-action configuration

The codetta reference in the pump-action design is not situated at the breech's terminal end. As a result, the alignment evaluation is based on a virtual (geometrically rebuilt) codetta that is obtained from the bindella's orientation and related reference characteristics. Additional sources of uncertainty pertaining to plane fitting, coordinate transformations, and sensitivity to fixture stability are introduced by this indirect formulation.

The relationship between Be-Line and CMM readings for pump-action barrels under suitable operating circumstances is shown in Figure 4-5. With a coefficient of determination of R2 = 0.8609, the scatter plot exhibits more dispersion in comparison to the semi-automatic scenario. Rather than the optical triangulation principle's inherent limits, this decreased correlation is a reflection of the reference definition's increased complexity.

The statistical analysis of the differences between Be-Line and CMM measurements for pump-action barrels yields an expanded uncertainty at a **95% confidence level** of:

$$U(95\%) = \pm 0.11 \text{ mm}$$

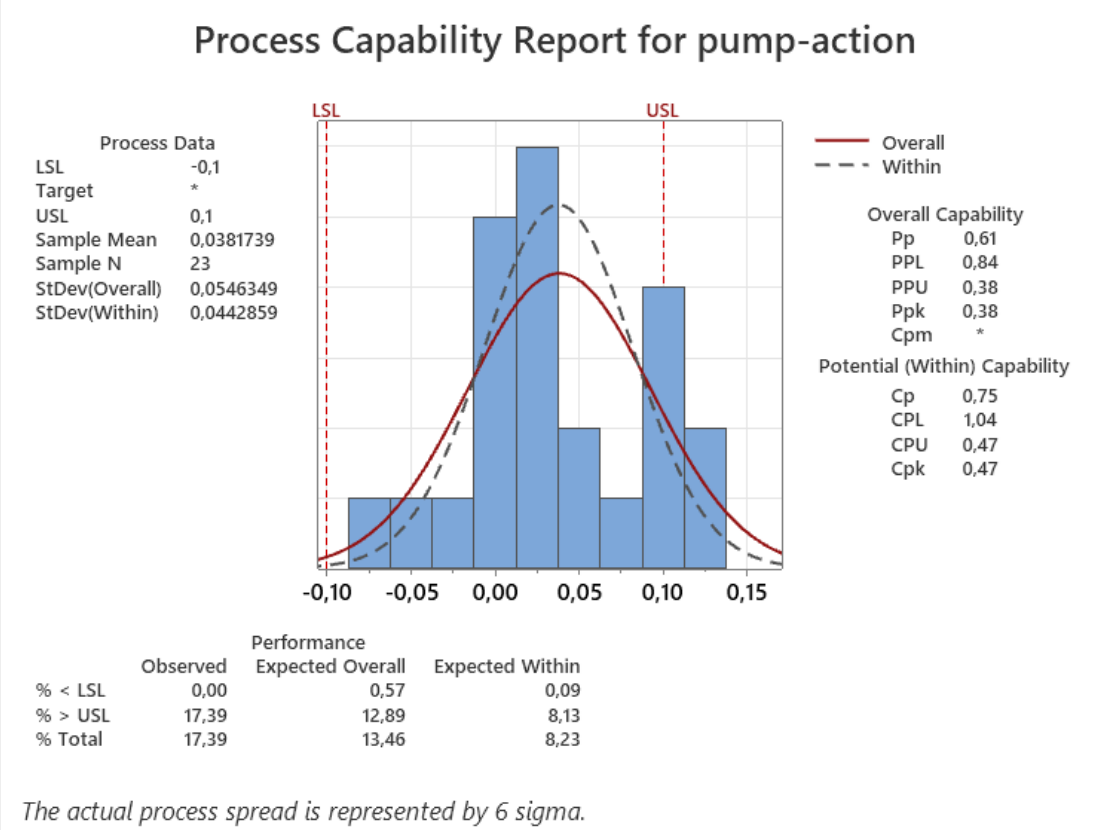

Figure 4-13: Process Capability Analysis of Pump-Action Measurement Results

4.5.1.3 Discussion of uncertainty results

The uncertainty analysis demonstrates how the definition of reference geometry has a significant impact on the overall performance of measurements. The inspection system attains near-CMM-level precision with minimum dispersion when an actual codetta is available. On the other hand, the combination of geometric reconstruction effects and mechanical sensitivity makes using a virtual reference more dubious.

Both designs exhibit uncertainty levels that are appropriate for industrial needs in spite of these variations. As a result, the inspection system works well for in-line dimensional inspection, providing a good trade-off between automation, inspection speed, and measurement precision.

Common metrological practice states that when a measuring system's measurement error is less than one-fourth of the tolerance interval related to the target characteristic, it can be deemed suitable for a particular application. The enlarged uncertainty in the semi-automatic arrangement is around ±0.068 mm, which is still less than the acceptance tolerance's 1/4 limit. The inspection system can thus be deemed suitable for semi-automatic alignment assessment.

The enlarged uncertainty in the pump-action arrangement is around ±0.11 mm, above the optimal 1/4 threshold in relation to the acceptance tolerance. Therefore, according to the precise metrological criterion, the system cannot be deemed completely suitable for this particular function under the existing circumstances. But given the current setup and reference definition, this figure is the least amount of uncertainty that can be achieved.

4.5.2 Measurement time

A crucial performance metric for evaluating the industrial viability of the Be-Line system is the assessment of inspection time, together with measurement accuracy and uncertainty. manufacture flow, operator workload, and overall process efficiency are all significantly impacted by inspection speed in a high-volume manufacturing setting like shotgun barrel manufacture. This led to a comparison of the measuring times used by the Be-Line laser scanning system and the Coordinate Measuring Machine (CMM).

A complete inspection cycle of the contact probing-based CMM measuring method took around five minutes and forty seconds. During this time, reference planes are defined, several bindella points are probed, the coordinate system is aligned, and the codetta position is assessed. The sequential nature of contact probing naturally restricts inspection speed, especially when several geometric characteristics need to be checked, even if the CMM offers great metrological dependability.

By comparison, the Be-Line system took around three minutes to finish the scanning and processing cycle. The non-contact optical triangulation technique, which permits the simultaneous capture of rich geometric information during a continuous vertical movement of the sensor units, is primarily responsible for the shorter inspection time. By capturing a complete three-dimensional depiction of the barrel surface rather than measuring discrete spots, the Be-Line method enables automatic extraction of geometric characteristics without the need for further probing procedures.

In compared to the CMM procedure, the comparison shows a substantial reduction in inspection time—nearly 50% less. From an industrial standpoint, this enhancement results in higher throughput and fewer production line bottlenecks. Additionally, the automated production of digital measurement reports reduces human involvement even more, improving overall operational effectiveness.

It is crucial to remember that the Be-Line system's goal is to offer a quick and dependable in-line inspection solution rather than to take the place of the CMM as a reference metrological instrument. The Be-Line system's capacity to enable real-time quality control while adhering to established metrology standards is demonstrated by its combination of acceptable measurement uncertainty, excellent correlation with CMM findings, and shorter inspection times.

5 DEFINITION OF ACCETABILITY TOLLERANCES

This chapter's goal is to provide quantitative acceptability standards for the assessment of shotgun barrel alignment, with an emphasis on geometric deviations like linearity and planarity as well as

line-of-sight assembly mistakes. This stage signifies the shift from measuring capacity evaluation to the creation of useful industrial decision thresholds, building on the metrological framework and validation findings discussed in the earlier chapters.

A statistical study of production data gathered during inspection operations serves as the foundation for the determination of acceptable tolerances. The technique attempts to convert operators' qualitative sense of misalignment into quantifiable and repeatable numerical criteria rather than just depending on subjective visual judgment. Tolerance limits that represent both geometric performance and real-world manufacturing restrictions can be defined by comparing measurement results with actual production choices, such as acceptance, reassembly, or rejection.

The process used to define tolerance is shown in Figure 5-1. Each component goes through a test process for dimensional verification following barrel assembly and internal manufacture. A dataset created by components labeled as non-compliant (KO) is utilized to examine common deviation patterns and pinpoint crucial thresholds connected to alignment flaws. After that, these barrels are put back together and tested again, allowing for the gathering of further data under modified circumstances. On the other hand, elements that are categorized as compliant (OK) add to a reference dataset that shows acceptable production variability. The foundation for establishing statistically supported acceptable limits is the combined examination of the KO and OK datasets.

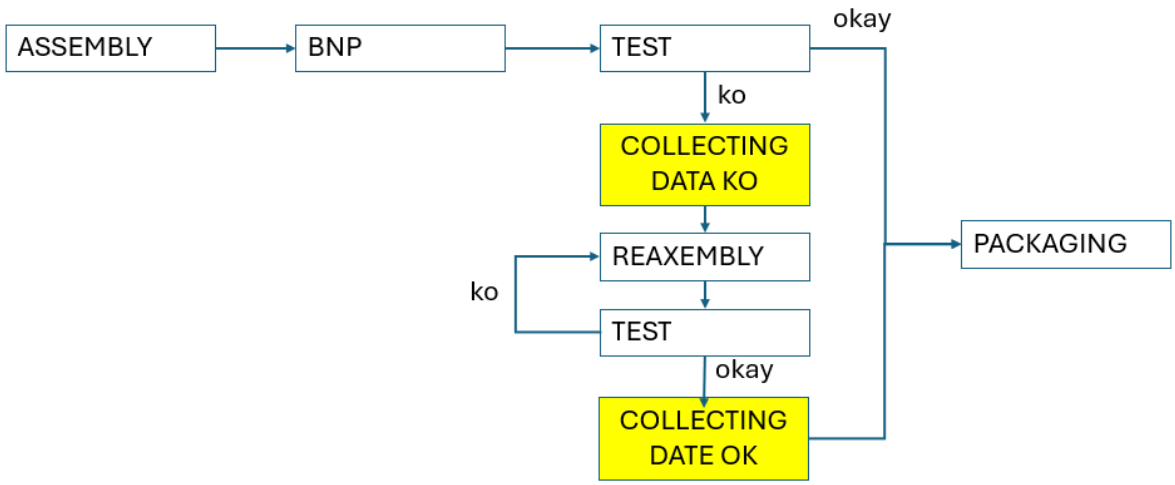

Figure 5-1: Inspection Decision Flow for OK/KO Classification and Tolerance Calibration

Within this framework, two main categories of indicators are considered:

Geometric mistakes that describe variations in the linearity and planarity of the sight line, which affect both functional performance and visual perception; positional errors related to the line-of-sight assembly, which indicate the relative alignment of structural reference pieces.

The method used in this thesis attempts to objectify the visual sensitivity that operators have historically used when doing manual inspections. It is feasible to determine threshold areas where variations start to impact perceived quality or assembly accuracy by examining the distribution of measurement values corresponding to approved and rejected barrels. These thresholds are based on actual industrial behavior seen during manufacturing rather than just theoretical bounds.

Additionally, the measurement uncertainty specified in Chapter 4 is considered in the formulation of acceptable tolerances. The chosen tolerance limits are set to guarantee that the uncertainty of the inspection system stays consistent with industrial metrological standards, as acceptance choices must remain resilient against measurement variability. Specifically, the statistical analysis takes into account the dispersion caused by pump-action and semi-automatic systems, enabling the tolerance framework to be uniform across various barrel topologies.

Therefore, this chapter's output is a systematic process for converting production data into objective acceptance criteria in addition to a set of numerical thresholds. The suggested method facilitates a shift in the shotgun barrel manufacturing process from experience-based inspection to data-driven decision-making by combining statistical analysis, measurement validation, and industrial workflow considerations.

5.1 Analysis samples

The examination of a genuine production dataset consisting of 217 shotgun barrel assemblies served as the basis for defining acceptability limits for the line-of-sight assembly. The samples, which comprise several barrel configurations denoted by various production codes and serial numbers, were taken straight from the industrial inspection procedure.

The dataset is divided into two main categories:

Barrels that exceeded the allowed visual alignment during the existing AS-IS procedure were categorized as unacceptable at the "prova in bianco" inspection stage.

After corrective assembly operations, barrels that represented components that were modified and reintroduced into the manufacturing flow were reassembled and measured once again.

This dual dataset offers a realistic depiction of the variability related to line-of-sight alignment in production by enabling the comparison between original non-conforming circumstances and repaired assemblies.

The misalignment value (disallineamento), reported in millimeters, is the primary metric for every sample. This indicator serves as the main variable in the statistical analysis carried out in this chapter and measures the positional deviation of the sight line. To aid in the understanding of assembly behavior, additional geometric indications pertaining to planarity and linearity were also gathered.

In contrast to isolated test instances, the selection of 217 samples guarantees a sufficiently enough population to reflect actual production variability. The gathered information offers an objective numerical foundation for converting visual inspection sensitivity into quantifiable acceptability limits rather than depending solely on operator judgment.

The study attempts to determine the statistical limits that distinguish acceptable alignment conditions from non-conforming assemblies by examining both non-acceptable barrels and reassembled acceptable barrels. These limits serve as the foundation for the standardized acceptability tolerances that are covered in the sections that follow segments.

5.2 Results analysis

One of the most important steps in establishing objective acceptability limits for the sight-line assembly is the examination of the measurement findings. After obtaining the experimental dataset

outlined in Section 5.1, the measurements were analyzed using statistical visualization and distribution analysis to find trends, dispersion behavior, and the distinction between barrels that were acceptable and those that weren't.

The distribution of line-of-sight misalignment values for the barrels under analysis is represented as a function of the progressive sample number in Figure 5-2. By employing two distinct categories to differentiate between acceptable and undesirable components, the graph makes it possible to directly visualize the variability seen in the production environment. Stable geometric behavior of the assembly process is shown by the acceptable barrels' rather compact distribution around the nominal region. The unsatisfactory samples, on the other hand, show more dispersion and bigger deviations, indicating the existence of alignment abnormalities that go beyond permitted bounds.

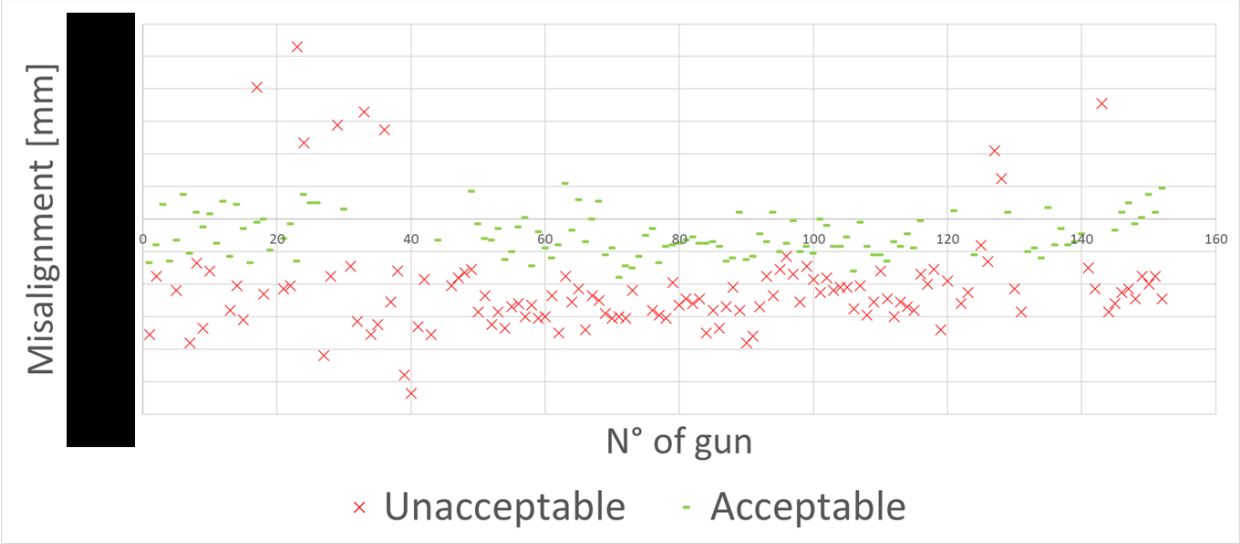

Figure 5-2: Results of Line-of-Sight Misalignment Analysis with OK, Acceptable, and KO Classification

From a process standpoint, Figure 5-2 progressive trend verifies that misalignment values follow a predictable range linked to typical production variability rather than being randomly distributed. While unsatisfactory components show up as outliers or clusters outside of this steady range, the bulk of acceptable barrels stay inside a small band. An essential foundation for establishing objective numerical thresholds that can take the place of subjective visual judgment is provided by this division between the two categories.

A frequency distribution study was carried out to further examine the dataset's statistical behavior, as seen in Figure 5-3. The histogram makes it easier to see how the two populations overlap by comparing the probability distribution of acceptable and undesirable measurements. Consistent assembly circumstances are suggested by the acceptable measures' concentrated distribution and decreased spread. On the other hand, the data that are deemed undesirable have a broader range and reach larger misalignment magnitudes, suggesting a greater degree of geometric instability.

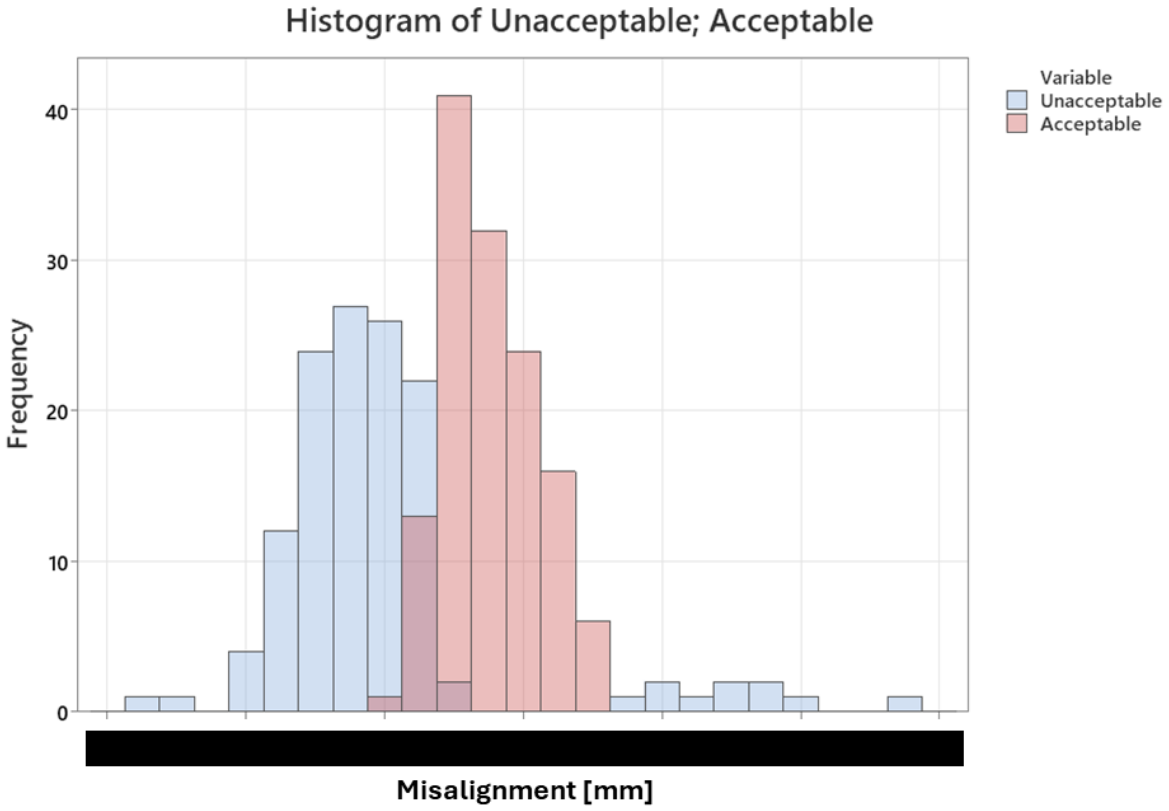

Figure 5-3: Misalignment Distribution for Acceptable and Non-Compliant Barrels

The existence of a transition area where acceptable and unacceptable outcomes partially overlap is shown by the comparison of the two distributions. This overlap supports the necessity of statistically determined acceptance criteria and validates the shortcomings of solely qualitative assessment techniques. A tolerance interval that can minimize both false acceptances and needless rejections can be found by examining the distribution shape, central tendency, and dispersion of the measurements.

Overall, the examination of the findings shows that the misalignment parameter offers a reliable quantitative signal for assessing sight-line conformance. The objective specification of acceptable limits established in this chapter is supported and a better comprehension of production variability is made possible by the combined interpretation of the scatter distribution and histogram representation. These results demonstrate how well a data-driven strategy can convert qualitative inspection sensitivity into quantifiable, repeatable acceptance criteria.

6 CONCLUSIONS

The development, validation, and industrial contextualization of a non-contact laser inspection approach for assessing sight-line alignment in shotgun barrels were the goals of this thesis. The goal of the project was to develop a quantitative, reproducible, and traceable measuring method based on three-dimensional optical acquisition and statistical analysis, replacing the previously subjective visual inspection technique.

Technologically speaking, the Be-Line measurement bench's implementation showed that dual-laser triangulation in conjunction with automated software processing can accurately reconstruct the barrel's geometry and line-of-sight for industrial inspection. Stable and repeatable measurements were made possible while reducing operator impact thanks to the integration of hardware architecture, acquisition settings, and data processing algorithms. Data-driven quality control was enabled and traceability was further improved with the introduction of structured digital reporting.

The dependability of the non-contact technique was validated metrologically by comparison with Coordinate Measuring Machine (CMM) data. The system's linearity and geometric consistency were confirmed by the calibration using a Si-SiC parallel reference artifact, which also showed that the measuring bench continues to behave steadily along the scanning axis.

The determination of acceptability limits drawn from actual production data is a key contribution of this study. The study converted operators' visual sensitivity into quantifiable numerical

thresholds by statistically analyzing 217 barrels, encompassing both acceptable and unacceptable components. The study of planarity, linearity, and misalignment indicators together made it possible to identify objective limitations that could differentiate between faulty and complying components. A shift from experience-based judgment to standardized inspection standards in line with contemporary industrial procedures is supported by this data-driven method.

From an industrial perspective, the findings show that automated optical inspection may greatly enhance consistency, lower operator variability, and facilitate the early identification of non-conformities within the manufacturing workflow. The system offers a solid basis for ongoing process improvement and future optimization, even if some configurations—like pump-action assemblies—still provide more uncertainty because of geometric complexity.

The thesis concludes by confirming that the Be-Line non-contact inspection method is a practical and efficient way to assess shotgun barrel alignment objectively. The project creates an organized framework for generating quantifiable acceptance criteria and improving quality assurance in an industrial setting by combining optical metrology, software-based analysis, and statistical validation. The approaches created in this study advance automated inspection systems in high-precision manufacturing as well as the particular application it addresses.

7 BIBLIOGRAPHY

[1] Wikipedia. “Semi-automatic firearm.” 2024.

https://en.wikipedia.org/wiki/Semi-automatic_firearm

[2] Wikipedia. “Pump-action.” 2024.

https://en.wikipedia.org/wiki/Pump-action

[3] Wikipedia. “Combination gun.” 2024.

https://en.wikipedia.org/wiki/Combination_gun

[4] Wikipedia. “Carbine.” 2024.

https://en.wikipedia.org/wiki/Carbine

[5] Wikipedia. “Gun barrel.” 2024.

https://en.wikipedia.org/wiki/Gun_barrel

[6] Wikipedia. “Shotgun.” 2024.

https://en.wikipedia.org/wiki/Shotgun

[7] UNISIG. “Firearms.” Available at:

https://unisig.com/industries/firearms/

[8] LibreTexts. “1.2: XYZ Coordinate Frame.” Engineering Mechanics – Statics. Available at: https://eng.libretexts.org/Bookshelves/Mechanical_Engineering/Engineering_Mechanics_-_Statics_%28Osgood_Cameron_and_Christensen%29/01%3A_Fundamental_Concepts/1.02%3A_XYZ_Coordinate_Frame

[9] Brighter Compliance. “ISO 9001 KPIs: What to Measure and Why.”

https://brightercompliance.co.uk/iso-9001-kpis/

[10] European Commission. “Commission Implementing Directive (EU) 2019/68.”

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024L0325&qid=1777987872617

[11] ASNT. “Visual Testing (VT) Method for NDT Inspections.” Available at: https://www.asnt.org/what-is-nondestructive-testing/methods/visual-testing

[12] SAAMI. “Firearms Inspection and Quality Control Practices.” https://saami.org/technical-information/

[13] *Semi-Automatic Shotguns Product Page*, Available at: https://www.basspro.com/shop/en/ProductDisplay?urlRequestType=Base&catalogId=3074457345616676768&categoryId=11223&productId=89442

[14] *Winchester SXP Pump-Action Shotgun*, Available at: https://allthingsoutdoors.ca/products/sxp-wtfl-max5-20-3-26-inv-3

[15] Gun Digest, *Browning Adds 20-Gauge to Citori 725 Line*, Available at: https://gundigest.com/gun-reviews/browning-adds-20-gauge-to-citori-725-line

[16] Shooting Times, “Benelli Lupo Bolt-Action Rifle Review,” Available at: https://www.shootingtimes.com/editorial/benelli-lupo-bolt-action-rifle-best/479565

[17] Armi Magazine, “Benelli Colombo Cal. 12,” Available at: https://www.armimagazine.it/benelli-colombo-cal-12/

[18] Bekas Hunt, “Shotgun Repair and Semi-Automatic Smoothbore Shotgun Configuration,” Available at: https://bekas-hunt.ru/uslugi-masterskoy/uslugi/masterskaya_ustranenie_vklinivaniya_gladk_ruzhya_poluavtomata/

[19] La Vetrina delle Armi, “Breda Canna Breda Benelli cal. 12/76 66cm,” Available at: https://www.lavetrinadellearmi.it/it/altro/breda-canna-breda-benelli-cal-12/76-66cm-i-560850.html

[20] Benelli USA Forum, “Benelli M4 Barrel Scratches,” Available at: https://forums.benelliusa.com/topic/25836-benelli-m4-barrel-scratches/