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Intelligent devices for process and quality control in a zero-defect production approach

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Chapter 1

Abstract

The research work presented is within the context of the European project GO0DMAN, one of the research projects promoted by the European Commission to develop a Zero-Defect-Manufacturing approach in production processes, Industry 4.0 compliant, integrating smart online inspection tools at local level and a real-time monitoring mediated by an Agent-based system and a big data analysis at global level.
The research activity is focused on the development of smart online inspection tools for two industrial use cases to demonstrate the GO0DMAN strategy: Volkswagen Autoeuropa (i.e. cars production) and the Electrolux Professional (i.e. professional ovens production).
For both the assembly lines the problem addressed is the assessment of the dimensional quantities, named gaps and flushes (spaces between different surfaces in the tangent and orthogonal directions respectively), which must be compliant to predetermined values.
The technology used for the tool realized is the well-know laser-triangulation technique. However, designing the laser triangulation sensor, different parameters must be taken into account (measuring range, laser and camera characteristics, gap&flush extraction algorithm selection).
Gap and flush can be measured in different stages along the production line and in different measurement points, with different material combinations.
The research activity done tries to answer also to the question: is it possible to measure on "difficult" surfaces as for example those of a car rearlight?

Furthermore, the inspection tool realized addresses the problem of keeping the operator in the measurement loop. Indeed, currently, dimensional checks on the assembled product are made manually by the operator. To improve ergonomics and to allow operator safety and guidance the developed device shows some ”smart” behaviors (interactive interface for the operator, automatic switching on-off of the laser source and automatic recognition of the measurement point).
The whole inspection system functionality has been integrated and proved in the GO0DMAN architecture.
An evaluation of the measurement uncertainty of the device has been assessed both in laboratory conditions and in-line and a study of the repeatability and the reproducibility has been set up to validate its functionality by different operators.
The smart online inspection tool developed for the Electrolux use case integrates also an ultrasound sensor for air and/or steam leakage tests. Indeed, an other parameter affecting the final product quality is the presence of leaks from the front oven door due for example to faulty seals. Currently, leakage detection is made manually by an operator during the functional test of the oven. When an air gap is detected the operator tries to fix it by re-screwing the door hinges or changing the seal. The integration of two inspections in a unique device allows to correlate both parameters, which are involved in the door tightness and the oven functional performances.

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Chapter 2

Introduction

1 Industry 4.0 and Zero-Defect Manufacturing

Digital Transformation is the Third Millennium revolution. Lifestyles, values creation and to be citizens are changing and this is accelerating day by day, if we think to new channels communication, widespread automation, to new online public services, to the multiplication of interactions online at work, at school and in everyday life.

The push for digitization comes from industry and in turn creates the need for a change inside industries (called "Industry 4.0" [2.1]), now called to compete between them in a different way, focusing not only on the quality of the product, but also on services and innovation.

Main benefits of the actual digital transformation are not only in the business in general but also in the process (costs reduction, improvement of process, real-time planning and simplification) and the people too: indeed, a greater enhancement of resources, a chance of bringing out the possibilities of individuals, better working conditions and greater motivations are basis for a deeper transformation and an innovative environment.

Digital enablers of Industry 4.0 revolution are the well-known Cloud, IoT, Big Data and Blockchain which permit the interconnection between both physical and digital systems, which is mandatory for a real compliant 4.0 transformation, together with real-time data flow through the entire supply chain, decentralization and interaction between machines remotely.

The fourth industrial revolution, made possible by the availability of sensors and low cost connections, permits an increasingly pervasive use of data and information, computational technologies and data analysis, of new materials, automated, digitized and connected machines, components and systems (i.e. IoT). This will permits to manage real networks that incorporate, integrate and connect machinery, plants and production facilities, logistics, warehousing systems and distribution channels.

According to the principles of Industry 4.0 in the last years the European Commission has focused on the "Factory of the future" (FoF), which is also a work programme for the 3-years 2018-2020, covering the three last calls under Horizon 2020, the EU Framework programme for Research and Innovation.
In the key priorities of a "Factory of the Future" there is "Excellence in manufacturing" [2.2], which consists in the application of advanced manufacturing processes and services for zero-defect and innovative processes and products. Indeed, ensuring the required quality and a sufficiently high productivity but guaranteeing cost-efficient manufacturing processes is driving in manufacturing industries to the introduction of new strategies and process improvement technologies.

These strategies are called "Zero Defect Manufacturing" (ZDM), which goal is to go beyond traditional Six-Sigma and Word Class Manufacturing approach, as is shown in Figure (2.1).
Six Sigma is a quality management program based on the control of standard deviation (indicated with the Greek letter sigma) which aims to bring the quality of production to a certain level. Despite the pervasiveness of Six Sigma program implementations there is an increasing concern about its failures. According to [2.3] many Six Sigma programs fail because there isn't an implementation model which describes the sequences to be done on the processes to run the methodology. Furthermore traditional Six-Sigma techniques can have limits where complex and changeable manufacturing contexts exist and where small batch productions and customized in-line product inspections characterizes the production processes.

Manufacturing industries show now more interest in the challenge of improving

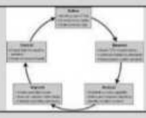
	Six Sigma	World Class Manufacturing	European Zero Defect Manufacturing Solution
			4ZDM Zero Defect Manufacturing
Manufacturing CONTEXT	• High-volume production • Serial Lines • Single product type	• High-volume production • Manufacturing and assembly lines. • Few product variants.	• Mass customization and one-of-a-kind production. • Complex and changeable manufacturing contexts
LEVEL	• Single critical resource and process. • Local improvements.	• Single critical process. • Local improvements at cost bottlenecks. • 10 management pillars.	• Multi-stage, Process-chain level. • System-level improvements in the shop floor.
MONITORING & CONTROL	• Only monitoring by control charts based on product data. • Process capability	• Monitoring and root cause analysis, by cause-effect, Pareto analysis and control charts.	• Monitoring and control. • Inter-stage correlation. • Multi-sensor information. • Advanced analytics
ACTIONS ON DEFECTS	• Scrap	• Scrap	• Defect Repair. • In-line rework. • Proactive prevention.

Figure 2.1. "Zero Defect Manufacturing" vs Six-Sigma and Word Class Manufacturing approach

their manufacturing processes and systems in order to assure the required production rates delivery with high quality products, while minimizing waste and reworking. In figure (2.2) is shown how ZDM strategy aims to run.
The ZDM line is to integrate specific technologies already present on the shop floor (e.g. automated lines, robots, sensors, etc.) used to detect and correct determined values with intelligent, autonomous, self–adaptive, self-learning and self-optimizing process control in order to prevent and predict future failures and keep process adaptation by data flow processed, Figure (2.2).
The ZDM approach is not new and has been first mentioned during the cold war within the US army regarding their defective weapon system (US Assistant Secretary of Defense, 1965) [2.4]. But over the years, this concept had been implemented only partially due to numerous technological limitations that restrain its implementation.

Currently, with the evolution of Industry 4.0, ZDM concept is easier to be implemented due to the availability of the required amount of data which are needed for such approach but still a lot of effort is needed for better coordination of the capabilities of each technology. Despite that, instruments required for such scope are often very expensive and companies not invest on that.

However the landscape is changing again with a significant drop of technologies cost required, accessible by everyone.

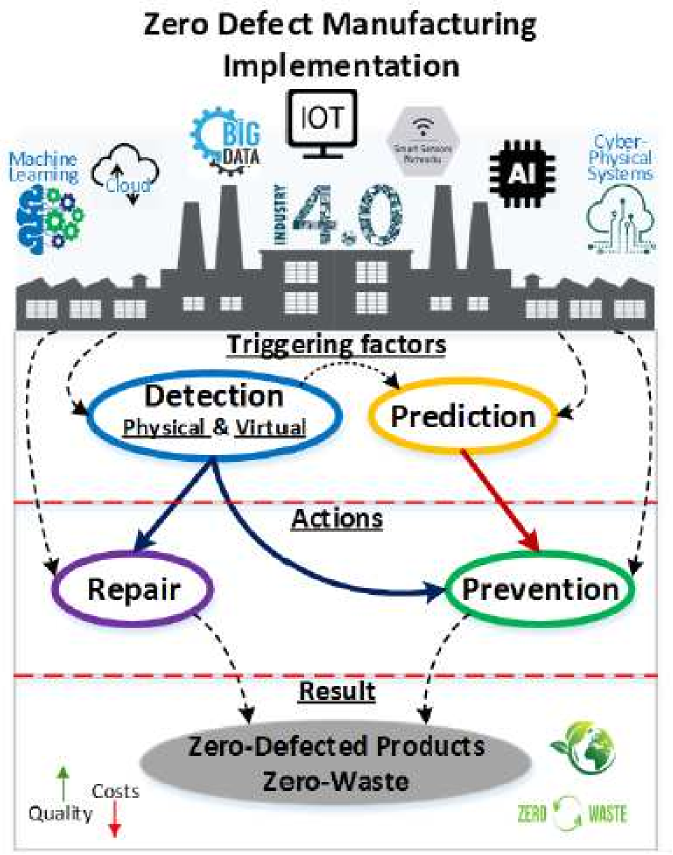


Figure 2.2. Zero Defect Manufacturing implementation [2.4]

2 The Go0dman Project

In line with the scope, in the EU Framework Programme for Research and Innovation, Horizon 2020, within the technologies for the factory of the future (FoF) initiatives, there is the GO0DMAN project, [2.5] (Contract no.H2020 FOF-03-2016-723764), which the name is an acronym for aGent Oriented Zero Defect Multi stage mANufacturing.

The project is based on the results achieved in other European Research Projects developed in recent years, such as GRACE [2.6], IDEAS [2.7] and Self-Learning [2.8], which aim is the development of zero-defect production, in particular at industrial prototyping level (TRL 7).

The project started in September 2016 and the results exploited in September 2019.

The main objective of GO0DMAN project is to implement an effective zero-defect strategy which should permit:

- To control and be aware of production data flow;
- To reduce waste;
- To reduce re-working;
- To reduce costs;
- To increase productivity.

These results can be reached only through the integration and combination of process and quality control in a multi level/stage production, creating a distributed production system architecture.
Actually, data from quality and process control are mostly used only at local level, sometimes in a real time monitoring process but without correlating each single stages.
The results are commonly an OK/NOK output, Figure (2.3), a defect classification, or a control feed-back. More rarely data are used for interstage feed-back or feed forward control and/or inter-process correlation.
In such sense a large potential for a factory global level control can be exploited. Professor Jianjun Shi, from Georgia Institute of Technology is one of the early pioneers of operational improvements of manufacturing and in particular of multistage manufacturing systems. He has been one of the supervisor of the Go0dman project and in [2.9] he explains: "A multistage system refers to a system consisting of multiple components, stations or stages required to finish the final product or service.

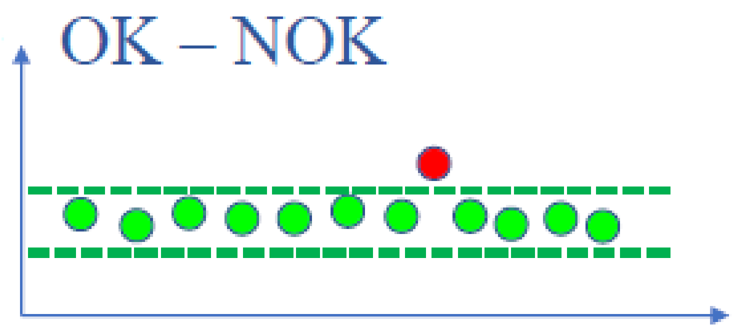


Figure 2.3. OK/NOK result from local level process control

Multistage systems are very common in practice and include a variety of modern manufacturing and service systems. In most cases, the quality of the final product or service produced by a multistage system is determined by complex interactions among multiple stages—the quality characteristics at one stage are not only influenced by local variations at that stage, but also by variations propagated from upstream stages. Multistage systems present significant challenges, yet also opportunities for quality engineering research."

Currently, traditional approaches for quality control are mainly based on Statistical Process Control (SPC) which treat the multi-stage system as a whole and lack the capability to discriminate among changes at different stages.

Nevertheless, multistage systems are very common and almost all modern manufacturing processes present this structure. In Figure (2.4) an example of a multi-stage production system, described by Professor Jianjun Shi is shown. As can be seen quality output of a single stage is strictly correlated to the quality output of the upstream process. Final product quality will depend on the performances at single process stage, variations propagated in the stream and on the interactions between all processes.

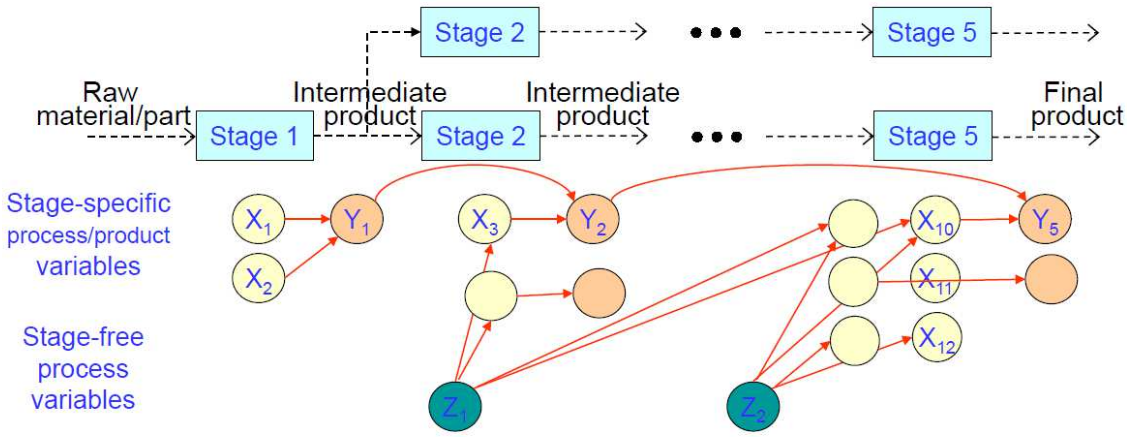


Figure 2.4. Multi Stage Production System [2.9]

The GO0DMAN project, runs on Zero-Defect Multi-Stage Manufacturing concepts, with the aim to prove their feasability in different industrial production processes with a multi-stage production line and different level of production rate and automation:

- Volkswagen Autoeuropa (VWAE)
- Electrolux Professional (ELUX)
- Zannini (ZAN)

In Figure (2.5) the three different scenarios are shown.

	VWAE	Zannini	Electrolux
Industrial Sector	Automotive: OEM	Automotive: metal part of hydraulic electro valves	Household appliances: professional kitchen equipment (i.e. ovens)
Production rates (per line)	Serial production: more than 625 vehicles per day. Cars are individually tracked on-line.	Batch production: about 400 pieces per day.	Customized production: not more than 30 pieces per day.
Production Process	Multi stage manual and semi-automatic assembly.	High precision multi stage machining operations.	Highly flexible multi stage manual and semi-automatic assembly.

Figure 2.5. The Go0dman project Industrial scenarios [2.10]

The different levels of the process flow involved are shown in the GO0DMAN architecture scheme, Figure (2.6):

- *Operational technology (OT)*, with a multi-stage production structure and where quality control stay;
- *Information technology (IT)*, where production data analysis and data management of resulting correlations are used to extract meaningful information about processes and production.

For these purposes the GO0DMAN project developed different instruments, such as:

- *Agent-based Cyber Physical System* to integrate process control and quality control both at local and global level. The agent-based CPS architecture comprises a society of distributed, autonomous and cooperative intelligent agents representing the production components disposed along the multi-stage production system, in some cases having a direct association to a physical resource

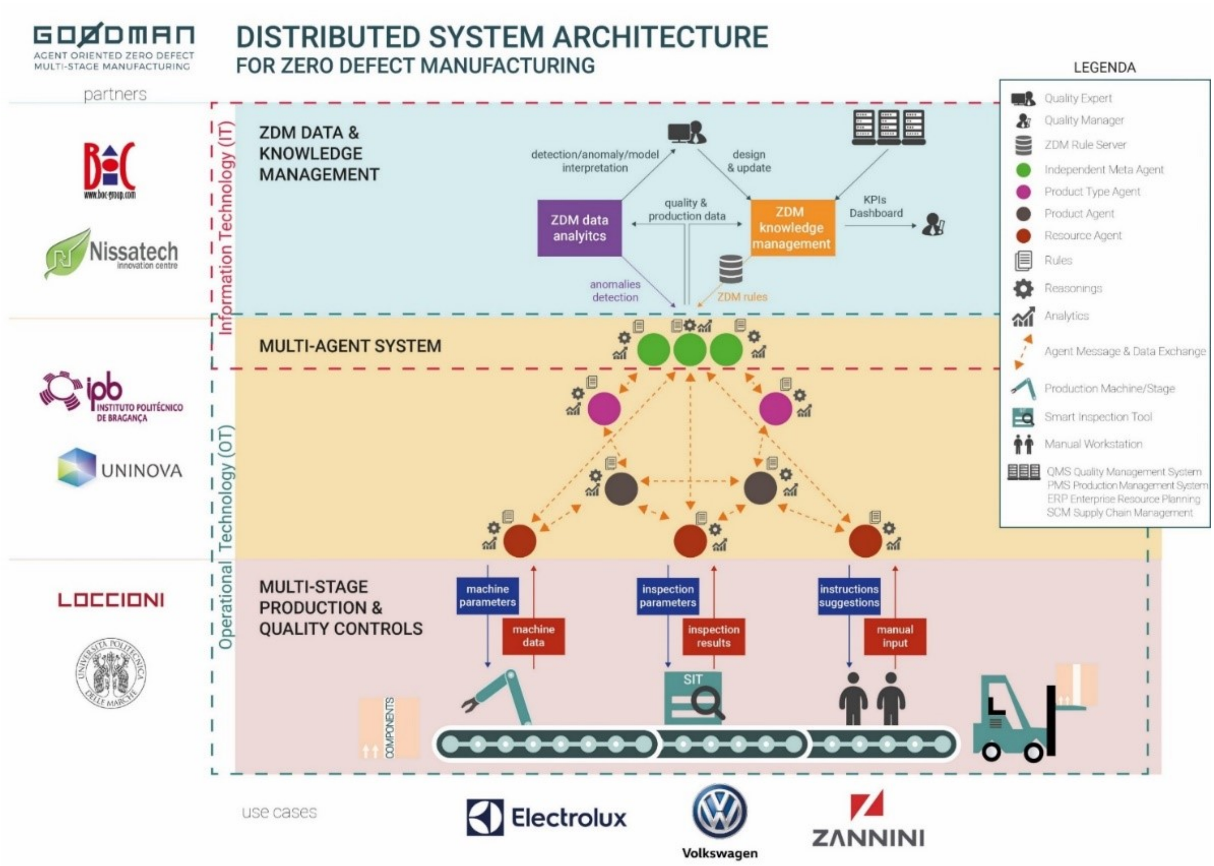


Figure 2.6. The GO0DMAN architecture

such as a quality control station or a sensor, but in other cases representing logical entities, such as data analytics and self-learning tools. In the GO0DMAN agent-based system the products being produced along the line have been associated with an intelligent agent, able to transform the physical product into an intelligent product, with capabilities to gather and store data from the production process, to make decisions both at local and global level, supporting a ZDM production;

- *Big data analytics* for real-time data processing and analysis by data mining techniques at both local and global levels. These features enable real-time and early detection of process/product quality deviations and trends, establish correlations between upstream and downstream process variables so to allow the updating downstream process parameters and acceptance thresholds for quality checks. The aim this data-driven approach is the extraction of data produced in the line, which are stored in the agents representing the shop floor level and to process them in order to extract meaningful information with the scope of prevent failures by real-time monitoring;

- *Knowledge management tools* to have human interfaces with graphical representation of the ZDM architecture models and dashboards as well as the machines' interface accessing the results of analytics and quality control output. This permit, for example for a manager or quality/process teams to find deviatiosn from the process and request configurations updates or process improvements in a real-time model strategy. The GO0DMAN project using this knowledge management strategy aim to keep an imporvement on the data awereness flowing among the line and to construct a real-time decision making approach;

- *Smart inspection tools* which act at the OT layer processing data to extract quality indicators and exibiting real-time adaptive behaviours to keep measurement under control even in case of variations of process/product and operation parameters.

2.1 Smart Online Inspection Tools

The focus of this research is the development of online inspection tools for two of the relevant industrial cases seen previously: Volkswagen Autoeuropa (VWAE) and Electrolux Professional (ELUX)
If we see in Figure (2.7) one of the segments of a smart production is measurement. Measurement science and sensing technologies constitute the backbone underlying Industry 4.0.

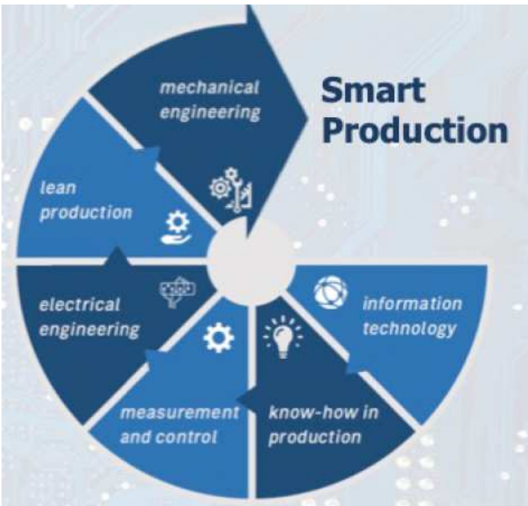


Figure 2.7. Smart Production [2.11]

Quantitive data about physical quantities , which are fundamental to do defect diagnosis and make corrections, originate from measurements. Meaurement system output is at first a data, then an information extracted and useful to take decisions on the processes. Sensors and measurements live at the stage of the shopfloor (OT), within operators and process recources.
Highly automated sectors use many sensors on the production line for process control and in line 100% quality control (on parts, subassemblies and final product). Nethertheless, simpler production environments continue to exist, where most operations are human based including quality controls and a rather limited number of sensors are used.
Furthermore, to construct a zero defect strategy information from the process under inspection are required to support any decision. Reliable information need a stream of regular and reliable measurement on the processed product. However, in a real

production scenario, there is a lack of availability of data which by itself can guarantee a reliable information build-up. Furthermore measurement uncertainty of these inspections is an important aspect to consider. The measurement uncertaninty must be known and kept under control and if deviation occur from the standards tolerances these must be adequately managed so to keep the measurement confidence level at the required level.
For this scope the GO0DMAN project has defined and implemented on the production scenarios Smart Online Inspection Systems.
A smart online inspection tool, in the GO0DMAN project approach, can be considered a quality control system with specific characteristics:

- *real-time defect diagnosis*
- *quality indicators extraction*
- *adaptive behaviours*
- *active management of measurement uncertainty*
- *self diagnosis and calibration*

These tools perform measurement, diagnosis and classification of defects/anomalies and keep the measurement uncertainty under control with developed smart behaviors to process production data to generate useful information.
A Smart inspection tool with smart behaviors, referring to the GO0DMAN strategy, means that an adaptation of the device functions to the basis of the variation on the product, the process parameters and to the environmental conditions is runned continuosly.
Measured data are then processed by the smart online inspection tool, at local level so to extract meaningful diagnostic information, with associated uncertainty and confidence level and shared at global level with just the right amount of detail in order to support decision making.
The agent architecture with its associated processing capacity has been exploited to implement such link.

Smart online inspection tools are made of hardware and software components able to acquire a physical quantity, acting as sensors or devices used to perform a test sequence and take measurement with the data acquisition and software environment for the setting of the system parameters (like acquisition time, sensor set-up, etc.). Once data are extracted and processed by the computational performance of the tools, the agent-based architecture will associate the Smart Online Inspection Tool to its agent, confering it autonomous behaviors and the name of a cyber-physical system (CPS).

2.2 Volkswagen use case

Volkswagen Autoeuropa (VWAE) is one of the production factories of the Volkswagen Group, located in Lisbon (Portugal), Figure (2.8).

Figure 2.8. Volkswagen Autoeuropa plant [2.5]

The main objective is to produce high quality vehicles, such as Sharan model car and the recent T-ROC car (Figure 2.9), while improving the production processes, the operators' competencies and operation performance.

Figure 2.9. Volkswagen T-Roc Model

For the GO0DMAN project the focus is to collect and correlate data generated by dimensional measurements in line, in particular the assessment of gaps and flushes on car frame, rear-lights assembly and tailgate alignment operation on the T-ROC model, distributed along the body shop and the assembly line.
A definition of gap and flush [2.12] can be provided as follow:

- *Gap* is the space between two adjacent surfaces, measured along the tangent plane to the surfaces in exam.

- *Flush* is the mismatch between two surfaces, i.e. the distance between the surfaces measured in the orthogonal direction to the tangent plane to the surfaces in exam, Figure (2.10).

Gap and flush need to be measured in several industrial sectors, from appliances to aerospace and automotive. In car assembly, gap and flush values are significant both from an aesthetic and a functional point of view. In fact, misaligned parts are perceived as defects by the customer and furthermore, they may cause decay in aerodynamic, aero-acoustic and sealing performance. Gap and flush are subject to geometrical specifications, which should be checked for 100% of the products being assembled in-line.

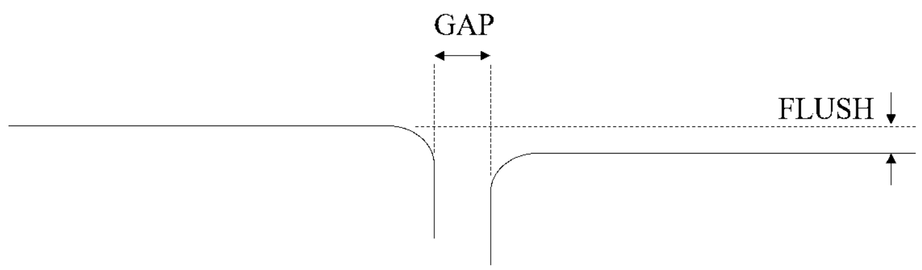


Figure 2.10. Gap and Flush definition

In the automotive sector during car production, the vehicle flows along the line passing through several stations starting its process in the Body Shop area and a gap and flush pre-fit inspection is done very often using laser-triangulation-based commercial sensors.
In the final assembly process, the inspection typically takes place at both the tailgate pre-fit (i.e. before rear lights assembly), after this pre-fit and at the end of the assembly line. This operation is important because is affecting the correct assembly of tailgate. Currently, this inspection is performed mainly manually (Figure 2.11), using a feeler gauge tool, Figure (2.12), by the operator, for gap check and without any tools, merely using the operator' s touch, for flush values. Sometimes they also use a digital comparator, as in Figure (2.13), for flush assessment, but only for statistical report.
In Tables (2.1) and (2.2) technical specifications of the feeeler gauge and the digital comparator are summarized.

Figure 2.11. Example of car assembly line [2.5]

Range	0,5 to 8 mm
Resolution	0,5 mm
Uncertainty	0-0,5 mm

Table 2.1. Feeler Gauge specifications

Range	0-5 mm
Resolution	0,01 mm
Uncertainty	+/- 0,02 mm

Table 2.2. Caliper specifications

If everything is well assembled and aligned, the car continues its path through the line. However, if any fault is detected at those stages, the operator tries to fix it. If the fault cannot be repaired, the operator must write it on the car's report card.

These systems however have some disadvantages. At first, these gauges involve physical contact with the target surface under measurement, so the risk is to damage the car.

Then, because these instruments operate manually, they are invasive and can cause an increase in the size of the gap measured because of the interaction force between the gauge and the gap and therefore can bias the measurement [2.12].

Furthermore, these instruments do not always provide high results. Generally,

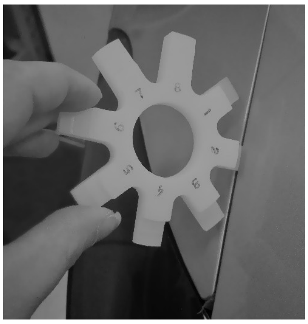


Figure 2.12. Feeler gauge

Figure 2.13. Digital electronic comparator

the quality of the measurement made is highly dependent to the feeler gauge positioning with respect to the surfaces upon which the measurement is done, Figure (2.14). So, the results can be subjective and many errors can occur due to time limitation.

Furthermore, feeler gauges have large resolutions which implies large measurement uncertainty (2.15); in addition, feeler gauges must be inserted in the gap, therefore they can only provide a measurement less or equal to the actual value.

Calipers for flush measurement are more accurate (typically 0.1 mm), but they require additional tools to work for flush assessment and the uncertainty strongly depends on operator manual skills.

Moreover, the process of measuring gaps and flushes with the above instruments is quite time-consuming. Moreover, feeler gauge become early worn out.

Last, but not least, such inspections means that no data are available at the end of the inspection but a compliant/not-compliant tag. In the perspective of a digital factory, this lack of stored information compromises any possible data analysis. In this context, the process as is does not permit to have systematically a correlation

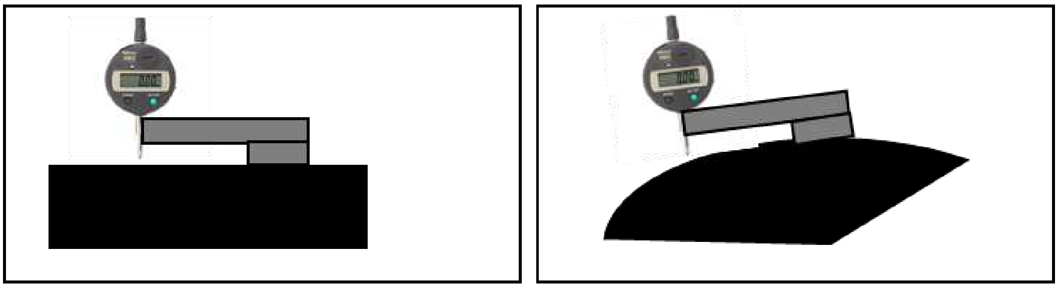


Figure 2.14. Caliper approach to the target surface

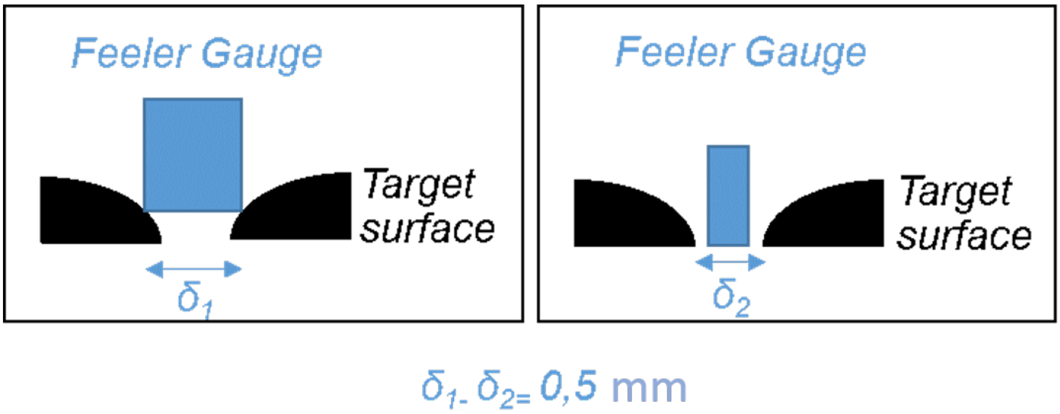


Figure 2.15. Feeler gauge resolution and approach to the target surface

between data in body shop and those in the assembly areas. Furthermore data cannot be processed locally and stored for statistical reports and there is no possibility to collect a continuous flow of data from the assembly process. Indeed, the only data stored and available for analysis by process engineers come from dedicated tests performed on car samples extracted from daily production.
Contrarily, the Industry 4.0 framework pushes towards continuous data flow from production line. In the car assembly context, this means acquiring gap and flush data during/along the assembly process, with the purpose of providing feed-back and guidance to the operators and storing data associated to each car produced, so to move from statistical process control to 100% quality control without any increase of takt-time.
VWAE, beeing one of Europe's most modern automotive production plant, in order to improve developments in automation production control and meet the high standards required on manufacturing a quality product, has been involved as end user

to demonstrate a 100% quality control within the GO0DMAN project.

2.3 Electrolux Professional use case

Electrolux Professional (ELUX) is a leading global manufacturer of appliances and equipment for professional use, offering a high variety of models (660 product codes) to fulfill the customers' needs and requirements.
The selected scenario for the GO0DMAN project is the assembly line of professional ovens at Vallenoncello Plant (Italy), Figure (2.16), for which an example of the products is represented in Figure 2.17.

Figure 2.16. Elecrolux professional plant [2.5]

The Electrolux Professional battlefields, which made the company a leading unit are:

- a wide range of standard products together with products "made to measure"
- an high demand variability

At the beginning of the project in Vallenoncello Plant three lines were dedicated to the oven assembly, accordingly to the models, from the most complex as combi series (hot air and/or steam cooking technology) to the simplest one (gas/electric). Actually there is also a new oven range with 6 different sizes and 32 design modules. All the lines were composed of several manual or semi-automatic assembly workstations, ending with the final quality test that selects what product can be admitted to the packaging. Products move along the line using roller conveyors and trolleys. Each product assembly stages and operations may vary accordingly to the daily production plan and the daily production of a single line is about 30 pieces.

Figure 2.17. Example of an Elecrolux professional oven [2.5]

Before the GO0DMAN project there weren't automatic and real time controls along the line, but the quality checks were mainly performed in the final testing station where all the functions of the oven are tested, with a considerable inspection time. To reduce cycle time and reach high quality ovens without defects, a new line with some intermediate testing area has been installed simultaneously to the GO0DMAN project development. The idea has been to develop and adopt the "Zero defect strategy" increasing the number of pre-inspection stations and data correlation, in order to reduce wastes and scraps, reduce of production cost, increasing the first time quality of execution with the introduction of flexible production processes due to distributed in process control and real-time information together with reduction of end-of-line test stations.
The distributed system architecture for Zero Defect Management at the shoop floor level included connected smart online inspection tools.
The idea has been to introduce new quality controls along the assembly process, on parts or subsystems which are relevant for the final quality of the product. After

analysis of the ELUX workflow these inspection tools have been selected:

- a system to detect leaks of air or steam from the front door seals;
- a device to measure gap&flush between the front door and the frame of the oven;
- a system to detect noisy/faulty fans on the motor group;
- an automatic inspection system to detect and identify wrongly assembled parts/components.

This research activity has been focused for the Electrolux Professional use case on the first two points.
Leakage detection from door seals is a relevant problem for quality control of all the appliances which have a door. Referring to the oven production; leaks from the internal cavity can occur from localized air or steam flow from the cavity, which pass through a defective seal and go out of it. The flow rate is typically little and is correlated to the size of the defect on the seal. The air leak can be detected when the oven is functioning, so this flow will have a temperature higher than the external, depending on the overpressure which occusr in ventilated ovens and correlated with the convective motion. If the oven is not operating, the leak flows at the same temperature of the external ambient one with a direction of flow through the seal which cannot be well established. This flow could also be ineffective if there is no pressure differences between internal and external environment.
Leaks of air and/or steam from the front door seals actually are detected during the "hot" functional test. Indeed, the oven is powered on, in dedicated areas, and an operator checks if steam/hot air is flowing through the seals, so no data are recorded, because the operator only positions the hand (with specific work gloves) near the seals. When a leak is detected because of a faulty seal the operator proceeds to reposition the upper hinge and a final screwing of such part it's done.
In this context, an automatic identification of leaks could allow correlation of this defect to other parameters. If identification is done in cold conditions, for example at the front door assembly stage, this would reduce time for final testing and would

Figure 2.18. Screwing procedure in appliances lines [2.5]

enable the operator to fix the problem while the oven is at room temperature, thus reducing repair time and improving operator safety.
Regarding gap and flush checks currently is mainly done by visual inspection and a screwdriver used to tighten well the door closure screws. But a correct positioning of the oven door with respect to the frame is important not only for aesthetical but also for functional purposes: indeed the door must correctly push over the seal to reduce the heat leaks that might cause thermal inefficiencies. Thus, leakage inspection and gap and flush assessment are correlated but not always made simultaneously.

A series of critical points are also related to the impossibility to store quantitative data and to a subjective identification of compliant/not compliant samples on the upstream-to-the-downstream process.

3 State of the art

3.1 Gap and Flush measurement

Measuring gap and flush quantities in manufacturing processes it is necessary to ensure these equal to certain pre-determined values and to know how this quantities change with time. In particular, dimensional inspection keep a great attention to process assessment because of the consequence of a relative fault. Indeed they are visible and can be the cause of a product non conformity, as for aerodinamic aspects (i.e. automotive and aerospace industry) and functionality and aesthetical needs (i.e. appliances).
Tipically, the dimensional inspections are done at the end of the assembly line by manual feeler gauges but recently manufacturers needs go to a 100% inspection, which must be done also before the final fitting, in order to reduce scraps and enhance their quality and competitiveness.
In order to address this requirement instrumentation manufacturers have developed different methods for gap and flush measurement between surfaces which involved optical techniques.

A lot of papers and commercial sensors sites [2.13] discuss about triangulation as the main technique to use for dimensional measurements. As explained in [2.14] during the past years optical triangulation sensors for dimensional measurements has experienced an increasing use. This is mainly due to the increase of laser diode as light source and an increase need for accurate non contact range sensors in a variety of applications, for which there is also the interest in the industrial environment. Indeed one of the task to be accomplished is the dimensional inspection in all the stages of assembly, which requires to have a non-contact, accurate and repeatable tecnique. Non-contact laser triangulation sensors are becoming more and more used instruments in substitution to CMM (Coordinate Measuring Machines) because of their fast processing speed, relative inexpensiveness and because they don't need to touch the target surface and to change object physical properties. This allows to take them into account to measure gap and flush of assembled parts.
Significant advantages compared to the other methods can be described. They work

quickly and the accuracy are tipically higher compared to those of feeler gauges and flush calipers and they can be used to measure them for both quantities allowing to be faster and more accurate at the same time.
Typically, these instruments are mounted on frames or robots, as is shown in Figure (2.19), assuring a 100% inspection of the product.

Figure 2.19. Optical methods used in car assembly stage [2.15]

The use of laser triangulation sensors have becomed more and more pervasive due also to the possibility to store data automatically into database and to evaluated the correlation between measured data and nominal values to correct them as they occur, in the optic of a real time monitoring and correction.
Nevertheless traditional optical methods have some problematics that can be summarized as follow:

- Traditional laser-based sensors used in industrial environments being mounted on a fixed frame across the line, cannot be used in assembly stages where the operators work is still predominant, as is shown in Figure (2.20), (1).

- Traditional laser-based sensors used in industrial environments measure difficulty transparent materials (i.e. glass or plastic), thus gaps formed by for example the headlights or rearlights are not always measurable, (2)
- Traditional laser-based sensors used in industrial environments permit to store data locally but often data are processed offline and do not permit to correlate results belonging to different stages of the line, (3).

Figure 2.20. Example of presence of the operator in final assembly inspection [2.15]

In order to cover point 1 and 2, because a lot of operations in the line are done simultaneously by the operator which manually assembles the car parts and iteratively measures gap and flush and then corrects the alignment until measurements fall within specifications, some manual instruments have been developed as is shown in Figure (2.21).
In [2.16], an evaluation and comparison of the variability of measurement between a caliper and a commercial hand-held laser instrument during production processes is presented and demonstrates the competitive advantages of a laser-based measurement device. For example, Third Dimension, who develop the Gapgun [2.17], has worked in partnership with different automotive companies to implement the instrument to help developing the quality of their vehicles. These portable systems are used for a variety of fields, not only in automotive industry. But, some disadvantage

Figure 2.21. Gapgun [2.17]

are present too. Indeed, these instruments present some limits such as their dimensions, their limited charge. Moreover, their performances can significantly decrease or even be unsuitable with some materials such as the rear lights.
A complex aspect, for the project research, was that not only metal sheets (tailgate/oven frame) but also plastic (rear light) and glass must be measured. Literature did not offer yet an answer for this: it is possible to measure gap and flush within transparent or semi-transparent and retro-reflective materials?
For these reasons, others explain how with a stereo pair of cameras can be reached more resolute and reproducible results. In [2.18], for example a non-contact detection method to measure car body gaps, based on stereo vision, has been proposed. In [2.19] an automated inspection with two calibrated stereo cameras and two infrared LED lamps which highlights the edges of gaps between the car body is presented. The aim to proof the advantages against the laser-based systems, mainly due to its color independency. On the same note, another possibility would be the use of ToF cameras which, similarly to stereo cameras, which provide dense 3D maps. However these methods presents complex algorithms for the gap and flush extraction, so they are not usable for an in-line inspection, done by the operator.
Furthermore, some commercial sensors have been also developed to cover this requirement. For example, in [2.20] a blue laser triangulation sensor for difficult surface types has been developed. The laser beam range is typically between 380-450

nm and is designed for direct reflection and find applications in the measurement of high-gloss, shiny and reflecting surfaces. Some papers give also solutions about visual inspection of transparent material, as in [2.21] , but nothing fits at best with rear light gap measurements case.
Furthermore these instruments are typically not portable.
In order to design a portable laser sensor with a blue laser Nextsense [2.22] delevoped a solution which seems to fit all problems analyzed. The instrument is shown in Figure (2.22). The solution is continuing the production of the company traditional

Figure 2.22. Calipri Instrument

instruments but with new blue laser source. Nevertheless, three disadvantages are present:

- A tablet PC runs the instrument software, affecting the ergonomics and usability in a complex and moving assembly line
- As for most of the commercial laser triangulation sensors present in the market they are very high-resolution and accurate at the expense of their high cost, while the dimensional inspection of gap and flush, mostly in automotive sectors, is done by 50-100 operators simultaneously on different stages of the line.
- How to correlate the data out from the instrument from different parts of the assembly process? In the development of a multi stage production and

in the optic of a zero defect production, this question is still opened and no commercial or experimental solution still occur.

3.2 Leakage detection

Typically two type of leakages can be detected in the appliance sector, mainly oven production plants, as the Electrolux Professional one: internal and external leakages.
Internal leakages are very difficult to detect, at the moment welding inside the oven is controlled with penetrant liquid technique [2.23].
Regarding external leakages, at present, in appliances industrial sectors, no innovative and automatic inspections are proposed.
Nevertheless, leakage detection is a well-know problem. Typically it concerns pipes or valves [2.24] where air leaks with a range of +35kHz can occur and where the main method used is the ultrasonic (US) technique.
This method is employed in different fields, mainly as a non-contact technique. For an ultrasound test in pipes is usually used a US sensor receiver. The typical output is a sound or a display colour pinpoints which alerts the operator if a leak is present.
Sometimes, leakage inspections are not on systems with pressurized air, so no ultrasound is emitted. In this case, for example for joints of aeronautics doors or buildings windows an US emitter is used to generate the ultrasound inside the system to be inspected and the US receiver performes the leak detection.

Figure 2.23. Example of valve control with US [2.24]

At present, the use of the ultrasonic technique for checking leaks on appliances, in particular on a front oven door is not under discussion and no literature is present. Neverthless, as the oven is a cavity (made of stainless steel), it is possible to apply the same procedure.

4 Smart Online Inspection Tools development

The sections below will describe the process and steps which bring to the development of two smart online inspection tools to be used in production line during real-time quality control check.

The main contribution of the work regards not only the development of two custom devices based on the specific industrial requirements and which can be used during quality control in inline production processes but also the use of smart features which allow the devices to be named a "quality control system".

This means that the systems must be able to do real-time defect diagnosis, extract quality indicators as for example those regarding the goodness of the measurement output and exploit adaptive behaviours which improve tha operator use. Finally the system must be equipped with self diagnosis in order to be "smart". Indeed these features allow the device to be used in a industry 4.0 compliant environment.

About this topic different papers [2.12], [3.2] and a patent [4.3] have been published and will be presented in the next sections.

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Chapter 3

Material and Methods

Since the measurement points in which the smart inspection tools should operate involve different material combinations (i.e. glass, metal, plastic, chromed parts) in order to guarantee an high performance and assure reliable transmission of gap&flush data, a custom device has been developed.

Furthermore, for the ELUX use case two different requirements must be accomplished: on one hand either a device to be used by the operator to check gap and flush on the oven door assembled and on the other hand a device able to detect air leaks through the defective seals of the front door.

The gap and flush inspection on the oven door does not involve "difficult" materials (indeed the oven door target surface is in stainless steel, with is a cooperative material from an optical point of view). Neverthless, this inspection is striclty correlated with the leakage one. Indeed a defective seal or a door not-well assembled can create a leakage or a leakage detected could need a re-assembly of the oven door. Thus, a unique device, which can be used by the operator for both the inspections in sequence or separately, has been developed. In Figure (3.1) the system functional scheme is presented.

In the next sections the principal design characteristics of the devices to be realized will be described. At first the design criteria of the smart online inspection tool for gap and flush measurement to be developed will be presented. Then, a section about the integration of an ultrasonic receiver for leakage tests of air and/or steam for the Electrolux use case will be shown.

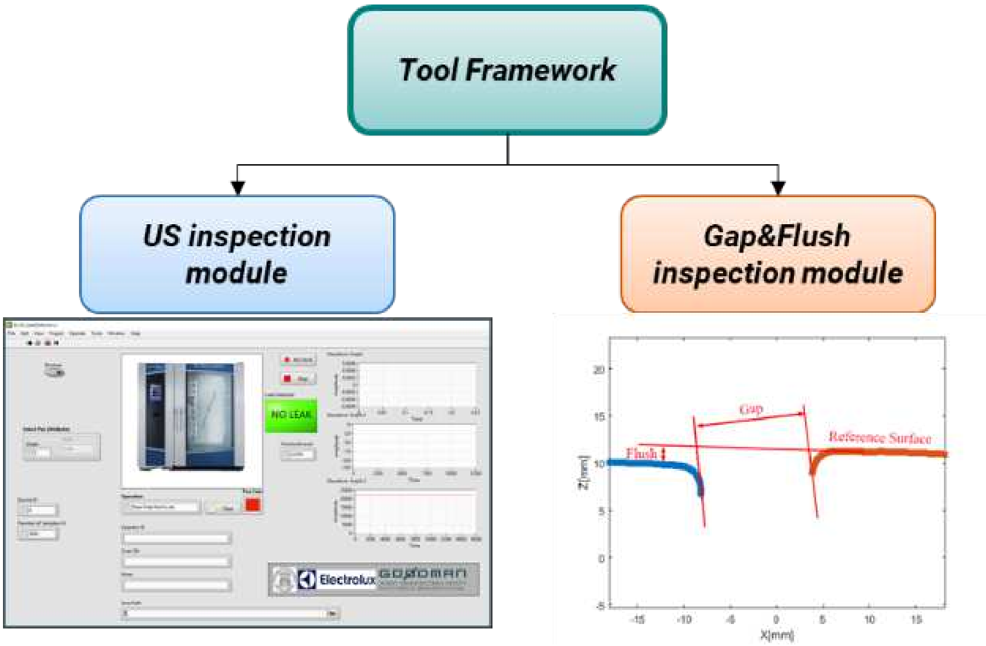

Figure 3.1. ELUX use case – Smart inspection tool concept design [3.1]

1 Concept Design

Regarding the requirements to measure gap and flush on different surfaces and to be used by the operator in line, they neede to have a:

- Triangulation based sensor: a camera, with proper optical characteristics (i.e. in terms of resolution, field of view and sensitivity) and a laser, with safety standard requirements for industrial use and proper wavelength. Indeed the dimensions of gaps and flushes to be measured can have a range of 0,1 to 10 mm for car checks and 0,5 to 50 mm for the oven one which means that the number of pixels to see the defect can vary a lot. Furthermore the whole triangulation sensor must be able to measure in non-optical cooperating surfaces as those of car lights or glasses;

- Ergonomics of the device: indeed, when operators measure gap and flush in the assembly line they have a range of time to do it (usually of 1 s per point) and the measurement instrument must be handling and ready to answer to the measurement requirement. Correlated to the ergonomics is the device dimension and weight, because the operators should be able to put it in a pocket when not in use as for the feeler gauge. In order to be as much as possible usable as a smartphone is the target dimensions and weight have been of 150 x 70 x 40 mm and 250 gr;

- Operator safety: in order to be sure the instrument will be safe for the operator the device must be equipped with features which limits errors and avoid laser hazards;

- Operator guidance: a smart inspection tool is not only a sensor to measure gap and flush but it needs to have smart behaviors which help measuring in a proper way, for example adjusting optical parameters when in presence of particular surfaces (i.e. lights or glass) and driving the operator in the measurement. As a target it has been set its use by an operator with 1-2 weeks of training;

- Measurement uncertainty of the system: not only in terms of target uncertainty (target $U < 0{,}5$ mm) but as all the measurement device the output must be repeatable and reproducible because different operators in on-line operations can be involved.

2 The laser triangulation device

Beeing an optical device for dimensional measurements, it will exploit the laser line triangulation technique.

As explained in [2.12] a laser triangulation system is composed by a laser and a camera. When the laser line is projected onto the target surface the camera detects the light scattered by the target from an angle.

The method requires the surface to be optically diffusive, so to form an image of the laser line on the camera, from which it can be computed the profile Z(X). Gap and flush can be then extracted by processing Z(X).

A schematic of the laser triangulation technique used is shown in Figure (3.2).

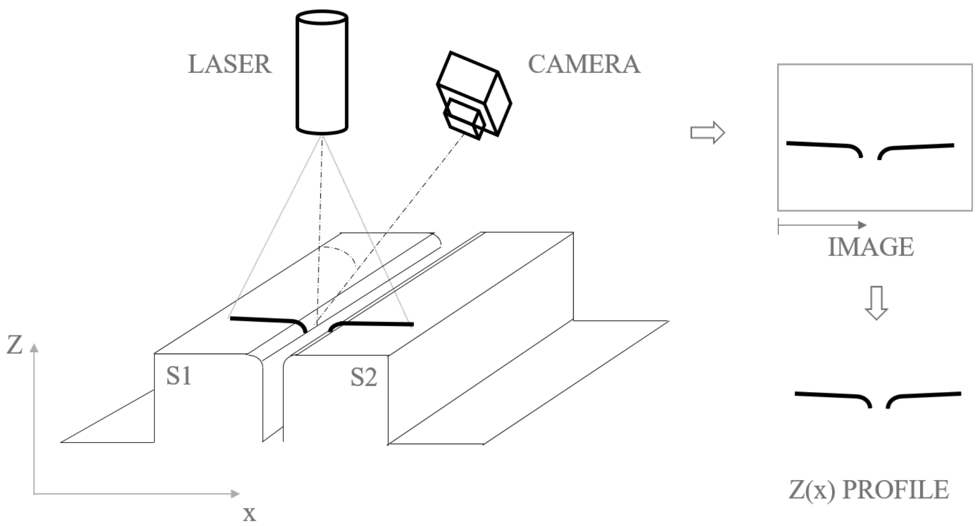

Figure 3.2. Triangulation measurement principle [3.2]

The functional schemes of a laser triangulation sensor can be two:

- camera axis perpendicular to the target and the laser line axis inclined,
- laser line axis perpendicular to the target and the camera axis inclined, Figure (3.3).

In both cases, the other optical axis is kept orthogonal to the surface (or close to orthogonal) and it represents the measurement direction Z(X).

As described in [3.3], in case of inclined camera, the model of the system may be written as:

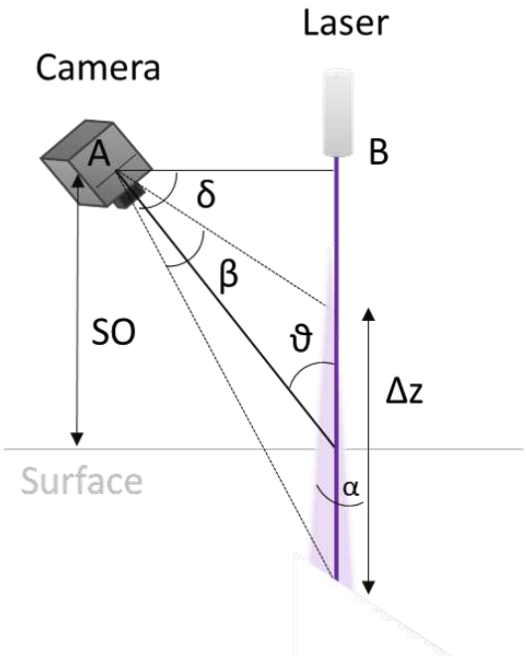

Figure 3.3. Triangulation sensor design

$$Z = \frac{SO \cdot r}{\cos\theta \cdot (r \cdot \cos\theta + F \cdot \sin\theta)}$$

where:

r is the camera sensor resolution and F is the focal lenght .

When designing a triangulation sensor device it must be taken into account how the triangulation is obtained, in particular which parameters interact and contribute to the final system deployment.

Indeed, the final output measurement range Δz can be also obtained by:

$$\Delta z = AB \cdot \frac{\sin\delta}{\cos\delta}$$

where AB is the camera-laser distance and δ is the angle formed by the camera inclined with respect to the laser. The maximum and minimum measurable distances are:

$$Zmin = AB \cdot \frac{\sin(\delta - \frac{\beta}{2})}{\cos(\delta - \frac{\beta}{2})}$$

$$Zmax = AB \cdot \frac{\sin(\delta + \frac{\beta}{2})}{\cos(\delta + \frac{\beta}{2})}$$

The camera-laser distance (AB) and the angle δ choosen are decisive in the final triangulation configuration and its operating stand-off distances (SO). Small AB, for example, are inversely proportional to δ, which means reducing the Δz range of the triangulation sensor.

2.1 Laser Selection

2.1.1 Laser safety

The hardware used must be compliant with the industrial standards permitted and this is particularly critical for lasers. Lasers used in industrial sectors must be compliant in terms of safety with the internationally binding standard IEC 60825-1 [3.4]. In fact, since the laser is a device that emits coherent electromagnetic radiations, the potential risk in its use depends on the device and the conditions of use. For this reason each laser system is associated with a class and in industrial environment generally triangulation systems used by operator are not above 3R/3B class, which means the operator is allowed to use it but must avoid the eye exposure. Furthermore, the hazard distance (NOHD) is an important aspect to be considered. The NOHD is power dependant, as is shown in Figure (3.4).

Figure 3.4. NOHD: relation to laser power

Following the legislation, the laser to be selected for the device realization must be 3R class compliant and with a power of 5 mW.
A further aspect that must be considered is the different sensitivity of the human eye to different wavelengths. As is known [3.5] the human eye is most sensitive to green light. As reported in [3.6] for visible lasers, the wavelength does not affects the eye hazard, skin hazard or fire hazard distances but wavelength affects the three visual interference distances: Flashblindness, glare and distraction. This is normally an important aspect to be considered in the aeronautic environment but in industrial context is relevant to.

2.1.2 Laser wavelength

The choice of the laser wavelength is extremely important. Indeed, it must be considered [3.2]:

- light scattering at the target surface;
- characteristics of available laser (i.e. wavelength);
- light absorption.

Concerning light scattering, focusing on a car body or oven production assembly lines, it can be found [2.12]:

- rough galvanized metal sheet, not painted (a);
- smooth, polished and painted metal sheet (b);
- smooth polished and painted polymeric surfaces (c);
- smooth transparent surfaces with different colour, in glass or polymers (d).

The laser system which must be developed is meant to be used principally at the final assembly of oven production, therefore it will operate on surfaces type a); or at assembly of the car doors, tailgate and lights, therefore it will operate on surfaces type b), c) and d). These surfaces can be smooth, with different colours and be sometimes made of transparent/semitransparent superficial materials.
Surface roughness Ra strongly influences the angular distribution of scattered light [2.12]. For smooth polished surfaces, such as those of a car body frame or a professional oven, Ra is very small and can be considered comparable to the magnitude of the wavelength of visible light λ. When the ratio Ra/λ decreases [3.7], the surface tends to become a mirror, therefore scattered light is very directional (3.9, a). In a laser triangulation system this will affect the measurement performance, because it will reduce the light collected by the camera lens, which looks at the laser line from an angle [2.12].
To improve diffusive light scattering (3.9, b) the choice of a short wavelength is

therefore mandatory, so to have an optically rougher surface.

The images below, Figure (3.8), (3.5), (3.6) and (3.7) are the results of the triangulation setup acquisitions, with the different laser wavelengths described in Table (3.1), on a car sample with material combinations of type b) on the left and type c) on the right.

Camera	Webcam Microsoft HD
Laser 1	Laser line 405 nm, power 5 mW
Laser 2	Laser line 520 nm, power 5 mW
Laser 3	Laser line 650 nm, power 5 mW
Laser 4	Laser line 980 nm, power 5 mW
HW 1	NI DAQ 6008
HW 2	Darlington transistor

Table 3.1. Optical setup: components

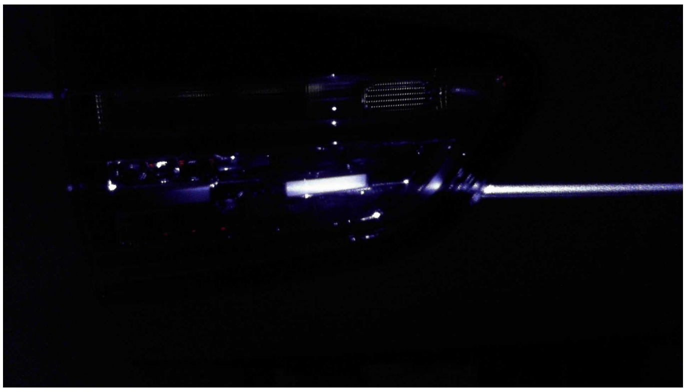

Figure 3.5. Laser wavelength selection: image acquired with Ir laser line

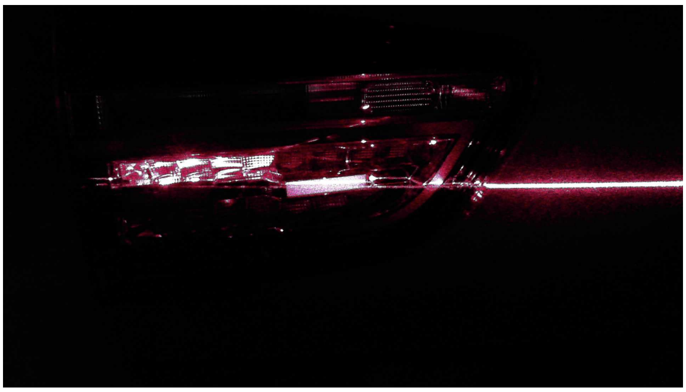

Figure 3.6. Laser wavelength selection: image acquired with Red laser line

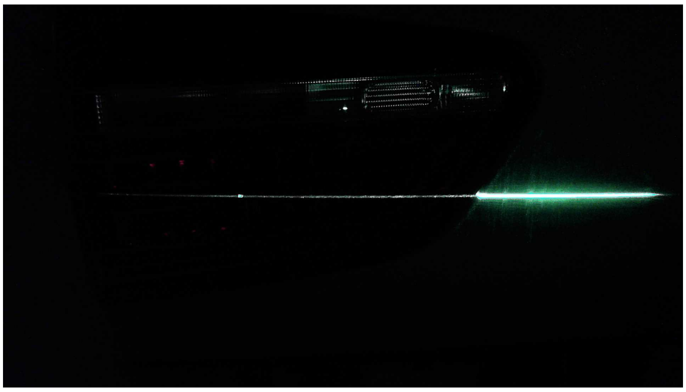

Figure 3.7. Laser wavelength selection: image acquired with Green laser line

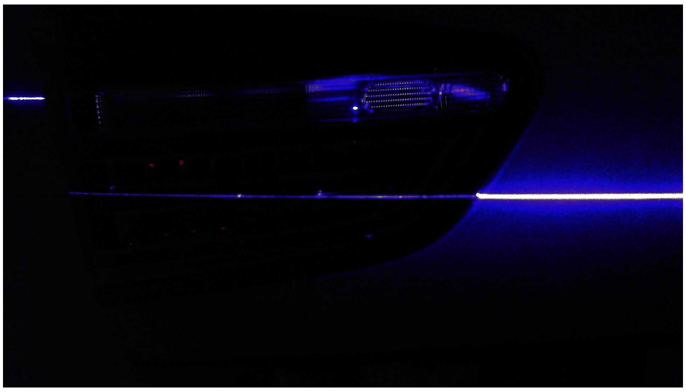

Figure 3.8. Laser wavelength selection: image acquired with Violet laser line

A further aspect to consider is light absorption, which depends on surface colours, its coating layers and pigments [2.12].
Indeed, different painting colours provide different reflectance values in different spectral regions. A white colour is characterized by the flattest and largest reflectance, as well as black is the one characterized by the lowest reflectance. Regarding lighting components, their optical performance depends on transparent plastic layer's colours, on the characteristics of the functional facets that are involved in redirecting the incoming light and on technology used for their fabrication [3.8]. If we measure with a spectrophotometer the reflectance values of these materials, Figure (3.10), there is an increase in the total reflectance percentage in the lower spectral range, i.e. blue to violet region.
Therefore, analysing the available laser sources and their characteristics, a violet laser having λ=405 nm, which satisfies requirements set by light scattering and

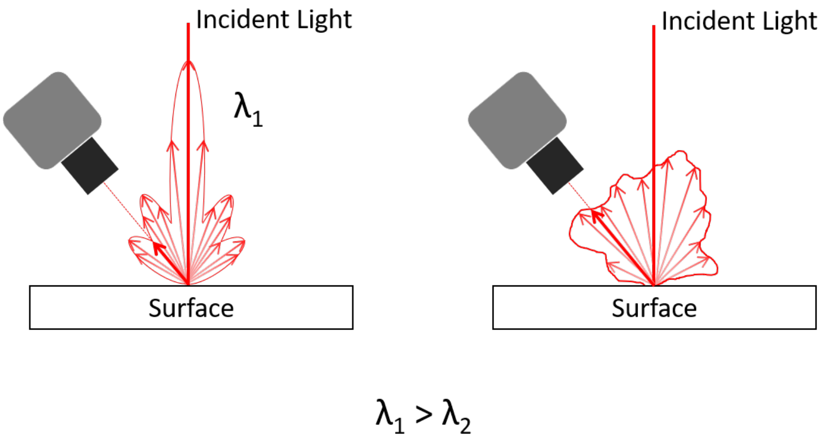

Figure 3.9. Scattering from a surface having roughness Ra

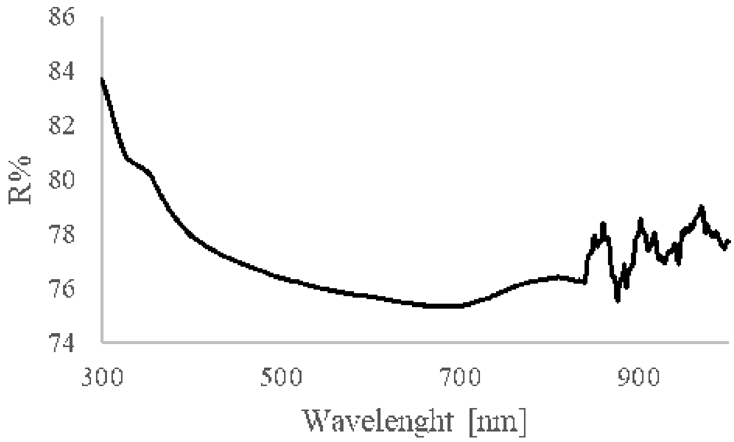

Figure 3.10. Total reflectance percentage in different wavelengths for a lighting component sample on the spectrophotometer

light absorption, has been selected.

2.2 Camera Selection

Camera choice should satisfy several requirements. At first, it should allows a good spectral sensitivity at the laser wavelength choosen, λ=405 nm .
Then, in order to realize a miniaturized laser triangulation system, it should be small (30 x 30 mm) but with adequate sensor resolution to measure gap and flush values typical of the target products.
Indeed, the field of view of the camera lens, β, depends on the camera sensor resolution (r) and on the focal lenght (F):

$$\beta = 2 \cdot \arctan \frac{r}{F}$$

So, a poor resoluted camera will affect the performance off the measurements itself.
Last but not least,the cost of the camera must be taken into account.
Different cameras have been adopted during the prototyping phase, each of these trying to cover the above requirements. The specifics of the three principal cameras adopted during the prototyping phase can be seen in Tables (3.2),(3.3) and (3.4). In Figure (3.11), (3.12) and (3.13) the spectral responses in the violet region are shown.

Model	Genie Nano M2590-NIR
Resolution (MegaPixels)	5,3
Camera Sensor Format	1”
Pixels (H x V)	2,592 x 2,048
Pixels size H x V (μm):	4.8 x 4.8
Type of Sensor	CMOS
Type	Monochrome Camera
Dimensions (mm)	38.9 x 29.0 x 44.0
Cost	500 euro

Table 3.2. Camera 1 characteristics

Model	BASLER DART DAA 1280-54 UM
Resolution (MegaPixels)	1,2
Camera Sensor Format	1/3”
Sensor size (mm)	4.8 x 3.6
Pixels size H x V (μm):	3.75 x 3.75
Type of Sensor	CMOS
Type	Color Camera
Dimensions (mm)	19.2 x 29.3 x 29
Cost	150 euro

Table 3.3. Camera 2 characteristics

Model	Raspberry PiCam
Resolution (MegaPixels)	5
Camera Sensor Format	1/4”
Sensor size (mm)	3.76 x 2.74
Pixels size H x V (μm):	1,4 x 1,4
Type of Sensor	CMOS
Type	Color Camera
Dimensions (mm)	25 x 24 x 9
Cost	30 euro

Table 3.4. Camera 3 characteristics

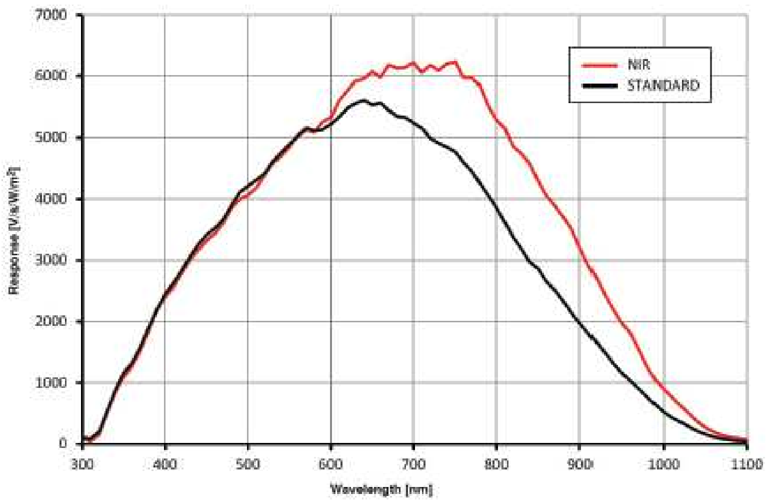

Figure 3.11. Spectral response of the selected camera sensor 1

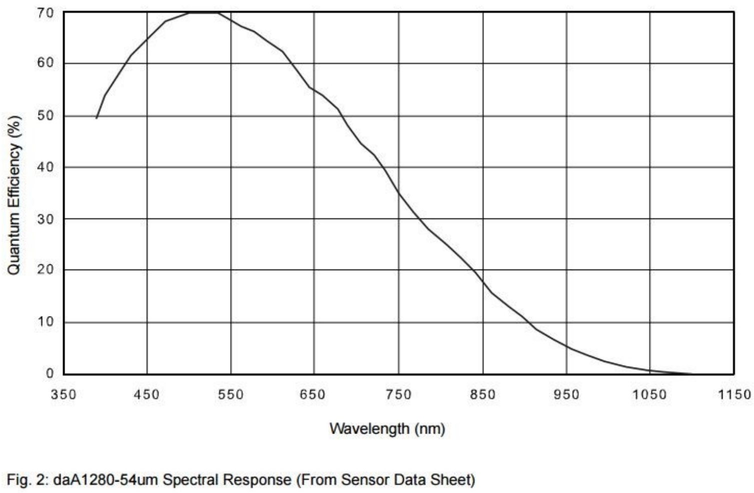

Figure 3.12. Spectral response of the selected camera sensor 2

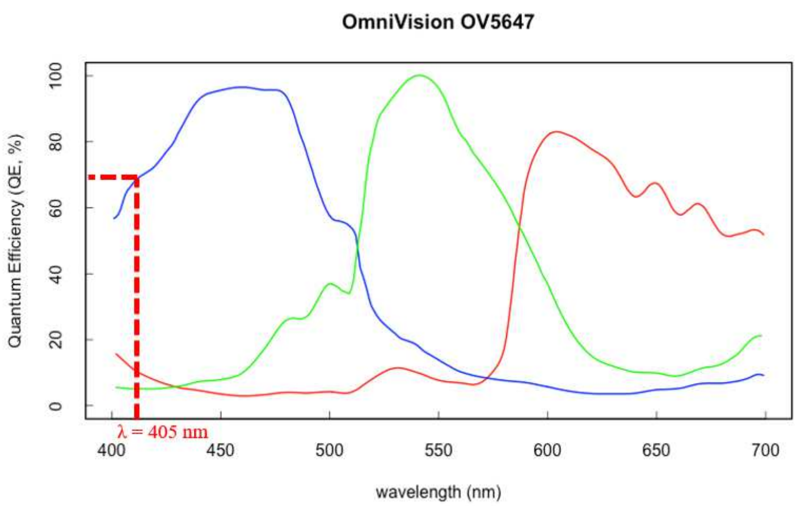

Figure 3.13. Spectral response of the selected camera sensor 3

2.3 Image Elaboration and Gap&Flush extraction

In the image elaboration process the first step is to process the image of the laser line projected o the target surface. The objective is to determine the position of the laser line with subpixel accuracy. Indeed, moving from camera coordinates (2-D) to world coordinates (3-D), the accuracy of the estimated 3-D coordinates of a point in the space is limited by the image resolution. If a large spatial volume is projected onto the imaging surface each single pixel of the image surface records information from a range of positions. Therefore, algorithms which estimate features positions

to subpixel accuracy by interpolating the sensor response function are useful [3.9]. The laser line image runs almost horizontal; its vertical position is found by processing light intensity profiles along the pixel columns, which are close to orthogonal to the line.
To determine the peaks position of the laser line into the image of the triangulation system in exam, three sub-pixel algorithms have been tried: weighted intensity, gaussian kernel [3.10] and Steger method [3.11].
Each algorithm is different from the others in terms of accuracy, robustness and computational time:

- Weighted intensity: this algorithm works considering vertical intensity profiles, despite the actual and local path of the laser line. Independently for each column, the location of the peaks is assumed as a weighted average method, considering some pixels across that with the maximum intensity:the larger is that number, the more accurate, but more sensitive the background noise is the estimate. In Figure (3.14) line reconstruction is shown.

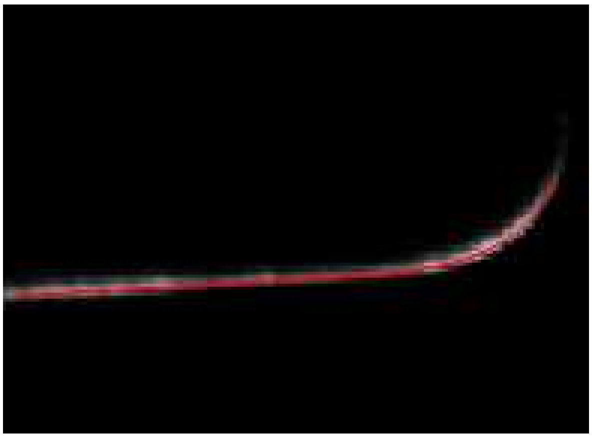

Figure 3.14. Line Reconstruction with Weighted intensity method

- Gaussian Kernel: also this algorithm works considering vertical intensity profiles, despite the actual and local path of the laser line. Independently for each column it uses the three highest, contiguous intensity values around the observed peak of the line and assume that the observed peak shape fits a Gaussian profile. In Figure (3.15) line reconstruction is shown.

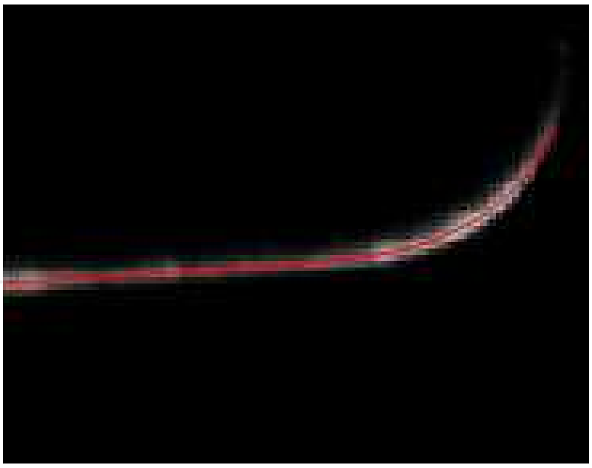

Figure 3.15. Line Reconstruction with Gaussian Kernel method

- Steger method: it uses an explicit model for lines and their surroundings, making possible the extraction of curvilinear structures. It is not considering a specific direction for the laser line (horizontal or vertical) and returns the precise subpixel line position and line width. In Figure (3.14) line reconstruction is shown.

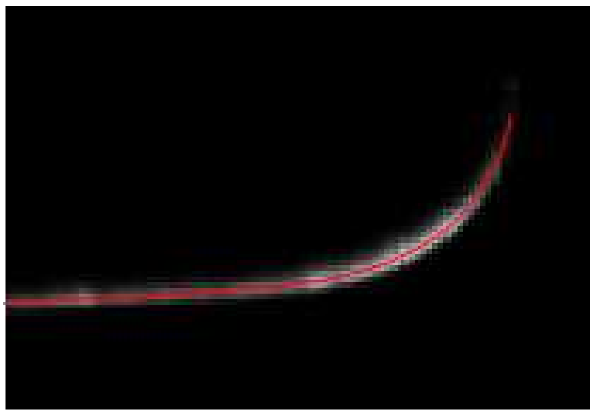

Figure 3.16. Line Reconstruction with Steger method

As it can be seen in the figure with Steger method there is a more accurate extraction of the line profile also on the curved profile, but this at the expense of a longer computing time (1 s).
While Steger algorithm provides separated results for left and right edges, the first two algorithms of profile extraction produce a single point cloud.
In those cases, it is then necessary to separate left and right clouds by a k-means clustering algorithm [3.12], as shown in Figure (3.17).

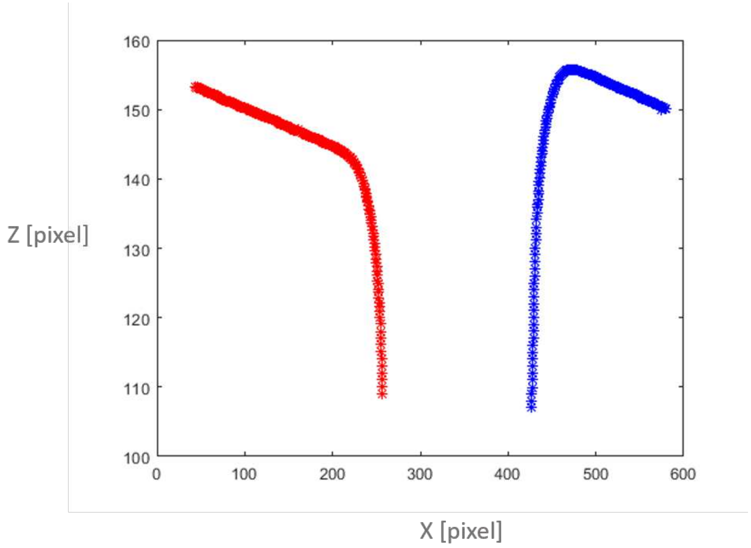

Figure 3.17. Kmeans clustering algorithm

Gaussian Kernel algorithm, which balances performances and computational load (0,5 s vs 1 s) has been choosen as the preferencial line extraction algorithm.

2.3.1 Gap and flush extraction

Point clouds shown in Figure (3.17) for left and right profiles must be processed to extract flush and gap values.
The processing has been performed with two different algorithms, Figure (3.18) and Figure (3.19):

- "Fitting" algorithm
- "Feeler gauge and caliper" (FG) algorithm

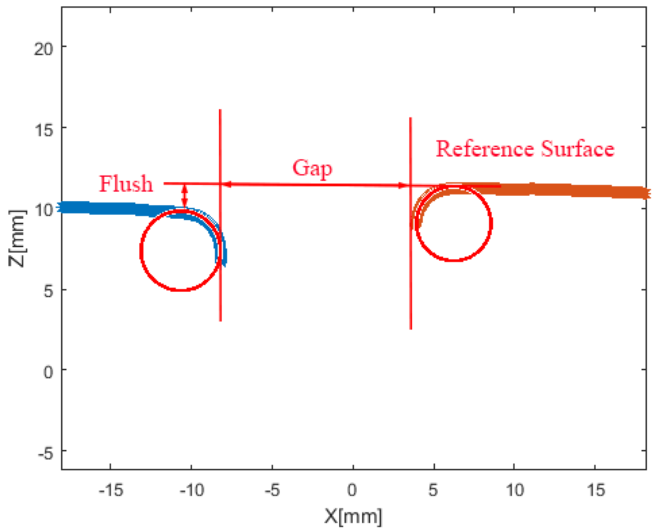

Figure 3.18. "Fitting" algorithm

The fitting algorithm is widely used in triangulation-based gap and flush measurements [3.13] and is based on the definition of Gap and Flush considering a linear edge rounded off. The algorithm involves the following steps:

- Recognition of the point cloud extremes (left and right respectively for right and left hem);
- Fitting the cloud with a straight line using the least square method;
- Recognition of the set of points, at the extremes, that deviate from the line more than a threshold;

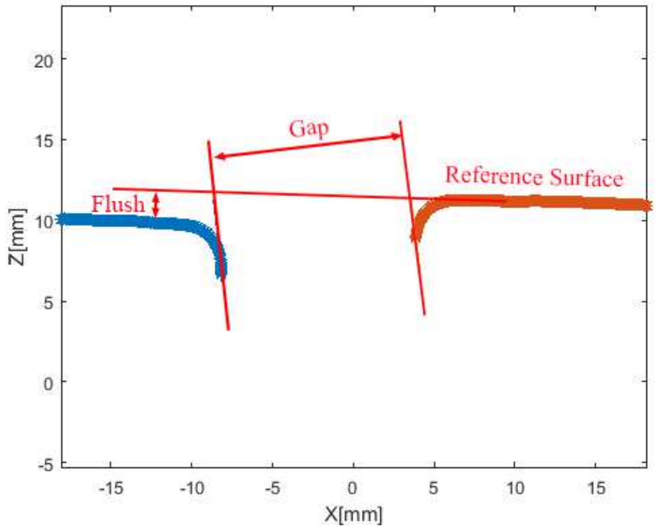

Figure 3.19. "FG" algorithm

- Fit those points with a circle;
- Iteratively modify the 2 populations so that both the line and the circle fit with a minimum square error.

This processing allows to have accurate results in terms of gap and flush values when in optimal conditions, but it turns out to be quite sensitive to the quality of data: even a small number of outliers (misaligned points due to image noise and/or reflections) can affect significantly the result. This happens mainly in the groove, due to poor optical conditions.
In Figure (3.20) an example of the obtained circle fit is shown. Right circle fitting is accurate, while the one in the left is evidently wrong, due to the presence of an isolated point, with tremendous effects on gap and flush measurement.

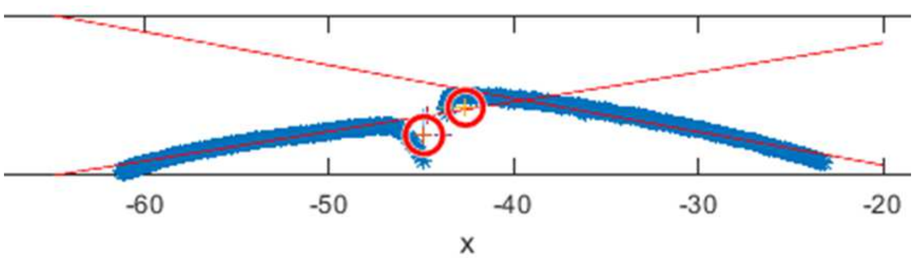

Figure 3.20. Gap and Flush assessment with fitting algorithm

The FG algorithm has been developed during this work basing on the emulation of

the procedure that operators are used to do with a physical feeler gauge.
For the gap determination the algorithm is based on the following steps:

- Recognition of the point cloud extremes (left and right respectively for right and left edge);
- Parametric launch of two parallel lines tangent to left and right edge (slope is varied in steps of 0,1 deg);
- Determination of the angle corresponding to the maximum distance between the two parallel lines.

For the flush determination the algorithm is based on the following steps:

- Recognition of the point cloud extremes;
- Fitting the "reference" cloud with a straight line (Figure (3.19))
- Determination of the angle corresponding to the maximum distance between the reference line and the other point cloud.

This algorithm is based on a brute force search approach:

- it is quite robust with respect to fittings algorithms, because fitting algorithms on noisy data can create artefact which severely affect the gap and flush measurement;
- a minimal overestimation of gap occurs quite always, because the image lacks of data points in the depth of the groove where the laser line image does not form, as is shown in Figure (3.21).
- it is fast, because the family of lines is quite small: the angle span is usually small and a fine resolution not really needed.

Following these considerations, the FG algorithm has been selected for the extraction of gap and flush values from the processed image. Indeed, besides its robustness and fast computational time, it permits to have a good repeatability of results, as it will be shown in the measurement uncertainty evaluation of the device.

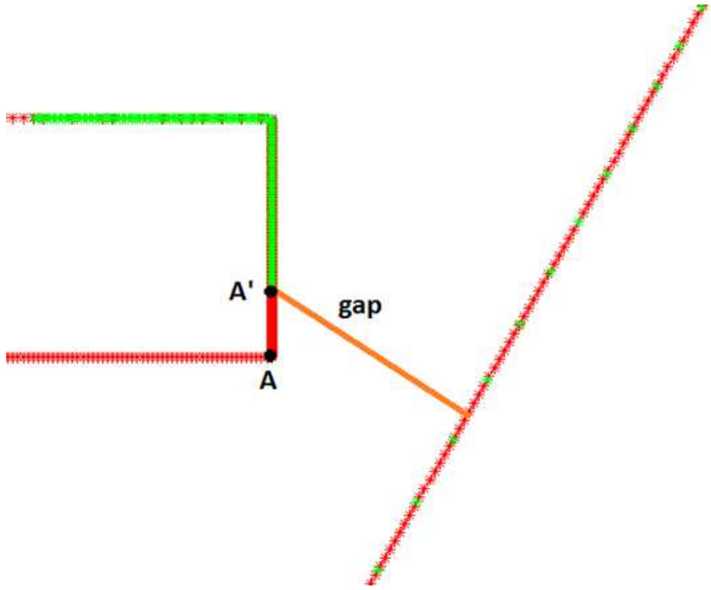

Figure 3.21. Gap error with FG algorithm: red dots represent the real groove, green ones the measured points

3 The human in the loop

Even in factories with a high level of automation, operators play fundamental roles. Indeed, for a variety of technical and skill reasons and at the same time to keep the occupational levels at an ethically and legally acceptable level, humans, are often involved in production operations, sometimes this can be complex and include measurements. Indeed, humans in the loop (HIL) not only perform production tasks but, and moreover, humans are involved with all the aspects with affects decision making, in a sort of human-autonomy. When operators are “in the measurement loop process”, specific problems can occur, mainly related to human behaviors, which could have an impact on the measurement result. Indeed, in these conditions, measurement uncertainty depends both on the measurement instrument but also on the operator skillness. This concept opens a series of points related to questions like ergonomy, operator training, design of well-established human-machine interface and contribute to the reproducibility of the results.

Figure 3.22. "Man in the loop"

Furthermore, the measurement device must be compliant to the task of keeping the operator in the measurement loop, giving ergonomy for its use but at the same time preventing operator accidents avoiding the laser eye contact or errors in the measurements procedure.

3.1 Ergonomics

The ergonomics has been an important aspect to consider because the operator must manage/carry the device during her/his working hours.
Several prototypes have been released, after designing with CAD tools and 3D printing of covers for the triangulation sensor, each implementing an incremental step towards the development of the final system.

3.2 Operator safety

Safety aspects must be considered when developing a device used in a production line by the operator.
To guarantee the operator safety it has been studied to equip the device with dedicated hardware enabling the development of smart behaviors.
The device has been equipped with a distance sensor. The aim of such sensor is to conditionally switch on/off the laser source when the device-to-target distance gets above functioning range. This helps in providing a feedback to the operator with the intent also of lowering the uncertainty associated to a manual measurement and to power off lasers when it isn't in its measurements range, this avoiding to point it toward eyes.
Two different distance sensors have been tried:

- a NIR time of flight (ToF) laser sensor, Figure (3.23) which uses optical principle to run. Indeed, a IR laser light from the sensor reaches the target and is reflected to the sensor that can measure how much distance there is from the sensor to the target.

- a ultrasound sensor, Figure (3.24) which principle is propagation of ultrasound. When ultrasounds, emitted from the sensor, impacts the target, they are reflected; then, the US sensor receives the signal back and the distance from the sensor can be measured.

The time of flight sensor for measurement of the target distance has been tested together with the US sensor to decide who was the best candidate for the device.

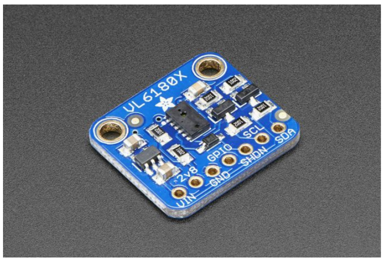

Figure 3.23. Laser sensor

Figure 3.24. Ultrasonic sensor

The comparison of the sensors for "measuring range" has been assessed in this way:

- a performance check of US and ToF sensors on flat dark opaque target
- a performance check of US and ToF sensor on rearlight sample (worst working condition)

Results are shown in Figure (3.25), (3.26) and (3.27). A calibration curve with the two-different sensor has been constructed and results showed that both sensors have an uncertainty of some mm.
As can be seen laser sensor outperforms US sensor on opaque surfaces but will suffer on transparent surfaces when the laser beam is not perpendicular to the target surface. This behavior is not a suprise because the same happens for laser line used in the triangulation system. So, this apparent drawback could turn out to be useful in order to provide information about the relative position between the device and the target: measurement is done on rearlight if device is sufficiently perpendicular to the surface. The choice felt in this way to the laser sensor.
Furthermore, the possibility to check whether the device is pointed towards the correct position and within the correct working target-to-sensor distance range is

an enabler for an embedded self-diagnosis feature of the device. Indeed, since the device provides a feedback to the operator for both the two phases, this is a way to autodiagnose whether the measurement conditions for which it was designed are respected or not. This is an innovative feature for a gap&flush measurement device. Indeed, commercial systems do not have this capability: they typically provide a feedback about the working range as in-out information since this check is performed directly on the image (if the laser line is captured in the image then the device is operating within its working range). A comparison between them showed also that

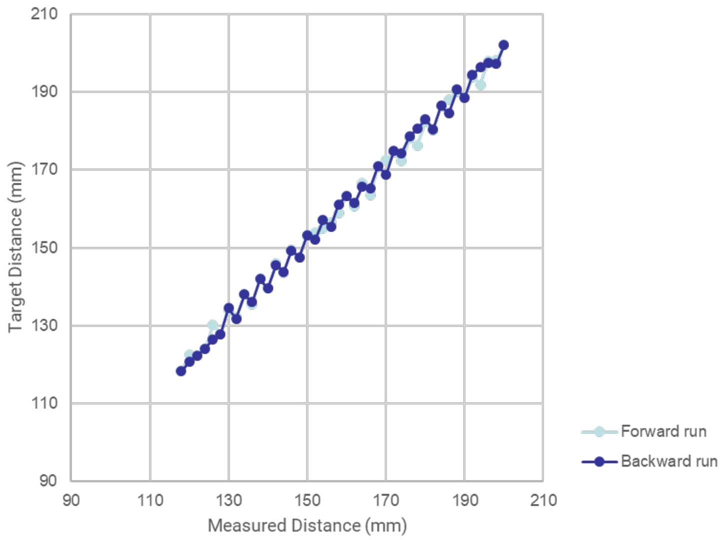

Figure 3.25. Ultrasonic sensor (US)

US sensor is more affected by deviation due to temperature and humidity. This dependence forces to calibrate the sensor when these parameters change.
From all these considerations, the NIR ToF sensor results the final candidate for the device.

Model	Adafruit VL6180X
Ranging (mm)	0-100
Size (mm)	20.5mm x 18.0mm x 3.0mm

Table 3.5. ToF sensor characteristics

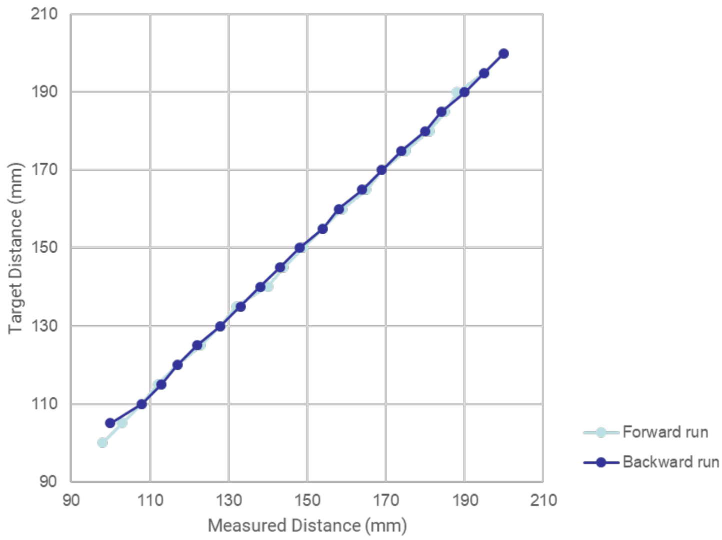

Figure 3.26. Laser sensor (ToF)

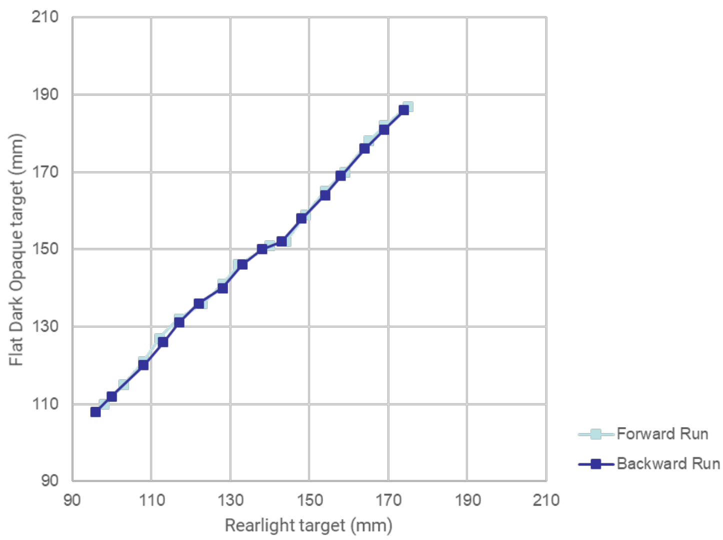

Figure 3.27. Laser sensor (ToF) on rearlight target

3.3 Operator guidance

Knowing the point to measure when in assembly process assures not only the best sequence for the system operation but it enables also to pre-set system parameters (i.e. exposure time), it enables to store data in the right way for correlation and again guarantee operator safety, avoiding for example eye hazard.
To accomplish this task different algorithms for target recognition have been tested. The measurement setup has been composed by a T-ROC car sample allocated in

the university laboratory and a camera (Webcam Microsoft LifeCam Studio). Different images at different points of the tailgate have been acquired, as it is shown in Figure (3.28) and then classified (i.e. metal-metal, metal-plastic, metal-chromed, plastic-plastic). Then, features recognition algorithms have been applied, for exam-

Figure 3.28. Measurement points

ple SURF, FAST, Harris, etc.[3.14]. Nonetheless, these algorithms are very good when the scene acquired has a lot of features but loss recognition performances on images with poor features associations. Another algorithm tried has been bag of features [3.15] which mixes the program structure of feature recognition algorithms with the classification function. Results with this algorithm can be considered more repeatable but sometimes fails with right or left images of the same object, for example rear lights.
The last algorithm investigated has been classification with convolutional neural network (CNN) [3.16]. A pre-trained neural network, called Alec has been used [3.17]. This is a pre-trained CNN that takes the colour image of the part (with laser source switched off) under inspection as input and classifies the image according to the classes defined during the learning phase.
The experimental setup has been repeated in the production line of VWAE, on dif-ferents cars. Figure (3.29) reports results from a set of 62 classification points of different parts of different car's painting samples. The CNN dataset has been populated with 650 images, with 30% of the images used for training and the remaining 70% for data validation. As it can be seen, the CNN correctly classifies 75% of the images. The CNN fails in classifying the image received in the 13% of the whole

population. Left to right inversion (LT/RT) represents the main source of classification error. This is quite predictable, since the CNN is invariant to image scaling and rotation.

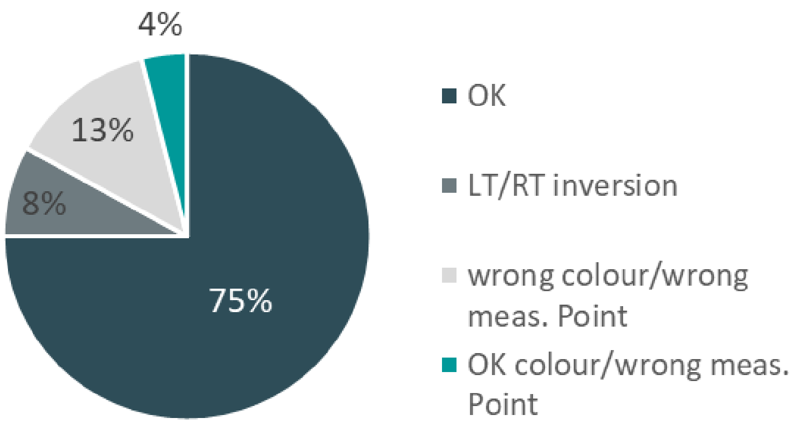

Figure 3.29. CNN classification results

Few images have been used for training the network with respects of the huge amount usually used, so these results can be considered remarkable and some misclassifications still present. However, when the device will run continuously in the production line and more images to do the classification will be available, the behavior of the CNN will become more and more stable, in a continous learning approach, thus providing more and more accurate classification results.

3.4 Measurement procedure

Being a hand-held device, the tool needs to ease the interaction with the operator. The measurement procedure involves the operator at different levels as it is shown in Figure (3.30).

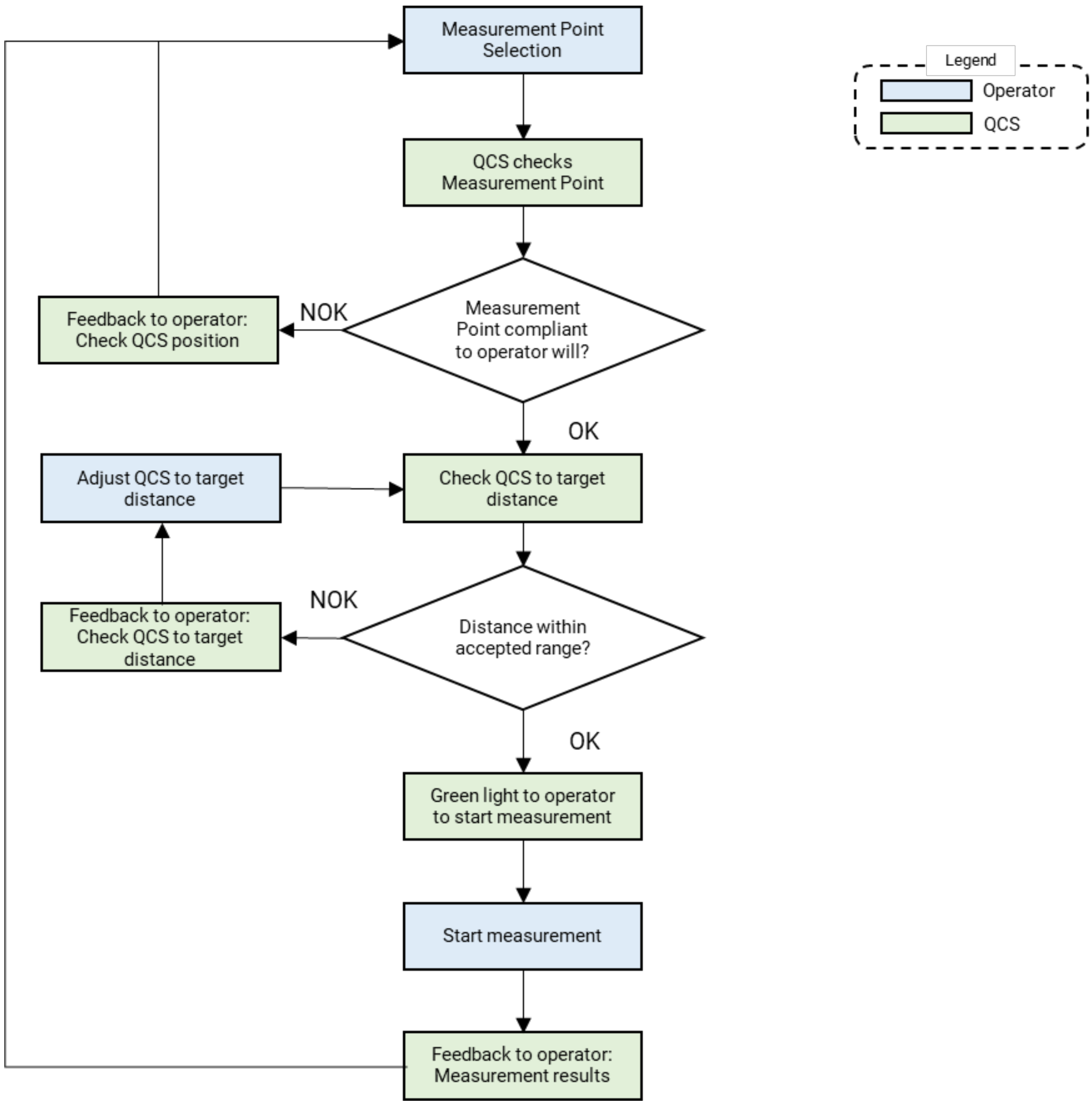

Figure 3.30. QCS for Gap&Flush: measurement procedure

To accomplish this task a continuous interaction loop must been implemented: the device checks operator decisions by comparing them with its own strategies. If and only if the results of these checks comply with pre-set acceptable strategies, then the permission to perform a measurement is provided.

When the operator want to start an inspection he/she know the measurement point he/she want to measure. The device must be able to ask to point the device towards the measurement that the operator has selected. To avoid that the operator has to measure in different points from the selection, a colour picture of the part must be automatically taken by the device, with laser source switched off, and the CNN algorithms previously seen for recognizing and classifying the framed part run. If the result of this classification check that the measurement point selected by the operator is really the one he/she pointed the device at, the procedure goes automatically on, but if not the operator will be asked to check the position of the device. This cross-check has a reciprocal implication: on one hand it makes possible the reduction of assigning gaps and flushes values to wrong measurement points, on the other hand it permits an optimization of the measurement conditions, in particular to optimize the exposure time of the camera with respect to materials/colours characterizing the part under inspection, which allows, guaranting the largest possible contrast of the laser line image, the lowest uncertainty on the results. Indeed, to guarantee a correct analysis for the GO0D MAN actors working at the higher layers, data provided by the quality control system must be as accurate as possible. This translates in reducing the uncertainty of the measurement.

Another relevant aspect for device is to assure safety for the operator. The time-of-flight distance sensor in the device has in this way a twofold purpose: enable the measurement to be consistent with its calibration range and ensure to be safe for operator use. In fact, laser is switched on only if the measurement point is recognized as valid and target-to-sensor distance is within the measuring range. If and only if the results of these checks comply with operator decisions, then the permission to start measurement is provided.

Finally, to enable a interactive procedure which involved the operator a feedback is required when the measurement is done.

As a measurement system (smart online inspection tool), the portable device for gap&flush must be calibrated periodically.

This calibration procedure regards three features of the device:

- Ability to correctly identify the measurement point;

- Correct functionality of the distance sensor;
- Correct evaluation of gap&flush values.

The first task of the list can be address if the device is pointed towards a series of known positions at regular intervals and checking also if the classification is running correctly or not, for example pointing it on different materials/colours target surface. If the procedure fails, the device should be sent to maintenance.

The second and the third items of the list above can be addressed together. Indeed, the device can be placed on a target with known gaps and flushes, and with a slide moving perpendicularly with respect to the target it is possible to check the correct functioning both of the gap&flush measurement part and the distance sensor.

4 The Leak Detection

For the leakage inspection the measurement technique identified is the ultrasound technique. Indeed the oven cavity can be considered as a source generating ultrasounds when a US emitter, as in Figure (3.31) is positioned inside it. The ultrasounds, which can be generated by a defective seal or not-well-screwed door hinges, can be then detected by an ultrasound receiver, an example in Figure (3.32), and the temporal history acquired.

Figure 3.31. Ultrasound Emitter (Model SDT 8)

Figure 3.32. Ultrasound Receiver (Model SDT 150)

The presence of leak corresponds to a increasing voltage output for the ultrasound signal which can be used to generate a compliant/non compliant tag for the operator. The measurement procedure concept and the results which can be visualized and stored at the end of the inspections are shown in Figure (3.33) and (3.34).

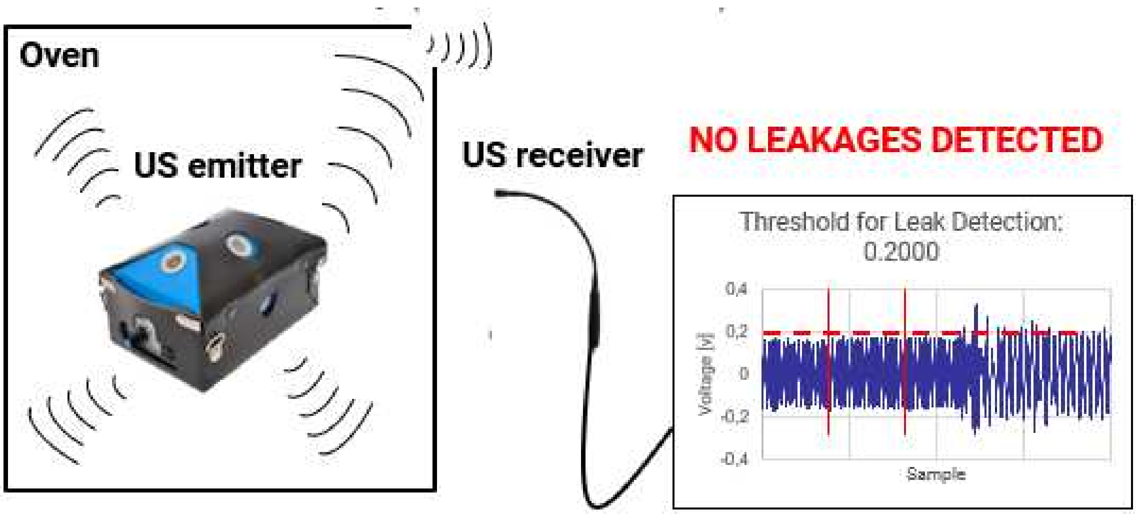

Figure 3.33. Measurement principle for leakage detection: no leak detected

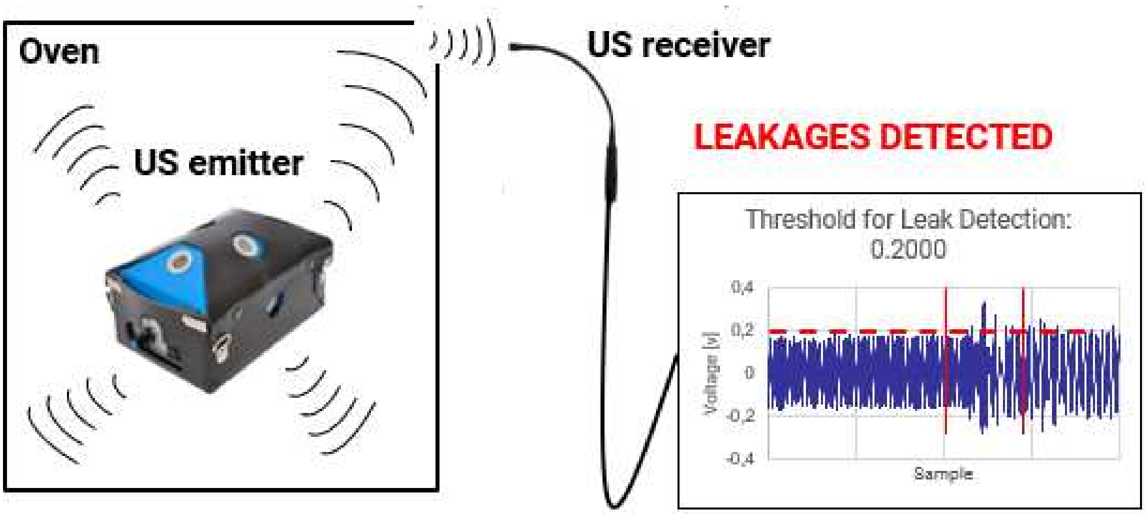

Figure 3.34. Measurement principle for leakage detection: leak detected

5 Integration in the Go0dman platform

The GO0D MAN project communication platform is given by the Multi-Agent control system architecture.

The communication between the device and its associated agent must take place exploiting specifc industrial protocol (i.e. OPC-UA) and exchanging strings containing results from the inspection performed, Figure (4.6).

Communication must be bidirectional: inspection results sent in real-time from the device to the associated Resource Agent (RA) but also received from the agent (e.g.

the number of measurement points to inspect). This communication makes it possible an optimization of the whole inspection.
The communication strategy is schematized in Figure (3.35).

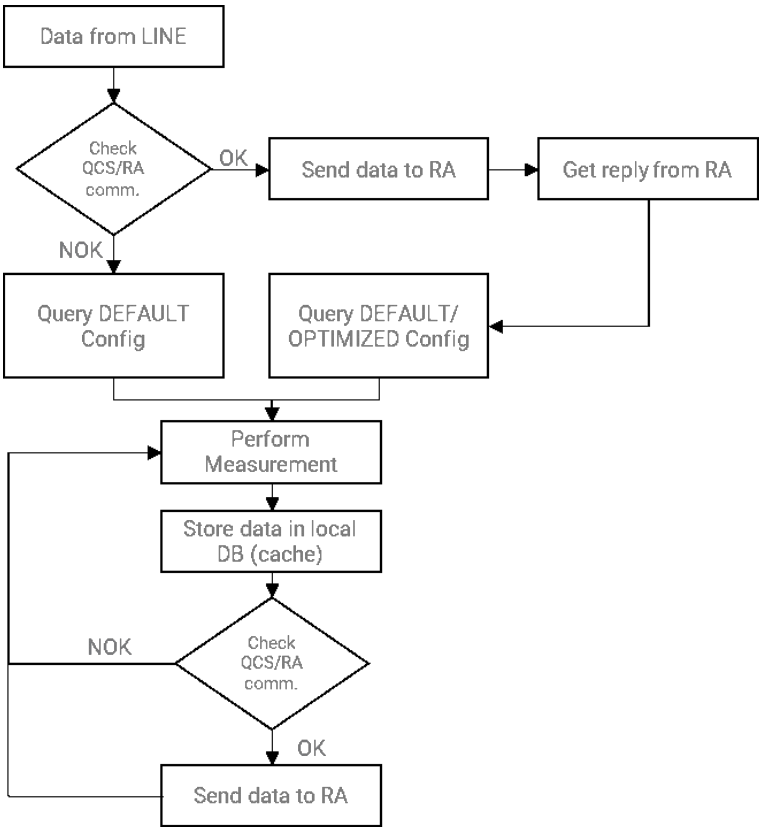

Figure 3.35. Communication strategy

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Chapter 4

Results

1 Prototypes

A series of prototypes have been designed during the research/project activity, as is shown in Figure (4.1).

Starting from cable solutions and calculation performed on a remote pc, in order to reach an high quality device able to be used by the operator in the line, prototyping has been moved toward wireless, cable-free hardware and calculation performed on board, with a minimized design.

The paragraphs below shown for each prototype a scheme with the characteristics and the deployment toward the final solution.

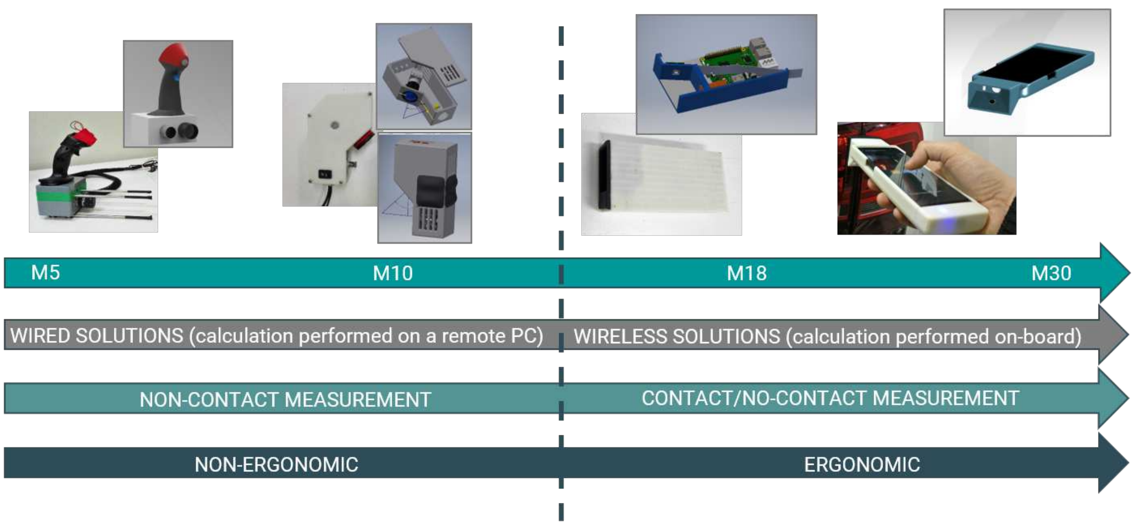

Figure 4.1. Prototypes deployment

1.1 First prototype

The first prototype realized is shown in Figure (4.2).

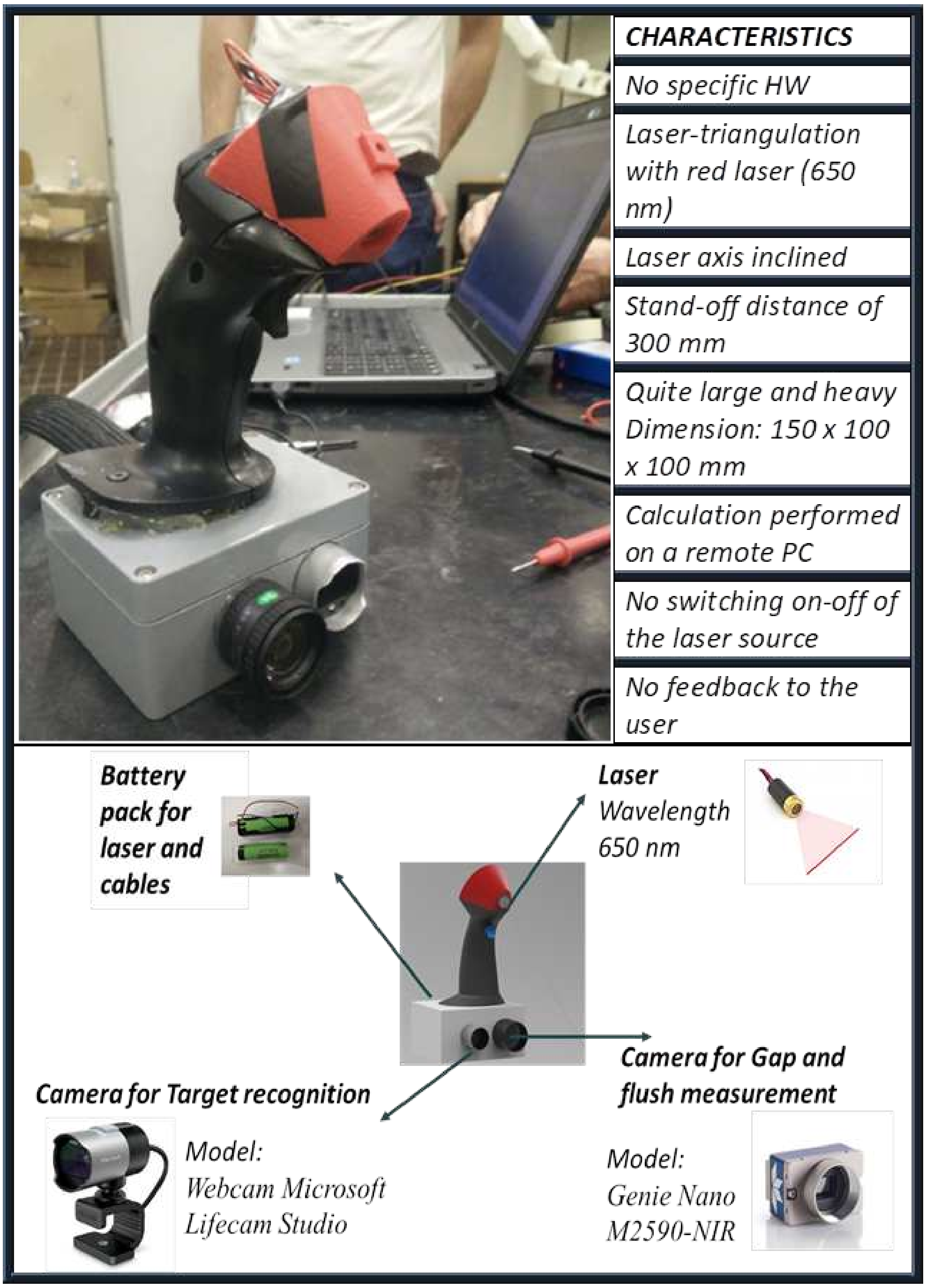

Figure 4.2. First prototype design

1.2 Second prototype

The second prototype realized is shown in Figure (4.3).

Figure 4.3. Second prototype design

1.3 Third prototype

The third prototype realized is shown in Figure (4.4).

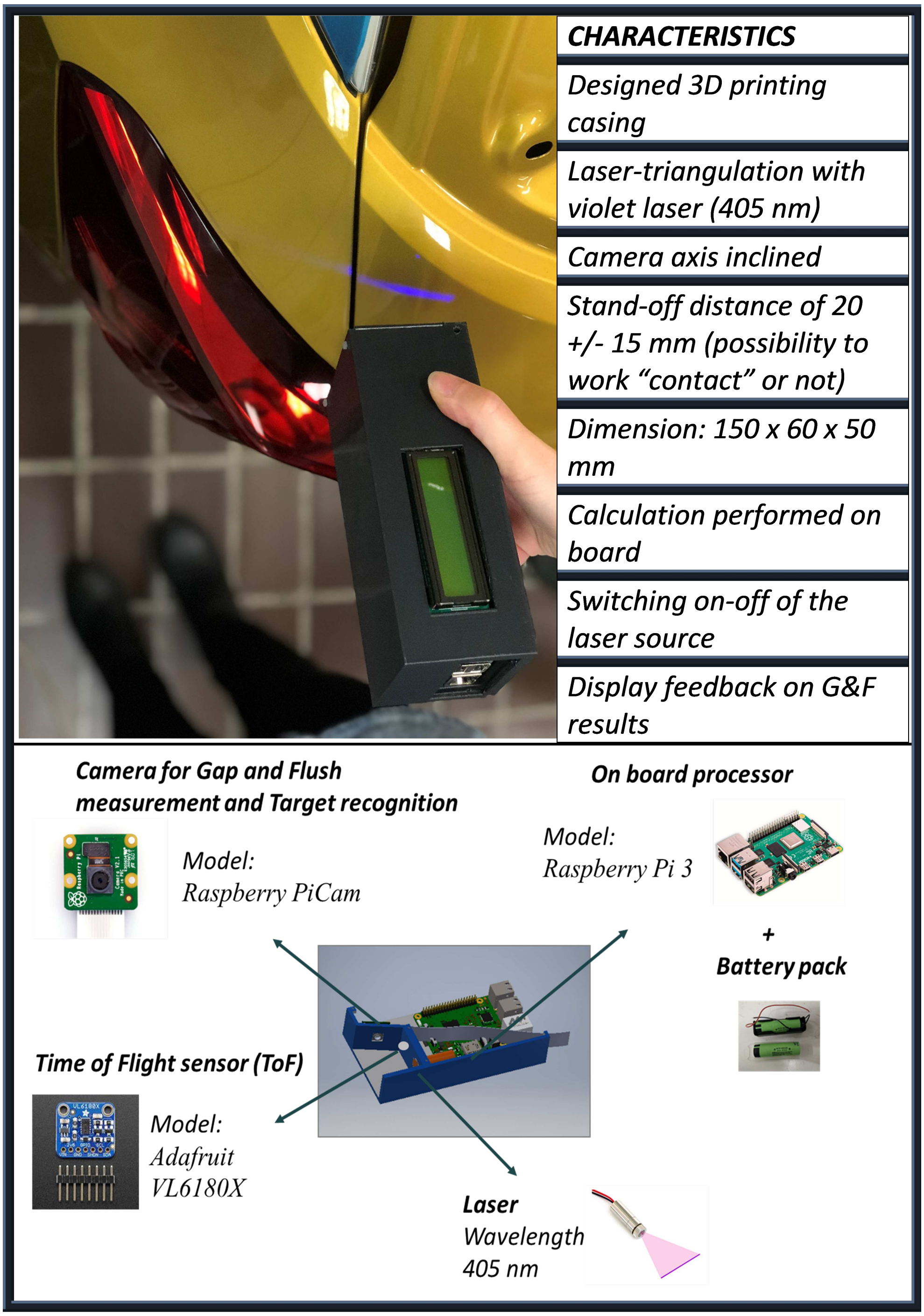

Figure 4.4. Third prototype design

2 G3F

The final prototype realized is shown in Figure (4.5).

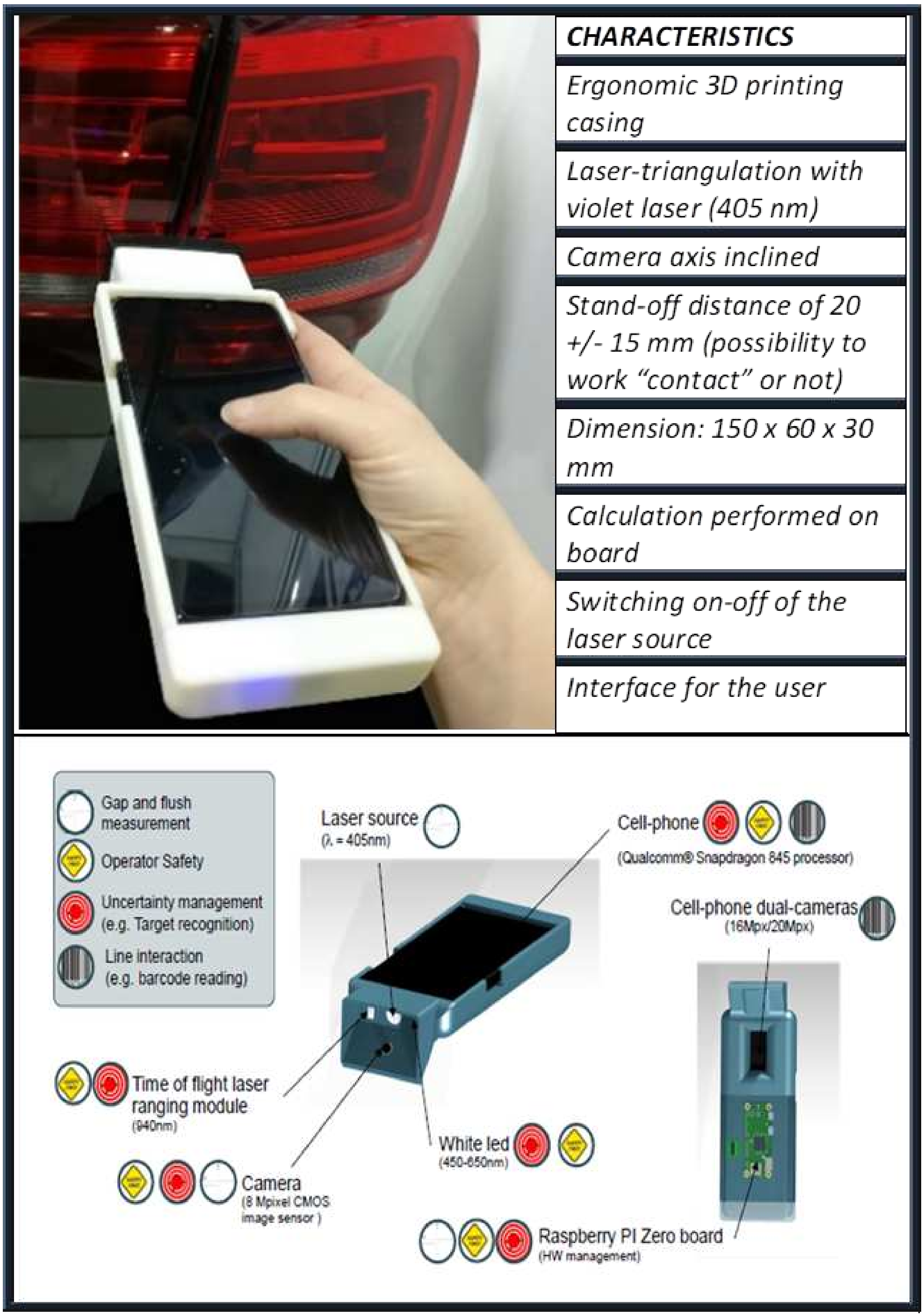

Figure 4.5. Final prototype design

2.1 Hardware characteristics

The final deployment of the device has been called "G3F", where G is for Gap and F is for Flush but also for Flexible, Fast and Functional.
In literature the use of smart-phones for dimensional inspection is under discussion. In [4.1], for example a "freehand" laser scanning using mobile phone is presented. In [4.2], furthermore, an interesting use of smartphone is made to do 3D image reconstruction, using a Samsung galaxy beam model and its embedded pico projector. In order to design a portable device, with computational power, wireless network connectivity, interface ports, on-board sensors, display, human-machine-interface and battery supply, an ideal candidate platform is in fact a smart-phone.
Thus, the idea for the system to be developed is to design a miniature laser scanner integrated into a smart-phone.
Starting from the triangulation system, it is installed on a casing in front of the smart-phone, realized in polymeric material (PLA) by additive manufacturing, which forms an enclosure hosting the laser and the camera.
The system is designed to operate at a stand-off distance SO=20 mm, over a range Δz=15 mm. These specifications allow for using the system either in contact with the target surface, or from a larger distance, without contact. The front part of the enclosure is surrounded by a rubber seal. When the operator puts the device in contact with the surface, the casing prevents the ambient light to reach the system and the rubber seal avoids scratches on the surface.
The camera is connected and driven by a Raspberry Pi Zero installed in the casing. The colour RGB image is acquired and the image is sent to the smart-phone via type-C USB link. The whole system weight is 250 gr.

2.2 Software characteristics

The software manage the whole device operating on four levels [3.2], Figure (4.6):

- Interaction with the operator;
- Interaction with the production line
- Processing of the image acquired and extraction of gap&flush data;
- Communication with the plant middleware.

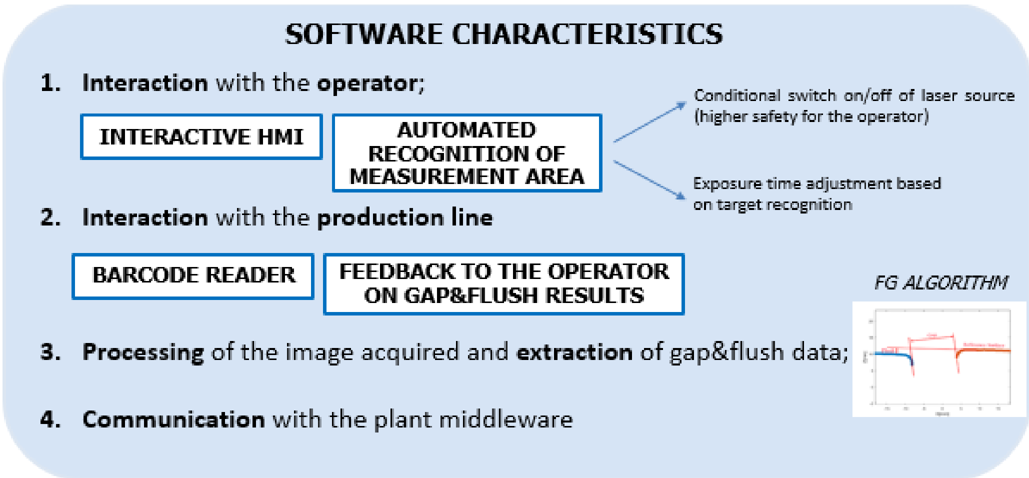

Figure 4.6. Software Chacteristics

The image is processed through the computation resources of the smart-phone. The smart-phone runs a Termux app as a terminal emulator and a Linux environment for Android, where a minimal base system is installed, and additional packages are available, in particular Python for image processing and php for web interface displayed to the operator (human-machine interface).Being the prototype an hand-held device the computational power is limited and the processing algorithm has been designed accordingly.
An interactive HMI has been specifically designed to guarantee a user-friendly interface for the operator who has to manage the device. The scheme is shown in Figure (4.7).

The web-service has been developed also to give the possibility of remotely connect to the device and access the user interface for supervision and debug purposes.

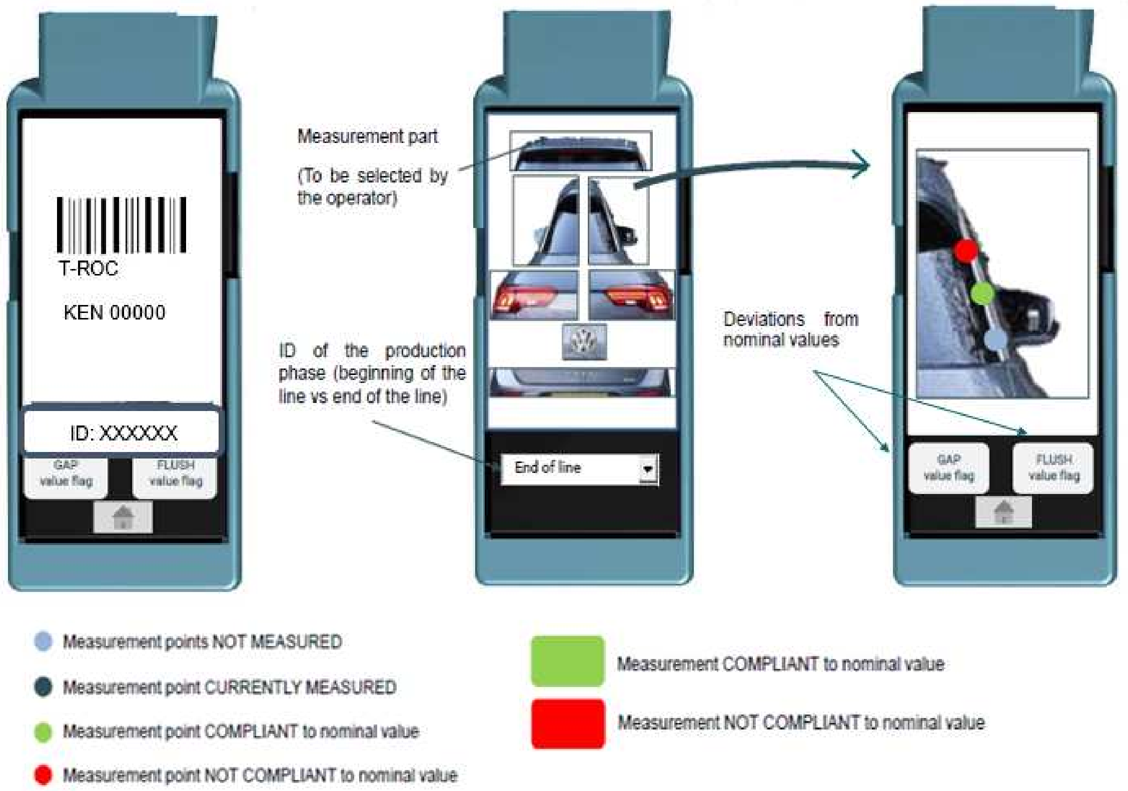

Figure 4.7. Device measurement interface: area definition

Regarding the interaction with the production line two features have been implemented. A barcode reading with the front-of camera of the smart-phone permits to track the product model and to associate gap and flush results. This process, through the Go0dman architecture, allows to correlate data with the up-stream measured results. Then, the instrument is able to give a feedback to the operator on gap and flush calculated. This permits to correct values on the assembled product during the measurement procedure.

In the calculation step of Gap&Flush one of the two strategies which have been implemented has been choosen: "FG" algorithm. This is the best solution for the great variety of geometric configurations characterizing the measurement points.

The communication with the production platform middleware is enabled by the Multi-Agent architecture, via OPC-UA protocol. In the idea of giving the possibility of correlation between up-stream and down-stream process in order to prevent scraps and waste, more than one device can be used. The configuration of the devices in the lines with the Agent ruled for the measurement setup are gived by a sincronous configuration between the device via rest service.

Local/global storage of data is permitted by a SQL database to permits debugging purpose when the device isn't in operation.

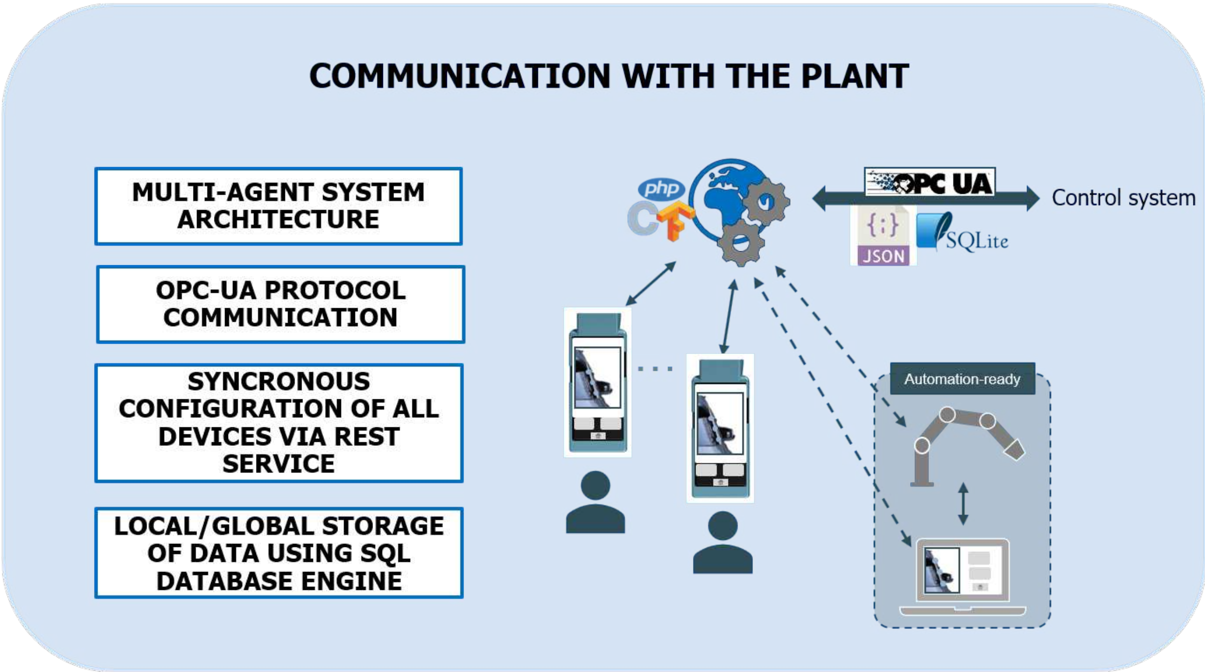

Figure 4.8. Communication with the plant

2.3 Smart behaviors

Acting as a quality control system and integrated in the ZDM strategy the device must have smart features which permits to integrate ”man in the loop” and to a real-time process monitoring. The list below summarize the principal features embedded:

- Automated identification of measurement point through CNN;
- Conditional Switch on/off of laser source;
- Hybrid contact/non-contact operating mode (<35mm target-to-device distance)
- Optimization of camera exposure time to improve image quality;
- Possibility to check whether the device is pointed towards the correct position;
- Possibility to check whether the device is used within the correct working target-to-sensor;
- Ability to correctly identify the measurement position by pointing the device towards a series of known positions and checking whether the classification is running correctly or not;
- Use of a reference Gap&Flush device to verify the correct functioning of the distance sensor and the evaluation of gap&flush values.

The whole system and its functionalities have been patented [4.3].

3 SealScan

The prototype realized for the Electrolux use case is shown in Figure (4.9).

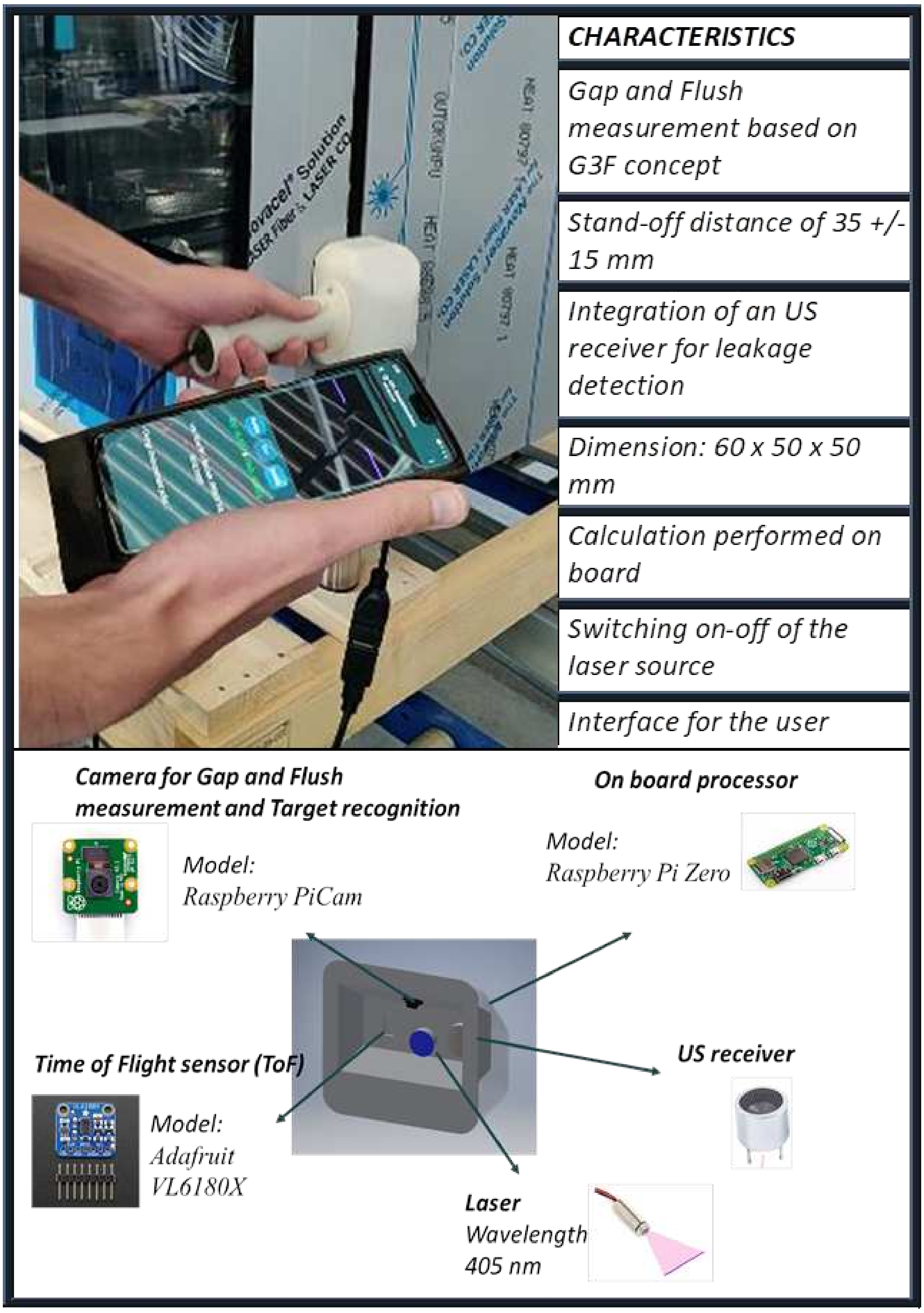

Figure 4.9. ”SealScan” prototype design

The idea was to integrate the leakage inspection with the gap and flush measurement in order to have a unique Smart device, able to be used for both.
An ultrasound receiver has been therefore integrated in the hosting casing of the laser triangulation device and an embedded processor board developed for the signal acquisition and processing. The integration of hardware managing the US in a cell-phone based solution to enable and also to increase the functionality of the inspections.
An operator managing the tool can therefore chooses if performing an US inspection, a gap & flush measurement or both using the same software framework.
Ovens are big appliances. Because it can be difficult to look at a screen on a device that is measuring at points at the top and bottom parts of the oven, some further specifications for the prototype have been assessed. The concept has been to design a separate, stethoscope-like, sensing tool, as shown in Figure (4.10).

Figure 4.10. SealScan prototype concept

Motivations have been:

- Ergonomics for the operator in order to scan along the oven;
- Smaller device in order to measure under the oven;
- Possibility to use different smart-phones;
- Easy and comfortable display of measured data.

4 Leak tests

Regarding the leakage detection, in order to validate the prototype version for the Electrolux use case an inline setup has been used. This comprises the ultrasound source emitter, model SDT 8 ,an oven in Electrolux line, as is shown in Figure (4.11) and the SealScan.

The test consisted in moving the prototype along the space between the hinged oven door and the case, Figure (4.12), while the emitter is positioned inside the oven cavity. The receiver prototype output has been acquired using the electronic board inside and a compliant/non compliant tag visualized on the smart-phone screen, Figure (4.13).

Figure 4.11. Measurement setup

In order to fix a threshold for leakage detection, a reference made with a needle and positioned as in Figure (4.14) has been used, creating an air gap similar to a small gasket defect. After positioning the emitter inside the oven, the prototype has been approached to the reference and the output (of 0,2 V) has been set as a threshold for leakage detection by acting on the PWM modulation on the embedded board.

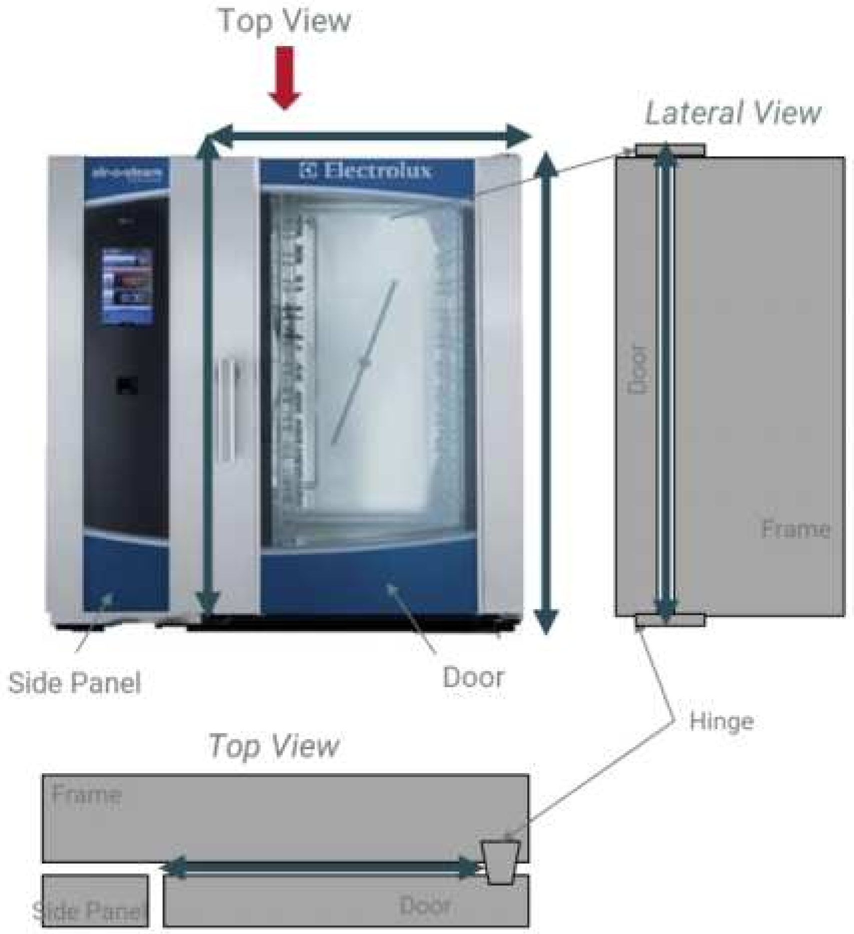

Figure 4.12. Measurement area to scan

For some of the points inspected, scanning with the SealScan along the oven, the tag was NOT OK.
For example, in Figure (4.15) the ultrasound temporal history for a non compliant point, named here as 5C is presented and it was corresponding to the upper hinge where the seal has been found defective, as is shown in Figure (4.16). The test have been repeated on different ovens and results obtained sent to the relative Resource Agent to be integrated in the GO0DMAN platform.

Figure 4.13. Leak tag

Figure 4.14. Reference

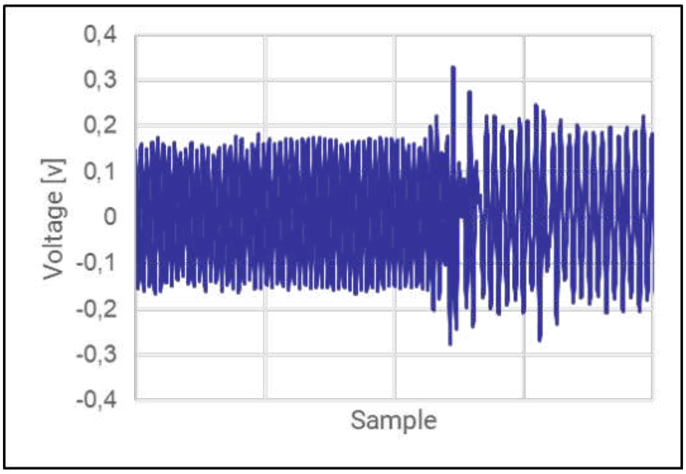

Figure 4.15. Ultrasound acquisition at Point 5C

Figure 4.16. Defective seal

5 Measurement Uncertainty

A study of the measurement uncertainty of a measurement instrument is indispensable to assess a measured quantity value. This is even more true when in the context of an assembly process of a industrial environment, where the results of a measurement system can be used in decision processes as well as in judging attribute of a specific action on the processes itself. Indeed when for example a car is flowing among a production line, the results of measurement process on it are used as reference for any correcting action made and any decision on assembly production process. As the tolerances applied in industrial production are becoming more and more demanding, specially in the automotive industry, the role of measurement uncertainty of an assembly quality control tool becomes more important when assessing conformity to these tolerances. Measurement uncertainty plays a central role in quality assessment and quality standards [4.4].
The next paragraphs are divided in four subsections. At first a calibration procedure in laboratory conditions will be presented and an evaluation of the standard uncertainty presented. Then, results from a sample car test will be shown together with the related expanded uncertainty and a study on the uncertainty during the on-line operation of the measurement device will be presented. Finally, a Repeatability&Reproducibility study to evaluate the prototype performance when used by different operators.

5.1 Calibration

In order to obtain quantitative information on gap and flush in metric units and to quantify measurement uncertainty, a calibration procedure has been developed.
At first a camera lens distortion correction has been set up to remove its effect from the image. Indeed normally cameras as the Raspberry Pi have a non-neglectable optical distortion that must be corrected when the image is used for 3D computation. The procedure is based on a number of acquisitions with the camera in front of a checkerboard pattern target and the estimation of the intrinsic and extrinsic camera parameters. This correlation has been then used to correct the image output used for the dimensional measurements.
Calibration consists in tranform of the target distance Z and the lateral position X to sensor coordinates (i,j). This can be done by traversing along Z a target made of parallel stripes orthogonal to X. The calibration target is tipically composed by a panel with equally spaced black and white parallel stripes. Stripes can be obtained by printing on a paper sheet,as shown in Figure (4.17), on a flat rigid support or by machining deep grooves on an aluminium block [3.3].
During the calibration procedure, the device has been fixed on a support. The laser line projects orthogonal to the target surface and by a micrometric stage the stripes target has been moved with step of 1 mm. The laser line has been scanned over the Z-range (or depth of field) of the sensor. For each Z-position an image is acquired.

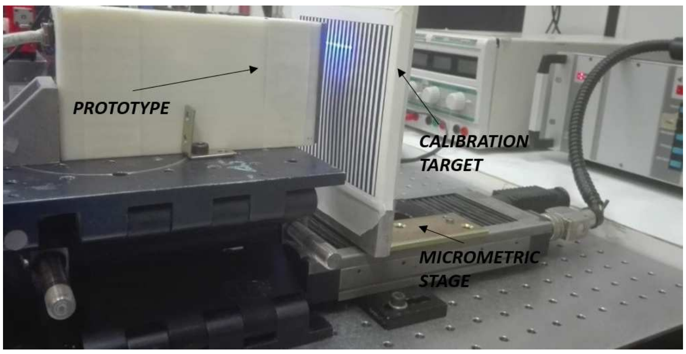

Figure 4.17. Calibration target on the micrometric stage

In Figure (4.18) an example of the acquired image is shown. For each image, start and end coordinates (i,j) of light segments are determined and their position is associated to the reference X and Z position.

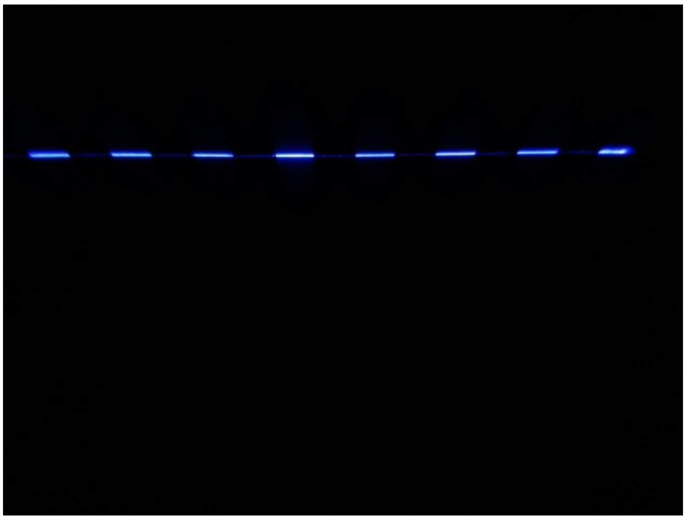

Figure 4.18. Example of image acquired for calibration

A point cloud X(i,j) and Z(i,j) with data acquired has been obtained and then fitted with two polynomial surfaces, which represent the calibration function, as shown in Figure (4.19) and (4.20).
The standard deviation of the calibration surface residuals has been of 0,15 mm and 0,12 mm respectively for X and Z surfaces. The expanded uncertainty is less then U_x= 0,30 mm in X direction (gap) and U_z=0,24 mm in Z direction (flush) (coverage factor k=2 and confidence level 95%) [3.3]. This is the calibration uncertainty of the device; in operating conditions uncertainty can increase, especially due to surface characteristics and to operator, as will be explained in the next subsection.

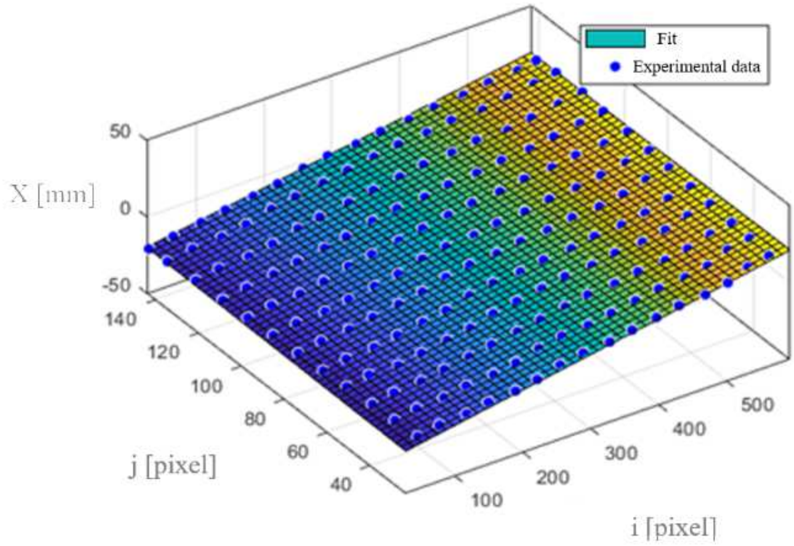

Figure 4.19. Hx (i,j) calibration surface

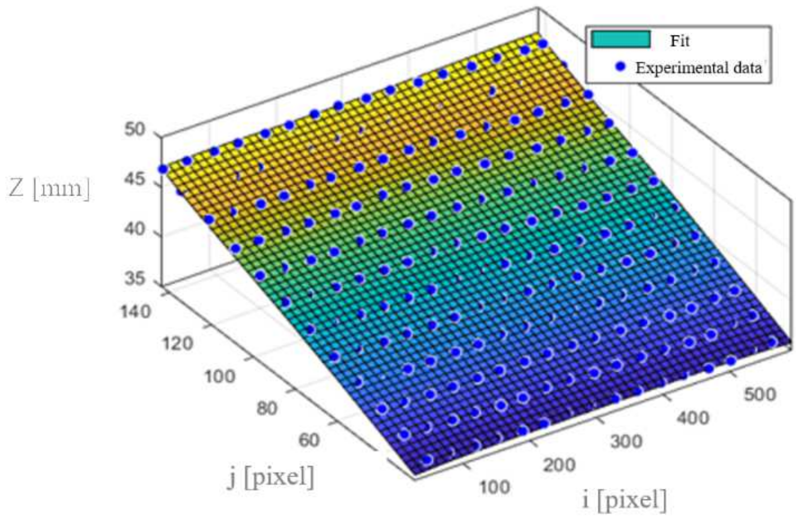

Figure 4.20. Hz(i,j) calibration surface

5.2 Laboratory tests: Cubing car

To estimate the uncertainty of the hand-held device in operation, a type-A analysis according to the GUM [4.5] has been performed in laboratory conditions, on reference gaps and flushes, with the G3F prototype.

These were provided by a cubing car frame, in the quality department of VWAE plant. Indeed in automotive industry this kind of tests is widely used and several companies have dedicated area where quality tests on assembly are repeated at fixed times. An example is shown in Figure (4.21).

Figure 4.21. Cubing car example [4.6]

A cubing car is realized by milling a full size auto-body from solid aluminium, not painted and then assembled with add-on tipical of a car such as lights, roof, bumpers. Typically, a cubing car is used in quality department in order to optimize and qualify assembly parts and make functional analysis of assembled parts. Technicians make check up at regular intervals of specific add-ons manufactured, in order to verify nominal values and measured values of gap and flush when parts are assembled on the cubing car. Usually deviation are in the order of 0,1 millimeters.
The choice of this measurement set-up permits to have stable, repeatable, conditions, and nominal values which can be used as a reference for the uncertainty analysis. Furthermore having an aluminium surface will allow to have light scattering sufficiently good to assure a good signal to noise ratio in the acquired images.
The cubing car frame has been used as a target for gap and flush measurement and cubing nominal values as nominal references. Furthermore, nominal values have been verified by measuring the same points with calibrated pins, for gap values, as is shown in Figure (4.22), with a 0,01 mm uncertainty.
Gap and flush values have been measured with the hand-held device in 5 different points, for a total of 42 acquisition. Because of the sensitivity of data extracted, results have been normalized with the mean and the standard deviation of the distribution.

Figure 4.22. A Calibrated pin [4.7]

In Figure (4.23) results from gap measured on the cubing car with device vs gap measured with calibrated pins are shown. The linear regression output of data measured with the device, in blue, with respect to calibrated pins permits to establish a relationship between nominal values and the instrument output. The ideal line should be y=x, as is shown in red. The instrument linear regression R-squared is 0,99, meaning that the device measured data are strongly correlated with the model result.

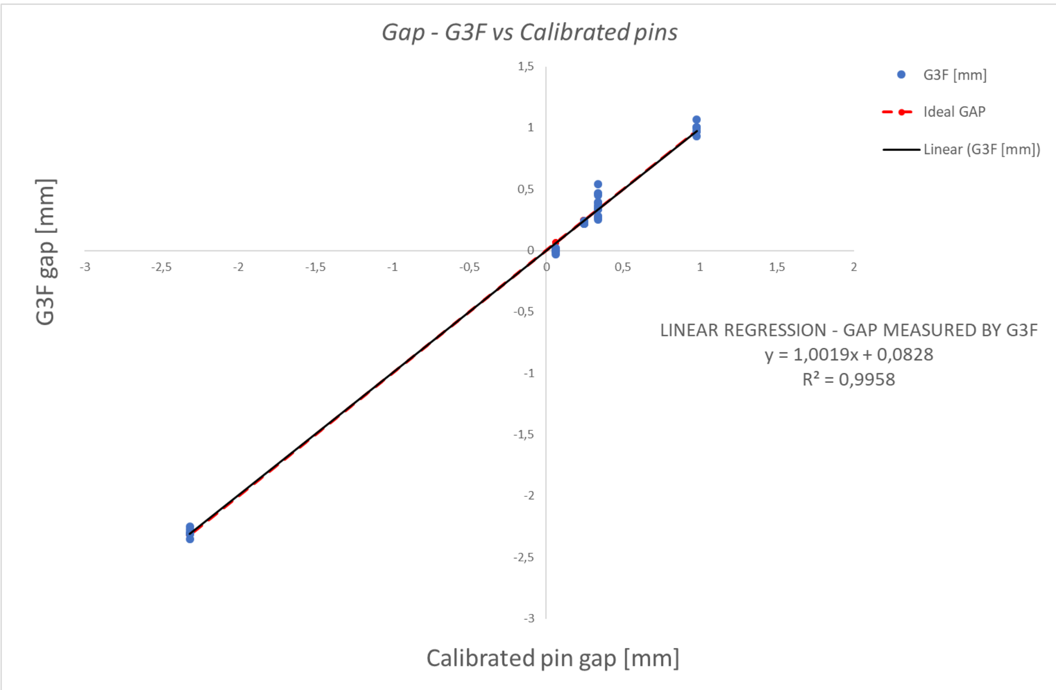

Figure 4.23. Cubing car: Gap - G3F vs Calibrated pins

The same approach has been used to model the output of the device when measuring flush values and using nominal values from cubing car as a reference. The result is shown in Figure (4.24).

Analyzing the linear regression output, the flush measured values are not strongly correlated as for gap values with the model and this is more and more clear when measuring "negative" flush. As a result the R-squared is 0,95.

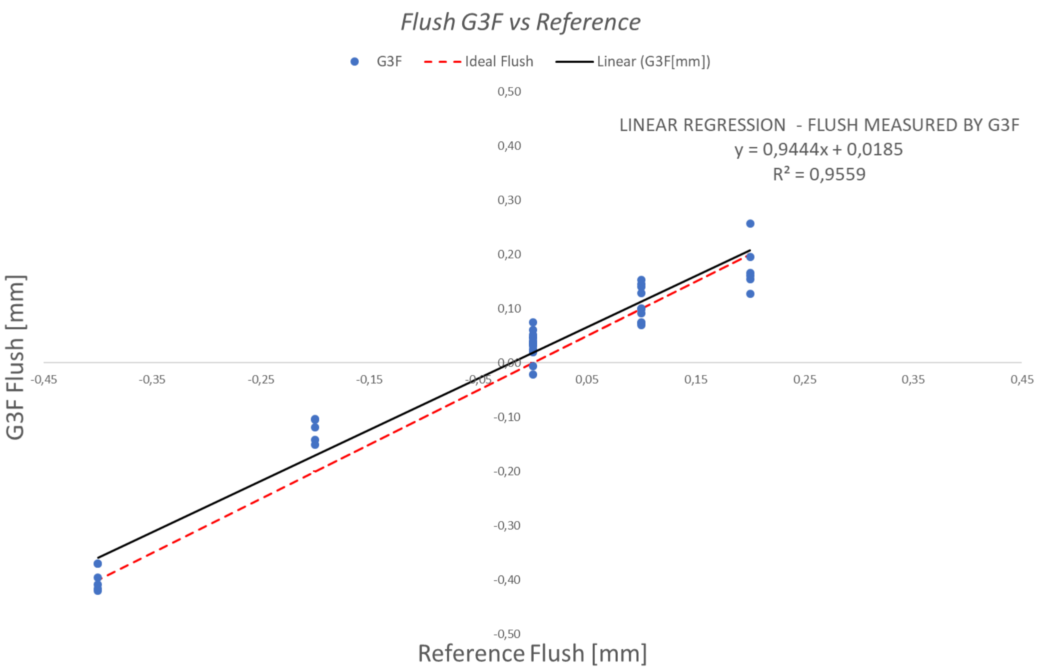

Figure 4.24. Cubing car: Flush - G3F vs Calibrated pins

Finally, the expanded uncertainty of measured data of gaps and flushes has been calculated as is shown in Tables (4.1) and (4.2).

Number of acquisitions	42
Standard uncertainty u_x	0,19 mm
Standard uncertainty of reference u_{pins}	0,03 mm
Combined uncertanty $u_{combined}$	0,19 mm
Expanded uncertanty U_x (95% confidence level)	0,38 mm

Table 4.1. GAP Uncertainty analysis

Number of acquisitions	42
Standard uncertainty u_z	0,15 mm
Standard uncertainty of reference u_{ref}	0,03 mm
Combined uncertanty $u_{combined}$	0,16 mm
Expanded uncertanty U_z (95% confidence level)	0,32 mm

Table 4.2. FLUSH Uncertainty analysis

5.3 In-line measurements on different points

A series of tests in assembly line have been performed by a trained operator in order to evaluate the measurement uncertainty of the device during the production process.
An example of measurement performed in the VWAE plant is shown in Figure (4.25).

Figure 4.25. Assembly Line measurements [2.5]

The experimental setup consisted in 28 different measurement points on the same car at the final assembly stage (car fully assembled) for a total of 145 acquisitions. The car painting was dark grey. The tests have been performed for gap values with G3F device, the feeler gauge typically used in automotive production and a digital caliper (with plastic ends to not damage the car with scratchs). For Flush values G3F operation has been compared with the electronic comparator of Figure 2.13. Because of the sensitivity of data extracted, results have been normalized with the mean and the standard deviation of the distribution.
In Figure (4.26) results from the measurements done with G3F vs measurements done with caliper, which has been assumed to be the reference, are shown (blue dots reference).
In terms of accuracy the goodness of fit between G3F gap values and caliper gap values is accurate (black linear fit superimposed to red ideal line). Furthermore, blue

dots are closely dispersed around linear fit. The linear regression of gap measured with G3F is R squared=0,98, meaning that also for in-line measurements, when different material combinations (glass, light, chromed) are present, the device output is well-correlated with the model identified.
On the other hand, in Figure (4.26) a correlation between results from feeler gauge measurements vs caliper has been obtained (green dots reference). The feeler gauge underestimates gap values with respect to caliper ideal line, in red. This behaviour mainly depends on feeler gauge resolution: the instrument does not fit the target so the operator must move to a lower step. As a result the linear regression R-squared is less than G3F R-squared.

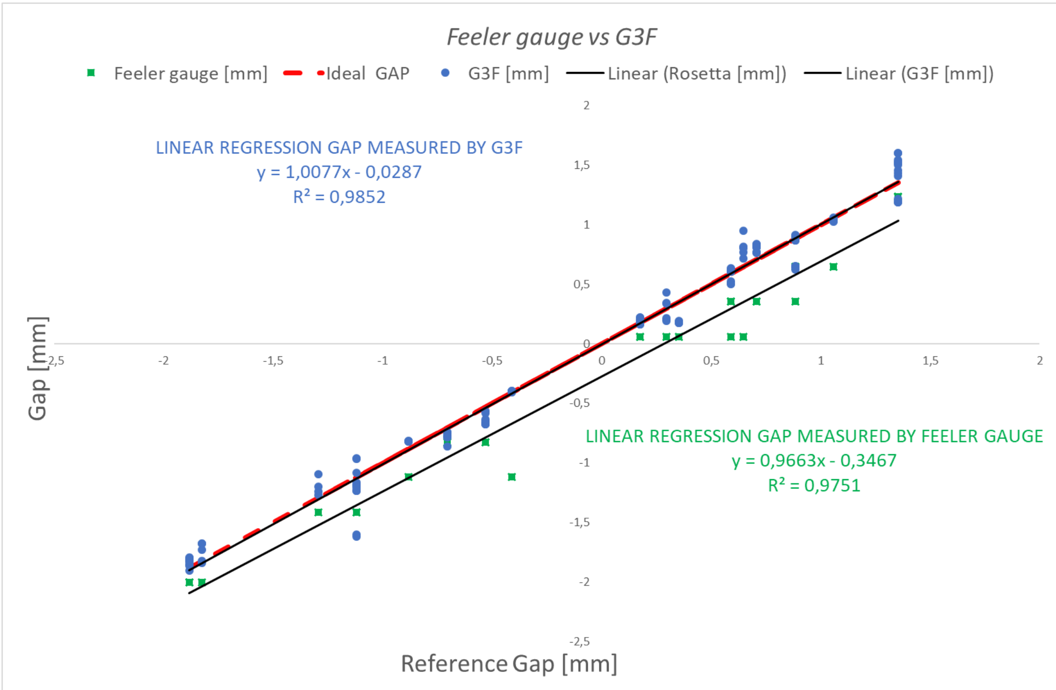

Figure 4.26. Assembly Line: Gap G3F and Feeler gauge vs Caliper

Resolution limits of the feeler gaauge are clearly evident if we compare its results with those of G3F, assuming the last one as reference, in Figure (4.27).
Regarding flush measurements, results of comparison between G3F and caliper are shown in Figure (4.28). It is evident that G3F overestimates flush values with respect to caliper. This depends also on the way flush is calculated with the reference. Indeed, zero reference has been assessed on a flat surface while during the measurement the instrument works on a non-flat surface, as shown in Figure (2.14).

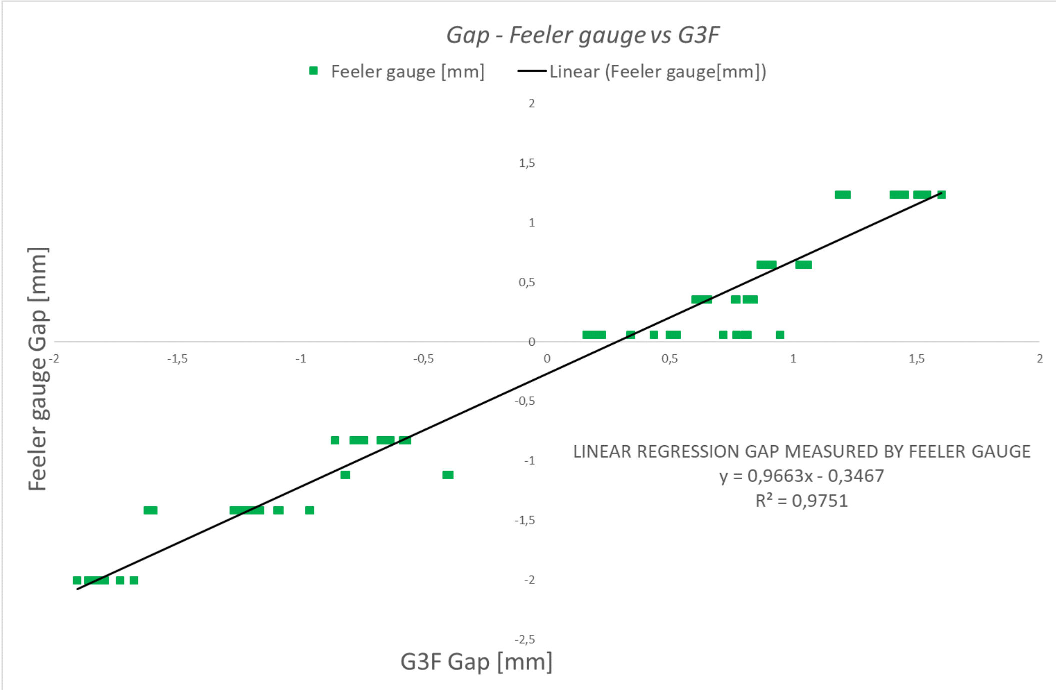

Figure 4.27. Feeler gauge resolution

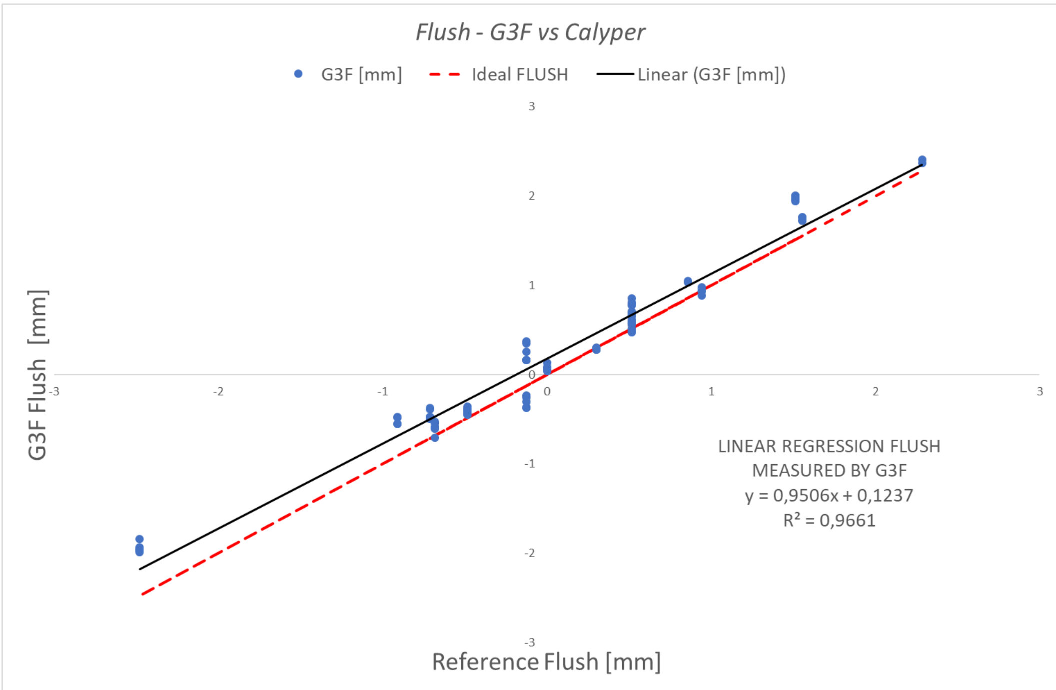

Figure 4.28. Assembly Line: Flush G3F vs Caliper

Finally the expanded uncertainty of G3F measured data of gap and flushes has been calculated as is shown in Tables (4.3) and (4.4).

Number of acquisitions	145
Standard uncertainty u_x	0,21 mm
Standard uncertainty of reference u_{ref}	0,03 mm
Combined uncertanty $u_{combined}$	0,22 mm
Expanded uncertanty U_x (95% confidence level)	0,44 mm

Table 4.3. GAP Uncertainty analysis - G3F

Number of acquisitions	97
Standard uncertainty u_z	0,29 mm
Standard uncertainty of reference u_{ref}	0,003 mm
Combined uncertanty $u_{combined}$	0,29 mm
Expanded uncertanty U_z (95% confidence level)	0,58 mm

Table 4.4. FLUSH Uncertainty analysis - G3F

5.4 R&R Study

The study of R&R (Repeatability and reproducibility) is the study of the capability of the measurement system, determining the degree of variability in the measurements caused by variations of the measurement system. The variations can regards the instrument itself and/or the operator [4.8].
Repeatability of a measurements refers to the variation in repeat measurements made on the same target under identical conditions. This means that measurements are made by the same instrument or method, the same observer if human input is required, and that the measurements are made over a short period of time, over which the underlying value can be considered to be constant. Variability in measurements made on the same subject in a repeatability study can then be ascribed only to errors due to the measurement process itself. Repeatability refers to the variation within the system when the measurements are defined and fixed [4.4].
On the other hand reproducibility is related to the variation in measurements made on a subject under changing conditions. In particular in [4.9] it is defined as the variation of the average of the measurements made by different evaluators using the same instrument under the same environmental conditions.
In the next subsections two different studies on R&R will be illustrated: at first a study of the measurement device repeatability on a reference target in laboratory conditions will be presented, then an R&R study involving three different operators has been set up in order to address the discussion on the results reproducibility due to the instrument use by different operators.

5.4.1 Repeatability

A series of tests on three different points, named here as Point 1, Point 2 and Point 3, of the cubing car has been assessed in order to evaluate the instrument repeatability. To assure stable, repeatable conditions a specific setup has been made as is shown in Table (4.5). The results of the repeatability test campaign have been used to represent data on a histogram in order to understand how measured values were distributed.
Figure (4.29),(4.30),(4.31),(4.32),(4.33) and (4.34) shows the probability distribution

Measurement target	Cubing car, not painted, solid aluminium
Number of Repetitions	70
Camera Exposure Time	800 μs
Calculating algorithm	FG algorithm
Temperature	20°C
Time between repeated measurements	1 s

Table 4.5. Repeatability Test Conditions

for each measured Point:1, 2 and 3. Data have been fitted with a normal distribution and related fitting parameters (σ,μ) are shown in the Tables below. Data have been normalized in order to avoid the distribution of confidential information. The intervals next to the parameter estimates are the 95% confidence intervals for the distribution parameters. For each Point an appropriate width and number of bins has been selected.

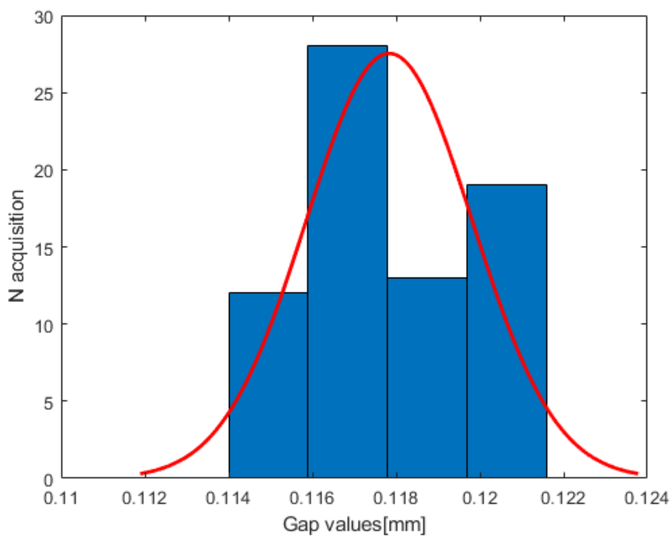

Figure 4.29. Gap repeatability: Point 1

σ	0,0595 mm
μ	0,12 mm

Table 4.6. Point 1 - GAP: Distribution parameters

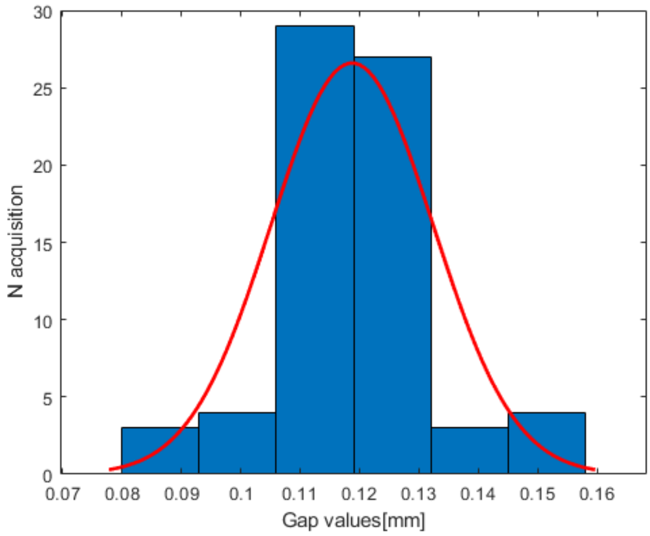

Figure 4.30. Gap repeatability: Point 2

σ	0,0774 mm
μ	0,12 mm

Table 4.7. Point 2 - GAP: Distribution parameters

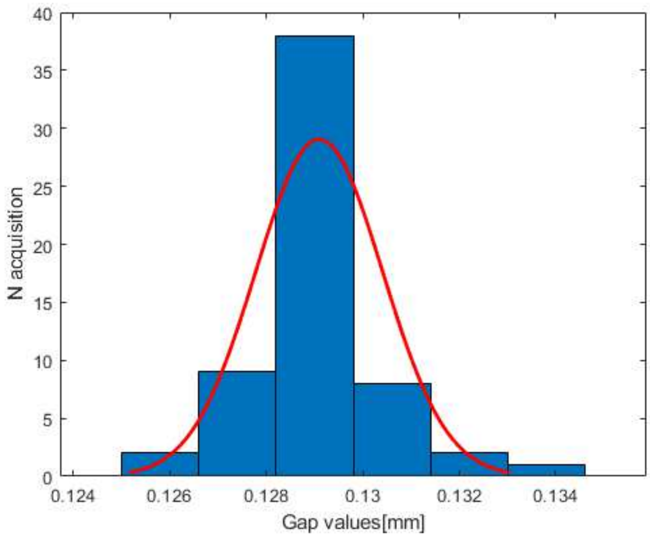

Figure 4.31. Gap repeatability: Point 3

σ	0,0444 mm
μ	0,13 mm

Table 4.8. Point 3 - GAP: Distribution parameters

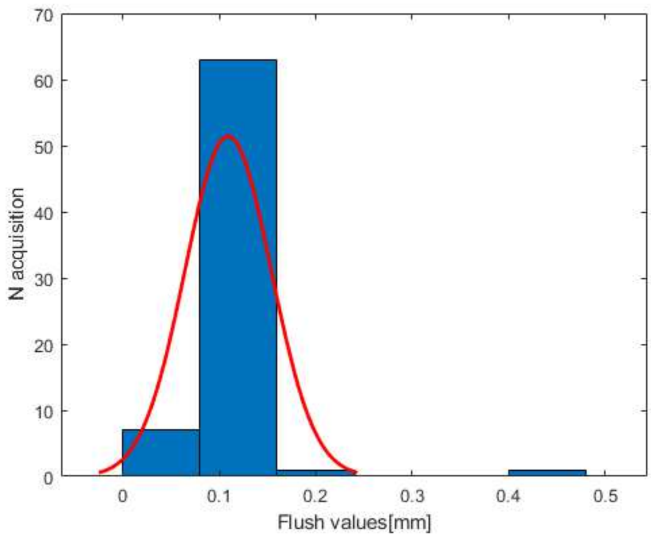

Figure 4.32. Flush repeatability: Point 1

σ	0,0447 mm
μ	0,12 mm

Table 4.9. Point 1 - FLUSH: Distribution parameters

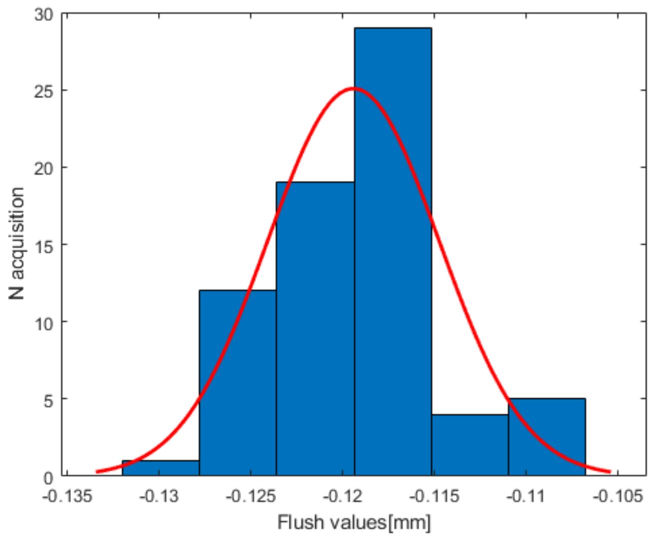

Figure 4.33. Flush repeatability: Point 2

σ	-0,12 mm
μ	-0,41 mm

Table 4.10. Point 2 - FLUSH: Distribution parameters

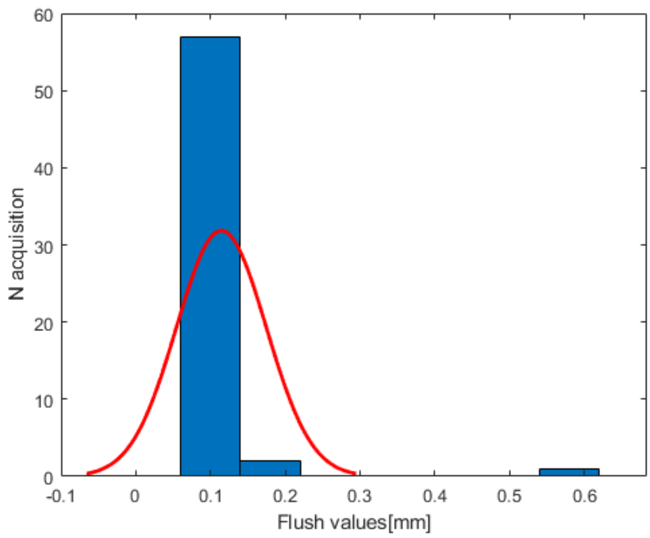

Figure 4.34. Flush repeatability: Point 3

σ	0,0943 mm
μ	0,11 mm

Table 4.11. Point 3 - FLUSH: Distribution parameters

Looking to the histograms' shape is clear how data for both three points can be considered consistent for gap measured data while flush values distribution presents outliers (for Point 1 and Point 3) which underlines the existence of some problems in the process in exam. Even if these outliers are a small quantity further evaluations have been done to establish the cause.
Analyzing results for Point 1, the outlier has been find at repetition 58, which processed image is shown in Figure (4.35). The surfaces assembly acquisition is clearly not centered with the result that gap calculation algorithm is not affected by error while the flush one it is because less point for the straight line reconstruction are present in one part of the image. Indeed the fitting line to the right surface has not enough points to reconstruct the real plane, as is shown in Figure (4.36).

Regarding results for Point 3, the outlier has been find at repetition 50. As the image acquired resulted again not centered, the same conclusion can be taken.
The analysis underlines how managing operator skill in the measurement process is significant to assure repeatable results, introducing to next subsection where a

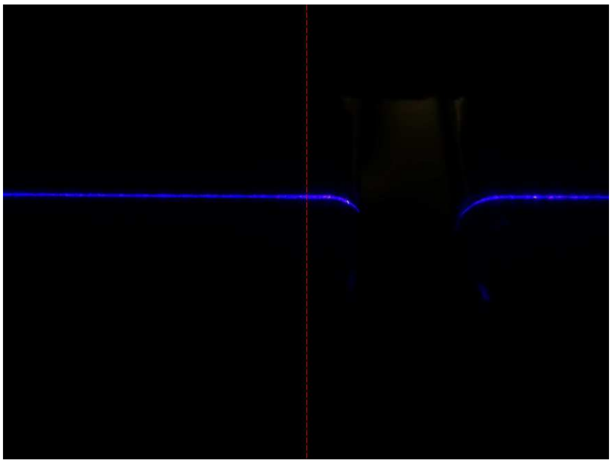

Figure 4.35. Flush histogram outlier - Point 1: acquired image

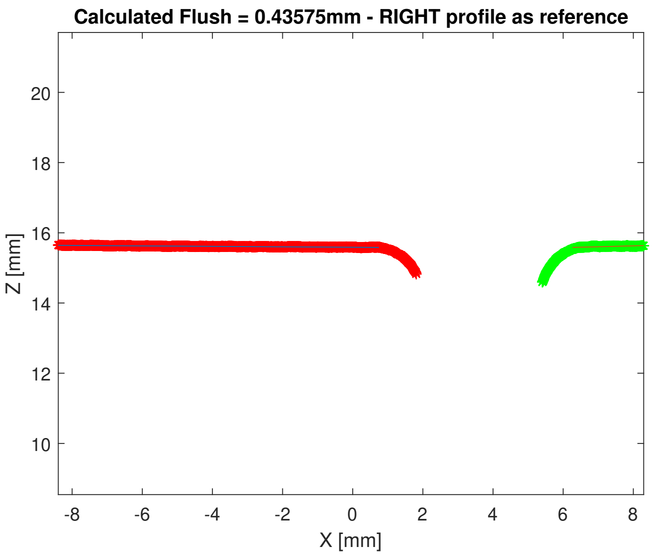

Figure 4.36. Flush histogram outlier - Point 1: Fitting process

specific study about reproducibility is presented.

5.4.2 Reproducibility

An R&R study has been performed in laboratory conditions on a car tailgate-to-body sample as shown in Figure (4.37). Data have been collected in three different points named here as Point 3a, Point 3b and Point 3c. The first two are metal-to-metal frame, while the third is plastic-to-plastic. Three different operators have been involved for the study, referred to by letters A, B and C. Each operator measured Point 3a, Point 3b and Point 3c, for a repetition of 25 measured gaps and 25 measured flushes respectively, with the G3F prototype. The idea is to understand how quantitatively is important the operator skillness (to put the device in the best direction for the measurement and avoid wrong acquisitions) in the device use.
At the same time Point 3a, Point 3b and Point 3c have been taken with different gauges: the manual feeler gauge usually used in shop floor, for gap, Figure (2.12); a conventional digital caliper by Mitutoyo, for gap; the digital comparator by Mitutoyo, usually in use in assembly operations, for flush, Figure (2.13). In fact, a such study permits also to generate a comparison between the measuring devices.

Figure 4.37. R&R measurement target

Data collected have been processed with a statistical software, Minitab 19, by method Gage R&R Study (X & R), applying Average method and amplitude (M&A) [4.10]. The R&R statistics method has been applied to all the instruments, as presented below and uses the same metodology presented in [2.16].
Regarding Variance Components as is illustrated in Figure (4.38) it is divided in

Repeatability, Reproducibility and Part-to-Part.
Part-to-Part is the variability in measurements due to different parts and must account most [4.8].
On the other hand, an analysis of the gage R&R protocol, %StudyVar (%SV) compares the measurement system variation to the total variation. The %StudyVar uses the process variation, as defined by 6 times the process standard deviation. According to the AIAG MSA manual system [4.11], ideal measurement should have a percentage of variation up to 10% to be considered acceptable, while if it is between 10% and 30% the acceptability depends on the application, the cost of the measurement device, repair and other factors. If the percentage is greater than 30%, then the measurement system is not acceptable and should be improved [2.16].
Starting from caliper in Figure (4.38), Figure (4.39) and Figure (4.40) is shown the gage R&R study result for Point 3a, Point 3b and Point 3c.
It is clear that the main contribution is due to Part-to-Part variation. Indeed, ideally, a very little variability should be due to repeatability and reproducibility while differences between parts should account for most of the variability.
In this case, the Total Gage R%R of the caliper is 10,52 %, with 3,31% of operators' influence. Further information can be obtained if we look at the S Chart by Operator, Figure (4.40), which shows whether points fall within the control limits. Only the Sample StDev of operator B is within the Upper and Lower Limits, confirming that the awareness and skillness of specialised technicians has a concrete impact on process quality. The same consideration can be obtained from the Point*Operator interaction graph. Indeed, it shows whether the lines that connect the measurements from each operator are similar or whether the lines cross each other. A line that is consistently higher or lower than the others indicates that an operator adds bias to the measurement by consistently measuring high or low. In this case for caliper analysis there are not consistent differences between the operators at each measured point.
The second R&R performed examined the measuring points of gap measured by the manual feeler gauge. Figure (4.41), Figure (4.42) and Figure (4.43) presents the R&R results.

As a result, the only contribution in the feeler gauge study is the Part-to-Part variation. Indeed these instruments have a resolution of 0,5 mm, so the variation due to repeatability and reproducibility is not appreciable.
This is even more clear when looking at the gage R&R report (4.43) which underlines how differences between repeated measurements and different operators are in some way hidden by a poor resolution instrument. This can be defined as an additional output of the R&R study.
Finally, regarding gap results it has been analysed R&R by the values obtained from the gage R&R study for gap measured by the G3F. Figure (4.44), Figure (4.45) and Figure (4.46) presents the analysis.
As a result, also for the G3F device the main contribution is due to Part-to-Part variation. But as it can be seen in Figure (4.45), the total gage percentage of variation is 29,05%, more than the caliper one, with 11,10% of operators' influence. If we look at the Gage R&R report other useful informations can be extracted, Figure (4.46). At first looking at the Gap by point Graph is clear how optical methods, as that used in the G3F, "suffers" when measuring on transparent/semi-translucent material (i.e. rearlights). Indeed the interval on Point 3c is larger than Point 3a and 3b. This is confirmed by the S Chart by Operator, where both Operator B and C gap results of Point 3c are out of the limit boundaries. At the same time, the graph shows how the operator skillness has a great impact on measuring in "difficult" points. Indeed regarding Operator A, measuring results on Point 3c is below the limit. The same conclusion can be optained from the Point*Operator Graph.
The same analysis has been repeated for Flush R&R study, respectively for Caliper and G3F, as is shown in Figures (4.47),(4.48),(4.49),(4.50),(4.51) and (4.52).
Regarding the total Gage R&R of the caliper, as is shown in Figure (4.48) is 25,98% while for the G3F device reachs 30,34%. Thus means that the device flush results are acceptable but the device performaces still need to be improved. Regarding the reproducibility the G3F device is less affected by uncertainty when measuring flush on rearlight while, again, the operator differences are evident if we look at the Point*Operator Graph in Figure (4.52), confirming how managing the operator skillness has a great impact on the measurement process itself.

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,002103	1,11
Repeatability	0,001895	1,00
Reproducibility	0,000208	0,11
Part-To-Part	0,187987	98,89
Total Variation	0,190090	100,00

Figure 4.38. Variance Components: Gap - caliper R&R study

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0,045860	0,27516	10,52
Repeatability	0,043533	0,26120	9,98
Reproducibility	0,014425	0,08655	3,31
Part-To-Part	0,433575	2,60145	99,45
Total Variation	0,435993	2,61596	100,00

Figure 4.39. Gage Evaluation: Gap - caliper R&R study

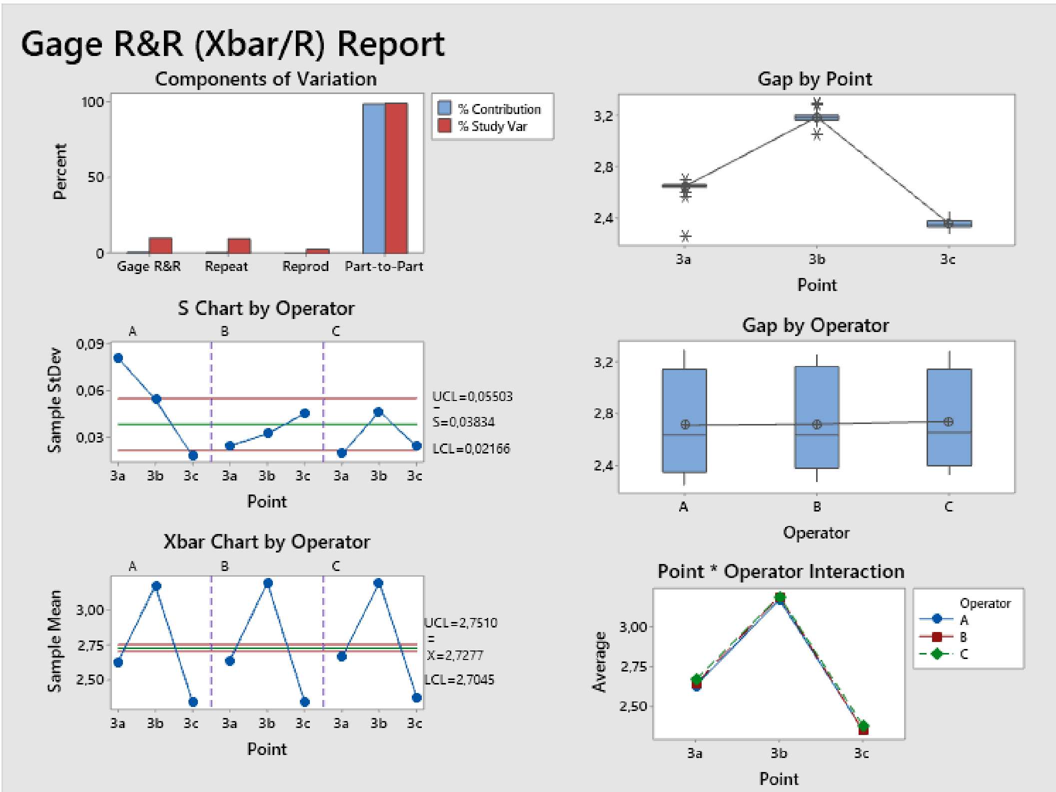

Figure 4.40. Gap - Caliper R&R study report

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,000000	0,00
Repeatability	0,000000	0,00
Reproducibility	0,000000	0,00
Part-To-Part	0,273671	100,00
Total Variation	0,273671	100,00

Figure 4.41. Variance Components: Gap - Feeler gauge R&R study

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0,000000	0,00000	0,00
Repeatability	0,000000	0,00000	0,00
Reproducibility	0,000000	0,00000	0,00
Part-To-Part	0,523136	3,13881	100,00
Total Variation	0,523136	3,13881	100,00

Figure 4.42. Gage Evaluation: Gap - Feeler gauge R&R study

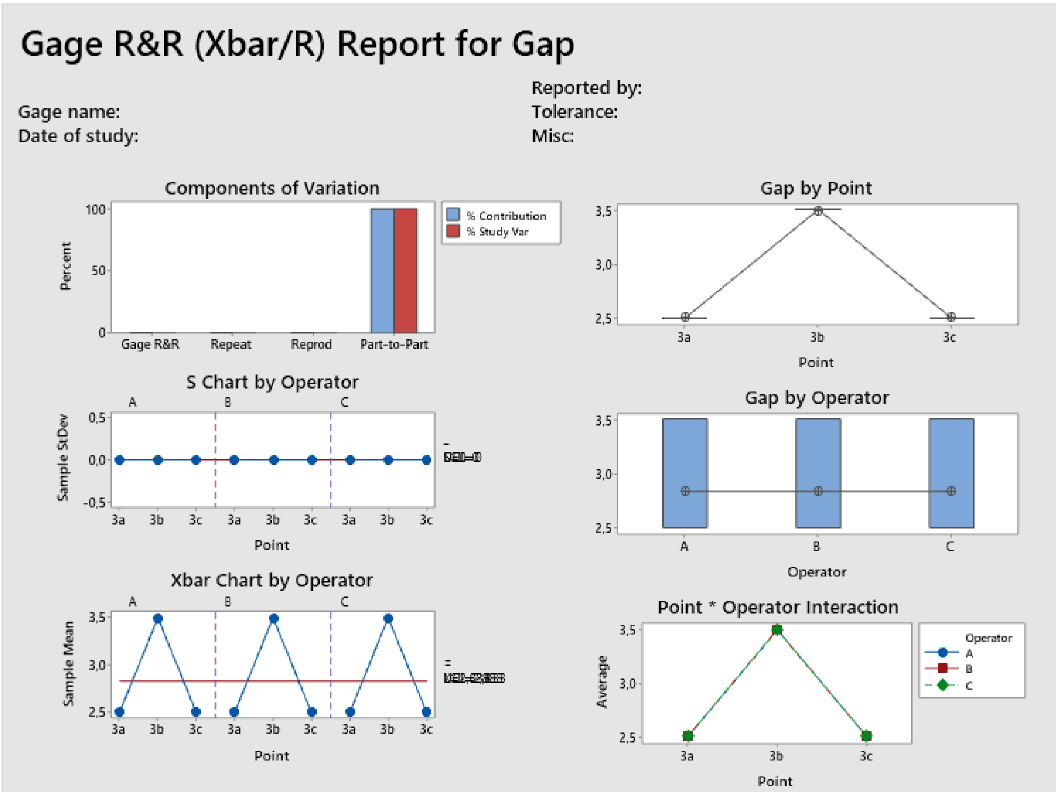

Figure 4.43. Gap - Feeler gauge R&R study report

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,0061775	8,44
Repeatability	0,0052760	7,21
Reproducibility	0,0009015	1,23
Part-To-Part	0,0670347	91,56
Total Variation	0,0732122	100,00

Figure 4.44. Variance Components: Gap - G3F R&R study

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0,078597	0,47158	29,05
Repeatability	0,072636	0,43582	26,84
Reproducibility	0,030024	0,18015	11,10
Part-To-Part	0,258911	1,55346	95,69
Total Variation	0,270578	1,62347	100,00

Figure 4.45. Gage Evaluation: Gap - G3F R&R study

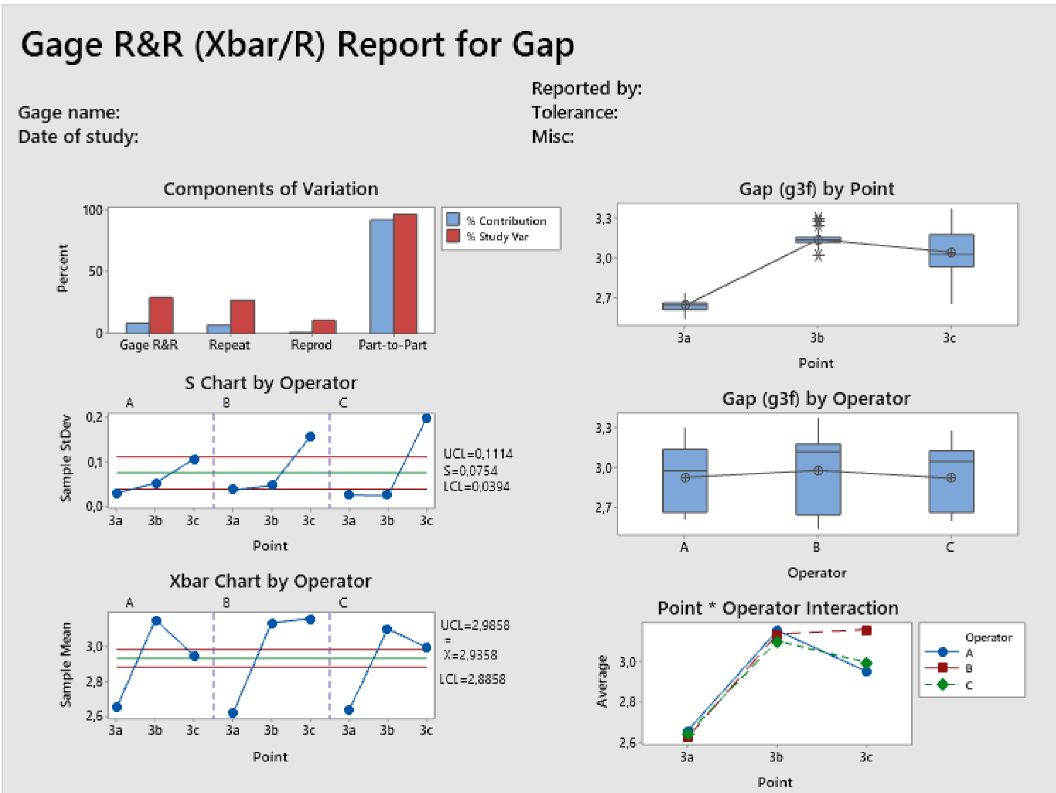

Figure 4.46. Gap - G3F R&R study report

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,023940	6,75
Repeatability	0,009845	2,78
Reproducibility	0,014095	3,97
Part-To-Part	0,330821	93,25
Total Variation	0,354761	100,00

Figure 4.47. Variance Components: Flush - caliper R&R study

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0,154726	0,92835	25,98
Repeatability	0,099221	0,59532	16,66
Reproducibility	0,118723	0,71234	19,93
Part-To-Part	0,575170	3,45102	96,57
Total Variation	0,595618	3,57371	100,00

Figure 4.48. Gage Evaluation: Flush - caliper R&R study

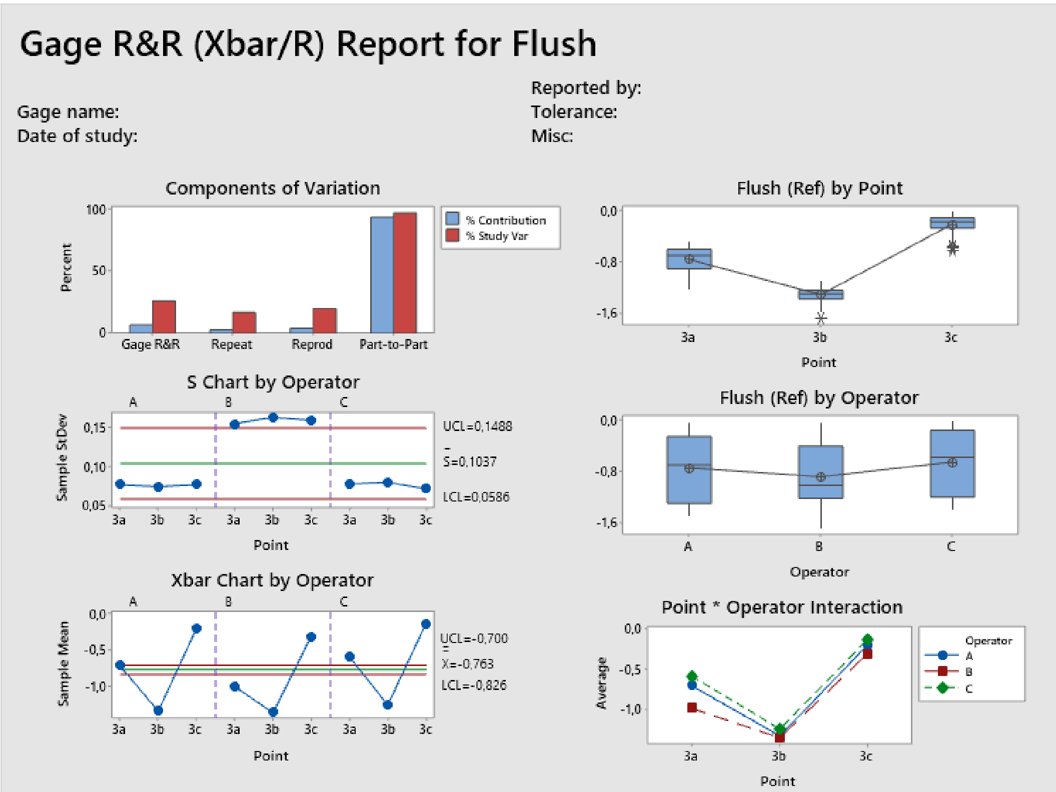

Figure 4.49. Flush - Caliper R&R study report

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,028186	9,21
Repeatability	0,017204	5,62
Reproducibility	0,010982	3,59
Part-To-Part	0,277994	90,79
Total Variation	0,306179	100,00

Figure 4.50. Variance Components: Flush - G3F R&R study

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0,167886	1,00731	30,34
Repeatability	0,131164	0,78698	23,70
Reproducibility	0,104794	0,62876	18,94
Part-To-Part	0,527251	3,16351	95,29
Total Variation	0,553335	3,32001	100,00

Figure 4.51. Gage Evaluation: Flush - G3F R&R study

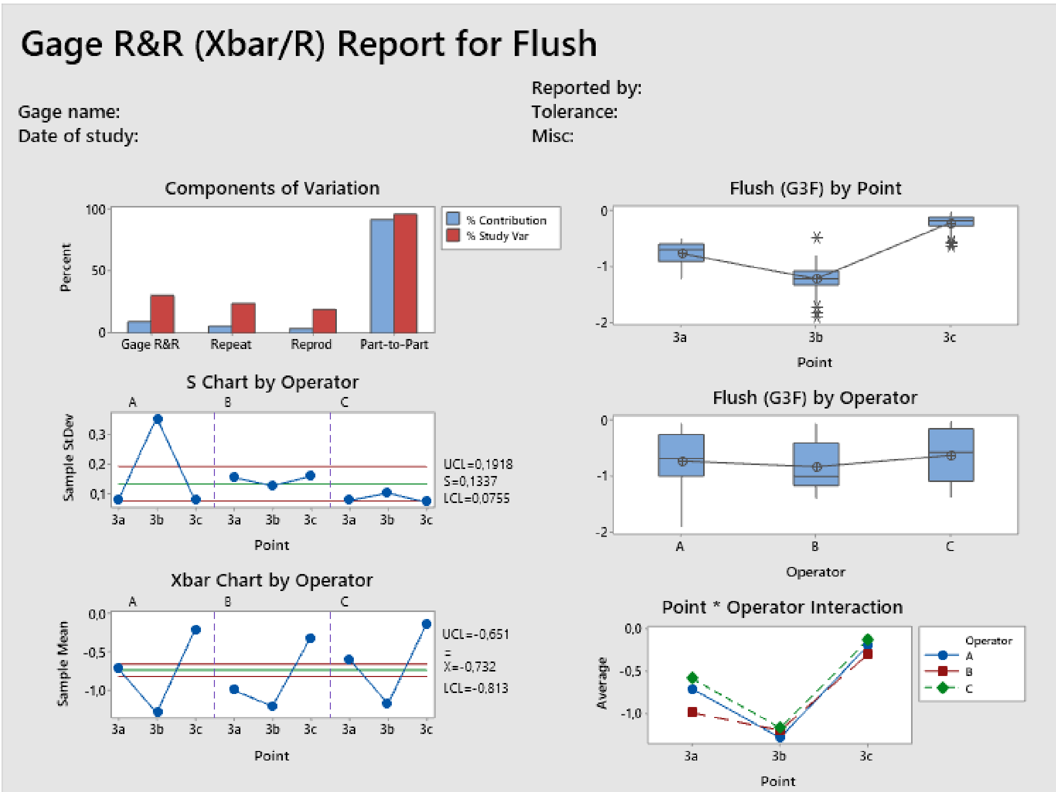

Figure 4.52. Flush - G3F R&R study report

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Chapter 5

Conclusion

The research activity has regarded the development of intelligent devices for process and quality control in two relevant industrial cases in which the GO0DMAN project approach has been demonstrated: Volkswagen Autoeuropa (car production) and Electrolux Professional (oven production).
The industrial requirement named the assessment of gap and flush during the assembly process, has been addressed by the deployment of a hand-held laser triangulation device, G3F, in which a proper laser source (λ=405 nm, P=5 mW) has been selected in order to measure on transparent or semi-transparent materials as those of a car rearlight and a proper camera characteristics in term of resolution r and spectral sensitivity in the laser range, has been choosen.
The system aimed also to exploit smart behaviors in order to keep the operator in the measurement loop. An ergonomic design integrated into a smart-phone together with an interactive interface, an automatic swithing on-off of the laser source and the integration of algorithms for the recognition of the measurement points have given to the device the boost to its smartness.
The system has been integrated in the GO0DMAN platform and linked to the production "Resource Agent" by on OPC-UA protocol of communication and a local/global storage of data via a SQL database.
The uncertainty analysis performed on the device showed an expanded uncertainty at calibration level of U_x= 0.30 mm for gap and U_z=0.24 mm for flush. Validation in laboratory conditions, on a cubing car, which can be considered a reference, showed

an expanded uncertainty of U_x=0,38 mm and U_z= 0,32 mm. When the hand-held device is used in operating conditions its uncertainty grows, reaching U_x=0.54 mm for gap and U_z=0.58 mm for flush. This result is mainly due to the repeatability of measurements on points with "difficult" surfaces (e.g. glass, lights) and to its reproducibility when used by different operators.

A further improvement could it be to develop a system that projects multiple laser lines over the surface, so that more data are available for the estimation, as proposed in [4.12]. Other aspects of the hardware that could improve the achievement of a better accuracy and repeatability of the measurements are the use of an industrial camera and a laser specifically designed for the requirements.

For the Electrolux use case, in order to perform on the same instrument both the gap and flush mesurement and a leak detection on the oven door, the hand-held device has been integrated with a ultrasound receiver. The whole device has been validated in operating conditions (oven assembly line) and the results sent to the multi-agent architecture to be processed at global level and contribute to the GO0DMAN results.

One of the objective of the GO0DMAN project was the demonstration of these prototypes in operating environment (TRL 7). It is expected that, with a continuous use in the production plants of Volkswagen Autoeuropa and Electrolux Professional and the boost done by their patenting [4.3], these systems could be validated also at production level (TRL 9).