POLITECNICO DI TORINO

Master of Science

in Automotive Engineering

Master's Degree Thesis

Use of optical systems in assembly process and quality control of automotive engines

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1. Machine Vision Systems

1.1 Definition an industrial vision system

Industrial vision can be defined as the set all those applications (industrial or not) that provide a guidance to the supported machine capturing and elaborating pictures, through a specific combination of hardware and software. Digital sensors are embedded in cameras with special optics, so that the system is able to elaborate, analyze and measure all the characteristics needed to take the decision.

A sketch of the typical composition of an industrial vision system is shown in Figure 1.

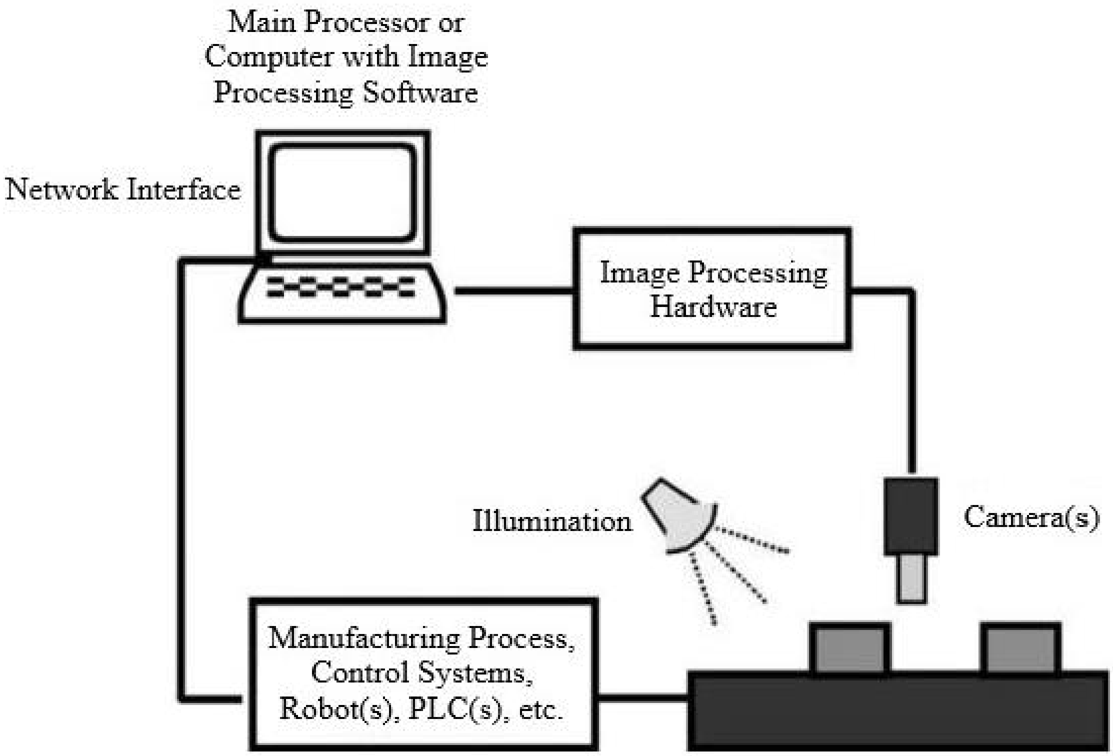


Figure 1. Basic industrial vision system scheme

One or more cameras are placed in the inspection environment, in the best position (usually fixed) to capture the needed pictures. Then, these images are processed by a computer, through software dedicated to image processing and classification.

A key role in a proper inspection is held by the illumination, which, together with a proper setup of the scene, is fundamental to allow a correct image acquisition, highlighting the features of interest.

Since the specific setup of a vision system clearly depends on the application field and on the operations to be performed, additional components are often installed.

When implementing and setting an industrial vision technology, one of the first steps of the process is teaching to the machine what is the target, in terms of defining which is the feature observed and in which case the inspection has a negative outcome, presenting a defect.

In a comparison between *human vision and artificial vision*, it is possible to state that the former is the best for a qualitative analysis in a very complex non-structured environment, while the latter is the best for a quantitative analysis in a structured environment, thanks to its high speed and repeatability.
Indeed, an advantage of the human eye over cameras is the ability to automatically and dynamically adapt to every change in the environmental light conditions, while a camera can very often fail trying to follow eventual rapid changes in the scene.
However, even if in some cases the human perception leads workers to perform the task better than machines, it is also true that they are slower and that they can keep an adequate level of accuracy only for a limited time window, because of getting tired.
The ideal circumstances to prefer machine vision over human vision are:

- *dangerous tasks*, like the ones requiring operations in adverse conditions (high temperatures, underwater, exposure to chemicals, etc.).
- *difficult tasks*, even for very skilled workers.
- tasks very demanding in terms of *production rate*.

Furthermore, an optical control system works collecting data automatically: this is an important aspect considering that it is possible to have a real time and accurate (in term of measurements) control of the process.

Once clarified the reasons why an industrial vision technology is needed, it is essential to look for a solution on the market that meets three main requirements: *high reliability*, *high robustness*, and *cost-effectiveness*.

1.1.1 Reliability

It is necessary to avoid any ambiguity, being careful of both *false-positives* and *false-negatives*. The first case refers to the situation in which a good quality product is reported as defected, while the second case is the opposite, that is when a poor-quality product is accepted by the inspection machine, allowing it to flow further in the process.

False-positive cases affect mainly the production rate, because it would be necessary to stop the line, check the product and reintroduce it after having ascertained that the defect does not exist (thus, a lot of potential productive time is wasted); when it is not possible to reintroduce the piece, then consequences are the losses both in components/material wrongly classified as scrap and in resources needed to actuate the process.

In false-negative cases, the consequences are much more serious because they represent situations very hard to detect. The system is unable to see a defect, and, especially in long and complicated production processes, this will lead to a significant waste in resources along the whole sequence of operations. Once the problem on the product arises in the following stages (or in the worst case, after the delivery to the customer), it carries with itself two main questions that make difficult the analysis of the inspection system failure: Which machine is not working properly? And, how many other pieces have been tested false-negative by that machine? Finding the source of the problem and how big its repercussions on the production have been is a very tough task, that, if not promptly fulfilled, could cause severe damage to the company involved.

Besides the need to properly classify and analyze every item, it should be underlined that another important factor affecting reliability is the quality of images captured.

Despite the great performances it can offer, an industrial vision system is not immediately fully reliable. Even if the algorithm implemented in the technology could be very advanced, problems like the ones described so far in this section are always around the corner.
Whenever a new case is detected (real defect, false negative or false positive), the software gets updated with a new reference so that in the following occurrences of the same event a proper and correct control analysis is performed.
This means that a learning curve is followed, and, according to how accurate is the algorithm, it can be longer or shorter. In the first case, the teaching phase is performed by operators who manually update the examples database, while in the second case the system is endowed with artificial intelligence, thus automatically and reactively classifying the new events.

1.1.2 Robustness

Despite any irregularity in the setup, a vision system should achieve constantly the requested performances, reacting systematically every time a change in the conditions occurs. The constant exposure to the variations of an industrial environment is very different than the almost always-constant conditions of a laboratory in which the machine is initially tested.

The components must be chosen not only according to their accuracy in the requested measurement, but also according to their ability to still remain effective after a long operative use. The main factors affecting the proper functioning of the vision system are: *differences among items analyzed*, *positioning and handling of the items*, *scene lighting setup*, *temperature*, *water*, *dust* and *oil* (or in general *dirt*), *vibrations* and *electromagnetic radiations*. All these contributions to the industrial environment conditions listed so far need to be monitored and controlled, because of the risk to damage the components installed and to have a wrong measurement.

Talking about *temperature*, nowadays cameras are designed to withstand a wide range of temperatures, from -5°C up 65°C.

In the hottest applications, the image's quality can be affected by an increased noise, however, sometimes, instead of trying to make the scene less hostile trying to lower the temperature through costly devices like fans or coolant sprayers, it is possible to act on the illumination setting it up until the proper signal-to-noise ratio is achieved.

High temperatures exposure is one of the most common cause of failure for industrial PCs, which need to keep always performing even in the case in which is not possible to install fans.

Temperature does not only affect components, but also the inspected object because of possible expansion (or contraction) that would prejudice the ongoing measurement.

Vibrations and shocks are certainly a threat to the correct functioning of the vision system. In the solutions in which the camera moves through robot or carriers it is required to adopt cables more flexible than the standard ones and lockable connectors to avoid disconnections caused by the vibrations.

As previously said, the PCs used must always guarantee a constant performance, and when it is about having a good mechanical stability they are very often strengthened.

Furthermore, vibrations can cause the picture taken to be blurred.

Dust, dirt, and water splashes can cause the reduction of the amount of light hitting the sensor, due to impurities sticking on both LEDs and lenses.

1.1.3 Cost-effectiveness

One key aspect influencing the choice of a company to implement or not an industrial vision technology is the economic one, both in term of purchase cost of the system and of cost savings associated to the new benefits introduced.

Concerning this last point, it is therefore worthy to briefly describe which are these cost savings.

The first one that comes to mind is of course the saving in *direct labor costs*: for example, in a production line endowed with optical systems for inspection, hundreds and thousands of pieces can be inspected every minute, every time with the same accuracy. Considering the same production line and the same throughput, the inspection could be performed by a certain number of workers, who will have a much lower inspection speed than that of the vision system. In the case of the introduction of the new optical technology, the workers could be relocated to other tasks, thus saving for this control operation an important percentage of direct labor cost.

But that is not all about cost savings. Another relevant reduction in cost - strictly connected to the labor cost - is related to *training cost*: an operator is not immediately ready to perform a task, especially when handling of components and tools during an inspection is complicated. With a proper setup of the vision system, the effects coming from this issue (regarding operation effectiveness and speed) are attenuated. This results in a reduction in training costs of about 90%: not 100% because it is necessary to have a tuning phase of the new system on the production line and to train those operators assigned to the support and maintenance of the vision machine.

A direct reduction in *scrap and reworking costs* is appreciable, because of the:

- Control of every piece: Thanks to the high speed of the industrial vision technologies, they are often implemented to perform a 100% control of pieces flowing on a line, especially in those fields where the effects of a defective item would have severe repercussions on the whole production chain, as for avionic and automotive systems.

- Absence of physical contact between parts: Artificial vision allows to avoid damage to the piece inspected and to save time and money that would be spent due to the wear and maintenance of the working tools.

After the installation of the vision system, it is estimated that the costs related to these two just discussed factors will be the 20% of the costs related to the same factors, but without the new technology. With several inspection points, the problem can be detected at the source, preventing situations in which other operations are performed after the defect is generated, wasting additional resources.
Consequently, a further reduction in costs is measurable thanks to lower *scrap disposal costs* and *scrap and rework inventory costs.*

Finally, achieving a higher quality level, another saving in costs is related to *warranty costs*.

To summarize what said until now about costs, industrial vision main goal and benefit is to reduce the *cost of quality*, that can be divided in two main branches: *prevention costs* and *failure costs*. The first one is related to inspection issues, in order to prevent any possible problem ensuring a constant control. Once the defect is detected, the second category of quality costs is involved. Failure costs can be either internal when the problem arises before the product leaves the production plant, or external when the product has already reached the customer.

1.2 Purposes and classification

1.2.1 Purposes

There are many functions that an application endowed with artificial vision can perform and they can be grouped together in the four work areas of Guiding, Identification, Gauging (measurement) and Inspection, summarized by the acronym *GIGI*. Below, a description of these groups:

- *Guiding:*

  The goal is to define the orientation and the position of the product analyzed, and then make a comparison with a pre-set tolerance, ensuring the correct positioning in the work environment for the following assembly processes.

  The guiding function can be used to communicate to robots the location of the piece in the space.

  Industrial vision guidance definitely allows to have higher speed and accuracy than the manual positioning in operations like alignment of pieces before their assembly with other components, movement of products on/off a pallet, and so on.

  Furthermore, when there is a certain variability of the product's position along the process the function of guiding is very useful thanks to the possibility of having different machine vision systems communicating with each other: location and orientation data are shared operation after operation and so each device is always ready to carry out its activity whichever is the position of the piece for example flowing on a conveyor.

- *Identification:*

  The constant pushing towards the minimization of waste and consequent maximization of productivity, also known as *lean manufacturing* methodology, is giving more and more important to the task of identification.

  Every item taking part to the production process is coded and tracked, using dedicated vision systems.

  The traceability along the manufacturing line is fundamental to have always under control all the variables of the process, keeping record of how many and which ones are the defected products, providing the needed tools and components according to the batch in production, ensuring the logistic flow of items entering/leaving the production line to be balanced, and so on. Moreover, this data collection about which specific piece

is part of a specific assembly is very useful in technical support during operations under warranty.
Among the main vision technology in this field there are: barcode readers, data-matrix code readers, Direct Part Marks – DPM code readers, Optical Character Recognition – OCR (to read alphanumeric characters) and Optical Character Verification – OCV (to check the presence of a string of characters).
Besides codes, products can be identified also on the base of shapes, colors, and dimensions.

- *Gauging:*
  The measurement task is performed by a vision system computing the distance between two or more points, or the geometric coordinates of the object under analysis according to a certain reference in the space.
  As previously mentioned, a significant benefit of the optical gauging technologies is the lack of physical contact between parts, avoiding so the situation in which the item is damaged by the measuring tools.

- *Inspection:*
  This area is related to the checking the presence of defects and of all the possible irregularities that can affect the proper working of the product inspected. To be more specific, inspection can be referred to:
    - Surface quality: analysis of components aimed at detecting eventual scratches, fractures, and wear-related imperfections.
    - Structural quality: analysis of an assembly, aimed at checking if some components are missing or if by chance some external piece is present (e.g. a screw fallen in a cavity of the product).
    - Operational quality: analysis aimed at verifying that the product's functioning meets the standards.

1.2.2 Classification

One way of classifying industrial vision can be to take into account the number of *degrees of freedom (DoFs)* of the operation involved, representing all those features the variability of which does not have any repercussion on the analysis performed. The less the number of DoFs

the more the system is depending on the features defining the single application, while conversely, the higher the number of DoFs the more the system is flexible and expandable to other applications.
Position, size, color, illumination, texture and shape are the most common considered DoFs. Clearly an high flexibility would be the best option, for example to reuse approximately the same configuration processing another product, thus saving the costs of buying a different vision technology. However, systems with high number of degrees of freedom requires very sophisticated and advanced software algorithms and components: a trade-off between flexibility and cost need to be found.

Considering the very high number of possible features belonging to the group of the degrees of freedom, the most adopted classification in the market of industrial vision systems is the one referring to the spatial geometry of the application, reducing to three main categories: 1D, 2D, and 3D.
A brief explanation is following in the next paragraphs.

1.2.2.1 1-D (mono-dimensional) vision systems

A digital signal is analyzed considering every time a single line, instead of a full picture. Then, data are processed comparing different groups of lines acquired in different moments.
Generally, a laser scanner is placed perpendicularly over a conveyor, throwing a laser beam on the product flowing on it and synchronizing to the movement of the item following the variations of the conveyor motor's angular speed.

This category is implemented mainly in those processes in which the production is continuous (metal sheets, paper, etc.) and so, when a defect like a bubble, scratch or whichever impurity is detected the signal correlated is a line different than the regular one.

1.2.2.2 2-D (bi-dimensional) vision systems

This category can be divided in 2 main sub-categories: *line-scan* and *area-scan*.

A line-scan vision system employs the same principle just described about 1D systems acquiring a single line of pixels per time and so, the final picture is obtained adding line by line.

Area-scan vision systems work taking 2D pictures, i.e. analyzing each time matrices of pixels and not a line of them. A graphical description of these two principles is in Fig.2.

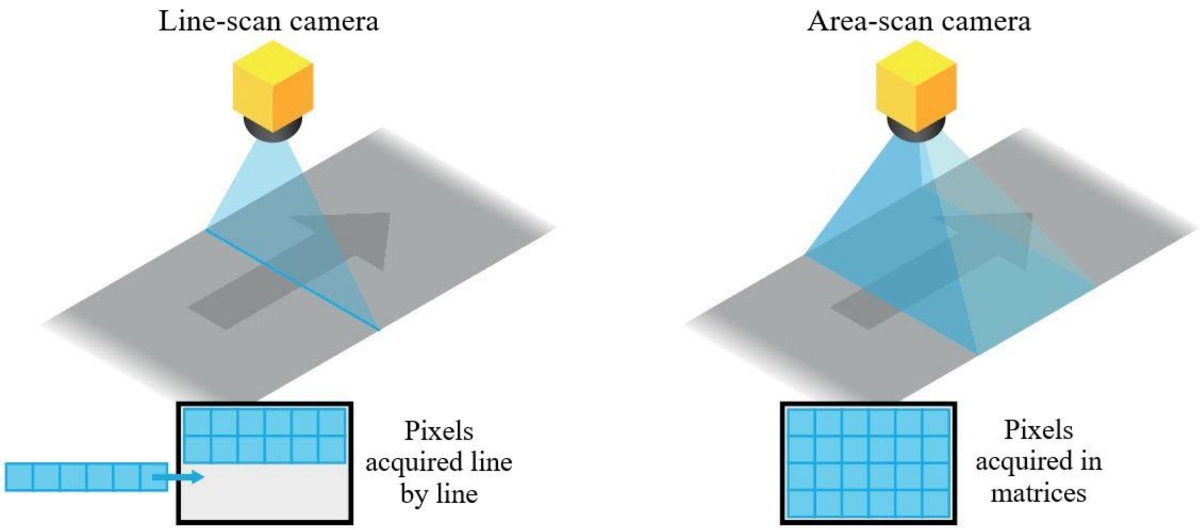


Figure 2. Comparison between line-scan and area-scan working principles

Line-scan systems need the movement either of the camera, like in a common documents scanner, or of the component itself, thus required it flowing on a conveyor or rotating on a special platform. This method is indeed the best when it comes to the inspection of cylindrical surfaces and of some products flowing at high-speed on a conveyor (some technologies achieve even capture speeds of 67000 lines per second).

Since they do not need a wide angle of scanning but just the necessary space to scan a line, line-scan systems perform very well in environment full of installation constraints such as the case in which a detail of a component requires be captured in between the rollers of a conveyor.

1.2.2.3 3-D (three-dimensional) vision systems

These systems usually can be endowed either with multiple cameras or with a single camera.

In the first cases cameras are placed in different positions and usually this combination is used to guide robots in understanding the orientation of the piece analyzed: signals from the different components are triangulated and data on the 3D position are obtained.

Several 3D multi-camera vision methods are present on the market, and some examples will in discussed in the following chapters of this thesis project.

Laser displacement sensors represent the case of 3D vision systems with single camera, dedicated to the measurement of surfaces and volumes. A laser beam is thrown on the object and its reflection is captured by the camera: the variation of the final signal will be processes to provide a depth map or a surface/volume profile.

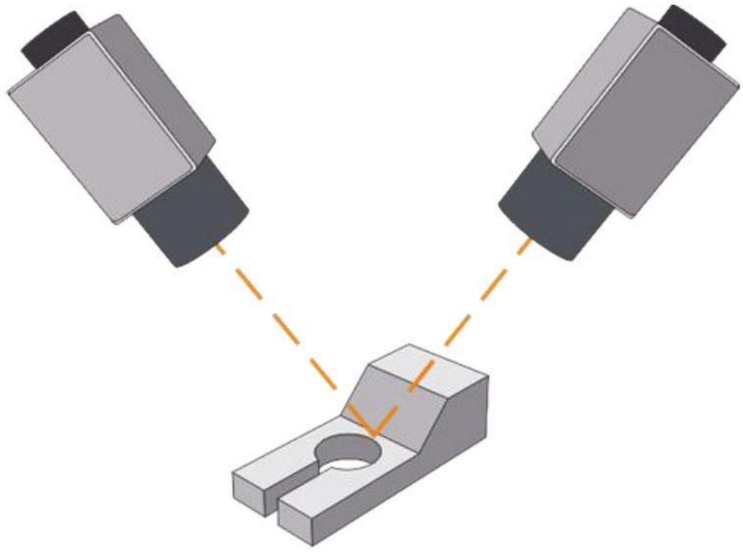


Figure 3. Schematic representation of a 3D multi-camera vision system

1.3 Industrial vision applications

Considering the description carried out so far concerning machine vision systems with their benefits and their wide range of fulfillable tasks, it can be understood why the industrial vision market is growing constantly year after year, finding applications in more and more different fields.

The first analyzed field is the *pharmaceutical industry*.
In the cases of a problem arising and so of a specific lot of drugs that has to be recalled, codes are fundamental in order to act fast and detect all the non-conforming products in the distribution line. A fundamental issue in this application field is the ability of tracking and tracing everything properly, from the production line up to the final user. The details that can be printed on the packaging are many, and the main ones are the serial number, the manufacturing date and the expiration date.
Furthermore, machine vision systems are employed for tasks like counting the number of capsules in blister packs and checking the filling level of vials.

Concerning *food and beverage industry*, a first function that can be performed by an industrial vision device is the checking of the correctness of the label indicating the ingredients of the product, trying to avoid critical problems like known allergens not reported.
Just like in pharmaceutical industry, in the case of perishable goods, printing and controlling the production and expiration dates are clearly essential to preserve the consumers' health. Another similarity with the previously described industry is relative to the control of the printed serial number so that an eventual recall action would be fast and accurate.
An example of a machine vision system applied to the food industry is the one referred to the control of the level of a beverage in its bottle, as shown in Fig. 4.

In the *electronics industry*, the use of artificial vision is nowadays an integral part of every manufacturing process. The inspection accuracy required is increasing due to the fact that components' dimensions are getting smaller and smaller, in a general trend towards miniaturization, as happening in the smartphones and personal computers' market.
Considering small items like microchips, resistors, and transistors, an inspection of these products without a machine vision apparatus would be slow and in addition it would require the use of a microscope. This explains why these systems are a must-have for every company working in this field.

Semiconductors are for sure among the most complicated electronic devices to manufacture.

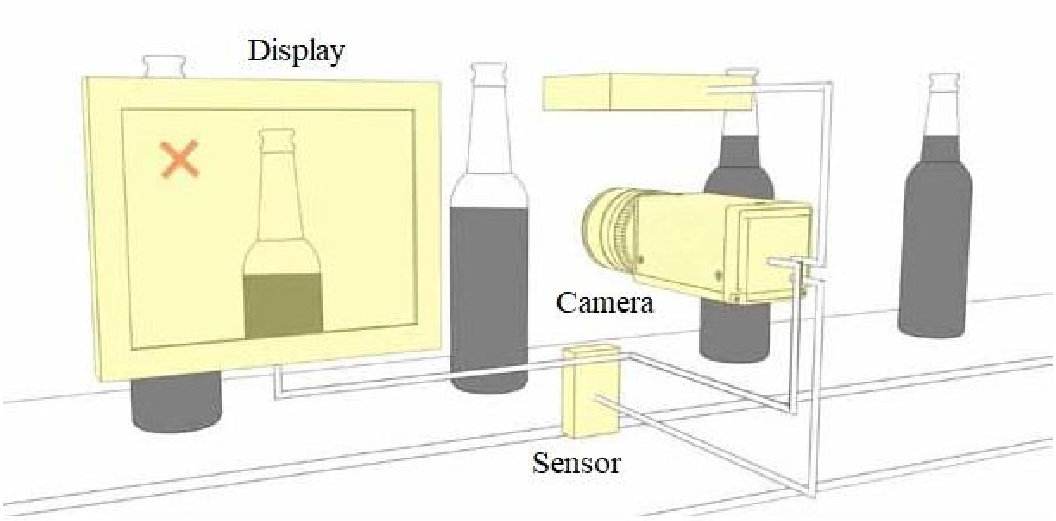


Figure 4. Optical control of the filling level of bottles flowing on a conveyor

Finally, the field of interest of this dissertation is the *automotive industry*.
In this sector even a small problem on a single piece can lead to the impairment of the final product and to a high safety risk for the final customer; thus, high accuracy and high quality standards are required. Considering that a car is composed at least by 30000 components, it is understandable how hard is to achieve these two targets.
Basically, almost every manufacturing operation in an automotive plant is assisted by a machine vision system.
As mentioned about the previously described application field, traceability has a great importance in the case of a recall action, allowing to quickly react to a problem preserving the brand-image and the user's safety.

In the following section, it will be described how industrial vision applies to the different branches of the automotive industry.

1.3.1 Automotive solutions

With the complexity of today's car growing more and more, in the same way does the possibility of having a problem arising during the manufacturing process: manufacturers have to set important countermeasures to keep being competitive in a market like the actual one, in which a lot of players are pushing towards innovation and higher quality in order to gain a larger piece of market share.

For this reason, machine vision technologies are implemented by all automotive OEMs, in almost every stage of the production process for all systems composing the final vehicle.

These systems are:

- *Chassis*: Industrial vision is used to make the vehicle frame assembly process faster and to efficiently inspect body panels. Significant tasks performed are:
    - Final assembly verification, checking the presence and the correct mounting of all items.
    - Guidance for automatic racking and de-racking of body panels, including their inspection-
    - Measurement of gaps between panels, through the use of laser profiles.
    - *VIN (Vehicle Identification Number)* code inspection.
    - Inspection of welding quality.
    - Etc.
- *Safety devices*: In order to meet the standards imposed by regulations, very high quality is required in the manufacturing process of devices like seatbelts, brakes, airbags and so on. Machine vision systems are used for:
    - Quality inspection of airbag's fabric, stitches, and capsule.
    - 3D profile analysis of brake pads, checking the dimensions of the added rivets.
    - Measurement of brake valve's dimensions and quality control of each feature.
    - Quality inspection of seatbelt's components, followed by the inspection of the complete assembly.
    - Control of the silicone bead for the installation of the windshield.
    - Etc.
- *Electronic devices*: The use of electronics in the automotive sector is growing year after year, both because of their high precision and high reliability and thanks to the new vision of a car as a network of communicating systems. For this reason, it is fundamental to carefully manufacture and manage these devices along the entire chain. Applications of artificial vision are:
    - Inspection of the battery module and of its assembly.
    - Sorting of electrical components through barcode reading.

    - Inspection of TEHCMs (Transmission Electro-Hydraulic Control Module), checking the conformity of pressure and temperature switches, solenoid valves and control module.
    - Etc.
- *Tires and wheel*: Several combinations of tires and wheels can be installed on the same vehicle model, thus increasing the need of an accurate and quick sorting before assembly. Clearly, a quality check is needed to meet safety and performance requirements.
  In particular, examples of machine vision controls are:
    - 3D measurement of tire profile patterns.
    - Identification of tires by reading codes like the *DOT (U.S. Department of Transportation code)*, that is a sequence of an alphanumeric characters molded on the sidewall of the tire allowing to identify it and its age.
    - Analysis of the wheel pattern in order to match it with the associate tire.
    - Etc.
- *Powertrain*: The process of manufacturing and assembly of an engine is very complex and involves the synchronization of a lot of players in the supply chain.
  Reliability of the system must be high, considering that an engine life nowadays can easily reach 200000 km ensuring an acceptable level of drivability throughout the entire lifecycle.
  With the increasing of the automotive production volumes, industrial vision is needed almost during or straight after any operation in an engine's production line, to check the correct assembly of subsystems, measure tolerances and trace the product step by step.
  A more accurate description of the use of vision systems in the automotive powertrain industry is provided in the next section.

1.3.1.1 Industrial vision in automotive powertrain industry

The focus of this thesis project is on the use in the automotive powertrain industry of machine vision systems, giving a detailed description in the following chapters about the main applications together with practical examples.

For what concerns this introductive chapter, a brief discussion about some of the most significant manufacturing and assembly operations of an engine's production line is reported.

Most of the engine components are assembled by means of screws. Considering the increasing levels of throughputs, fastening bolts and screws manually would take too much time and furthermore, it would create an ergonomic problem for the workers due to handling a tool to repeat the same operation a lot of times during the same shift.
It is then clear that *automatic screw fastening systems* are adopted, and so are vision systems for their guidance. Location and orientation of screws is determined by the system, which is then able to communicate with the automatic fastening instrument so that the needed amount of torque for the correct duration of time is applied.

The concept on which the engine is built is the reciprocating motion of the pistons inside the cylinders, and many are the controls that this pistons-cylinders group requires.

Cylinders are usually made of aluminum or cast iron. The walls must guarantee a high durability due to the continuous mechanical contact with the piston itself, and even if during the engine manufacturing process some irregularities on their quality can be tolerated (attenuated then by mechanical wear), it is necessary to avoid the presence of pores or fractures. In fact, both lubrication (and therefore the smoothness of movement) and reliability could be affected by these problems.
Due to light reflections and to the difficulty in positioning a camera to take a picture of the surface, the *inspection of cylinder walls* can be very hard requiring advanced technologies.

Regarding pistons, one of the critical aspects is to *check the conformity of piston rings*. Their function is to seal the combustion chamber preventing gases to reach the crankcase and to maintain an adequate level of lubricating oil between the piston and the cylinder walls.
The analysis is performed through 2D pictures and 3D profiles' measurements, checking that no defects are present and that tolerances are respected.

Another application of industrial vision in the assembly line of an automotive powertrain is related to the *installation of o-ring seals for the oil filler caps*. Generally, these torus-shaped silicone components have a bead on one side so that their orientation when installed is fixed.
Even if a generic feeder can be endowed with a mechanical system to control the part's orientation, when it comes to deformable components such as o-rings this check is very difficult: a vision system can be implemented, so that pictures taken by a camera are analyzed

to verify the proper positioning of the component. If the result is negative, a mechanism could for example reintroduce the wrong-oriented seal in the feeder bowl.

Parts of the engine like oil sump and timing cover require gaskets or silicone profile paths before being connected to the main body by means of screws. This step is necessary to avoid leakages and intrusions.
The visual *inspection of the sealing silicone* would not be accurate if performed by the human eye, and so an automated system can be introduced in the line to verify that the proper amount of sealing glue is injected and that the profile followed is the right one.
3D vision systems are also used when also the volume of the glue bead needs to be controlled.

Spark plugs in spark-ignition internal combustion engines can be different among models, according to several parameters such as for example the diameter and the length of the thread. The robot involved in the assembly of these components can be helped by an artificial vision guidance so that a precise *identification of spark plugs* is obtained.
The optical control can check details on shape, surface and dimensions of the items.

Finally, another case that requires the assistance of an industrial vision apparatus regards the *traceability of engines*.
Engine blocks are tracked along the whole process through a 10-characters alphanumeric code laser printed on its surface. Being this code unique, it helps to restrict the group of recalled engines in case of an eventual problem detected on the line or when product is already in the distribution chain.
It is understandable then how important is to preserve the integrity of this code along the production line, keeping it readable.
The vision system can be configured with a 2D (in some cases 3D) technology to detect where the code is printed, and with an *OCR (Optical character recognition)* software to read it and verify its completeness.

2. The Research Environment

2.1 The Automotive Powertrain Plant

As mentioned in the previous chapter, the study for this thesis project about industrial machine vision has been conducted in an *automotive powertrain plant*, belonging to an important car manufacturing group operating worldwide.

The plant involves more than 1000 employees, with a throughput higher in average than 2700 engines per day.
Three main engines are produced, each of them in a dedicated building where both machining and assembly operations are performed. Consequently, the shift schedule varies according to the specific market demands for the three engine models.
Until few years ago, the products were sold also to other important car manufacturing groups but nowadays, due to the growing of the group and of the level of competitiveness among different carmakers, the production is kept only for internal purposes serving the various brands managed by the company.

During a 5-months internship, the main activity carried out was to follow and support the engineers of the production engineering office in the application of specific control plans on the various production lines constituting the plant, focusing on the numerous machine vision systems installed.

The entire dissertation will be carried out describing the core idea behind the technologies and processes of interest, without providing too-in-depth-information that could lead to an unwanted exposure of the intellectual property of the car manufacturer group.

2.1.1 World Class Manufacturing (WCM) methodology

The company applies in its plants a set of rules and techniques that falls under the name of *World Class Manufacturing (WCM)*.
This methodology was developed by the *Fiat Chrysler Automobiles (FCA)* group and it is aimed at the continuous improvement not only of the production process itself, but also of the organization, the workplace, the maintenance, and the logistics. The goal is to enhance the quality of the product in order to satisfy the customer needs, minimizing all possible losses and waste.

WCM can be also described as the integration of four main approaches:

- *Lean Manufacturing*: A production strategy whose goal is detecting and minimizing all the wastes, until eliminating them completely, such as waiting time, excessive handling of goods, and defects.
  The focus is on what the customer wants and on the value chain of each product, removing those activities that are not adding any value in the direction the market is oriented to.

- *Total Productive Maintenance (TPM)*: This way of managing maintenance focuses on the continuous improvement of the performances of the equipment used, increasing the Overall Equipment Effectiveness (OEE) of the plant, a parameter based on the combination of three factors: availability, performance and quality.
  In order to proper identify and minimize losses, a series of specific strategies concerning the equipment need to be actuated, like planned and autonomous maintenance and *EEM (Early Equipment Manufacturing)*, related to a design phase of the equipment oriented to high reliability and flexibility.

- *Total Quality Management (TQM)*: This approach is based on the fact that all the parties in an organization should work to achieve the maximum possible quality, so that the company is able to achieve optimal results in every activity within the business.
  The main principles on which this approach is based are: focus on customer, integration of all systems, continuous improvement and involvement of all employees.

- *Cost deployment:* The technique of deploy every cost along all the level of the organization arriving until the last step, that is the single operation. In this way, it is possible to make clear the relationships among costs, what generates them and so also what leads to extra-cost due to losses and waste.
  Once the source of the loss is identified, a reduction in cost is then possible.

The application of the World Class Manufacturing system in the plant of the study has led to important results both on the savings (30% reduction of the total cost of one engine from the application of the methodology) and on the quality indicators, gone up thanks also to the continuous application of the voice of the customer on the workplace.

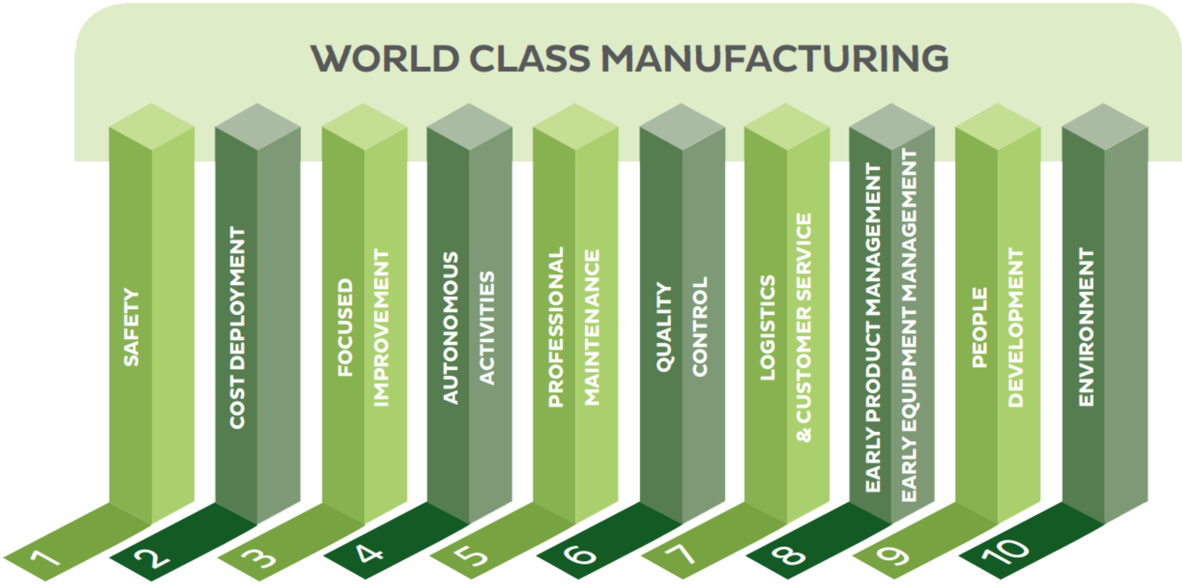


Figure 5. The 10 Pillars of WCM

As previously said concerning the Total Quality Management (TQM), it is fundamental to integrate in the continuous improvement philosophy all the employees: *kaizen* (from the Japanese "kai" meaning "change" and "zen" meaning "good") is what defines this concept. The idea is that every worker should give his contribute, even small, to the optimization of the workplace.

The main advantage is that these changes suggested by the workforce are not radical as they could be if coming from the technical department, thus usually they are cheap and easy to implement. Moreover, this approach of workers looking for solutions for the process in which they are participating helps in creating in them a sense of belonging to the company and in making them feel valued.

In the plant under consideration, everyday there are in average 30 suggestions for ergonomic improvements coming from the employees on the line. These contributions are written on a notebook placed near the line and it is the job of the team leaders to discuss about them with the responsible of the workplace design.

Talking about Total Productive Maintenance (TPM):

- an *internal maintenance department* is integrated with the production line, in order both to cut the costs of an eventual external maintenance and to give to workers growth opportunities becoming maintenance specialists.

- To ensure that the automatic control equipment is working properly, the *error-proofing* technique is usually adopted.
  At the beginning of each shift, each machine tests two different engine/component samples: the first one (usually totally colored in green) is the good master, which respects the product standards required and the second one (usually totally colored in red) is the bad master, which presents an error on the feature of interest.
  In case of problems detected during the test of the good master and/or nothing to report during the test of the bad master, it is ascertained that the equipment is not working properly and so, knowing it before the shift, this preventive check of the machines allows to prevent control failures.

Finally, going back to the main topic of this thesis, the *machine vision systems* installed along the production lines are essential to achieve one of the fundamental principles of lean manufacturing, and so of WCM: zero waste and zero losses.
In fact, automatic industrial vision can ensure 100% quality control, canceling the possibility that the defect on a product is not detected and then hidden during the following steps of the process.

2.2 The Products

The company produces in this plant three models of 4-Strokes internal combustion engines, of which two are fueled by gasoline and the other one by diesel.
A description of each one of these engines is carried out in the following paragraphs.

2.2.1 The 3/4 Cylinders 4-Strokes Gasoline Engine

The first model of engine is a 4-Strokes Gasoline Engine. Among its main features it is possible to appreciate the same single-cylinder displacement and the choice of aluminum as material of the engine block, allowing a significant reduction in weight with respect to the competitors in the market.

The production is split in two different versions:

- The *3 in-line Cylinders version* with 999 cubic centimeters engine displacement.
- The *4 in-line Cylinders version* with 1.332 cubic centimeters engine displacement.

For each of the two previous versions there are two main possibilities concerning the induction of air in the system: natural aspiration and turbocharging.

Naturally aspirated engines are characterized by having two valves per cylinder, low specific power delivered and indirect injection. They are intended for the LATAM (Latin America) Market.
The 3-Cylinders variant has peak power equal to 72 CV (at 6000 rpm) and peak torque equal to 102 Nm (at 3250 rpm), while the 4-Cylinders version has peak power equal to 101 CV (at 6000 rpm) and peak torque equal to 134 Nm (at 3500 rpm).
They are mainly installed on Segment B vehicles.

Turbocharged engines are characterized by having four valves per cylinders, direct injection and an advanced variable valve timing technology. They are intended for the EMEA (Europe, Middle-East, Africa) and NAFTA (North America) markets.
The 3-Cylinders variant has peak power equal to 120 CV (at 5750 rpm) and peak torque equal to 190 Nm (at 1750 rpm), while the 4-Cylinders version has peak power equal to 150 CV (at 5500 rpm) and peak torque equal to 270 Nm (at 1850 rpm).
They are mainly installed on Segment C vehicles and SUV.

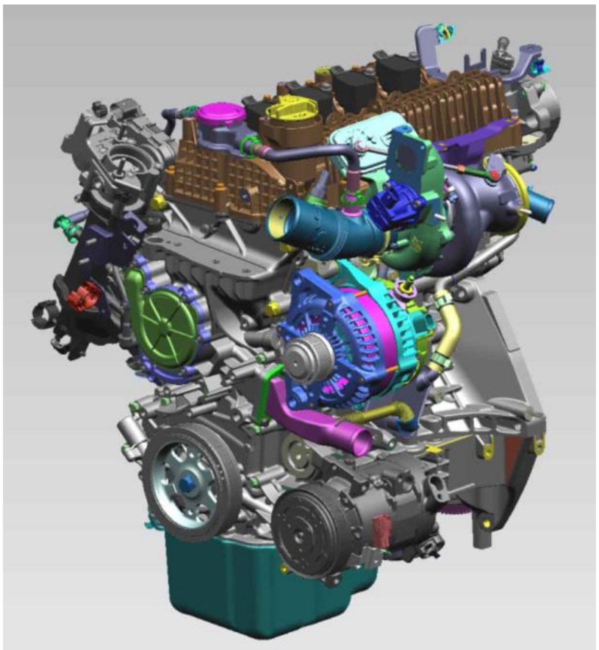


Figure 6. A 3D rendering of the 4-Cylinders 1.332cc Turbocharged Gasoline Engine

The company started to produce these engines in the 2016 in a different plant, and then from 2018 the production has been extended to the plant of interest, where in June 2019 it has been reached the important milestone of 100000 engines assembled.

Concerning emissions of pollutants, *EURO 6D* is the highest level of standards reached by this class of engines. However also older standards are applied on different batches, according to the market of destination.

The car manufacturer strategy is moving towards the electrification of its fleet: starting from the beginning of the 2020 the OEM will endow some of its vehicles with *hybrid engines*.
In particular, the 3-Cylinders naturally-aspirated engines design has been modified for the implementation of the *mild-hybrid* technology, which consists very briefly in a parallel-hybrid configuration in which a lithium battery is recharged during decelerations and it is supplying energy to an electric motor supporting the combustion engine in the most demanding phases, by means of a belt connection.
The 4-Cylinders Turbocharged engine has been chosen for the implementation of the *hybrid plug-in* technology, which allows to charge the battery with an external energy source, and so to work in full electric mode.

2.2.2 The 2 Cylinders 4-Strokes Gasoline Engine

This engine is in production in the plant since 2010, with volumes around *60000 units per year*. Their application is found mainly in Segment A vehicles, with some cases in Segment B vehicles.

It belongs to the same family of engines previously described and in fact its most significant feature is the company-property *variable valve timing* technology.
This system allows to manage the engine valves in a very flexible way, adapting to different operating conditions controlling dynamically the opening time and the opening phasing. The movement of the valves depends on the action of hydraulics pistons, fed by the same oil lubricating the engine.
Having this total control, it is possible to remove the throttle valve and consequently improve the pumping efficiency by getting rid of pumping losses at part-loads.

This engine has been designed in line with the *downsizing philosophy*: a relative small engine displacement (875cc split in two cylinders, four valves each) and the adoption of a turbocharging engine allow to have same performance of higher engine displacement engines, but with lower fuel consumption and emissions.
The performance obtained are peak power equal to 85 CV (at 5500 rpm) and peak torque equal to 145 Nm (at 2000 rpm), with emissions meeting the *EURO 6* requirements.

2.2.3 The 4 Cylinders 4-Strokes Diesel Engine

This model is the oldest one produced in the plant, launched in the far 2003.
It is a 4 in-line Cylinders 4-Strokes Diesel engine, with four valves per cylinder. The engine displacement of 1300cc and the turbocharging technology make it suitable for applications in Segment B vehicles, Light Commercial Vehicles and in the last years in some Segment C vehicles.

The most peculiar characteristic of this model is the *multiple-injection technique*, that allows a smoother combustion in the cylinder, with a lower peak heat release. Consequently, the main benefits are a reduction in emissions and in noise.
In the first generation of this diesel engine, there were just two injections: a pilot one and, some crank angle degree after, the main one.

With the introduction of the second generation, the injections number passed to 5, bringing better performances in cold running and fuel consumption.

The engine is produced in 3 main versions:

- A 75 CV (at 4000 rpm) version, with peak torque equal to 190 Nm (at 1500 rpm) and Euro 5 emissions homologation.
- An 85 CV (at 3500 rpm) version, with peak torque equal to 200 Nm (at 1500 rpm) and Euro 5 emissions homologation.
- A 95 CV (at 4000 rpm) version, with peak torque equal to 200 Nm (at 1500 rpm) and Euro 6 emissions homologation.

Figure 7. A full pallet containing several 4-Cylinders 4-Strokes Diesel engines

Considering that in the last years the policies applied by worldwide governments are trying to cut out as much as possible the circulation of cars endowed with diesel engines (in favor of an electric/hybrid fleet), the production volumes of this engine are decreasing.
In fact, if from one side the company is experiencing a lower market demand for this model of engine, from the other side the volumes are increasing for gasoline engines, still able to compete even with these strict emission regulations and most of all easily configurable into the hybrid solutions.

2.3 The Process

The assembly operations take place in a different building for each of the three classes of engines described so far.
Concerning the machining part of the production process, the operations related to the 2-Cylinders Gasoline engine are split between the machining lines of the diesel engine and the machining lines of the other gasoline engine.
In the following paragraphs, further details will be added about these two groups of activities performed on the engines.

2.3.1 Machining

The strategy of the company is to receive, from a foundry internal to the group, raw components which are then machined in dedicated lines where operations like milling, threading, drilling and so on are performed by means of CNC (Computer Numerical Control) machines and other specific equipment.

The raw pieces involved are:

- *Cylinder Block*
- *Cylinder Head*, which in the case of the 4-Cylinder Diesel engine is split in two sub-components (lower cylinder head and upper cylinder head)
- *Crankshaft*

Checking the accuracy and correctness of these preliminary operations is essential to guarantee adequate performances of the engine and an optimal fit with the other components which will be installed on the assembly lines.
In the following chapters, the most important applications of industrial vision in the machining processes will be described.

2.3.2 Assembly

For all the 3 engines, the assembly process line is divided into two main consecutive areas: the *short block* and the *long block*. In the first, the main operations are related to the assembly of the crankshaft and of the piston-group, while in the second all the other components are mounted, and tests are performed.

According to the technology of the engines produced, some sub-assemblies are produced on parallel lines and then introduced in specific stage of either the short or the long block.

The thesis activity in the plant was conducted under the coordination of the production engineering office present in the building dedicated to the diesel engine. For this reason, it was possible to collect more information about this engine's assembly process flow than about the other two classes' ones.
In the next section it is reported a complete scheme of the 4-Cylinders 4-Strokes Diesel engine's assembly process, listing the main operations involved in each area.

2.3.2.1 The Diesel Engine Assembly Process

Before going further in the discussion, it is necessary to highlight two differences in the assembly process of the diesel engine with respect to the other two models:

- The cylinder head is split in two components, that are the *lower cylinder head* and the *upper cylinder head*. To each of them specific machining and assembly lines are dedicated.
- The Long Block area is subdivided in two areas: The *Long Block 1* and the *Long Block 2*.

Coming from the machining line, the engine body enters the *Short Block* area and as already mentioned, the principal activities executed are related to mounting of the crankshaft and of the piston-connecting rod groups. At the end of this line the Lower Cylinder Head Assembly joins the engine body.
In the *Lower Cylinder Head Assembly line* the process is centered around the installation of exhaust and intake valves, together with guides, retainers, springs and locks. When the operations are concluded, a leak test for the valves is performed.

The engine is moved by means of a gantry system in the *Long Block 1* area, in which valves' rocker arms, upper cylinder head, oil and water pumps, timing wheels, distribution chain, oil sump, gearbox and flywheel are assembled.
The Upper Cylinder Head arrives from the *Upper Cylinder Head Assembly line*, where activities like the installation of camshaft, high injection pressure pump and timing gears are performed.

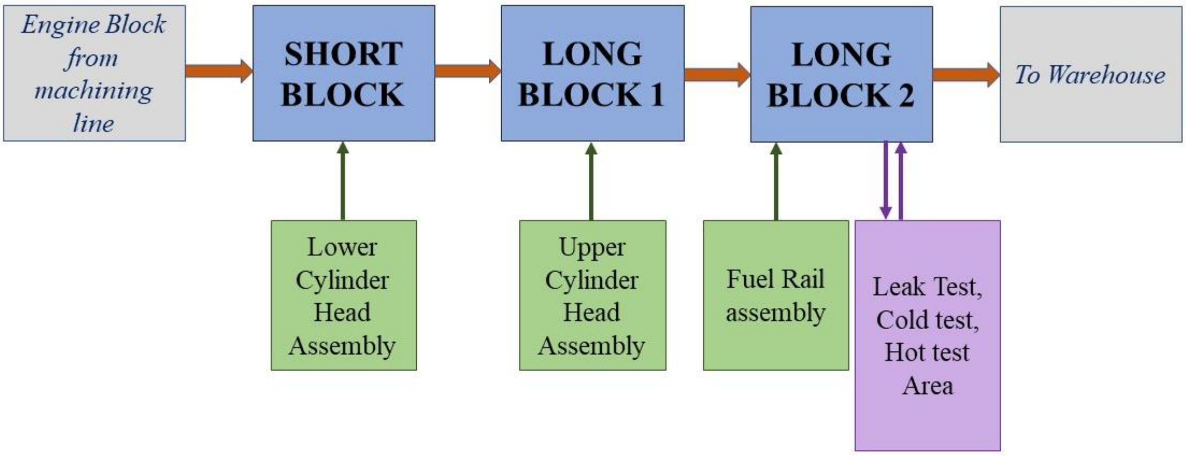


Figure 8. Block diagram of the 4-Cylinder Diesel engine assembly process

The engine is then moved again, to the *Long Block 2* area, involving the last set of operations in which the engine is processed. The parts that are mounted are: glow plugs, intake and exhaust manifolds, clutch, fuel rail group, catalyst, EGR (Exhaust Gas Recirculation) system, turbocompressor system and the engine mount bracket.
The fuel rail system is coming from a separate low automation assembly line (*fuel rail assembly line*), in which the accumulator, the injectors and the injectors' pipes are combined together.
Before the final stages, the engine needs to be tested, and so it leaves the Long Block 2 line to visit the *Test Area*. Tests conducted are:

- *VIPP (Verification In-Process Product) test*: checking the presence of possible leaks, verifying that the pressures in the water and oil circuits are adequate.
- *Cold test*: An external motor applies a torque to crankshaft (no firing of the cylinders), and then many parameters are analyzed. All the engines are subjected to this test.
- *Hot test*: The power to the crankshaft rotation is given by the internal combustion of the engine itself. Only 3% of the engines takes part to this test.

Finally, after these tests the engine goes back the main line and it enters the *Dressing Area*, where covers, sensors and wiring harnesses are installed, and a final control is performed.

The engine is now a finished product, and so it is loaded on a pallet and moved to the *Warehouse*.

3. Traceability

In the first chapter the importance of tracking and tracing each component/product along its whole life starting from the production phases up to the final phases when the customer is interfacing with the vehicle bought was emphasized several times.

Summing up, it was pointed out that tracing all parts along the manufacturing process is fundamental in order to keep the process' variables under control, in terms of defective units, machines' setups, logistics flows and so on. Tracking in real-time every unit helps in shortening the lead time of the operation and to have an overall optimization of the supply chain.
Furthermore, in case of the unfortunate event of a recall action, knowing the life of a component step by step would help to reach the customers who are dealing with a finished product quickly including a component coming from a defective batch, and so preserving the customer's safety and/or the brand's image.

The tracked information usually includes:

- part number, model number, serial number, and lot number
- assembly/manufacturing plant
- origin of the part
- production's place, time, and date

All this information is stored and transferred to the ERP (Enterprise Resource Planning) software, a system that is constantly updated following the evolution of the activities both in the process and in the company itself.

The technologies implemented in the automotive industry to fulfill the full traceability mission are: Barcodes, Radio Frequency Identification (RFID) and Optical Character Recognition (OCR) for alphanumeric codes.
Details about these systems are provided in the following paragraphs.

3.1 Barcodes

A barcode is a symbol that is applied or printed on products and packages. This pattern can be read by machines by means of special scanners which are able to extract the information contained in a barcode and to send it to the main information management system, in charge on analyzing and process the acquired data.

3.1.1 Barcodes classification

The actual market presents many different solutions concerning the barcodes' field, but a substantial differentiation can be made considering whether the barcode is 1D (one-dimensional) or 2D (two-dimensional).

3.1.1.1 1D Barcodes

In the first case, barcodes are named *linear barcodes* and they consist in a horizontal sequence of vertical lines, read from left to right. They can contain information only as an alphanumeric code, which is then decoded by a software which assigns a meaning to each of the digit of the code.

Usually they are found on labels sticked on the package or on the component itself.

The structure of a linear barcode is shown in the next figure.

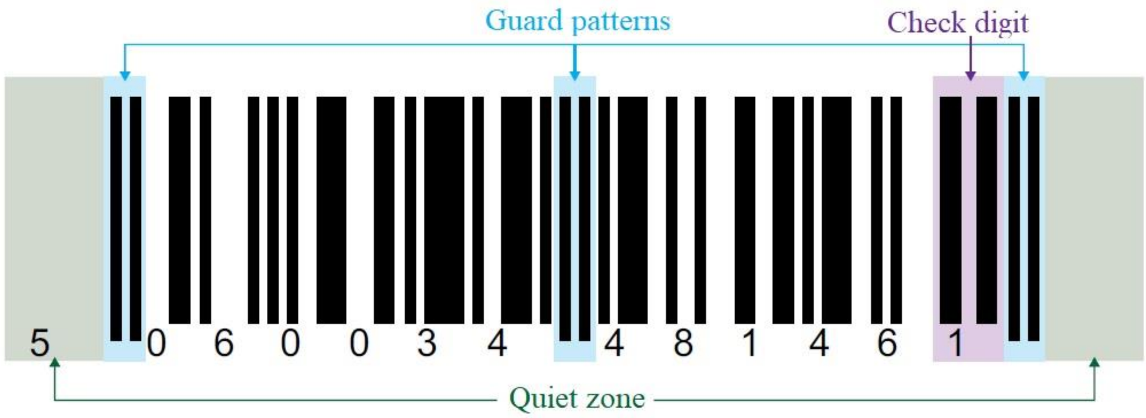


Figure 9. Structure of a linear barcode

The first element to take into account is the *quiet zone* (or margin), the function of which is to help the reader to locate the barcode and proceed to the data acquisition. The width of these bands is usually between 7 and 10 times the width of the thinnest bar.

At the beginning, the center and the end of the symbol there are the *guard patterns* (each of them as a couple of narrow bars), needed for the scanner to understand where the barcode starts and ends.

A *check digit* is located before the last guard pattern: this extra digit is added to implement an error detection algorithm and so to verify that the information acquired corresponds to the correct one. In this way cases of damaged or not complete barcodes can be recognized.

Among the several types of linear barcodes, *Code 39*, *Code 93*, *Code 128* and *ITF* (Interleaved 2 of 5) are the main ones used in the automotive industry. The last two find application mainly in the distribution and logistics' activities.

Without going into deep details too much, these numbers describe how the digits are represented in the code.

For example, concerning Code 39 (also known as Code "3 of 9"), it is possible to encode 43 different digits (26 from the alphabet, 10 numerical and other special symbols). Each digit is described by 9 elements, 5 black bars and 4 empty spaces, and the name comes from the fact that 3 out of the 9 elements are wide (binary value 1) and the other 6 are narrow (binary value 0). The maximum number of characters in a Code 39 can be 39.

CODE39

Figure 10. A generic Code 39 barcode

3.1.1.2 2D Barcodes

This class of barcodes allows to store information both horizontally and vertically. This means that the amount of information that can be encoded in a 2D barcode is way higher than the possible amount of a linear barcode. Indeed, as previously mentioned, the Code 39 can store up to 39 characters while a 2D code is able to store 3116 numeric characters or 2335 alphanumeric characters.

Each data is encoded 3 times in a 2D code, giving a quite high robustness to the system against errors.

The structure of a 2D code (in this case a *Data Matrix Code*) is illustrated in Figure 11.

The shape of the code is squared and considering the four edges, one couple (left and bottom) forms the *Finder or "L" pattern* and the other one forms the *Clock pattern*.

The Finder includes two continuous edges with width equal to the one of a cell and its function is to give the proper orientation while reading the code.

The Clock includes two edges in which black and empty cells are alternating: the function is to communicate how big a cell is and how many cells are present in the code in the decoding phase.

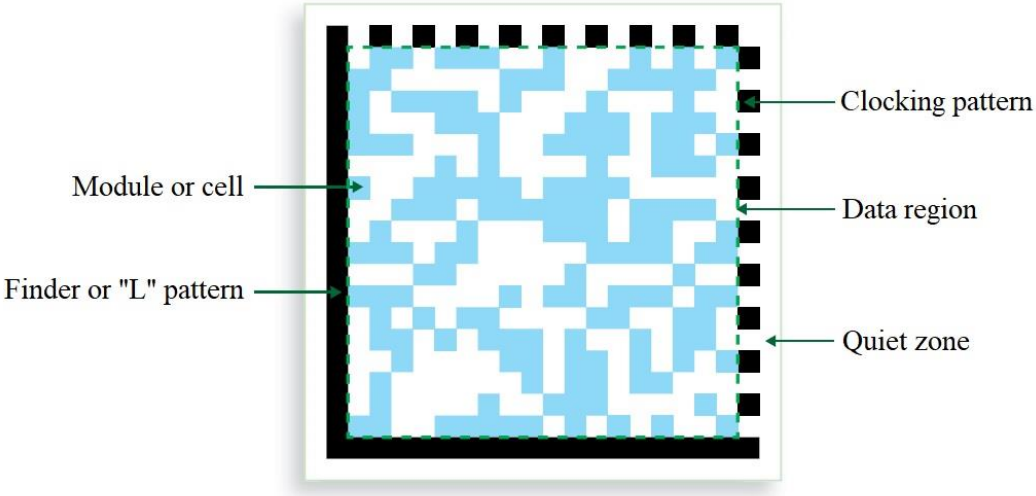


Figure 11. Structure of a Data Matrix Code

In the automotive industry the majority of 2D codes are either Data Matrix Codes or QR (Quick-Response) Codes.
This second type of 2D code is growing in importance thanks to its versality and for this reason, it finds application in a lot of fields. A peculiar characteristic of this barcode is the presence of three squared outlines (squares with black edges containing another black square) located in the top left, top right, and bottom left corners: the function of these outlines is to indicate to the reader the proper orientation of the code.

Figure 12. An example of QR Code

2D codes for an automotive component require to be very durable considering both the high number of machining and assembly operations to which a component/product is subjected during the transformation process and the very variable (and sometimes harsh) conditions to

which it is subjected during the use by the final customer.
For these reasons, the most used technique to link the code to a component/product is the *DPM*, meaning *Direct Part Marking*.
There are three main possibilities of directly marking a part:

- *Laser marking*
- *Dot peen*: an oscillating needle is pressed on the metal so that every cavity created represents a black cell of the 2D code
- *Electrochemical etching*: The code is marked on the component exploiting the ability of the metal to dissolve when a sodium-based solution is matched with a low voltage current.

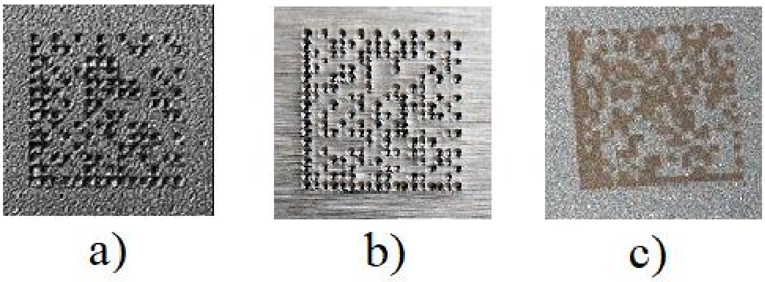


Figure 13. DPM techniques: a) laser marking; b) Dot peen; c) Electrochemical etching

3.1.2 Barcodes readers classification

According to the task to be fulfilled, barcode readers can be classified as:

- *Fixed barcode readers*: usually implemented on production lines where items are flowing at high speed on a conveyor always keeping the same orientation. Operators are not needed in the functioning of these devices.

- *Handheld barcode readers*: Operators handle these devices which are usually connected to the main network by cable or wireless. They are mostly used for logistics operation for incoming and outcoming items.

- *Mobile readers*: Used in specific situations on the field (like a technician who needs to know specifics about the equipment analyzed), the device includes a software to make information available immediately.

Besides this first classification related to reading environment, it is necessary to go deeper in details to discuss about the two main reader's classes on the market: laser scanners and image-based readers.

3.1.2.1 Laser scanners

The first and oldest technology concerning barcode reader is the laser scanners one, that can be described briefly as a system including mirrors and lenses which make a sensor (a photodiode) acquire the light coming from a laser source after reflecting on the scanned element.
A scheme of this device is presented in Figure 14.

These systems are very fast (maximum 1300 scan per seconds), and they are able to read a code even from a long distance because lasers do not diverge, so keeping an adequate accuracy. Furthermore, the cost of these readers is not high because their structure is pretty simple and made of quite cheap components (for example no image processors are needed).

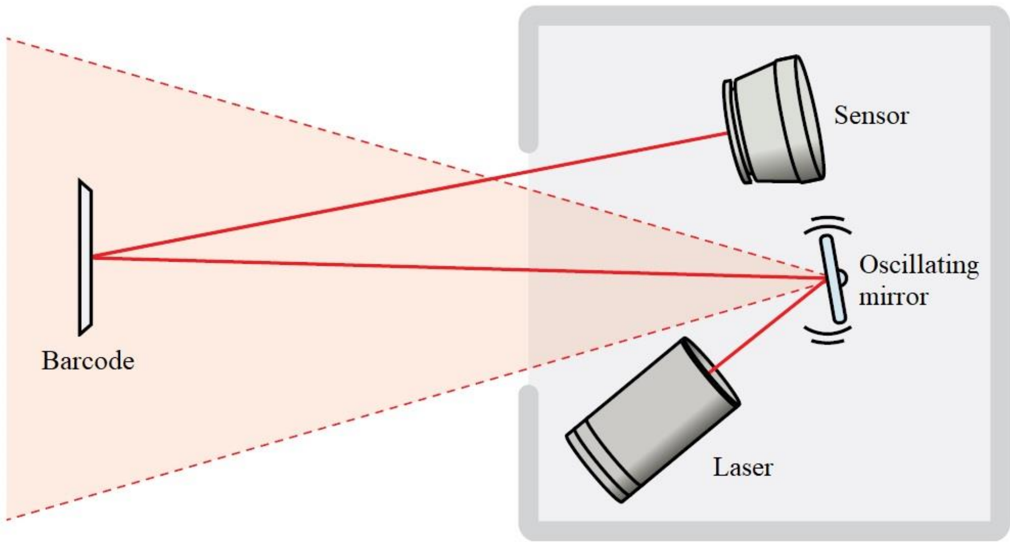


Figure 14. The structure of a laser scanner

The oscillating mirror allows the light to move along the whole length of the barcode, but since this oscillation is performed only around one axis it is impossible for this kind of readers to perform a scansion on a 2D code. This is clearly a disadvantage, considering that 2D codes are getting more and more spread in the industry sector.

Moreover, these mirrors mechanisms are subjected to wear and tend to break, affecting the reliability of the system.

It is not all about the drawbacks of these systems yet: the device must be shielded in order to avoid the laser beam to reach the workers' eyes and, since a 1D barcode usually needs to be read from left to right, there are constraints in its installation.

3.1.2.2 Image-based barcode readers

Images-based barcode readers use a sensor able to acquire 2D pictures both of 1D and 2D barcodes. An important difference between laser scanners and image-based barcode readers is that the latter are endowed with a *microprocessor* which is able to identify the location and orientation of the code before sending the data to the information management system.

The cost of these readers is higher than the laser scanners' one due to the more complex configuration of the system. Nevertheless, with the constant expanding of the number of companies which are using this technology, its cost is going down and down up to the point that nowadays it is comparable with the cost of the laser-based readers, so a switch to the new image-based readers is more feasible financially.

This class of readers is gaining market thanks to many advantages over the other class.
Among the most significant features, it is worth to mention that catching the whole area covered by the barcode instead of a single array makes possible to overcome situations when the code is partially damaged or not readable in some regions. Furthermore, every code can be read whatever is its orientation, being elaborated by the microprocessor.

3.2 OCR - Optical Character Recognition

Core components of a car like chassis and engine are univocally identified by dedicated alphanumeric codes.
In the case of an engine it is called *engine serial number* and it is directly printed on the engine block, usually by means of laser marking. This code is important both inside the plant, to identify which lot of engines is in the process and so to prepare machines to a specific set of operations, and outside the plant, when spare parts need to be ordered and again in the unfortunate event of a recall action on a lot of engines.
Besides sharing the aforementioned reasons concerning the importance of the engine serial number, the chassis identification code, also known as *VIN – Vehicle Identification Number*, is used to identify the vehicle itself, bearing in mind that the engine identification code is unique for the engine but not necessarily unique for the vehicle since the engine can be replaced in case of failure.

Therefore it is clear that during the process these codes need to be read constantly as their integrity needs to be checked constantly: special systems are then equipped with an *OCR – Optical Character Recognition* software, which is able to read and verify alphanumeric codes.

In short, the system acquires a picture, processes it, extracts the characters, and then recognizes them. The goal is then to transform into a digital output (so not just taking a picture) a code present on a real object that in the field of interest can be the engine serial number, but in the everyday life can be an the number of the identification plate of a car, a text from a book, and so on.

It is possible to identify three main steps in the OCR process:

1) *Image Pre-Processing*: The system optimizes the characteristics of the picture taken, such as improving contrast and eliminates distortion caused by bad orientation of the item. This is very important especially in the case of engines, on which the serial number is usually laser printed on surface which do not ensure the proper contrast.

2) *Recognition of characters*: To be sure that the code is fully in the pictures, the choice is often to take a picture including a wide safe margin around the code. After the image has been optimized in the first step, this extra amount of data is deleted, and so software can focus only on the region of interest, consequently increasing the reading performances.

3) *Post-processing*: To further increase its accuracy, the OCR software relies on a pre-assigned alphabet of symbols, each of them with a set of pictures representing the different conditions such as environmental lights and variations due to the intrinsic variability of the printing tool. The software can then assign a meaning to the portions of pictures analyzed as characters.

Another technology that is very similar to OCR, and so for this reason very often confused with it, is the *OCV - Optical Character Verification*.
Both algorithms' premise is that the code to be analyzed is unknow and moreover, OCV algorithm shares the first steps of the OCR process, until the "recognition of characters" phase included, in which the area occupied by the single characters is identified.

However, the difference between these two technologies is the task to be fulfilled: Optical Character Recognition is employed to identify the characters of a code or a string of text, while Optical Character verification is employed to assess the quality of what is printed on the item. In the *OCV* the system knows already which are most of the patterns of the variability field of a character, thus allowing a *speed-oriented* reading. In the *OCR* software reading is *accuracy-oriented*, considering that, especially in the first stages of activity, the system does not know which patterns to expect.

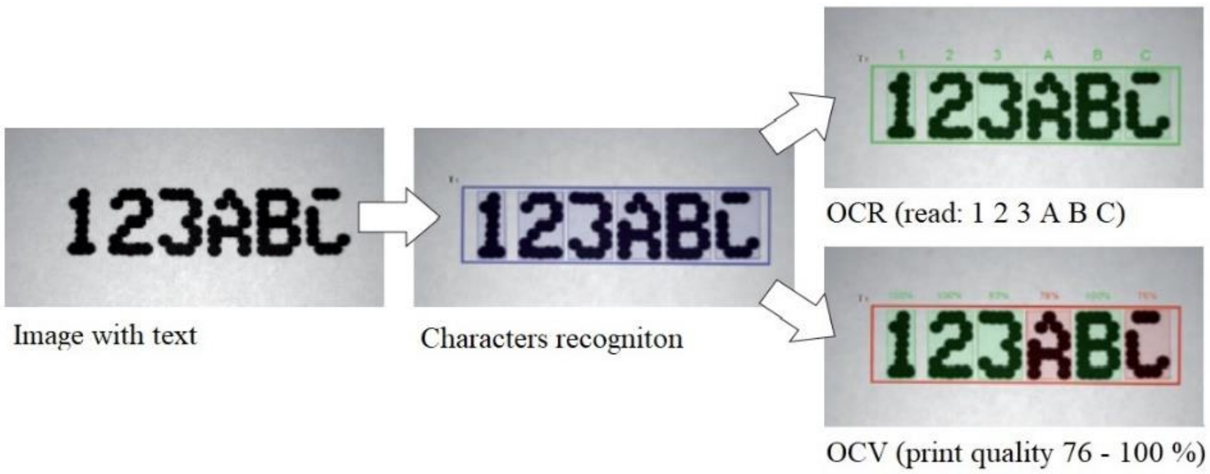


Figure 15. OCR process vs OCV process

3.3 RFID - Radio Frequency Identification

The basic principle behind the *RFID - Radio Frequency Identification* technology is that a magnetic tag is linked to the product and it communicates to the network when it is detected by a scanning antenna. The exchange of information takes place by means of radio waves.
There are three main components in a RFID system:

- the *magnetic tag*, carrying the data relative to product and process.
- the *scanning antenn*a, transmitting a radio signal which will be the mean of the data transmission.
- the *transceiver*, decoding the data carried by the tag.

When the item, and consequently the tag, enters in the field of the signal shared by the scanning antenna, the communication starts, and it ends when the item moves past the just cited field.

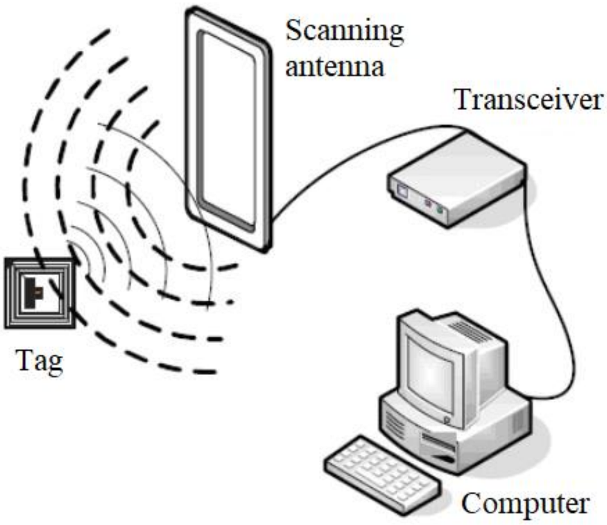


Figure 16. Scheme of a RFID system

The RFID technology is widely applied in the automotive industry.

Considering *warehouses*, performing an inventory task manually with devices like scanners and reader would increase the possibility of errors, such as missing registrations, wrong destinations and in general not correct data entry. This because managing the inventory of an automotive industry plant is usually a very intensive activity, taking into account the continuous ingoing and outgoing flow of material/components required by the complexity of the production processes.

For these reasons, an automatic identification (by means of a RFID system) of the warehouse's elements would prevent the previously described problems. A solution could be to install the tag on the pallet which would communicate with antennas installed both on the transportation medium (AGVs – Automatic Guided Vehicles, Manual Transpallets, Forklifts, etc.) and on the storage location.

On the *production line*, RFID tags can be installed either directly on the processed item or on the fixture which is carrying it on a conveyor.
One of the advantages of using the RFID technology on a line is that there is no need to install the scanning antenna in line-of-sight with the tag, allowing more flexibility in the process equipment positioning.

More information about the advantages (and disadvantages) of the Radio-Frequency Identification systems are illustrated in the next paragraph.

3.3.1 RFID vs Barcodes

It is not possible to state if there is a winner in the comparison between RFID technology and Barcodes, and the choice depends mainly on the specific task to be fulfilled.
In the following table a briefly comment for both technologies on 10 points: cost, positioning, dimensions, amount of data, speed, universality, accuracy on different materials, labor requirement, security, and possible failures.
Cells on a red background contain a disadvantage, while cells on a green background highlight an advantage.

	RFID	**Barcodes**
Cost	High: tags are expensive components	Low: Barcodes are usually printed on labels (except for DPM cases)
Positioning	Maximum distance: 91,5 m No need to be placed in line-of-sight	Maximum distance: 4,5 m Need to be placed in line-of-sight
Dimensions	Bigger and heavier than barcodes	Smaller and lighter
Amount of data	High: up to 2000 bytes	Not high

Speed	High (up to 40 tags read at the same time)	Lower than RFID
Universality	Dependance on the specific network rules and decryption algorithms (Closed system)	Can be read everywhere also by means of different readers (Open system)
Accuracy on materials	Problems when the information passes through metals and liquids	Same accuracy on every material
Labor requirement	Zero or minimum labor required	Labor Intensive (except for cases when the reader is fixed)
Security	High: Possibility of data encryption and use of passwords	Low: Barcodes can be easily created and copied
Possible failures	Risk of overlapping signals when multiple tags are read at the same time	Barcodes are more exposed to be damaged since they are applied on the external surface of the item

Table 1. RFID vs barcodes

3.4 Traceability: The applications in the studied plant

The company managing the automotive powertrain plant object of this thesis project has chosen to implement all the three technologies described so far concerning the traceability issue.
The main devices and workstations involving barcodes reading, OCR, and RFID are described in the following paragraphs.

3.4.1 Barcodes readers in the plant

Fixed, handled and mobile barcodes readers are used in the plant according to the item to be identified and the task's environmental conditions.
In the following, two paragraphs to describe two devices used in the plant: a fixed barcode reader and a handheld one.

3.4.1.1 Fixed barcode reader: KEYENCE Series SR-1000

On the machining line for the Diesel engine body, the Data Matrix Code printed on the body is read by the *KEYENCE Series SR-1000 fixed barcode reader*.
Keyence is a Japanese company working in the field of sensors, machine vision systems, barcode readers, laser printing systems, gauging devices and digital microscopes. The firm does not own any plant but works exclusively in the planning and development of the products, then manufactured by third companies.

Figure 17. The diesel engine body's Data Matrix Code

In this workstation the analysis is performed on a computer thanks to the software coming along with this camera. If the Data Matric Code is missing or not readable, the engine body is considered as a waste and so it is moved towards a labeling machine where a label containing a 1D barcode is applied on it, containing information about the problem.

The reader's configuration is very easy. Indeed, pushing a button the system will:

- *Focus automatically*: With this feature it is possible to use a single reader to analyze codes coming at different distances. Very small/far codes can be read with high accuracy, thanks also to a wider field of view.
- *Adjust automatically*: Images are corrected through an automatic contrast setting, an automatic light acquisition setting, and an automatic geometrical distortion fixing.
- *Control the polarization automatically*: Light reflections are removed, and the system adapts automatically to the external lights.

This last feature paired with the automatic focus makes the reader extremely flexible, without posing any constrain for its installation.

3.4.1.2 Handeld barcode reader: COGNEX Dataman 8700DX

One of the latest introductions in the plant is the handheld image-based barcode reader *COGNEX Dataman 8700DX.*

Cognex Corporation is an American company operating in the market of machine vision systems and software, barcode readers, and sensors. It is one of the leader companies in this sector, and as proof of this, the name of this company will appear again several times in the course of this dissertation.

Figure 18. Cognex Dataman 8700DX Barcode reader

The reader can be connected to the network through wire, Bluetooth or wireless, and it is certified IP65, showing then a high resistance to water, oil, and dirt.

The reading performances are excellent up to the point that a code can be read in less than 150 milliseconds. The most important features of the Cognex Dataman 8700DX are:

- *1Dmax with Hotbars* and *2Dmax with Powergrid*: these two decoding algorithms are extremely effective when the code to be read is damaged, of low quality and in general in conditions not favorable to the reading.
- *HDR (High dynamic range)*: CMOS sensors are used to acquire images with higher level of detail compared to the standard image-acquisition sensors. The quality of the picture is enhanced thanks to a better contrast, a lower intensity of light and a higher depth of field.
- *High speed multi-core processor*
- *Integrated illumination*: Light can be direct, diffused, or polarized. This variety of options helps especially in difficult cases like DPM codes that are often printed on reflecting metals and with a low contrast.
- *Liquid lens technology*: Working like a human eye, this lens is able to change its curvature in order to refocus according to the distance from the analyzed object.
  The lens is composed by a cell containing two unmixable liquids: a layer of water (conductive liquid) and a layer of oil (non-conductive liquid). Applying a voltage/current at the interface between the two liquids, the curvature of this separation area will change (phenomenon called *electrowetting*) and so the focus of the lens.
  With this technology it is possible to avoid manual setups of the device which could represent a loss of time and reading accuracy.

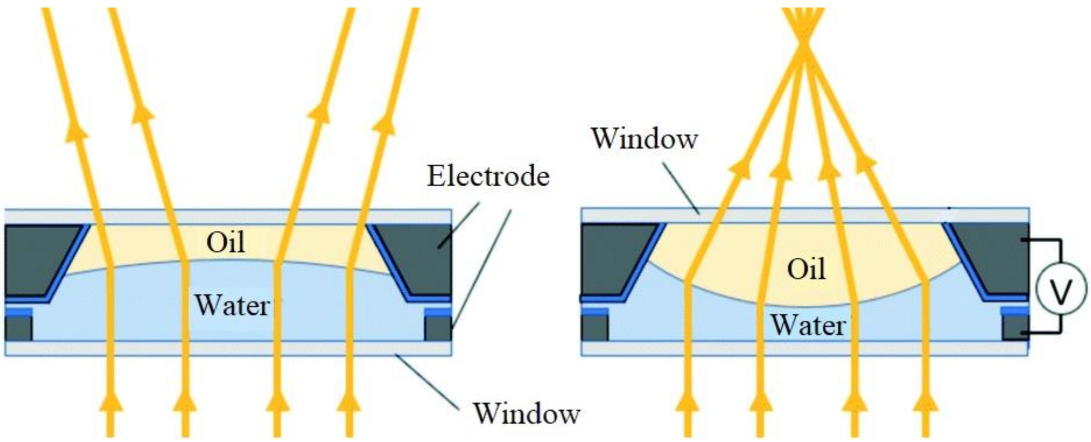


Figure 19. Functioning of the liquid lens technology

3.4.2 OCR/OCV systems in the plant

As discussed in the previous paragraph, *Optical Character Recognition/Verification* systems are implemented on the production line to read the engine serial number, both to verify its correctness (just after printing it) and to identify the model and version of engine, in order to perform the proper operation with the proper equipment.

Clearly, these systems are present in each of the production line dedicated to the three engine models produced by the company. In particular, two significant applications can be found on the 3/4 Cylinders Gasoline Engine's line and on the 4 Cylinders Diesel Engine' s line.

3.4.2.1 OCR/OCV on the 4 - Cylinders Diesel engine's production line

In the Short Block of Diesel engine's production line, there is an automatic station in which the engine serial number is printed and checked on the engine body.
The engines are flowing on a conveyor passing first through the marking unit and then through the marking control unit. This flow of engines is independent from the rest of the production line.

The machine vision system is designed by *MATEC s.r.l.*, an Italian company based in Turin.
A camera (*Cognex 8100*) takes pictures of the alphanumeric code and the information is elaborated by the *OCR/OCV software* named *VerBas*, developed by Matec.

It is possible to teach the system how a specific character can look like considering all the possible variations in the printing process. The operator, using the VerBas software, has to select the whole area occupied by the code and then select singularly the smaller areas occupied by all the characters with the same meaning of the one that is being taught to the system.

Another Matec OCR/OCV vision system is installed along the Long Block 1 line, just before mounting the crankcase to the engine block. Here the identification code of the crankcase is read to verify its integrity and that is properly matching with the processed engine model.

3.4.2.2 OCR/OCV on the 3/4 - Cylinders Gasoline engine's production line

As for the Diesel engine, an OCR/OCV vision system in installed in the short block of the assembly line for the 3/4 - Cylinders Gasoline engine.
The job of this workstation is to check if the engine serial number is correct and readable.

The camera is again from Cognex Corporation, but this time the OCR/OCV software is developed by Cognex itself and it is name "*In-sight*".
A significant feature of this software is the *OCRMax*: after operating in several different conditions the system is able to auto-setup according to the actual conditions of the reading environment.

The software has an interface very similar to the software Microsoft Excel's one, but obviously the functions and the algorithm of the Cognex software are totally different.
To make the system understand which shapes of the various digits are correct it is necessary to submit to it a series of pictures to teach it all the possible combinations and differences.

An interesting tool in the software is the *Difference Table*, which takes into account that each digit of an alphanumeric code differs from other ones in a more or less significant way.
This table shows on both vertical and horizontal axis all the digits and so each cell of the table links two different characters. The content of a cell is a numerical value assessing the difference rate of the two involved digits: the higher the value the higher the difference, with values ranging between 0 to 99.
The scoring mode varies according to the reading performance indicator chosen (speed or accuracy).

3.4.3 RFID in the plant

The RFID tracking and tracing systems implemented in the plant is called *MOBY*, and it is developed by the German company *Siemens AG*.

While on the Diesel engine's line the magnetic tags are installed only on the pallets (on which the processed engines are placed) flowing on conveyors, on some portions of the 3/4 Cylinders Gasoline Engine's line *Databolts* are used instead of the tags: they look like normal bolts tightened in a dedicated hole on the engine body, but on their heads there is a magnetic tag.
Examples of a magnetic tag on a pallet and a of a Databolt are shown in the Figure 20.

The tags have no battery since they receive power by the magnetic communication with the reader. Because of this electromagnetic-waves exchange, the temperature of the readers is generally warm due to the energy transmitted and received.

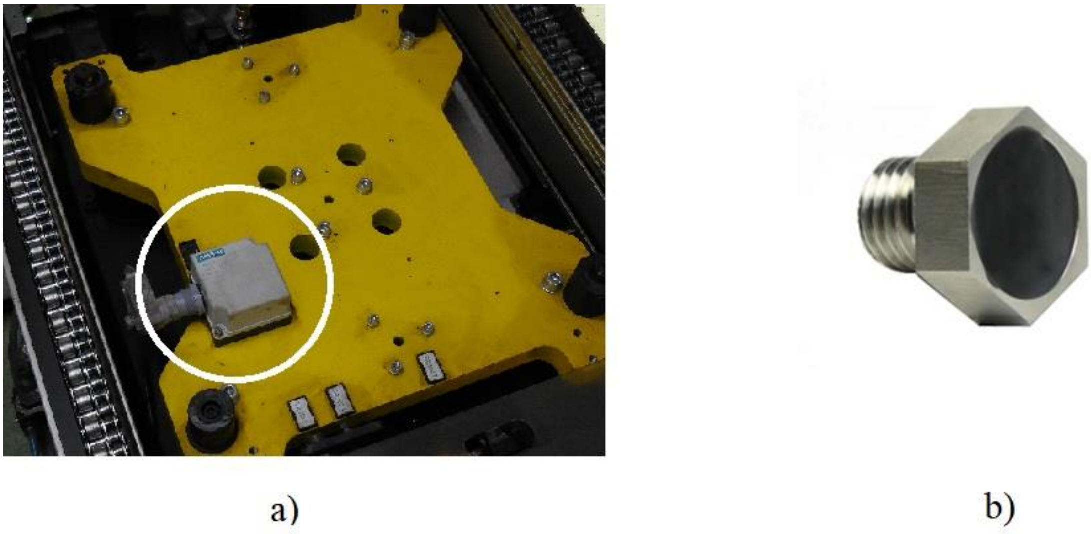


Figure 20. a) Magnetic tag on a pallet; b) a generic Databolt

The Moby system implemented on the 3/4 Cylinders Gasoline engine's production line is very similar in terms of functioning to the one of Diesel engine's production line. However, since this Gasoline engine's development is more recent than the Diesel engine's one, the components dedicated to its RFID system are more avant-garde.

An example is the *Siemens SIMATIC RF340R*, one of the latest models of RFID reader: its peculiarity is to have two led indicators useful for fast diagnosis (e.g. the color green of one led indicates a good functioning of the system).

The information flow of a MOBY system is the following:

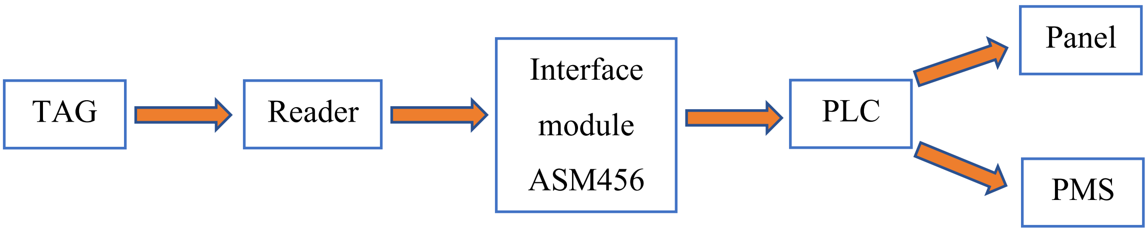


Figure 21. Information flow of a Moby system

The module ASM456 is the interface between the Reader and the PLC (Programmable Logical Controller). Information is finally sent both to the Panel nearby the automatic line through a cable connection (named *Profibus network*) and to the *PMS (Production Management System)* through the Ethernet network.

The communication to the PMS takes place only at the last step of a group of related process' operations, when all data from MOBY are recorded and saved. This last station is called *SRS - Set release station*.

3.4.3.1 How data are encoded in the MOBY system

Data written on the tag are mainly of two kinds:

- *Dressing data*: defining the composition of the mounted group. A *short code* (2 digits) is assigned to each item, in order to be identified in the production area.
  Reading dressing data, every station can choose properly the components to assemble on the engine.

- *Process data:* defining the type of cycle to be performed by the automatic stations and showing the results coming from the various automatic, manual and repair stations along the whole production process.
  Data classified as process data are: quality data, cycle type code, operative control data, waste data, traceability data and auxiliary data.

This information is usually encoded in many formats: ASCII, binary and *bcd (binary coded decimal)*.

At the beginning of an automatic line, dressing data are transferred to the tag and the process data are initialized.
Every station of the line reads the cycle code and the dressing information (to understand which component to mount), verify eventual connections in the process with previous stations and writes on the tag the final process data (outcome and quality).
In case of decision tags, the system can also decide if the workpiece can proceed on the line or needs to go to a repair station. For instance, if after an operation of screws tightening one or more of the applied tightening torques reported are not acceptable, at the decision tag the engine will be moved to the repair station, where all the screws will be untightened by the operator. Then, by means of a trolley, the engine will be moved again at the beginning of the station, so that the automatic operation can be performed again.
Finally, at the last step of the automatic line data are sent to the PMS and the tag memory is almost completely cleared, apart from the identification data of the memory itself.

An interesting example to understand how data on MOBY tag can be interpreted is the byte referred to the *operative control data*.

Bit	Description
Bit 0	Operation performed on an automatic station (AUTOMATIC)
Bit 1	Operation performed on a manual back-up station (MANUAL)
Bit 2	Operation with waste (WASTE)
Bit 3	Repair on repair station (REPAIRED)
Bit 4	Operation to not be performed (NOT PERFORMED)

Table 2. Moby system: Composition of the operative control data's byte

If a condition present in the table is verified, the related bit pass from the starting status 0 to 1. The last bits (5, 6 and 7) are reserved for future developments.

In the case of 10100000 (the bit 0 is at the left), the interpretation is that operation has be performed on an automatic station but the result is considered waste.

4. Silicone Adhesive Path Application

The topic discussed in this chapter is the automatic application of a silicone adhesive profile on some engine components, in order to ensure a proper sealing and a proper connection to a substrate.
Machine vision systems are employed in this field because of their possibility to be used as a guidance for the silicone dispenser and as an inspection tool to check the quality of the job done.

Before describing the solutions installed in the analyzed automotive powertrain plant, it is worth to have an overview about engine sealing.

4.1 Engine sealing

An internal combustion engine can work at the best of its performances only if all components are sealed properly, avoiding every sort of leakage. This sealing must work on both directions, i.e. both from inside the engine to the outside and from outside the engine to the inside:

- *Pressure* coming from the combustion process must be kept inside the cylinder in order to transmit as much force as possible to the piston.
- *Oil* must be kept inside so that its level is not diminishing where it is needed (avoiding for example pistons seizures) and it does not contribute to pollutants formation.
- *Coolant* must not be able to mix with either the oil (loss in its lubricating action) or with the air-fuel mixture (resulting in more pollutants in the exhaust gases.
- External elements like *dirt particles* and other impurities must be kept outside the engine, avoiding problems for the moving subgroups.

Almost every connection between parts of an engine is performed by means of bolts, but even with the best possible machining equipment it is practically impossible to ensure the proper sealing between parts by just using the compression force coming from the bolt connection.
To overcome this problem *gaskets* are used, which also help damping vibrations and acting as a wear protection. Considering this last point, a material softer than the ones of the joining components is chosen for the gasket, so reducing the friction during expansions and

compressions acting as a cushion. Usually the materials chosen are either metals or polymers (rubber).

In the next picture is presented the exploded view of an engine, highlighting gaskets and seals. In few words, these last components have a function very similar to the gasket's one, but they are used in connections where one of the two components is in movement.

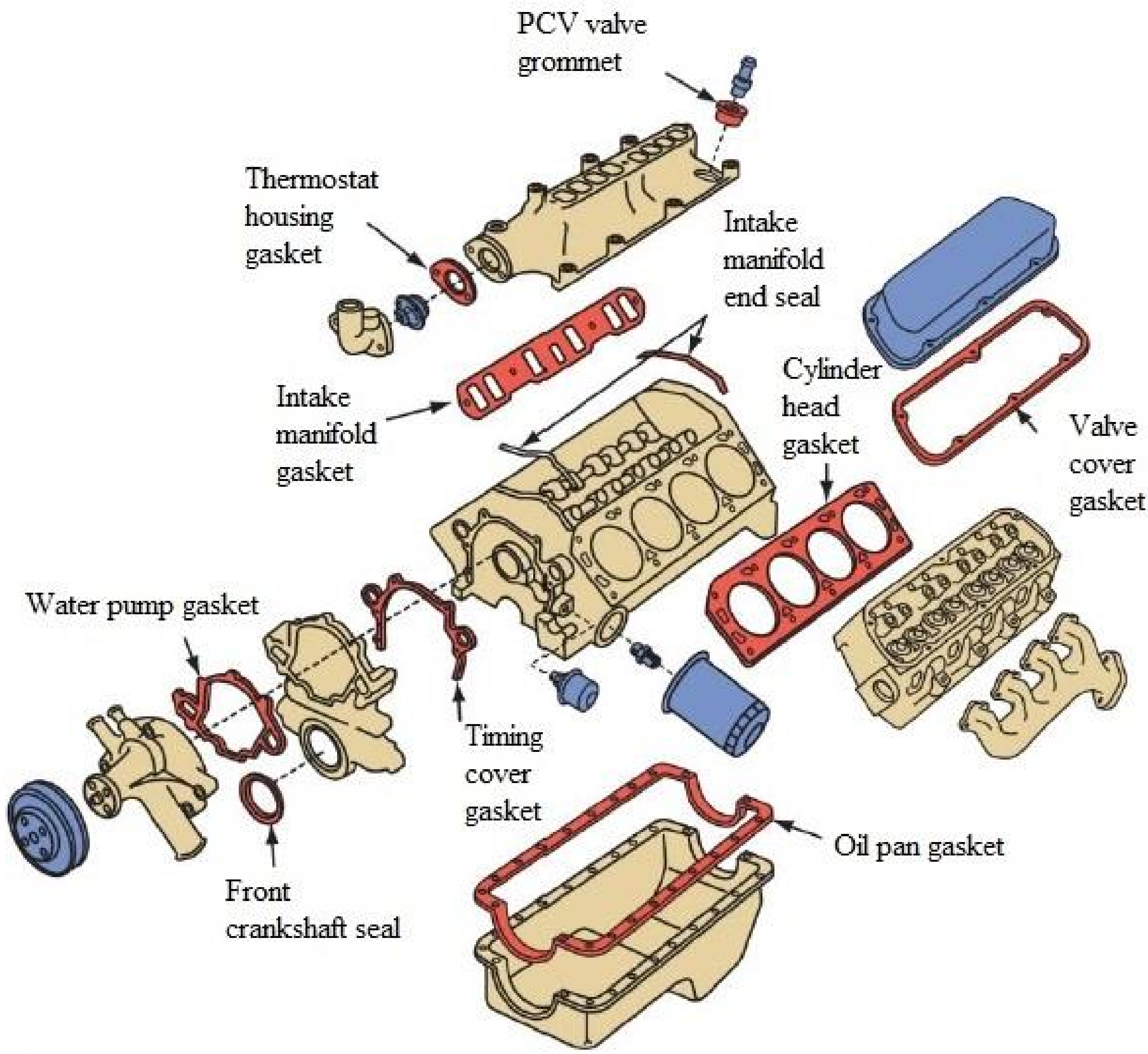


Figure 22. Gaskets and seals in the exploded view of an engine

And now a brief description of the most significant among engine gaskets:

- *Cylinder head gasket*: This gasket is placed between the engine body and the lower surface of the cylinder head, and its function is to avoid leakages of both pressure/charge from the combustion chamber and oil/coolant from the passages between the two connecting components. Taking into account the extremely high pressure and temperature gradients of the cylinder head, it goes without saying that the job assigned to the cylinder head gasket is very hard.

- *Valve cover gasket*: This gasket is placed between the valve cover and the upper surface of the cylinder head. The task assigned to this component is very demanding, considering both the high temperature levels of the cylinder head and the difference in materials of the two joining components.

- *Oil pan gasket*: This gasket is placed between the lower surface of the engine block and the oil pan. Due to the added weight of the collected oil, the oil pan needs to be clamped to the engine block with an amount of bolts higher than the one used in the connection of other components: consequently this gasket is exposed to a very high compression force.

After this short digression on the importance and function of the gaskets, it must be clarified that when it comes to engine sealing, they are not the only players. In fact, *adhesives and chemical sealants* have an important role too.
They can be used both as elements to strengthen the sealing capacity and the grip of gaskets and as their substitutes, for example when the application's geometries are too complex to manufacture a gasket with the required sealing properties.

The main difference between *adhesives* and sealants is that the first ones do not give an improvement concerning the sealing function, but they are used to hold in position the gasket while the engine components are being assembled.

There are four main classifications of sealant:

- *General-purpose sealants:* Used to help the positioning of the gasket in the assembly process. They are present both in the liquid format and the spray one.

- *Thread sealants:* Used when bolts are passing transversally through ducts in which liquids are flowing, to fill the gaps between the bolt.
  Being always in contact with these fluids, thread sealants are very resistant to every kind of chemical agent contained in the just mentioned liquids.

- *Silicone sealants:* Also called *Formed-In-Place (FIP) gaskets*, they are dispensed in the liquid state, but they harden after a while in the presence of air (aerobic process).
  The most used among silicone sealants are the *Room Temperature Vulcanizing (RTV)*,

very common in the automotive field because they are resistant to oil, they do not impair the functioning of the oxygen-sensor, and they are very flexible ad strongly adherent to many different materials. RTV silicone sealants are present on the market in three different colors according to their application: black for generic situations, blue for specific applications and red in case of applications involving high temperatures.

- *Anaerobic sealants:* This kind of sealant hardens in the absence of air (anaerobic process) and it is used in a restricted number of situations, such as thread-locking and to damp vibrations.

  Once hardened anaerobic sealants bonding strength is so high that, if the applied quantity is too much, a future disassembly is almost impossible.

4.2 Vision systems in the automatic application of silicone sealants

To ensure the required quality in terms of assembly, functioning, and appearance of the interface sealed with a silicone adhesive bead, it is necessary to be extremely accurate both in the quantity dispensed and in the following of the ideal bead profile.
Furthermore, besides these product-related requirements, a company must respond also to production-related requirements such as throughput, cost of the application, and safety.

The best way to achieve this goal is to consider the use of *robots* or robotic arms, thanks to their high operational flexibility, dispensing accuracy (up to ± 4 micrometers) and repeatability. Usually the component on which the silicone will be placed is positioned on a fixture and the robot is moving over it dispensing the fluid.
Furthermore, in the less recent applications of silicone dispensing automatic machines, the needle can be moved over the workpiece by means of a *gantry system* composed of one servo motor and one linear drive module for each of the three axes X, Y, and Z.

Another possible schematization includes a needle in a fixed position on the workstation's frame and the workpiece moved below it. However, this setting is more used on applications related to windshields rather than in sealants application for automotive internal combustion engines. The main reason is that the path to follow in the case of an engine is much more complex than that of a windshield, and so having the workpiece fixed gives more guarantees on the overall precision of the operation.

Therefore, in the light of the subsequent focus on the applications of these technologies in an automotive powertrain plant, the considerations made from here on will refer only to the configurations with fixed workpiece.

In the case of robotic arms used, one of the initial steps is the setting of the robot.
A first method to program the movements sequence of a dispensing robot is the *point-to-point* one. During the setup of the machine, an operator drags manually the tip of the robot along a profile corresponding to the shape of the surface on which the silicone bead will be placed during the production phase. The tip can be moved along all of the three space axes X, Y and Z and a software is continuously saving the changes in coordinates. The result is a univocally defined set of points that the robotic arm will cover while performing the task.
However, the main drawback of this method is the lack of flexibility: in the case of slight variations of the position of the workpiece on the fixture, the system would not be able to

understand the new position and it would go on placing the adhesive following the assigned coordinates, thus contributing to a poor quality result or even worse, a waste.

The solution to this problem is the use of a *vision guiding system*, with a single or multiple camera which can be installed either in a fixed position on the workstation's frame or on the robotic arm itself.

Figure 23. A sealant-dispensing robotic arm embedded with a camera

Coming back to the configurations previously discussed case of an item placed in a different position than the standard one, the vision system can assign a new movement path to the robot, combining the a priori knowledge of the to-be-processed profile and the new coordinates of some specified reference points on the workpiece surface.

An important parameter that must be kept always under control during the dispensing process is the vertical position of the needle over the workpiece's surface. The phenomenon to take into account is the surface tension both between the adhesive and the substrate and between the needle and again the adhesive.
If the gap between the needle and the surface is too high, the accuracy of the process would decrease significatively. If this gap is too small there is the risk of the needle leaving a groove on the just deposited adhesive.
The challenge is to have the needle on a vertical position so that the dispensed material would tend more to lay on the surface than to follow the movements of the needle.

If it is not possible to use a contact-measuring device, a laser sensor could be included in the vision-guiding apparatus, to help in detecting in real time the variations of the object's height and then communicate it to the system which will adjust accordingly the needle's vertical position, and consequently the robotic arm movement.

The use of a machine vision system in a silicone adhesive path application workstation is not only related to the guiding purpose, but also to the *inspection* one. Since it is not possible to perform experimental tests on every single product (to verify that bonding and sealing strengths of a connection are withing acceptable ranges) due to cost and throughput issues, it becomes essential to inspect the sealant profile before joining the two components.

The inspection can be:

- *In-process*: the application of the silicone bead and its inspection take place simultaneously.
- *Post-process*: the inspection of the silicon bead takes place straight after its application.

In-process inspection systems are more effective in terms of throughput, since there is no need of any additional time required by a separated inspection phase, but at the same time the cost of the vision equipment is usually higher due to more advanced software and hardware implemented.

4.2.1 3D silicone bead inspection

A two-dimensional bead inspection is focused on the analysis of width, fluid presence, position, and gaps, on the X-Y plane.
To have a more complete picture of the process quality, in the last years the importance of checking height and volume of the bead is growing in importance.

One of the main problems of the 2D vision inspection system in relation to the silicone application, is the difficulty in situations with low contrast. Indeed, as mentioned in the section about engine sealing, the RTV sealants are present in the markets in three colors (black, blue, and red) according to the task assigned. It is clear that an application in which a black silicone sealant is dispensed on a black/dark gray surface (like many components of an automotive engine) is very challenging for a vision system.
To overcome these inconvenient situations, it is possible either to upgrade the 2D cameras with

a more powerful hardware solution or switching to a *3D scanning systems*, exploiting the characteristics of *laser sensors*.

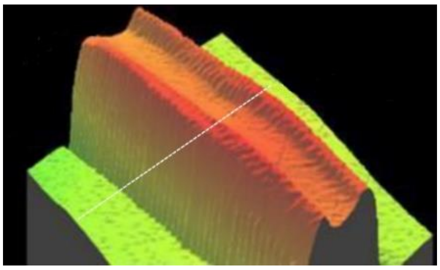


Figure 24. A 3D inspection of a silicone bead on which the needle left a groove while dispensing

The most robust laser technique used in a 3D inspection system is the *laser triangulation*. A laser source (or more than one) is paired with a camera/sensor pointing together at the scanned spot, but from a different angle. As shown in the next picture, the sensor is able to recognize the differences in height of the workpiece according to where on the sensor surface the laser beam is detected after the reflection on the analyzed item.

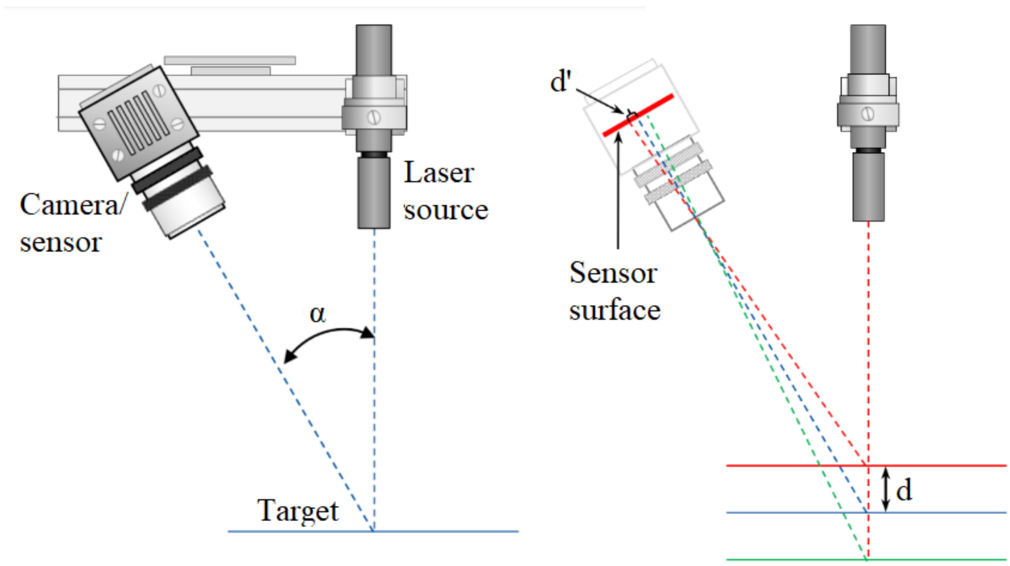


Figure 25. The working principle of laser triangulation

The most important players in the field of the 3D silicone bead inspection are the American company *Coherix* with the product *Predator3D*, and the German company *ISRA Vision AG* with the product *Beadmaster3D*.

a) b)

Figure 26. 3D silicone bead inspection systems: a) Coherix Predator3D; b) ISRA Vision Beadmaster3D

In the *Coherix Predator3D* system the dispensing needle is surrounded continuously by four sensor-laser couples, allowing to have a 360° inspection. As shown in the description of the laser triangulation principle, each laser source has a certain offset from the dedicated camera. Every sensor-laser set is able to scan up to 400 profiles per second, leading to the incredible total amount of 1600 profile per second.

The configuration of the ISRA Vision Beadmaster3D is the same as that of its competitor but using the blue lasers, which, having shorter waves than the usual red lasers, ensure a lower level of noise in the scansions and lower reflections issues on shiny components.

4.3 Silicone Adhesive Path Application: The applications in the studied plant

All the three engine models produced by the company show in their own assembly line the automatic application and inspection of a silicone bead in two operations: the assembly of the oil sump and the assembly of the timing cover.

For each of the six total cases, the item on which the fluid is dispensed is laying on a fixture and a robot is moving the needle over it following the designated profile.

Since the technology adopted in every line is the same for both oil sump and timing cover, three paragraphs dedicated to each of the three engine models produced are proposed below.

4.3.1 Silicone Adhesive Path Application: Diesel engine's line

Being the 4 - Cylinders Diesel engine's production line a quite old assembly line, the workstations (both in the Long Block 1) assigned to the application and inspection of silicon beads on oil sump and timing cover do not contemplate any robot but a gantry system moving the dispensing needle over the component.

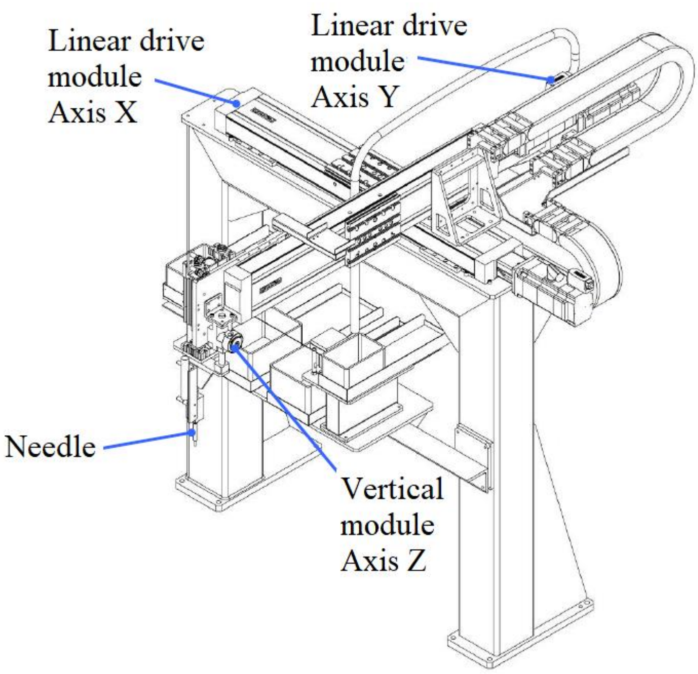


Figure 27. The gantry system for moving the silicone dispensing needle over half profile

The engine is laying on a fixture and the dispensing task is split between two dispensing subassemblies: for each of the subassembly the gantry system is composed by two belt-driven linear modules (to cover the axes X and Y with a maximum stroke of 60 cm), which are moving the structure on which the needle is placed, able to move vertically along this structure.

Splitting the silicone application on two different subassemblies which work simultaneously makes possible to halve the cycle of the workstation. Furthermore, in case of one of the two systems' failure, the other can work on the whole profile, allowing the production flow to go on.

The silicone used is the *Loctite SI 5900*, a Room Temperature Vulcanizing silicone which is stored in two barrels placed close to the workstation. Each of the subassembly is connected to a dedicated barrel via overhead pipes.

The vision system is developed by *Matec s.r.l.* and its function is to perform a *2D post-process analysis* of the correctness and integrity of the applied sealant. The software highlights the bead profile marking it green when the quality is good, yellow when there could be a problem, and red when there is a serious quality issue.

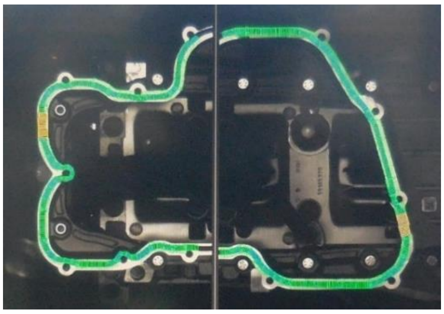


Figure 28. The bead profile analyzed by the Matec s.r.l.'s software

Four *Cognex* cameras are placed in the upper part of the station on two different height levels, surrounded by a lighting system and connected to a PC placed outside the station covers: through the images displayed on a panel, the operator can control the result of the application.

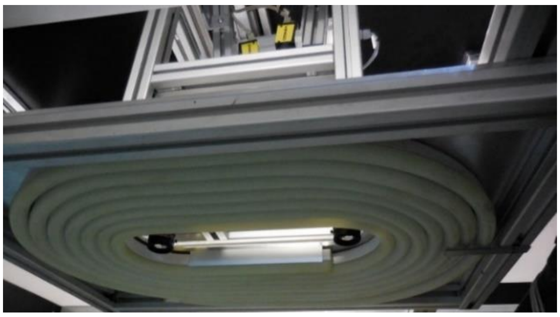


Figure 29. The cameras-lighting system in the silicone profile inspection stations on the Diesel engine's line

4.3.2 Silicone Adhesive Path Application: 3/4 - Cylinders Gasoline engine's line

Even though the 3/4 – Cylinders Gasoline engine's production started in the studied plant quite recently (2018), the choice of the company regarding the automatic silicone application and inspection technology was to carry some of the already engineered workstations coming from the Diesel engine's production line. For this reason, also for this model a gantry system is used to move the needle over the workpiece instead of a robot.

The timing cover is mounted in the final steps of the Short Block line, while the oil sump is assembled on the Long Block line.

The structure is the same as that of the configuration described in the previous section dedicated to the Diesel engine's process technology. Each of two symmetric dispensing needles covers half of the surface profile, being able to move vertically on the frames on which it is mounted and on the axes X and Y, thanks to two belt-driven linear modules.
Every subassembly exploits the power coming from three servo motors (axes X, Y, and Z), for a total of six servo motors.

According to production requirements, the RTV silicone can either be the *Loctite 5103* or the *Threebond 1227E*.

The vision system is composed by the software *EASI (Enhanced Adhesive & Silicone Inspection)*, developed by ISRA Vision AG and by two Cognex cameras surrounded by a lighting system.
Also in this production line, the inspection is two-dimensional and-post process.

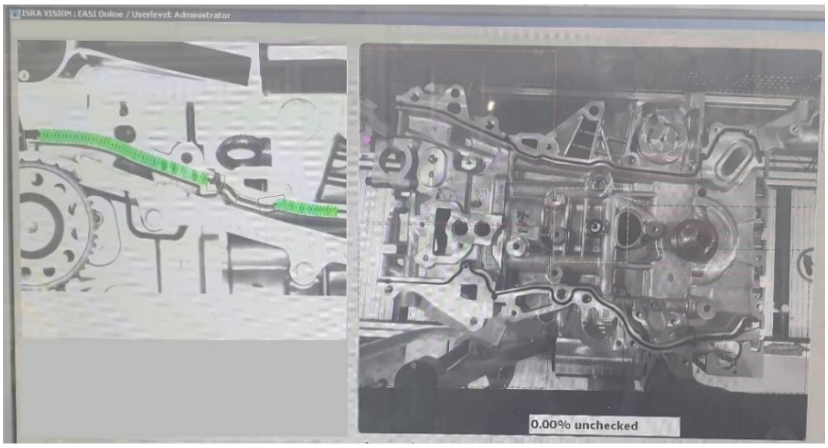


Figure 30. ISRA Vision EASI: bead inspection results on the operator panel

The software shows on the operator monitor the result of the inspection, highlighting the captured bead profile following this legend of colors and symbols:

Too wide	Too narrow	Unwanted gaps	Position error	Additional control required	General error
●	▲	□	✛	◆	✕

Table 3. The legend of the ISRA Vision EASI software bead inspection

4.3.3 Silicone Adhesive Path Application: 2 - Cylinders Gasoline engine's line

Among the three main assembly lines, the silicone dispensing workstations in the production line of the 2 – Cylinders Gasoline engine are the only one involving a robotic arm moving the needle over the workpiece.

Besides this first difference, another important unique characteristic of these stations is that the silicone is not applied on the engine side but on the component side for both timing cover and oil sump, as shown in the next picture.

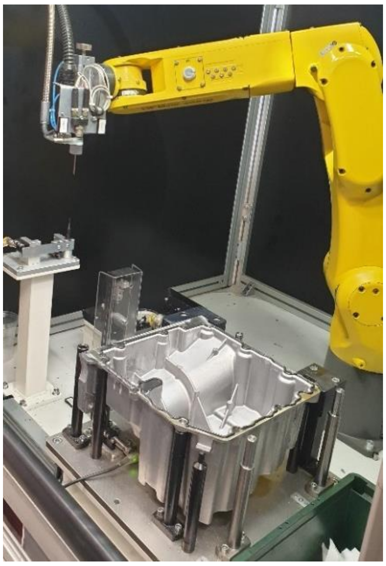


Figure 31. A robotic arm dispensing silicone on the component surface, the oil sump.

The robot is produced by *Fanuc*, a Japanese company operating in the industrial automation field. The model is the *Fanuc R30-iB*.

There is no guidance vision for the robotic arm, which follows during every operation the taught path, after detecting the presence of the workpiece thanks to two proximity sensors placed on the fixture where the component is placed.

As for the lines of the other two engine's model, the feeding group of the RTV silicone is placed close to the machine, and through a pneumatic system and overhead pipes the sealant is made available to the needle.

Finally, concerning the vision inspection systems for the adhesive bead profile, the analysis is again two-dimensional and post-process. A single *Cognex camera* is installed on a frame over the robot working area and it is surrounded by four longitudinal lights placed to form a squared shape.

Figure 32. 2-Cylinders Gasoline engine' s bead profile inspection system: the Cognex camera and the lighting system

In the operator panel's monitor the result of the inspection is displayed highlighting either in green (good), yellow (possible problem), or red (problem) the identification codes of reference points on the bead profile, as shown in the following picture.

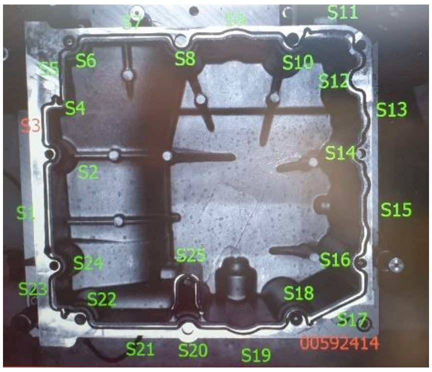


Figure 33. 2-Cylinders Gasoline engine' s bead profile inspection results on the operator' s monitor (oil sump processing workstation)

5. Metrology

Measurement technologies are a fundamental component of a production process, contributing to the achievement of determined quality requirements, both for products and equipment. Measuring devices can be installed in dedicated laboratories, nearby a production line, or on the production line itself, according to the level of accuracy required and the type of inspection performed.

In the automotive industrial sector, the focus on quality is growing exponentially, due to a scenario in which many strong OEMs are competing for market shares. Having quality issues on a batch of sold cars could lead to very hard to recover market losses on the short-medium run.

Moreover, the growing constantly growing production volumes are adding a significant constraint to the time available to assess the product's matching level with the set standards.

To ensure a reliable production process, the equipment, starting from a single screwdriver up to a more complex machine, must be constantly kept under control to avoid slow and imperceptible deviations from the correct parameters' values, and eventually damages to the products processed.

Once briefly defined the importance of the measuring operations to preserve the process and product's quality, it is worth to point out the main questions that a company should ask itself about the right choice of a gauging system. If every element in the analysis is properly considered, switching to the metrology technology most fitting with the operating conditions would make possible to decrease the inspection duration by 90% and increase the repeatability of the task of a 50% compared to current measurement methods.

The factors to be taken into account during the decision process for the acquisition of a new measurement system are:

- *Target*: It is important to understand which is the purpose of the inspection, consequently defining the needs in terms of speed, accuracy, and cost. It is almost impossible to find a solution in which all these three elements are at the ideal level, and indeed, in this case the way of saying "*Better, faster, cheaper: choose any two*" is very explicative of the difficulty of the decision process.

- *Accuracy*: It is necessary to evaluate which is the product/equipment that has the most narrow range of acceptability for the measured parameter, and to forecast if any product/equipment's accuracy requirement could change in the future, getting tighter. Furthermore, a serious analysis about the effective tolerances should be done, defining in which cases the acceptability range is arbitrarily narrow and in which other cases as a choice lead by strict quality needs.

- *Speed*: When a measurement needs to be performed on the production line, the time available is probably short, thus requiring high examination speeds. This often results in a lower reachable level of accuracy.
  In order to perform a longer analysis (and so more accurate), the solution could be to sample the products, for example measuring one part every twenty parts. In this way, the time available for the task increases with a factor 20 compared to the 100% on-line measurement.

- *Cost/Budget*: As just mentioned, if the needs of the metrology team are great speed and great accuracy, the cost of the measuring device will be certainly high. The price of a gauging system can vary from few hundreds of euros to hundreds of thousands of euros, according to the level of complexity of the applied technology.
  Although the investment could be very high, a company should always consider the long-term benefits such as the saved losses coming from bad quality products (scrap, recall action, and so on).

Another important point to consider is the choice of the system, which can be belonging to two main different classes: *contact* and *non-contact gauging devices*.
The study of the differences between these two families is reported in the next paragraph.

5.1 Contact vs Non-contact measuring devices

Contact solutions are usually *CMMs – Coordinate measuring machines*, while non-contact solutions can be identified as optical measuring devices, representing a family of systems exploiting many of the already discussed principles about vision systems, such as laser triangulation, cameras taking pictures, etcetera.

5.1.1 CMMs: Coordinate Measuring Machines

The basic configuration of Coordinate Measuring Machine (CMM) includes a mechanical probe which is kept always in contact with the part's surface and that is dragged until the number of discrete points in the XYZ space is enough to represent a model of the studied object.

Coordinate Measuring Machines can be:

- *Stationary CMMs*: The system is composed by a gantry system which moves the probe along the observed surface. The structure is so bulky that is impossible to move the system to the part's location, but it is the part that needs to be moved where the CMM is.
  The measurement performed with these machines is usually very accurate but requires a long processing time. Furthermore, the cost is by no means negligible.
- *Portable CMMs*: These systems can be moved where the parts to be measured are.
  Even if the accuracy is lower than in the stationary case, the cost is significantly lower. The probe is moved manually and it is possible to analyze complex and large parts without the need of complex machine settings and highly trained operator.
  These devices can be used as an additional gauging tool working together with a stationary CMM, thus decreasing the inspection time.

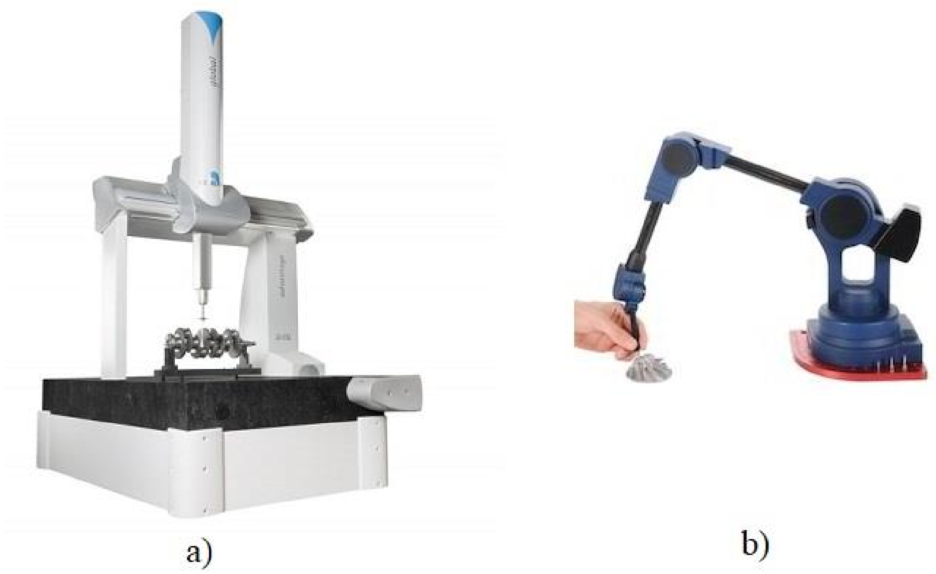


Figure 34. CMM: a) stationary; b) portable

The main advantage of the Coordinate Measuring Machines is their high accuracy.
However, there are two main drawbacks, concerning the duration of the analysis and the effects of using a component (the probe) always in contact with the item checked.

The first drawback is that the capturing of data is a very slow process and if this issue is added to the fact that the setup times are quite long too, it can be understood why CMMs are mostly used sampling components instead of measuring 100% of the item flowing on a line.

The second drawback regards the use of the probe:

- Being subjected to wear, the analysis can vary over time leading to deviations of the collected data from the real ones.
- Being an element touching the observed object, it can induce the risk of damaging the surface on which it is moving.

5.1.2 Optical measuring devices

The non-contact metrology systems perform measurements without the need of touching the observed element, using components like cameras, sensors, lasers, lighting systems, and of course a software application to communicate and elaborate the data collected.
Usually, pictures are captured by many sensors located at different angles. Since these parts are very costly, a first challenge in the use of optical measuring devices is the maximization of the volume covered in the analysis by a single sensor.

Among the most used non-contact measuring technologies in the automotive field, it is worth to talk about:

- *Camera probe sensors*: These probes are used when it is difficult to collect sets of data with the tactile method, due to complex geometries that do not make possible the use of a contact-probe, like in the case of very small bores.
- *Laser scanners*: These systems exploit the already discussed principle of the laser triangulation, for a 3D analysis. The amount of data collected is quite high, and so the inspection/process times are not the shortest among the optical measuring devices.
  One of the main advantages of laser scanners is the operational flexibility, that provides the possibility for them to be integrated to a CMM. Problems arise when the scanned surface is very reflective.

- *Structured light scanners:* These scanners are less flexible than laser scanners, but they show no problems in dealing with shiny parts.
  The principle of their functioning is the projection of patterns of light which reflect on the observed object. A camera/sensor receives this reflected light, producing a 3D model of the part according to the analysis of the deviation between the source light patterns and the reflected ones.

- *Industrial CT (Computed Tomography) scanners:* These devices are used mainly when it is necessary to control the internal part of a component without performing a destructive analysis. Industrial CT scanners uses waves such as X-Rays to generate a 3D model of the inspected element.
  Is it possible to check the material in order to control its porosity, the presence of eventual cracks, and so on.
  The price of CT scanners is the highest among the non-contact technology, and there are limitations also on which materials can be scanned.

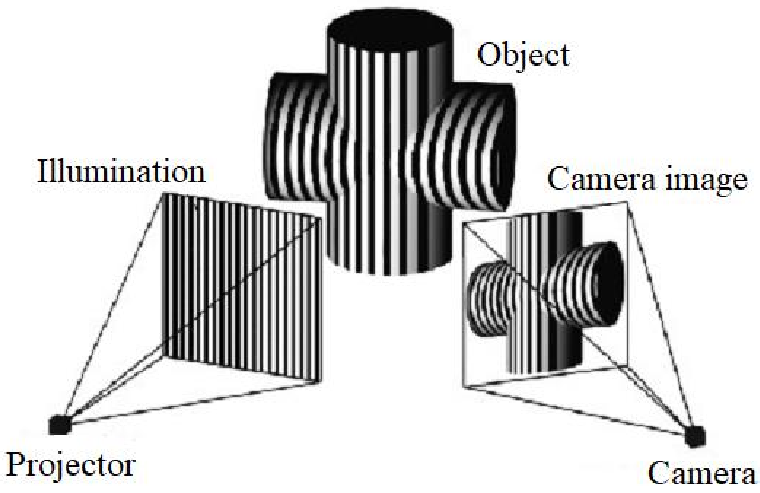


Figure 35. The working principle of a structured light scanner

The choice between a traditional CMM and an optical metrology device is not so easy.
It is therefore interesting to focus on the main differences between these two families of gauging systems.

Coordinate Measuring Machines offer generally a higher level of accuracy, with tolerances up to two microns, compared to the best optical measuring devices which can reach tolerances of maximum five microns.

However, the inspection times of a non-contact measuring system are much lower compared to those of the contact technologies, contributing to an increase in the processing speed by a factor that starts from three and can even reach 20000. As a direct consequence, these optical systems are much more suitable for a 100% measurement analysis, while, as already discussed, CMMs are mostly used sampling components.

Concerning the cost issue, a contact measuring device is usually cheaper than non-contact one, but on the long run the costs coming from the losses of time in the long setup times and the replacement of worn probes can lead the company to choose the second option as the best one from the economical point of view.

Finally, many experts agree on the fact that sometimes the best choice is the combination of both contact and non-contact measuring devices in a single apparatus, allowing companies to analyze much more products than in the case of the adoption of just one of the two technologies.

5.2 Optical metrology: The applications in the studied plant

In the automotive powertrain plant of interest, quality measurements are performed on three different levels, ranked in the following list from the highest to the lowest in terms of precision of the operations:

- *Metrology Laboratory*
- *Quality Boxes*
- *Gauging stations nearby the production lines*

The *Metrology Lab* is unique, and it is the reference and the center of all measuring activities performed in the whole plant, so working for the quality inspection tasks related to the three produced engine models.

The function of this laboratory is to check and verify that measurement devices and gauges are calibrated to the required quality standards, and verify that *masters*, which are workpiece used to assess if a workstation is working properly, are keeping their characteristics in the acceptability ranges.
Moreover, gauge blocks for lengths and round surfaces are certified by external companies and used in the laboratory as the primary reference to calibrate the measuring devices.

In this laboratory the conditions of temperature and relative humidity must be kept in determined ranges, respectively 19,7 °C ÷ 20,9 °C and 37,8 % ÷ 50,3%, ensuring that the physical properties of the equipment and the products are constant. A product coming from the production line can have been subjected to high or low temperatures (e.g. after machining and washings), and for this reason before being analyzed it needs to "rest" for at least 4 hours inside the lab, so that its conditions will reach the same of the metrology laboratory.

The second precision level for the measuring activities is represented by two *quality boxes*, of which one located in the building dedicated to the machining and assembly lines of the 3/4 Cylinders Gasoline Engine, and the other located in the building related to the Diesel engine's production process.
In these quality boxed the complexity of the analysis is still high but not as much as in the metrology lab, and the environmental conditions are not kept fixed.

Finally, the third level is represented by the *gauging stations nearby the production lines*.
Here conditions are not perfect, considering for example the influence of vibrations coming

from the operating machines. Consequently, the measurements can lead to results not properly accurate, but at least they could highlight macro-problems.
The activities performed in these stations do not require a long processing time, and, being not that complicate to require the experience of a specialist, they are executed by normal workers from the production lines.

It is the case for example of the *go/no-go gauging stations*: a hole present in the engine/engine component is checked using an inspection tool (shown in the next picture) having at the two extremities two cylinders of different diameters. To complete the analysis with a positive result, the smaller diameter extremity must be able to fit in the hole (go test) while the bigger diameter extremity must not be able to fit in the hole (no-go test).
The same kind of operation can be done having at the extremities of the tool, two threads with different diameters.

Figure 36. A go/no-go gauge

On all the three levels, many measuring devices are used, including optical metrology systems. Some of the most significant non-contact applications are described in the following paragraphs.

5.2.1 Metrology Lab: Multi-sensor CMM HEXAGON Optiv Classic

One of the systems present in the metrology laboratory is the Coordinate Measuring Machine *HEXAGON Optiv Classic*, which is endowed both with a tactile sensor and with a vision system. This machine is the entry level of a set of three models of the Hexagon Optiv apparatus.

Hexagon AB is a Swedish company operating with geospatial and industrial metrology technologies.

Using both contact and non-contact inspection technologies, this multi-sensor CMM shows an incredible *flexibility*, being able to adapt to many different tasks and to provide set of complementary data in a single cycle, without the need of multiple steps in separated machines.

This makes possible the inspection of a very wide range of items, from large to small parts, adapting to all the differences regarding the material, the geometry and the level of precision required.

The Classic model is endowed with a CMOS camera and for the specific version used by the company (*Hexagon Optiv Classic 432*) the stroke on the axes X, Y, Z is respectively 400 mm, 300 mm, 200 mm. The maximum load that the support table can sustain is 16 kg.
An important feature is CNC zoom, powered by motors, which allows a continuous variation of the field of view according to the needs of the task.

Figure 37. The CMM HEXAGON Optiv Classic 432

The system is composed by four principal modules: sensors, computer, controller, and software application.

The *vision sensors* are used for the situations in which the components to be analyzed are very small and easily damageable, and also when the measurement's speed required is high.
The elaboration of pictures is very advanced, thanks to features like autofocus, wide set of filters and automatic recognition of item's reference characteristics.

Moreover, the illumination can be chosen among three setups: top light coaxial LED, back light LED and ring light LED.

The *tactile sensors* are used mostly in situations when the item inspected is not flat, having details that cannot be seen from the top view (camera's perspective).

The two set of sensors can be used either together in the same analysis or separately. Here are few examples regarding this last statement:

- *Flat parts*: Items like gaskets, stampings, and electronic circuits are usually made from thin materials, and there is always a high risk to damage them, being delicate and easily deformable. The best strategy is to use only vision sensors, to perform a non-contact inspection.
- *Injection-molded / die-cast parts*: Elements produced with these techniques have very often complex three-dimensional shapes. In order to shorten the duration of the analysis and have a higher level of accuracy, using both class of sensors is the best option.
- *Precision parts*: These components are usually very small, and their tolerances are very strict, as in the case of gears and nozzles. Again, the suggestion is to perform the inspection only with Vision sensors, exploiting their advanced features for image processing.

5.2.2 Metrology Lab: Profile Projector MICROTECNICA Anteus

Another optical measuring device present in the metrology laboratory is the *profile projector MICROTECNICA Anteus*, produced *MICROTECNICA s.r.l.*, an Italian company operating in the field of the mechanical precision.

A profile projector, also known as *optical comparator*, is a system which exploits the principle of optics, using a set of lenses and mirrors to project on a screen the contours of an item. The shape of the object can be magnified, allowing the operator to measure details that would not be measurable just gauging directly on the piece.

The analysis carried on with this device can be performed in two different ways:

- Aligning edges of the contours with *reference lines, angles and points* that are printed either on the screen or on a transparent and rotating circular mask laying on the screen itself.
- Using a *software* which captures the image projected on the screen, providing the questioned data.

The second method is much more recent than the first one, and for this reason it is not yet widespread in the industrial sector.

Indeed, the Microtecnica Anteus belongs to the class of profile projectors working without a dedicated software. To properly understand the functioning of this non-contact metrology technology it is necessary to focus on the next picture.

Figure 38. Structure of the profile project MICROTECNICA Anteus

The observed object is clamped at its two extremities, and its shape is projected on the screen thanks to a system of mirrors reflecting the light acquired by the lens.
The lens, placed behind the inspected item, focalizes the light coming from a light source, placed in front of the item, except for the light absorbed by the object. The result on the screen is then the projection of the shape of the item.

The Microtecnica Anteus comes with a set of lenses with different levels of magnification, from 5x to 100x.

The table on which the clamping system is placed can be moved by the operator either by means of a joystick or of mechanical knobs connected to the table itself.
The system is able to detect the coordinates of the table, showing on a panel placed next to the machine real-time data, about its displacements on the axis X and Y (but not on the vertical axis Z) and rotation around the vertical axis.

An example of the use of this profile projector can be the measurement of the thread flanks' inclination of a thread go/no-go gauge, as shown in the following figure.

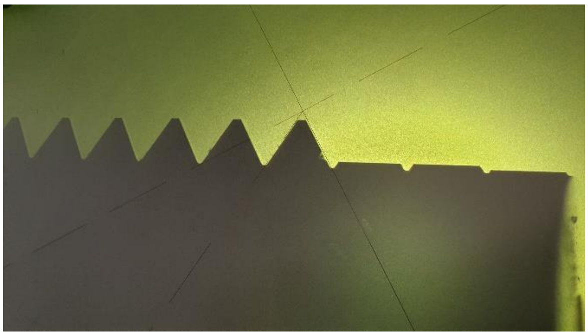


Figure 39. Profile projector Microtecnica Anteus: Screen results for the analysis of the thread flanks' inclination of a thread go/no-go gauge.

5.2.3 Gauging Stations: Crankshaft's oil passageways holes – ROSFER systems

A gauging station dedicated to the control of the oil passageways holes of the crankshafts is present in each of the two crankshaft machining lines for the two gasoline engine's models.
The system is designed by *ROSFER SNC*, an Italian company producing and design mechanical precision systems.

As shown in the next pictures, the oil passages can either pass perpendicularly through a rod bearing journal or connect transversally a main bearing journal and a rod bearing journal.

The ROSFER gauging station is not automatic, requiring an operator to handle both camera and crankshaft. In few words, the operator clamps the component on a fixture and moves the camera (sliding on an above frame parallel to the crankshaft axis) aligning it singularly to each oil hole, to check its *shape, position and chamfer*.
The software on the computer connected to the camera provides the results of the measurements, with an accuracy of six microns.

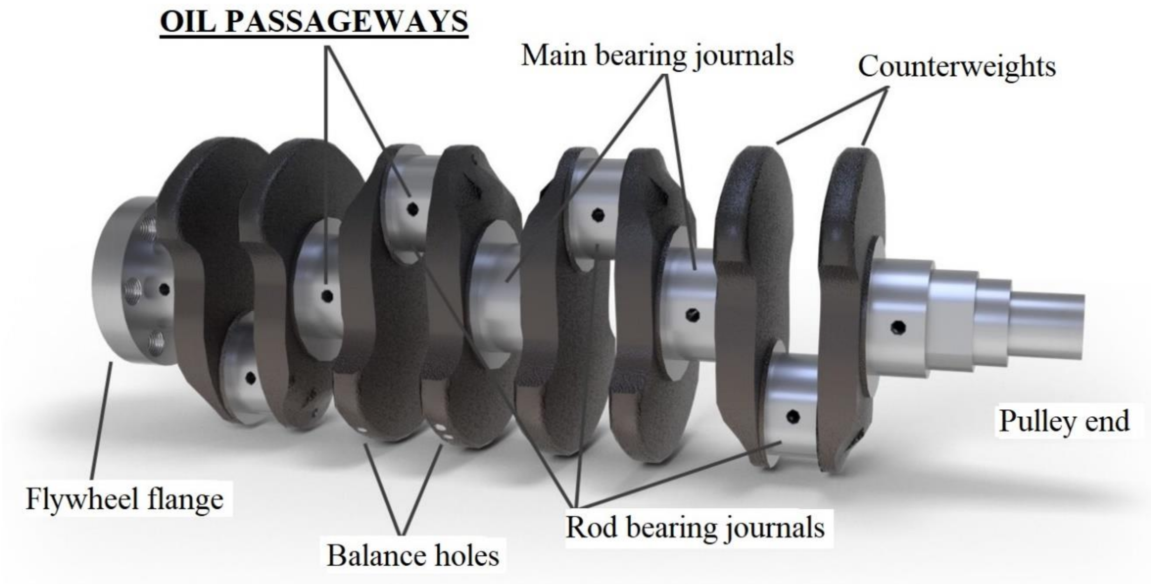


Figure 40. Structure of a crankshaft

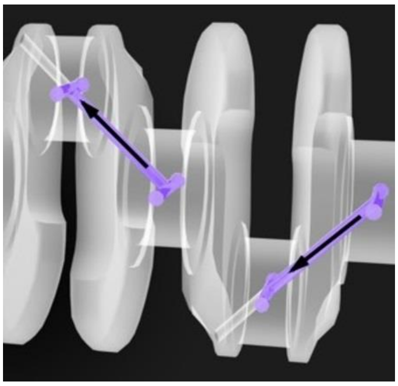


Figure 41. Crankshaft oil passageways

The control on the *2-Cylinders Gasoline engine's crankshaft machining line* is simpler than the one in the other line, relying mostly on the operator's ability to perform a correct and precise analysis.

For what concerns the control on the *3/4 -Cylinders Gasoline engine's crankshaft machining line*, the process is much more complicated, with an operation cycle time around 15 minutes. If in the previous case the process' variability was very influenced by the operator's skills (e.g. in matching properly the hole), in this case there are much more constraints, such as the camera guide having slots at fixed positions according to the crankshaft's version.
Furthermore, the amount of information provided by the software application is greater.

Since the oil passages are not aligned with each other, the crankshaft can be rotated around its axis, to place the inspected hole below the camera. Once in the correct site, the camera is lowered until the contact with the component.
Working on the computer interface, the operator fixes the origin of the reference system on the external edge of the first journal.
The analysis proceeds hole after hole, with the operator moving up the camera, sliding it towards the new oil passageway hole's location and moving it down for the inspection.

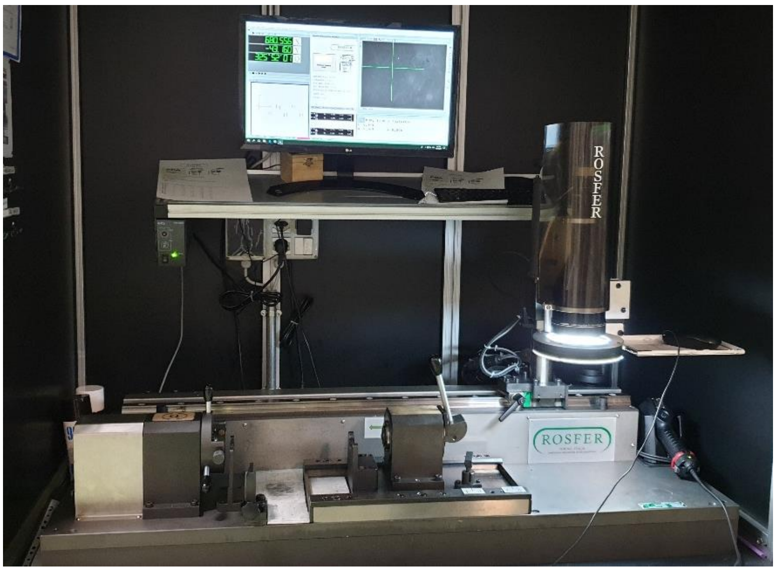


Figure 42. The gauging station for the crankshaft's oil passageways holes control. The configuration in the picture shows: the clamping system, the sliding camera with lighting system and the computer running the dedicated software.

5.2.4 Gauging Stations: Cylinder liners' crosshatch – TAYLOR HOBSON Talyseries

One important analysis performed on all the three engine models' body machining lines is the control of the *cylinder liners' crosshatch* patterns.

The cylinder walls are machined in an automated process called *honing*, in which an abrasive material is rubbed against the metal surface, following assigned trajectories. The result is a set of multiple light grooves that are imprinted in two different and incident directions. These grooves will retain the lubricating oil in order to ensure a correct lubrication of pistons and rings.

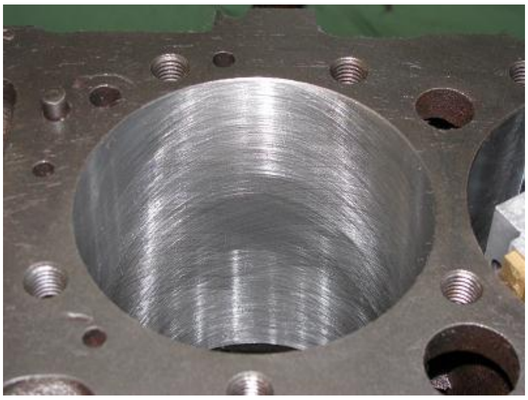


Figure 43. Crosshatch of a cylinder liner

If the crosshatch lines are following wrong angles, the rings could scuff on the cylinder walls due to an improper lubrication, leading to the loss of their main function and possible damages to the pistons, due to their interaction with abrasive material coming from the wear of the rings. In the long-run these problems can lead to an irreversible piston seizure.

It is then very important for the company to keep under control the quality of the honing process' results, and the device used to do so is the optical measurement system *TAYLOR HOBSON Talyseries*, designed and produced by *TAYLOR HOBSON Inc.*, an English company working in the field of contact and non-contact metrology technologies.

For all the three engine body's machining lines, the system is installed in a gauging station located nearby the line. Although the principle of operation is the same, three different Talyseries versions are used on the three lines, with the Diesel engine's line showing the older version, the 3/4 Cylinder Gasoline engine's line showing the newer one and finally, that of the 2-Cylinder Gasoline engine's line showing the intermediate one.

According to control plans, the crosshatch control is set at a frequency of one piece every four hours. This means that one piece is controlled at the beginning of the shift, one at half of it and one at the end.

The parameters analyzed are the angle of the crosshatch, the width of the grooves, and eventually the distance between two points on the cylinder wall.

The visions system is connected to an industrial manipulator, and it is moved by the operator who is holding two handles that are on the frames of the structure on which the vision sensors are installed. This vision system is composed by a high-resolution camera and a LED illumination ring, as shown in the next picture.

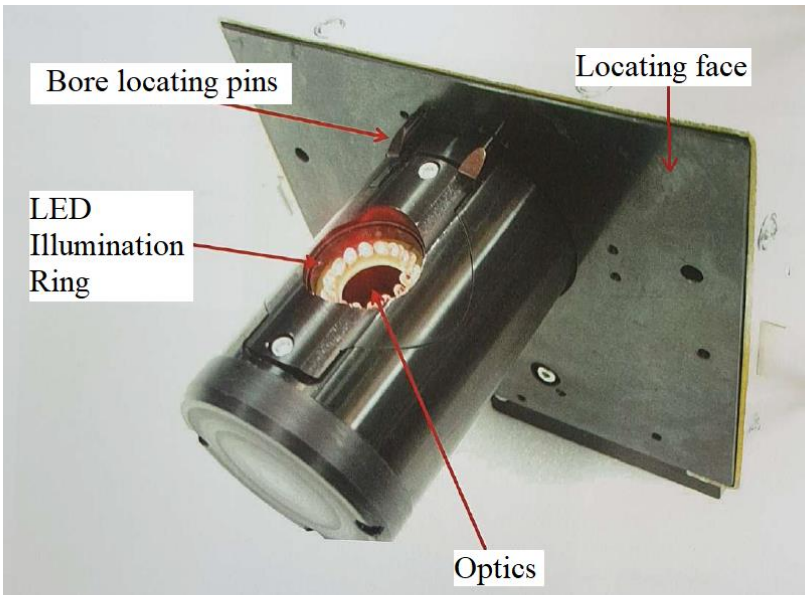


Figure 44. TAYLOR HOBSON Talyseries Crosshatch vision system

After being placed on a trolley, the engine body is moved to the gauging station where a dedicated area is assigned to the positioning of the trolley.
The operator then grabs the lifting handles of the vision system pulling it up from the calibration cylinder, where it is placed when there are no analyses in process and obviously when it needs to be calibrated. Indeed, the calibration cylinder's walls are reference for the desired crosshatch angle.

The camera group is then placed inside the inspected cylinder and it holds in position thanks to a set of bore-locating pins.
Finally, the vision system starts to scan the liner and a high-resolution picture of the crosshatch patterns is shown in the software application, together with the investigated numerical results.

Figure 45. Gauging station for the cylinder liners' crosshatch: TAYLOR HOBSON Talyseries

6. Assembly Operations

As easily understandable by reading the first introductive chapter and the chapter dedicated to the optical inspection of silicone adhesive beads, machine vision systems are widely applied in assembly operations, ranging between all the optical technologies listed so far.

Although the types of applications are many and varied, an indicative subdivision could be the following:

- *Pre-assembly check:* Before the assembly operation, a vision system is used to determine if the to-be-installed component is the proper one, matching with the model and version of the substrate of the mounting process.
- *Post-assembly check:* A vision system analyzes the result of the assembly operation, verifying specific parameters and features, which must be compliant with determined acceptability ranges.
- *Robot visual tracking:* In the case of an automated assembly operation involving a robot picking and placing items, a vision system is implemented to indicate to the robot the coordinates of the to-be-mounted components, which for example are flowing without alignment on a conveyor.

This last class of technology belongs to the category of the *VGRs – Vision Guided Robots*, which represent the latest step in the robotic automation's technological process.

Endowing a robot with a vision system means giving it the possibility to see what is around it, adapting to the variability of the handled components in terms of shape, size and orientation and also simplifying the structure of the workstation in which it is installed (e.g. avoiding the need of machines to align the pieces before the beginning of the robot's task).

The basic principle of robot's vision guidance is that a camera takes pictures of the work area or of the items in it, and the dedicated software analyzes them and communicates to the robot controller the effective coordinates of both the part that needs to be picked and of the destination spot where to release it.

A bi-dimensional analysis of the operation's field is often enough for the robot's task, but sometimes knowing the heights of the various elements involved can be fundamental to perform properly the assembly activity. An example is the case of stacked parts to be picked/placed from/in a pallet.

For this reason, in some applications, vision systems for vision guided robots perform a three-dimensional analysis, exploiting for example the laser triangulation principle.

Cameras and sensors can be placed either on the robot itself or on a fixed frame from where the perspective allows to have a full view of the working area.
The main advantage of using a *robot-mounted camera* is the possibility of choosing low-resolution (and then cheaper) cameras, since it is required a field of view covering just a portion of the whole working area. Consequently, the durations of the image processing analysis are shorter and so the system is able to respond more reactively to the variability of the process.
However, there some disadvantages related to mounting cameras directly on the robot. For example, the complexity of 3D vision systems makes them sometimes too bulky to be installed on a moving robotic arm. Moreover, since the camera is constantly following the movements of the robot, it could happen that it would lose the reference system, requiring the workstation to stop in order to be recalibrated.

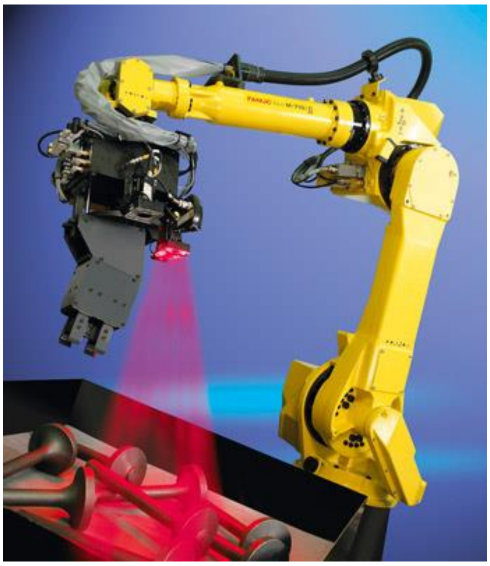


Figure 46. Vision Guided Robots: case of a 3D camera mounted on a robotic arm

6.1 Vision systems for assembly operations: the applications in the plant

Recalling what said about the company's continuous seek for quality applying the WCM methodology, it follows that a major contribution to the good outcome of most of the assembly workstations is given by the collaboration with an industrial vision system.
Indeed, many are the optical control devices installed along the assembly lines of the three engine's models, starting from the beginning of the short blocks until the end of the long blocks (dressing areas).

In the following sections, a description of some of the most significant applications.

6.1.1. Robot Visual Tracking: Assembly of valve retainers

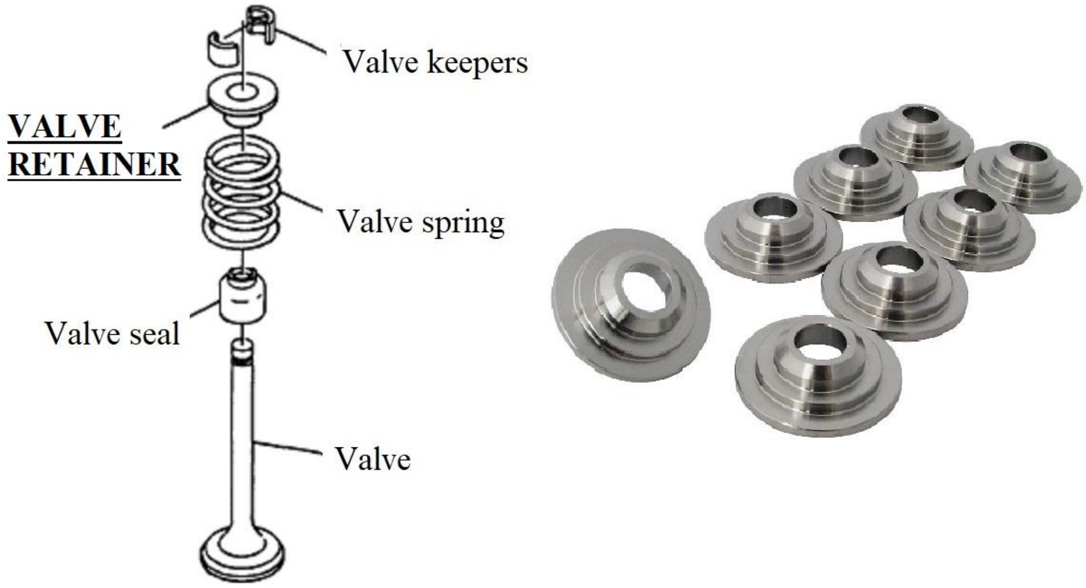
On the Diesel engine's line, the workstation dedicated to assembly of the 16 upper valve retainers (8 on the suction side, 8 on the exhaust side) is automated and endowed with a machine vision system, the role of which is to give indications to a robot about where to pick the retainers flowing on the conveyor.
To be more precise, the station is located in the assembly line dedicated to the lower cylinder head, inside the Long Block 1.

The function of a valve retainer is to keep in position the valve spring, and it can be described as washer made of steel, shaped to fit with its bump into the top of the area enclosed by the spring.
An exploded view of an engine's valve assembly is reported in Figure 46, together with an example of valve retainers.

The operation is very complex from a technological implementation point of view, and indeed the company has been through different stages of development of the workstation.

At the beginning, the operation was supposed to be performed *manually*, with an operator picking the retainers and placing them in position.
Considering that the pick-and-place movement needed to be executed 16 times (8 if using both hands simultaneously), it is clear that the task performed in this way was too burdensome.
In addition to this, handling these small components meant increasing the risk of them falling inside the engine cavities, so requiring to disassemble the engine in order to extract them and

so to continue the operation.



a) b)

Figure 47. a) exploded view of an engine's valve assembly; b) upper valve retainers

The second configuration step was centered around the *low-cost automation*.
When the engine was in position, a transparent mask frame was automatically sliding just above the lower cylinder head, over the face from where the retainers need to be positioned. This mask had 16 holes in correspondence of the 16 destinations, making easier the job of the operator in centering the correct site and avoiding the components to fall inside the engine.
However, even if in this way the worker was more effective, the process was still too slow.

Finally, the actual configuration of this workstation includes the *FANUC Robot M-3iA/6S* picking and placing the retainers, guided by the *FANUC iRVision* visual tracking system.

The retainers are fed to a belt conveyor by means of a *vibrator feeder*, the task of which is to serve the retainers with the right orientation, i.e. with the bump side facing down.
Once on the feeding conveyor, the randomly positioned components pass through the field of view of a high-resolution camera (*SONY XC-56*), which is placed perpendicularly to the plane on which the flowing items are.
The camera takes continuously pictures, the vision system elaborates them and then communicates to the robot controller the information about the coordinates of the various retainers.

The robot, thanks to a special gripper, picks two valve retainers from the conveyor and place them on the engine. The other components flowing on the feeding conveyor and not picked by the robot fall onto another conveyor which returns them to the dispensing system.

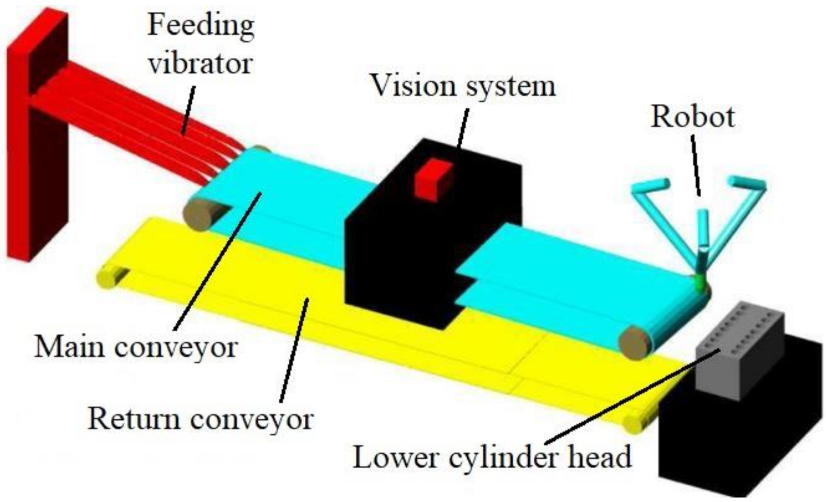


Figure 48. Upper valve retainers' assembly: Configuration of the actual workstation endowed with the robot visual tracking system

After having described the complex structure of this workstation, it is worth to mention more details about the *FANUC iRVision vision system*.

The software receives the data about the speed of the conveyor from an *encoder*, and it uses this information in order to optimize the quality of the images.
The goal is to avoid blurred pictures which would be useless for the robot visual tracking function, not allowing the detection of the correct coordinates of the items.
Considering that the retainers are moving with the conveyor and the camera is fixed, if the exposure time is too long, the images would not be accurate enough. For this reason, the higher the conveyor speed, the shorter must be the exposure time.
Processing the data coming from the encoder, the vision system is then able to vary continuously the camera's exposure time in order to provide always the best pictures in terms of accuracy and detail.

Taking again into account the fact that the valve retainers are moving, there is the possibility that a specific piece is captured in more than a picture. To overcome this problem, the Fanuc iRVision software uses the *overlap tolerance*, representing a distance in millimeters.
If the images including the suspected "duplicating" component are at a travelling distance

lower than this overlap distance, it means that the two pictures are dealing with the same component. If the distance is higher than the overlap distance, it means that images have captured two different components.
The overlap tolerance is set by default to 10 millimeters, but if during the operation time it is noticed that the robot tries to pick the same component twice, it is possible to modify this value in the system, making it higher.

To conclude this section, just some words about the *FANUC Robot M-3iA/6S*.
A peculiarity of this automation device is that it is not a classic robotic arm but it has a proper structure dedicated to the pick-and-place function, as shown in the next picture.
The geometry with a central body and the long and thin steel connections to the gripper reminds the shape of a *spider*, name with which the device is called informally.

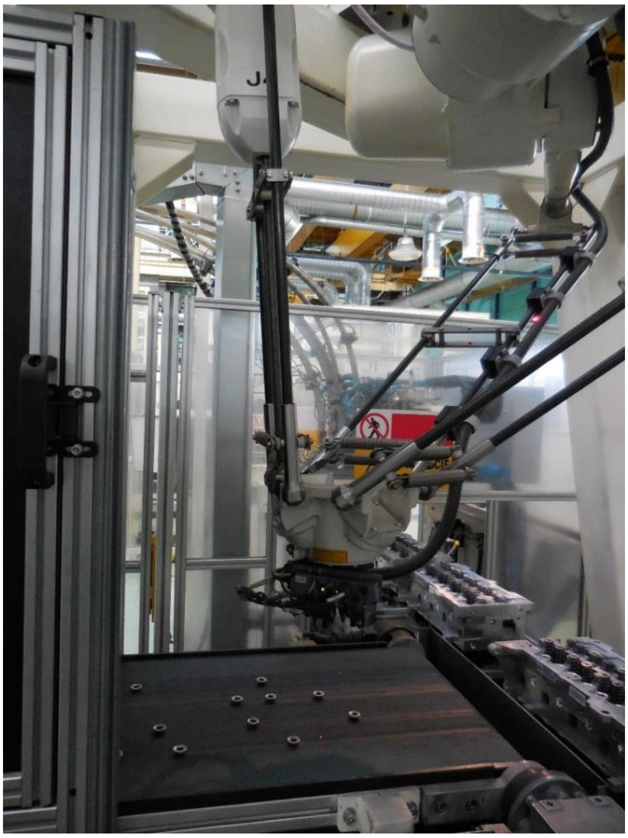


Figure 49. Upper valve retainers' assembly: the FANUC Robot M-3iA/6S about to pick items from the conveyor and place them on the lower cylinder head

The robot has four controlled axes, a single rotation axis for the wrist and a maximum payload of 6 kg. As already mentioned, the gripper connected to the wrist is designed for this specific application to handle simultaneously two retainers at a time.

6.1.2 Post-Assembly Check: Assembly of snap rings

One of the assembly verification technologies implemented in the plant is the one related to the *control of the snap rings' presence and positioning*, installed in a workstation of the Short Block section of the 3/4 Cylinders Gasoline engine's assembly line.

The function of the snap rings (also known as *circlips*) is to avoid side movements of the piston pin, which is the component allowing the connection of piston and connecting rod, being also the pivot around which the small end of the connecting rod rotates.
The number of snap rings for each piston pin is two, one per each of its extremities.

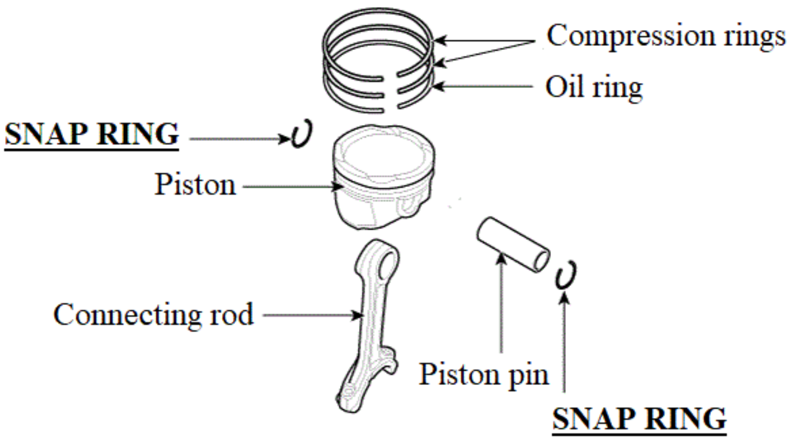


Figure 50. Exploded view of the piston-connecting rod subassembly

Taking into account how stressed are the components of an internal combustion engines, without a snap ring, the piston pin would float in its dedicated bore, risking escaping its assigned position and leading to a possible disconnection of the parts.
The consequences of this event for an engine would be extremely serious, and it is for this reason that having snap rings becomes essential to guarantee the correct functioning of the system. Therefore, a necessary step of the assembly process to ensure the engine's quality is the control of the circlips' presence and positioning.

The assembly of the snap rings is performed in the same automated workstation where the subassembly piston-connecting rod is produced.
A robotic arm picks a set of three/four connecting rods (according to the version of the engine) from a pallet flowing on a conveyor, and simultaneously places them in correspondence of a

set of three/four pistons, aligning each small end bore with a piston pin's bore. Then, a pneumatic system inserts the three/four piston pins and the six/eight snap rings.

When the subassembly is ready, it is moved to another area of the workstation, where the *assembly visual inspection* takes place.
The analysis is three-dimensional and it is conducted by means of the vision system *COHERIX Robust3D,* which provides a 3D model of the inspected item. The system, thanks to the *software COHERIX i-Cite*, verifies the presence and orientation of circlips, if there are by mistake double circlips and if the piston pin inserted in the bore is the correct one.
An example of the inspection's results is illustrated in the next picture.

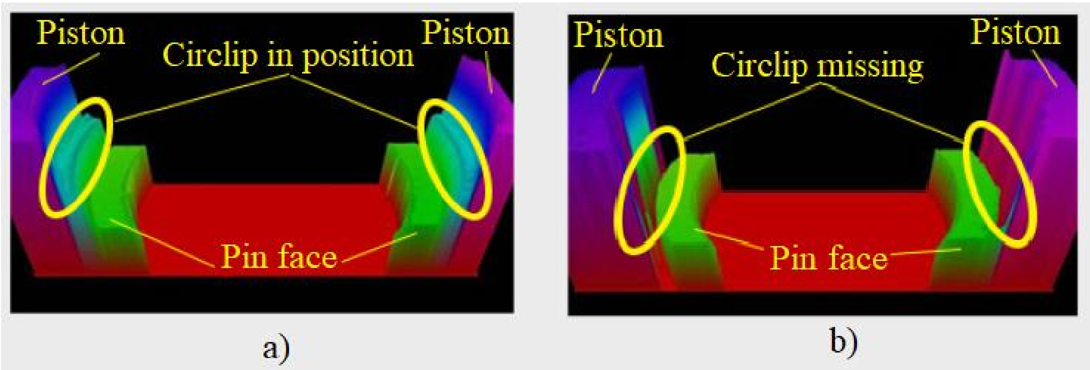


Figure 51. Result of 3D inspection of the snap rings assembly: a) circlip in position; b) circlip missing

The image acquisition frequency of the apparatus is 1 second per scan, with an inspection duration of four seconds.

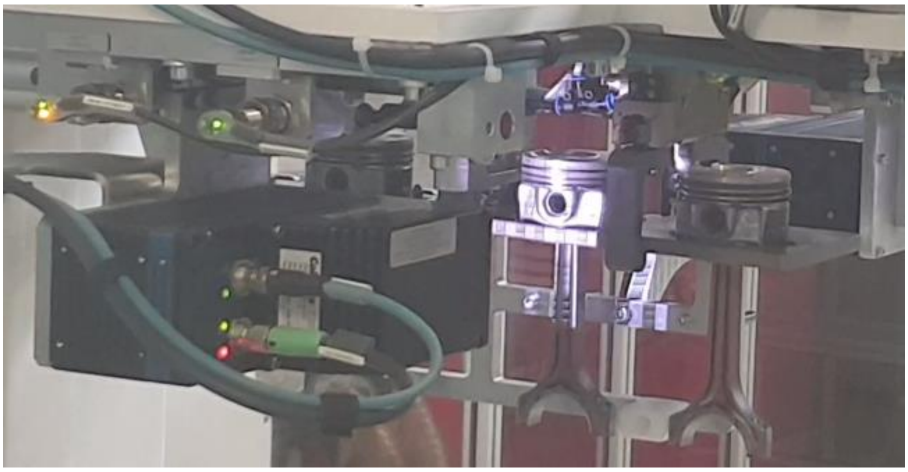


Figure 52. 3D snap rings assembly verification: COHERIX Robust3D vision system

The system scans one piston at a time, with the pistons' group suspended on a frame and the camera sliding in front of them (as shown in Figure 51).
The scanner exploits the principles of the high intensity white light scanning technique.

6.1.3 Post-Assembly Check: Placement and tightening of oil pump's bolts

A component installed on the Diesel engine along the Long Block 1 line is the oil pump, which is fixed to the engine by a series of bolts.
The tightening of these components is performed in an automatic workstation, topic of this section.

The bolts, placed by an operator on a tray, are sent to vibratory feeder bowl, which rotating aligns them and sends them to the ducts-system connected to the tightening group. The bolts are moved by means of compressed air.
After the oil pump is placed in the station prior to the one being analyzed, the engine, placed on a pallet flowing on the conveyor, arrives to the workstation. At this point, the bolts are placed in position and automatically tightened.

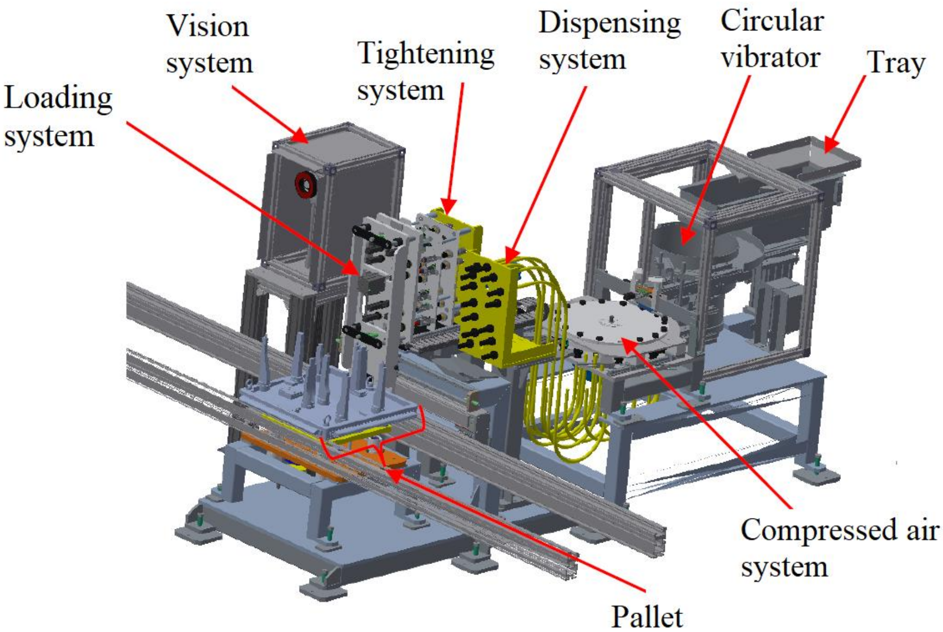


Figure 53. Oil pump's bolts automatic tightening station

When the assembly task is completed, the engine moves forward on the conveyor until it reaches the video inspection station, in which a camera takes pictures of the just tightened oil pump's bolts and sends these images to a software, which analyzes them in order to verify the presence of all bolts.
If the answer coming from the vision system is negative, the workstation has a dedicated area for the manual assembly (called *Back-Up station*) where the engine is automatically moved.

Even if this visual assembly verification system could seem not that advanced from a technological point of view, it is very representative of how vision systems can find application in basic operations like this just described. In fact, along the three main assembly lines, there are many automatic tightening stations that use an optical apparatus to verify the results of the operations.

7. Final controls

In this chapter it will be discussed about the final control inspection systems, the function of which is to analyze the final products of the lines on which they are implemented.
The goal is to check in a single station many characteristics that have not being checked after or during their relative process' steps.

7.1 Final controls: The applications in the studied plant

In the automotive powertrain plant of interest, the number of operations in both machining and assembly lines is very high, and consequently, as pointed out in the previous chapters, vision systems are many and various.

In the case of machining lines the workpieces are processed by a set of CNC (Computerized Numerical Control) machines, of which each contributes with a defined number of activities (drilling holes, milling, honing, etc.) before sending the piece to the next station.
Considering how complicated is the structure of an engine, the features to be given to the pieces are many and so, in order to respect the intensive production's schedule, the inspection phases are few along the lines and generally not involving 100% of the parts, but sampling them.
For this reason, a final control at the end of the line is needed to ensure that the machined components are compliant to the requirements before being processed on the assembly lines.

Concerning the assembly lines, despite the high use of vision systems, there are often problems that an optical inspection apparatus fails to detect, for example in case of bad lighting conditions.
Moreover, in the last stages of the assembly process (*dressing area*) many modules are coming from external suppliers and, although the company focuses a lot on the suppliers' selection and control processes, the incoming parts' quality is not always granted.
Therefore, also in this case, a step for a final automatic visual inspection is required to validate the quality of the final products.

In the next paragraphs, it will be discussed about the applications in the plant of the final control's vision systems, describing the case of the diesel engine's assembly line and other platforms present at the end of the machining lines.

7.1.1 Assembly line's final control: The Quality Gate

An automated final visual inspection station is installed at the end of the dressing area of the Long Block 2, in the Diesel engine's assembly line. Its name is *Quality Gate*.

The dressing area is composed by several manual (mostly) stations where the operators mount on the engine elements like covers, pipes, cables, and sensors, according to the configuration of the processed version.

These stations are not automated both because sensors can be damaged if handled by machines, and because elements like cables and pipes would be difficult to install by an automatic equipment, due to their flexibility.

After these steps, the complete engine moves on the conveyor, towards the Quality Gate.

Two robotic arms endowed with cameras are installed in the station at two different and consecutive points along the conveyor. The engine is first inspected by one robot, which is moving around it taking pictures of an assigned set of spots, and then, after a 180 degrees rotation on a pallet rotating table, it is inspected by the other robot, which analyzes another complementary set of assigned spots.

Figure 54. Diesel engine's assembly line: The Quality Gate

In the first years of production of the diesel engines, this station was not automated, but the visual inspection was performed manually by two operators. Their working area was placed basically following the same disposition of the actual robots, and again, like in the actual configuration, the list of engines' features to check was split between the two positions.

The manual workstation had many problems:

- The controlled points were few, only 22.
- The labor cost was high, requiring two operators per shift.
- There was a very high risk of mistakes during the inspection, due to the fact that the number of engines to be analyzed was around 1000 per shift.
- The analysis was subjective, and so there was the risk of different evaluations among different operators.
- The registration of the detected problems was manual, risking wrong or missing transcriptions.
- The ergonomic conditions of the task were poor, due to the difficulty to reach every point to inspect.
- There was not an immediate feedback to the problematic station where the defect was generated.

For these reasons, the company decided to rearrange completely the workstation dedicated to the final control of the diesel engines, so ending up in the development of the Quality Gate's apparatus.

The cameras on the robot check *101 control points* on the engine, taking grayscale pictures which can contain more than a single analyzed feature.
All the images of the engine are compared with master references encoded in a computer system. In case of a difference detected between a master photo and the actual photo, the system signals on the operator panel (placed just after the Quality Gate's enclosures) the possible presence of a defect.

Consequently, the worker checks on the monitor which is the problem and verify on the physical engine if the problem is real and, if it is possible, fixes it (like in the case of a cable not properly connected).

In the case of a severe issue which the operator cannot solve due to an eventual too long and complicate repair operation, the engine is transported to dedicated repair stations off the main line.
Afterwards, once sure that the signaled defect is legitimate, the same operator performs a backwards control of the other engines that are waiting for their inspection into the quality gate.

At the same time in which the operator is acknowledging from the panel the possible problematic situation, the team leader is informed about the problem on a mobile personal palmtop. Then this operator detects the station where the problem is generated and goes there to control the way the operation is performed, in order to verify which is the source of that defect.
If there are not intrinsic problems with the installed component or with the used equipment, it means that the source of the defect is an improper carrying out of the assembly operations from the workers assigned to that workstation.

The main advantages of the new automated visual inspection system are:

- The controlled points are now 101, after the first increment from 22 to 72.
- The workforce required has been halved, passing from two to one needed operator.
- The control is objective, reducing the variability of the evaluations.
- The ergonomic conditions for the workers are improved, thanks to a requested job focused only on the analysis of the few features reported by Quality Gate. No human effort is required for the visual inspection.
- The feedback to the workstation source of the defects is fast.
- All engines' photos recorded after every control are archived in the PMS (Production Management System). Thanks to this data collection system, the production engineering team is able to define in how many possible ways a problem can be generated and to detect the presence of new defects not yet contemplated in the checked control points.

Concerning the hardware of the Quality Gate, the cameras installed on the robotic arms are made by COGNEX and the specific model is *IS5603*. These devices are able to take up to 14 high-resolution pictures per second.
The robots used are the *FANUC M-20iA/10L*.

In the following picture is reported an example of what can be shown on the operator panel as results from the Quality Gate's inspection process.

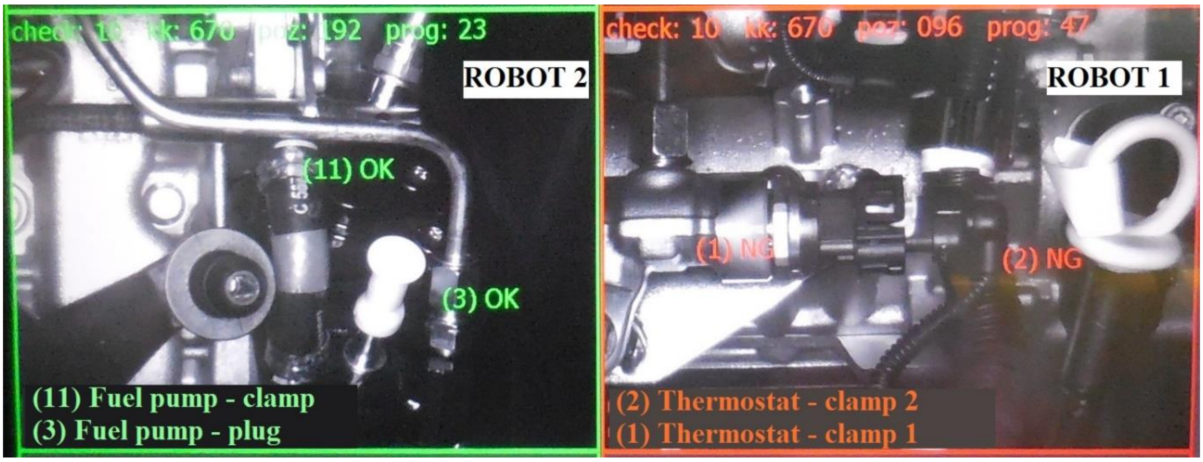


Figure 55. Quality Gate's results on the operator panel: on the left the Robot 2's results regarding the fuel pump (OK), on the right the Robot 1's results regarding the thermostat (NG - Not Good)

Finally, the *Quality Gate* system is not only implemented on the Diesel engine's assembly line but also on the 3/4 Cylinders Gasoline engine's assembly line, with a more recent configuration.

The station is very similar to the one just described, with the main difference of having installed one robotic arm instead of two.

7.1.2 Machining line's final control: Diesel engine's body

The final products of the machining line for the Diesel engine's body are inspected in an automatic final control station.

The analysis involves 22 features spread on the four side faces of the engine block, so not taking into account the top and bottom faces. Most of the time, the problems found by the system have origin from the supplier (foundry errors, like holes not in the proper axis).

The vision system is composed by four *COGNEX 1403 cameras*, each of which has the function of taking pictures of an assigned face among the four inspected. Together with every camera is present a lighting system using the red-light technique.

The engine body, placed on a pallet which is moved by a conveyor, enters in the workstation, the walls of which are darkened in order to avoid problems with the environmental lights. Once in position, the workpiece is lifted in order to avoid problems related to the vibrations coming from the movement of conveyor's parts.

In the meantime, presence sensors (inductive and laser) have detected the pallet coming into the inspection area and have sent information about it to the controller of the system, which in turn sent a signal to the cameras to make them start taking pictures.
The software application (*COGNEX In-Sight*) displays the images on a LCD monitor placed next to the station, recording them on the computer's hard disk and analyzing them to detect eventual structural defects of the body.

If the controller receives a signal informing about the incorrectness of an engine body, then a short beep is generated, and a red signal lamp placed on the workstation lights up. Otherwise, a green signal lamp lights up without an additional sound signal.
In this way the operators assigned to this line can quickly understand if there is a problem with a workpiece, thus inspecting it according to the results provided by the final control system.

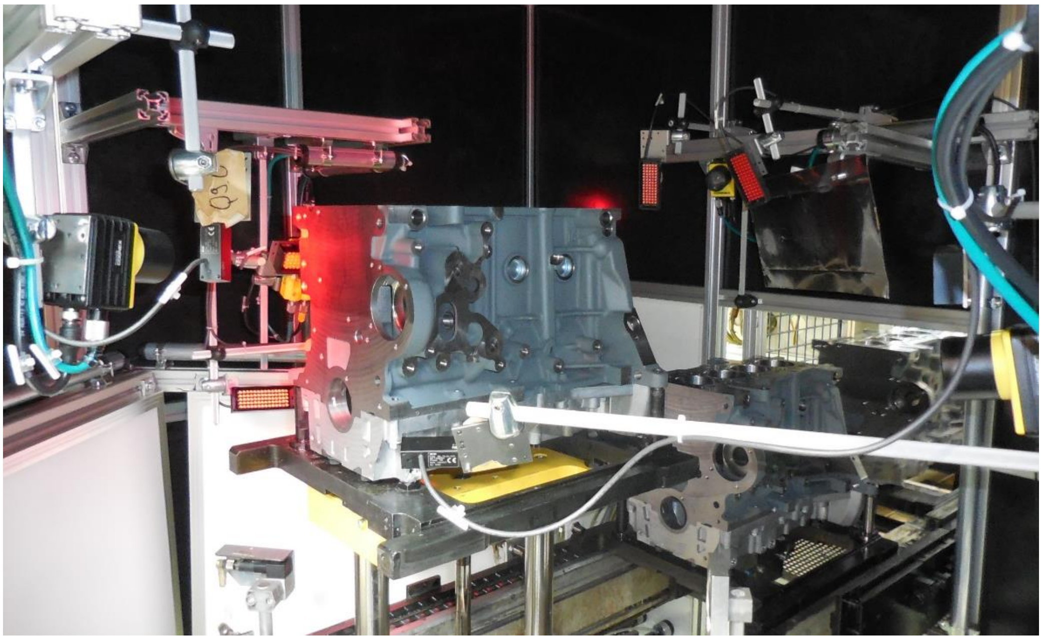


Figure 56. Final control on the machining line for the Diesel engine's body: The vision system

In the panel reporting the results of the inspection there are four windows, each of them dedicated to one of the four cameras.
Each window, as shown in the next picture, contains the image of the related engine body's face, on which there are highlighted the features of interest. In case of problems with a specific

characteristic the identification symbol is shown in red, and if there are no problems, in green. The checkpoints' classes analyzed by the optical system are three: Threads (T), Protrusions (P) and Holes (H).

Figure 57. Final control on the machining line for the Diesel engine's body: Example of one of the four result windows shown on the operator's panel

7.1.3 Machining line's final control: 3/4 Cylinders Gasoline engine's body

The final stage of the machining line for the 3/4 Cylinders Gasoline engine's body is an automatic inspection station with the function of detecting eventual surface defects and possible porosity.

The system is designed by *CODITECH*, an Italian company specialized in devices for industrial inspection and traceability.

Part of the apparatus is a *Robot FANUC model R-2000iC 165F (Robot 1)*, the task of which is to retrieve parts from the inlet conveyor (where the machined engine's bodies are positioned) and place them on the outlet conveyor.
Its task is also to collect details in which defects occur and put them in a discard box, from where they are removed by an operator. Next to the discard box, it is placed a buffer bay, where up to three faulty engine's bodies can be collected on before the line stops due to an excessive accumulation of items.

Inside the area of the station there are two *Robots FANUC LR Mate R-200iD (Robot 2 and 3)*, with the function of performing the inspection, thanks to the use of a camera installed on their tip.

The two cameras used are produced by *BASLER*, a German company operating in the field of the industrial vision. The model of these devices is the *BASLER Ace acA3800-10gm*.
The dedicated lighting system (red backlight) allows to enclose the workstation area just in metallic safety grids, instead of darkened walls like in the previously described case related to the final control of Diesel engine's bodies.

All the six faces of the workpiece are analyzed and, in order to control the bottom one, the Robot 1 clamps again the detail and lifts it, letting the Robot 3 to conclude the inspection on this last face.

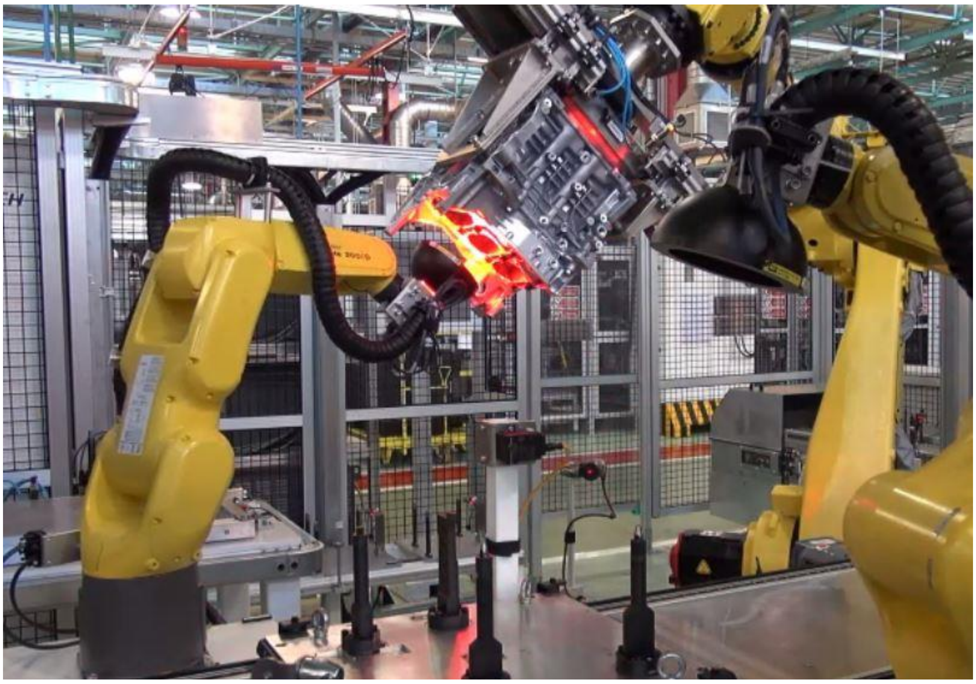


Figure 58. Final control on the machining line for the 3/4 Cylinders Gasoline engine's body: The vision system

The software application (*CODITECH VisionTech Pro*) shows on the operator's panel the results for each of the six faces (head side, intake side, exhaust side, timing side, flywheel side, bedplate side), in six separate windows.
If the system detects problems on a side of the engine's body, the dedicated window is framed in red, and the suspected non-compliant profiles are highlighted. Otherwise, if no problems are noticed, the results' windows are colored in green.
It is then the job of the operator to understand if these highlighted defects are real or not. Hence, the machine is in constantly calibration.

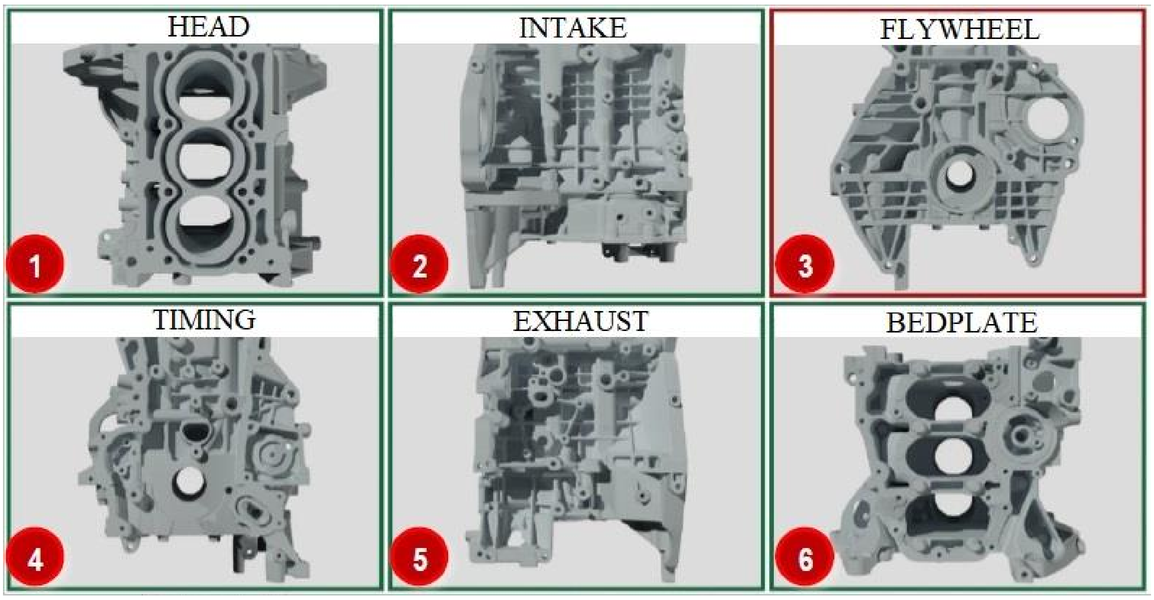


Figure 59. Final control on the machining line for the 3/4 Cylinders Gasoline engine's body: Example of the results shown on the operator's panel

7.1.4 Machining line's final control: Diesel engine's lower cylinder head

The last final control inspection system to be described in this chapter is the one related to the machining line of the Diesel engine's lower cylinder head.

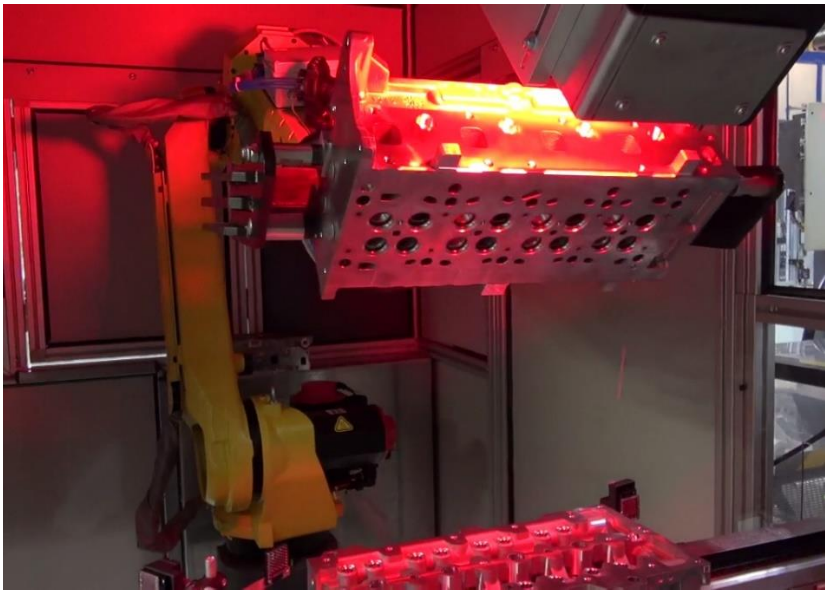


Figure 60. Final control on the machining line for the Diesel engine's lower cylinder head: The vision system

The items flowing on a conveyor enters in the station, the walls of which are also in this case opaque, to avoid interferences from the environmental lights.
The system includes a *Robot FANUC M-20iA-35M*, which is endowed with a special gripper that makes possible to clamp the lower cylinder head from the two opposite faces of smaller surfaces. These two sides of the workpiece are not part of the inspection.

After the part stops in position, a *COGNEX DM260S-0540 fixed linear barcode scanner* reads the barcode printed on a label stuck on the piece, while at the same time the robot is clamping it.

Subsequently, the robot lifts the lower cylinder head and places it in position to be scanned by the *COGNEX IS5705-11 camera*, which is fixed on a frame of the workstation.
While lifted, the workpiece is moved by the robot both to change the face to be inspected and also along the plane of the face being inspected, to give to the vision system a complete view of the object.
After the control of the four faces, the lower cylinder head is downloaded again on the conveyor and then the process starts again for another item.

Just after the enclosures of the system there is a desk assigned to an operator, whose job is to take, by means of a manipulator, the part that the system is signaling as having problems and then to inspect it.
A panel in front of the operator displays the four pictures taken of the four lower cylinder head's faces, and so the worker controls the suspected points of the workpiece using these images as a reference.

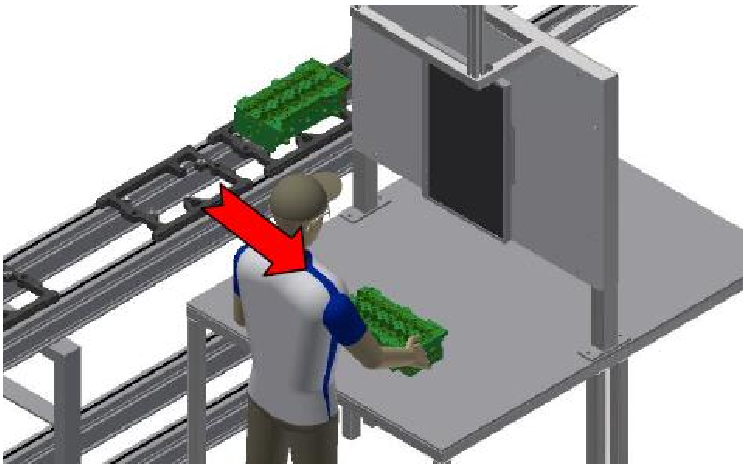


Figure 61. Final control on the machining line for the Diesel engine's lower cylinder head: The operator's desk

8. Conclusions

The goal of this thesis project was to describe how the use of industrial vision systems can improve the productive and commercial results of a company producing internal combustion engines for automotive application.
The dissertation has covered many different sub-categories, following the common thread of the industrial vision. The integration of the technological fields of traceability, silicone adhesive path application, metrology, assembly operations and final controls, has led the company to achieve important product and process' quality targets, having a significant impact on the final customers' satisfaction.

Machine vision is one of the main pillars of a *smart factory*, in which systems are communicating between each other on a shared network. The role of industrial vision in this information net is to be the sight of the factory, digitalizing and acquiring data that in the past were acquired (if acquired) only manually.
In this way, being this collection of information faster and more complete, it is possible to better control the production process, examining for example data about the states of the machines, in order to ensure a proper and proactive maintenance.

The technological process in the industrial vision systems' field is heading towards smaller and smaller devices, with a continuous increase in their processing speed and accuracy. It is therefore easy to understand how the market demand for these technologies is growing a lot in the past few years and it is expected to grow a lot more in the coming years.

A study conducted by *MarketsandMarkets Research Private Ltd.*, a British company operating in business-to-business researches for future growth opportunities/threats, affirms that in the time span between 2020 and 2025, the worldwide vision market will expand from an overall actual value of € 9.2 billions to the 2025's value of € 12.6 billions, with an annual growth rate of 6.5%.

Since the pursuit of better quality and the implementation of automatic solutions are becoming the core focus of manufacturing companies, the substantial market expansion will be involving mainly vision guidance for robotic systems and smart cameras.
Smart cameras are compact vision systems for which optics and digitalizing/processing images' modules are in the same case. The ease of installation of these devices, as well as their flexibility, are making them be appreciated more and more by many companies.

In the specific case of the *automotive field*, as deducible after reading this deep analysis of the studied automotive powertrain plant, vision systems are fundamental in many aspects of the production process, especially for improving the accuracy of critical operations.
The rate at which automation is being introduced in the automotive industry is rising, mostly because the market is asking for lower final products' prices (and consequently lower manufacturing costs) and because there is a lack of availability of skilled operators.
For these reasons, the automotive sector will be the major player in the future vision market.

The most significant growth will be found in the *APAC (Asia Pacific) countries*, mentioning Japan, South Korea, India, and China.
Some of the main companies involved in machine vision systems' field have been already mentioned in the course of this thesis project, such as *COGNEX Corp.*, *Keyence* and *ISRA Vision AG*. Moreover, being this market so flourishing, many other firms are and will be participating to development and trade of these systems.

Concerning the major future technological trends for the industrial vision sector, it is possible to list six main points, of which the first three refer to the hardware's aspect, while the last three to the software's one.

Hardware's trends:

- *Higher-resolution sensors*: The technological progress will provide more advanced sensors, with an increasing adoption of CMOS (complementary metal oxide semiconductor) sensors instead of CCDs (charge coupled devices).

- *Faster communication interfaces*: CoaXPress (CXP) will become the most used digital interface standard, thanks to its high transmission speed and its benefits in terms of CPU load, industrial stability, and bandwidth.

- *Higher use of optical devices for 3D analysis*: The number of three-dimensional inspections will increase, thanks to the possibility of collecting more complete sets of data compared to a bi-dimensional analysis and thanks to the higher incoming data processing speeds.

Software's trends:

- *On board processing*: As mentioned when discussing about smart cameras, companies will switch to devices able to process data without the need of an additional PC. This result in high flexibility and great cost-effectiveness.
- *Vision guidance for robots*: The price of robots will go down, meanwhile the labor cost will go up. Consequently, the number of robotics applications will grow, requiring a strong implementation of vision operating systems for robots.
- *Deep learning*: Many machine vision systems' software will be more and more based on this machine learning technique thanks to which machines are able to learn through examples and to be ready for any kind of unexpected variability.

Talking about this last element, the *deep learning*, the main principle behind it is the ability of the system to self-learn from unpredicted situations and so working like a human brain, which can memorize new unwanted cases in order to take them into account in the next analysis.

This innovation in the field of machine learning is a specific application of the *artificial neural networks'* theory, for which connected nodes of a network communicates between each other like the neurons of biological neural network (human brain).
In the deep learning neural network there are multiple hidden data processing layers, and each of them elaborates the information for the following layer in the hierarchy, having as results extremely complete answers.

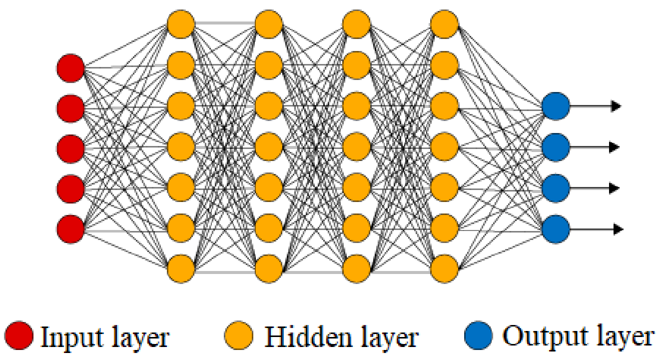


Figure 62. Deep learning neural network

This strong chain of data elaboration allows systems to inspect complex surface and to catch superficial defects, for example small scratches on materials that have been through particular machining processes or on shiny surfaces. Furthermore, other situations in which deep learning would give better results over the traditional vision's algorithms are OCR applications, location of parts and counting of parts.

Finally, after having discussed about the main future trends of vision systems, it is good to emphasize once again how industrial vision is a key component of the *industry 4.0*, in which the growing communication between machines and the continuous technological development allow to reach new production levels in terms of volumes and quality.
This description of the various possible applications of optical systems in the assembly process and quality control of automotive engines has therefore served to prove how this integration between production processes and vision systems is nowadays something vital for any plant operating at these high levels.

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