## Work Package 3

Modular and Self-Optimizing Quality Control

### Deliverable D3.2

**Self-optimizing/self-adapting quality control systems**

<table>
<thead>
<tr>
<th>Document type</th>
<th>Deliverable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Document version</td>
<td>Final</td>
</tr>
<tr>
<td>Document Preparation Date</td>
<td>16/12/2011</td>
</tr>
<tr>
<td>Classification</td>
<td>Public</td>
</tr>
<tr>
<td>Author(s)</td>
<td>AEA, UNIVPM, WHI</td>
</tr>
<tr>
<td>File Name</td>
<td>Deliverable_D3.2_v1_0.pdf</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project Ref. Number</th>
<th>246203</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Start Date</td>
<td>01/07/2010</td>
</tr>
<tr>
<td>Project Duration</td>
<td>36 months</td>
</tr>
<tr>
<td>Website</td>
<td><a href="http://www.grace-project.org">www.grace-project.org</a></td>
</tr>
</tbody>
</table>

Project funded by the European Commission under the "Seventh Framework Programme" (2007-2013)  
Contract n° NMP2-SL-2010-246203
Deliverable D3.2
Self-optimizing/self-adapting quality control systems

<table>
<thead>
<tr>
<th>Rev.</th>
<th>Content</th>
<th>Resp. Partner</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Template and first draft</td>
<td>UNIVPM</td>
<td>06/10/2011</td>
</tr>
<tr>
<td>0.2</td>
<td>Collection of inputs from partners</td>
<td>UNIVPM, AEA</td>
<td>31/10/2011</td>
</tr>
<tr>
<td>0.3</td>
<td>Revised draft</td>
<td>UNIVPM, AEA, WHI</td>
<td>15/11/2011</td>
</tr>
<tr>
<td>1.0</td>
<td>Final version</td>
<td>UNIVPM, AEA, WHI</td>
<td>16/12/2011</td>
</tr>
</tbody>
</table>
Table of Contents

1. Introduction .................................................................................................................................................. 4
2. Drum geometry control station .................................................................................................................... 6
   2.1. Purpose .................................................................................................................................................. 6
   2.2. Concept of operation and system lay-out ............................................................................................ 7
   2.3. Description of self-adaptation ............................................................................................................. 12
3. Vision inspection stations ............................................................................................................................. 13
   3.1. Purpose .................................................................................................................................................. 13
   3.2. Concept of operation and system lay-out ............................................................................................ 14
       3.2.1. Robotised vision system .............................................................................................................. 17
       3.2.2. Controllable illuminator ............................................................................................................... 25
   3.3. Description of self-adaptation ............................................................................................................. 26
4. Vibration and noise control station ............................................................................................................. 32
   4.1. Purpose .................................................................................................................................................. 32
   4.2. Concept of operation and system lay-out ............................................................................................ 33
   4.3. Description of self-adaptation ............................................................................................................. 34
   4.4. Input and output information ............................................................................................................ 37
5. Functional testing ......................................................................................................................................... 38
   5.1. Purpose .................................................................................................................................................. 38
   5.2. Concept of operation and system lay-out ............................................................................................ 41
       5.2.1. Test sequence reconfiguration: ................................................................................................... 41
   5.3. Description of self-adaptation ............................................................................................................. 45
   5.4. Input and output information ............................................................................................................ 45
6. References .................................................................................................................................................... 46
1. Introduction

This Deliverable D3.2 – “Self-optimizing/self-adapting quality control systems” outlines the main characteristics of the prototypes of quality control (QC) systems that have been developed during this first part of the GRACE project.

The main characteristic of the QC systems developed in GRACE project is that they are designed to exhibit self-optimizing and self-adapting behaviours.

The meaning of the concepts of self-optimization and self-adaptation for quality control systems are outlined hereafter.

The term Measurement System is used to globally denote the hardware and software components able to acquire a physical quantity, such as sensors and transducers and the relative mechatronic devices used to handle the measurement, the data acquisition electronic boards for the signal A/D conversion and the software environment for the setting of the system parameters (like sampling frequencies, acquisition time windows, gains, sensor set-up, etc.). The output of the Measurement System is the Measured Signal (numerical representation of the physical quantity object of the measurement).

A fundamental prerequisite to obtain the highest level of confidence on the output of a quality control station is to minimize measurement uncertainty. Therefore the problem of choosing the optimal set of parameters of a measurement system can be considered, by all means, as an Optimization/Optimal estimate problem where:

- The cost function to optimize (specifically, to minimize) is exactly the measurement uncertainty;
- The measurement system parameters are the independent variables of the optimization problem;
- The Constraints of the independent variables are due to physical and/or design restrictions of the values that the system parameters can assume (for example acquisition time, focal length of the camera, rotation angles of a robotic arm, etc.).

In this context optimization algorithms can be used to find the optimal configuration of the measurement system parameters, in optimal (theoretical) measurement conditions. Those algorithms can be used off-line both during the QC system design and set-up phases and periodically, during the normal activity of the production line, whenever new data on the production are available and/or variations on production configurations happen and/or new measurement needs occur.

Depending on specific cases, parameter optimization could be carried out through the modelling of the measurement system or just through empirical experiments. Indeed, if a parameter can assume just a limited discrete set of values, for example, it could be more advantageous to perform an “exhaustive search” by empirically testing all the values in order to obtain the optimal configuration. Strictly speaking, in case of discrete finite domains, the “exhaustive search” is an optimization technique (even if pretty rough and often not so efficient).
**Self-adaptation** is a concept employed to denote the search for the optimal configuration of system parameters, subject to real measurement conditions, that usually differ from the theoretical ones and can be seen as local displacement of the optimal solution. Adaptive techniques can therefore be employed on-line, during normal functioning of the production line, in order to iteratively approach the local minimum of the measurement uncertainty, which depends on specific measurement conditions. The following Figure 1 outlines the general behaviour of a self-adapting QC system; a reference signal is used to determine a reference quality indicator. A feedback control loop (Figure 1) performs a control action on an influencing parameter acting on the measurement system, so to keep signal quality at the desired level. A practical example could be the automatic repositioning of a transducer (a camera for example) around the theoretical optimal position in order to center the target object of the image or the control of the illumination for image contrast enhancement.

The quality control systems selected for demonstration of the GRACE project were:

1. Drum geometry control station
2. Vision inspection stations
3. Vibration and noise control station
4. Functional testing

Each of them is presented in the following sections.
2. Drum geometry control station

2.1. Purpose

The Drum Geometry control station prototype consists in an automatic test bench that will be installed in the Washing Unit (WU) line after the welding of the front and rear tub (Branson station). It will perform a quality control on the assembled Washing Unit (WU) and it will provide as an output to the MAS both the measure of the gap between the front tub and the drum, and the Pass/Fail result according to predefined thresholds. Referring to Figure 2, a WU is basically composed of a polymeric tub (rear and front parts), the bearings (inner and outer bearings), an internal metal drum with its pulley and a rubber seal.

![Figure 2 Scheme of Washing Unit (WU) resulting from marriage of drum and tub](image)

The objective of this control station is to measure the final gap existing between the rotating drum and the front tub, in particular its seal, whose thickness depends both on the marriage process and on the geometry of the components being assembled (that is basically the front and rear tubs and the drum). For this reason the station will be placed right after the marriage of the rear tub and the front tub (Branson machine), before the pulley assembly.

The width of this gap is important because if it is too large cloths may be trapped between the rotating part and the tub, damaging the appliance and the cloths, while if it is too little the drum may touch the rubber seal in the front tub, causing friction, noise, wear and an increase in energy consumption due to friction losses.
2.2. Concept of operation and system lay-out

An automatic test bench has been developed for this purpose; it carries out the measurement through a vision system based on a conic mirror, to get a 360° view of the gap with a single acquisition [1], [2], [3].

Figure 3 a) depicts the measurement principle behind cone mirror inspection technique. A conic mirror is aligned with its axis coincident with the optical axis of the camera objective. The cone mirror has a tip angle equal to 90°. The imaging system forms on the camera sensor an image of a cylinder centred in the cone axis; in particular, the cone mirror performs an optical transformation that generates a circular image of a cylindrical region. Any segment AB parallel to the cylinder axis at a distance r from the axis is imaged into a radial segment A’B’ on the image sensor. The magnification ratio is constant along any radius of the image, while it may vary from radius to radius, due to possible misalignment of the conic mirror with respect to the cylinder axis that we need to image.

The layout of the vision system configuration for the drum geometry control station is schematically shown in Figure 3 b). It is basically composed of the cone mirror and a camera that must be placed in axis with the mirror itself. During the inspection, the system must be positioned so that the gap lies inside the mirror’s cylindrical field of view.

In such a way, the theoretical image we expect to obtain using this configuration is reported in Figure 4 a). In this Figure, the gap between the drum and the tub is mapped into a ring-shaped dark region, while the rubber seal on the top of the gap is mapped into a clearer internal ring shaped area. Figure 4 b) shows the theoretical greyscale level along the green radius; since the seal thickness is known by design and guaranteed within precise
tolerances by the supplier, it can be used as a metric reference useful to derive the magnification factor along each radius and then the gap thickness within an acceptable measurement uncertainty.

![Diagram](image)

Figure 4 a) Theoretical Acquired Image; b) greyscale levels along the green line in a)

Therefore the gap measurement consists in analysing the grey level profile along a radius and measure the gap thickness with reference to the seal thickness. This operation is repeated along the whole circumference, so that with a single acquired image, the gap thickness can be measured for a fixed position of the drum.

An additional point to consider is that during the image acquisition the internal part of the washing unit has to be illuminated so to maximize the contrast between the dark region of the gap and the clearer surrounding regions (the drum on the lower side and the rubber seal on the upper side) and, in the meanwhile, to minimize the camera exposure time so to satisfy the strict time constraints.

The illumination system is composed of:

- Two LED illuminators placed at fixed distance outside the cone mirror’s field of view and equipped with light diffusers to avoid direct reflections by the internal metal drum;
- An holding element for the cone mirror also assuring the coaxiality between the mirror itself and the camera.

The engineered version of the probe is represented in the following Figure 5 and will be installed in the final prototype of the drum geometry control station in production line.
Finally, Figure 6 reports an example picture obtained in a laboratory setup with the conic vision system on a tub. It can be observed as the obtained real image is very similar to the theoretical one, that the gap is clearly identifiable from the greyscale levels measured along the green line in the Figure, and that the gap thickness can be derived with acceptable measurement accuracy (0.1 mm).
The conic vision system is mounted in an automated test bench (Figure 7) which is in charge of:

1) placing the conic vision system into the drum at the target position;
2) controlling camera axial position so to optimize image quality (self-adaptation online);
3) managing image acquisition and processing;
4) controlling the angular position of the drum;
5) generating output information (gap thickness values).

The main components of the system are:

- The mechanical structure made of aluminum profile to integrate the measurement unit and the other components of the station in the existing conveyor line; in order to protect the vision system during acquisitions, the structure is closed with panels on the lateral and back sides, and with a two shutter paneled door on the front side;

- A control cabinet placed aside the production line, integrating the PC, a touch screen monitor for I/O interface with the operator, the main data acquisition hardware and electrical components;

- A waiting station placed right before the drum geometry control station on the conveyor line and used to stop the incoming pallets during the test;
• The conic vision system shown in Figure 7, composed of two LED illuminators, a camera and the cone mirror holding element; the system is mounted on a vertical line axis for its correct positioning inside the WU;
  • A pallet lifter system used to separate the WU being inspected from the conveyor line during the measure
  • A system for the drum rotation, composed of a stepper motor and a pulley gripping system;
  • Safety protections made by open able doors (with safety lock), and safety fence to protect the area.

![Figure 7 The gap control station](image)

A typical test cycle is performed in 18.5” and it is composed of the following steps:

1. Pallet loading: if the station is free and a pallet is detected at the waiting station, the pallet is unblocked and loaded in the measure station;
2. Check the presence of WU: the presence of the washing unit on the loaded pallet is verified, then the MOBY information is read and the correct test plan loaded
3. Vision system positioning: the pallet is lifted and the vision system moved down inside the WU at the optimal position defined by design; in the meanwhile the pulley gripping system is fastened to the pulley and the gripping force checked;
4. Adaptation of gap-vision system alignment (as described in paragraph 2.3)
5. Acquisition and data processing: N acquisitions are performed while the drum rotates of 360°: to have a complete characterization of the drum geometry, the gap must be measured on the whole circumference and through a 360° rotation of the drum
during the inspection; the number N of acquisitions are adapted on line, basing on the IMA indications and on the available time (if step 4 requires a high time, step 5 must be shorter in order to respect the cycle time).

6. Display of measure and pass/fail test results on the monitor;
7. Retraction of the vision system: the vision system is retracted, the pallet repositioned on the conveyor line and unloaded.

2.3. Description of self-adaptation

As previously described it is important to have a correct axial positioning of the cone mirror in the plane containing the gap during the image acquisitions. The axial positioning of the vision system is done through a motorized electrical axis. Even though the theoretical “optimal” position of the vision system is determined off-line, since all the design geometries are known, misalignments and misplacement of the tub can occur in production line due to pallet wear, tolerances on the components, tolerances on the pallet lifter positioning and so on. This means that the alignment of the cone mirror must be checked and adapted on line before each acquisition.

The adaptation for the Drum Geometry control station is implemented by iterating the following three steps until the stopping criteria is met:

a) **acquire environment**: an image of the gap at the current preset alignment is taken; the amount and direction of misalignment is determined from the acquired image;

b) **stopping criteria**: if the misalignment is under a predefined threshold we can proceed with the measure, otherwise

c) **adaptation**: the axial position of the conic vision system is adapted, based on the amount and direction of the misalignment determined in b).

After the optimal alignment is determined, the number of acquisitions to perform (i.e.: the angle resolution) is also “adapted” so to satisfy the cycle time constraints. Therefore measurement system adaptation is very important to minimize measurement uncertainty and reduce false scraps due to measurement system positioning.

Each washing unit entering the gap QC station will be subject to a gap measurement. The gap QC system outputs gap thickness values along the whole circumference, in the form of gap profiles. Maximum and minimum gap values are of interest; they are determined on each profile. Measurements are repeated for at least two drum angular positions.
3. Vision inspection stations

Vision inspection stations in GRACE implement adaptive procedures, local optimization and local self-learning; the scope of this is to reduce measurement uncertainty and therefore to increase confidence level of output information. This also allows for the future development of a modular approach to feature extraction to be used for diagnosis and classification.

The objective has been achieved by developing a robotized vision system equipped with adaptive illumination and enhanced recognition algorithms as described below:

a) The robotized vision system makes use of a 6 Degrees Of Freedom (DOF) anthropomorphic robot arm to displace the camera and the illuminator at specific locations on the washing unit or the washing machine (WM), with the purpose to reposition the sensor in order to adapt to changes in product lay-out, position and geometry.

b) Use of vision system with camera having controllable exposure time

c) Controllable illumination systems designed to compensate changes of the environmental light conditions and/or of the characteristics of the surfaces in order to optimize image quality, thus the result of the inspection, realized by:
   - variable intensity/colour (diffuse light ring LED RGB illuminators);
   - illumination system with capacity to project programmable structured light in space and time (Digital Light Projectors DLP).

d) Implementation of software algorithms for image processing suited to deal with varying conditions, such as:
   - Multi-template feature recognition

3.1. Purpose

Vision inspection systems perform presence/absence tests of manually assembled components checking also the correctness of the installation. The state of the art of the vision quality control system is represented by on-line vision inspection stations realized by a fixed constellation of cameras and fixed fluorescent illumination, such as the ones installed at the Whirlpool washing unit production line in Naples.

The design has some limitations, caused by the fixed camera position and the fixed illumination. Flexibility of such a system is low; if products on the line are variable in geometry, position and configuration, it is necessary to install redundant cameras in order to correctly image the desired parts and, if illumination conditions vary, image quality is affected.
A robotized vision system equipped with controllable illuminators solves these limitations. Indeed, each element of the vision system (robot, illuminator, enhanced software algorithms) improves flexibility of the quality control station. This robotized vision system, the programmable illuminator and the recognition algorithms implement the concepts of self-adaptation and self-optimization.

Robotized vision system:

1) One robot moving sequentially one camera to multiple positions can replace a constellation of cameras.

2) The vision system can be reconfigured to inspect new features or can adapt to different positioning of the parts to be inspected.

3) The vision system can be reconfigured to acquire multiple images of the same scene to increase confidence level of the analysis (i.e. feature matching with slightly below-optimal score); this is a self-optimization.

4) The vision system can be reconfigured to inspect components which may be randomly hidden by others; this is a self-adaptation.

Controllable illumination:

1) It adapts illumination (colour, intensity and spatial distribution) to the feature in inspection so to improve image quality (for example image contrast); this is a self-optimization.

2) It improves image quality when unwanted reflection create glare in the image; this is a self-adaptation.

Multi-template feature extraction:

1) Algorithms of pattern or geometric matching implemented by multiple templates improve inspection reliability.

2) Continuous update of the template batch is implemented; this is a self-optimization.

3) Improved robustness of the inspection against changes in the scene; this is a self-adaptation.

3.2. Concept of operation and system lay-out

Three automatic vision stations mounting fixed cameras are already installed at different positions along the production line of the Whirlpool factory in Naples, performing different vision inspection tasks on different components of the WM:

- WU Vision station: placed at the end of the WU line
- WMA and WMB are vision stations placed along the assembly line

These vision stations make automatic visual inspection of WM components using a set of cameras mounted at fixed locations inside the station by means of mechanical supports. The systems check the right installation (presence and right positioning/connections) of
components of the WM, mainly focusing on components installed by human operators (manual processes). They provide as output the Pass/Fail results according to preset parameters and reference images.

The stations are placed and integrated on the existing conveyor line. The WM stops in a fixed position and its information (model, s/n, results of previous tests, etc.) is transferred to the vision station.

The main features of the testing equipment are:

- Mechanical structure made of aluminum profiles to integrate the vision station in the existing conveyor line. The structure is covered with panels for lighting system. Front, left and right panels are open able as standard doors.
- Control cabinet integrating the PC and main data acquisition hardware and the I/O interface to the conveyor line for test cycle and pass/fail management
- The vision system composed of a constellation of digital color cameras (uEye iDS UI-1540M)
- Lighting system (fixed fluorescent illumination)
- Blocking system for WM, made by cylinder that gives fixed reference to the unit under test (X-Y).
- Touch screen display for video output analysis and push buttons panel for operator management
- Safety protections made by open able doors (with safety lock), and safety fence to protect the area.

The software analyzes the acquired images (Figure 8) following already prefixed criteria using different techniques like Template Matching, Edge Detection, Blob Analysis.

The acquired images are displayed on a monitor and the result GOOD or FAIL is shown.

If the result is FAIL, the failed components is underlined on the monitor and the operator has the possibility to confirm the result or to change it (manual operating mode).

Regarding the definition and/or modification of the test plans proper software has been developed using the National Instrument Vision software. It allows to define the testing parameters for each area (camera) and to execute the vision programs.
The main problem of state-of-art vision systems are related to the change of measurement conditions. In fact if ambient conditions (like illumination, shadows, position of the target, etc.) or target parameters (WU model and lay-out, accessibility of components, info to be extracted etc.) change, then the vision hardware and software may require important adaptation. Some examples of such adaptation are reported hereafter:

- position and direction of sight of the camera;
- illumination tuning (colour and intensity);
- calibration, including:
  - threshold level;
  - magnification parameter;
- definition of parameters to be extracted and of processing algorithms.

To allow this kind of adaptation/optimization there are several strategies that can be undertaken, related to the different components of the machine vision system. These strategies involve camera positioning, controlling illumination and system learning.
The possible actions that can be done are related to:

- Camera positioning. By moving the camera, the system can change the line of sight so to achieve:
  - Proper imaging of different details.
  - Same scene seen from slightly different positions in order to improve accuracy in matching with templates.

- Controlling illumination:
  - Color changing can improve contrast of certain features.
  - Intensity can be lowered so that the image is not saturated or can be increased to reduce the influence of ambient light.

- Enhanced analysis algorithms:
  - Multi-template to improve inspection result.

In GRACE project all these strategies have been realized in two different prototypes:

- A robotized vision system where camera and illuminator are mounted on a 6 DOF anthropomorphic arm in order to have a high degree of freedom in camera positioning and displacement [16], [17], [18].

- A programmable illuminator where light can be changed in accordance to the environment light condition so to improve image quality (contrast or other parameters).

The two prototypes are presented below.

3.2.1. Robotised vision system

The robotized vision system has been designed to allow moving the camera in the workspace (see Figure 9 and Figure 10) in order to optimize the camera line of sight and to adapt to the current conditions of the object under inspection, by using a six degree of freedom anthropomorphic arm to displace the vision system. The robot is a Denso VS 6577G.

The robot allows displacing the camera in a workspace whose dimensions are shown in the following two pictures. Such dimensions allow for inspecting a washing unit on a pallet or a complete washing machine on a pallet. Therefore the prototype is suited for realizing an on-line WU inspection station or a WM inspection station.
The robot is mounted upside down, hanging on a portal structure, while the parts under inspection are positioned below the portal; Figure 11 shows the prototype system installed in the laboratory. This mount scheme was chosen in order to allow the arm to go around the washing machine. Another reason is because most of the features to be inspected are on the upper half of the washing unit/machine.

The vision system is equipped with an Ethernet camera (mod. Prosilica GC1380H, 1360x1024 pixels).
The illuminator for the robot mounted vision system is a Metaphase RGB ring near axis light (MB-RL204-RGB). Dedicated circuitry allows for ring illuminator control (Figure 12); the control board is connected to external power (15 Vcc), to each LED channel (red, green, blue) and to a National Instrument 6008 USB device interfaced to the PC in order to trigger the digital outputs that turns on and off the light. The illuminator can be controlled in color and intensity.

The vision system (the camera, the ring illuminator and the custom led driver board) is fixed on a custom made flange, screwed to the robot end effector; Figure 13 shows the scheme of this assembly.

The links and the connections of the several components of the robotized station are described in the picture Figure 14.
Figure 14 Layout of the robotized vision system (LAN Network in blue).

One link is between the PC, the NI6008, the custom led driver board and the ring light as already described. Then there is a Local Area Network (100/1000 Mb/s) that allows the communication between the PC, the Ethernet camera and the robot. The PC is equipped with a Gigabit Ethernet card that allows to simultaneously control the robot, acquire the images and perform the inspection.

The macro-tasks that the system executes for every feature to inspect are represented in the following block diagram (Figure 15).
The flowing series of pictures describes an inspection sequence; the robot moves at a number of selected fixed positions (for example see Figure 16) and acquires a set of images (for example the series reported in Figure 17); it therefore substitutes a fixed constellation of cameras. Positions can be reprogrammed depending on the model of the part to be inspected; this allows for flexibility. Trajectory has been optimized by genetic algorithms [15].
Figure 16 Robot vision: images taken from different line of sight to substitute a constellation of cameras
This implementation is realized for the inspection of the washing unit and of the complete washing machine; these controls will take place at different locations on the production line, on the WU assembly line and in the WM assembly line.

Figure 18 represents a sequence of control to be done on a WU: three clamps and one electric connector, whose presence and position has to be verified. Similarly Figure 19 shows a series of controls to be done on a complete washing machine. Similar sequences are collected depending on the inspections to be done.
The prototype robot vision system is capable of performing a complete sequence of inspections on the WU (4 features to check) in less than 10s, with the robot running at 80% of its full speed, while acquiring a total of 10 images with camera auto-exposure.

The longest inspection (WM, 6 features to check) takes about 13s with robot running at 40% of its full speed, 6 images acquired, camera auto-exposure.

These results match the constraint of the cycle-time which is currently set to 20s.
3.2.2. Controllable illuminator

The prototype of controllable illuminator is realized by a Digital Light Projector (DLP). It is realized as a stand-alone test bench for laboratory demonstration, but later can be installed on the robotized vision system and substitute the LED ring illuminator. DLP technology allows projection of spatially controllable light distributions as well as to control light intensity and colour and is directly interfaced to a PC through a VGA port.

The prototype layout is described hereafter in Figure 20.

![Figure 20 Layout of the bench for adaptive illumination.](image)

The test bench is composed by the following devices:

1) Controllable illuminator;
2) One camera;
3) A camera sync device;
4) PC interface;

The core of the test bench is the illuminator. The idea is to replace a standard illuminator with a fully controllable one so to have the possibility to change the illumination in order to optimize the image quality in a Region of Interest (RoI).

DLPs are realized by MEMS active micromirrors; they determine the spatial distribution of RGB colour and white illumination and project an image whose structure is fully programmable. One main limit in using them as illuminators is that they project pulsating light at high frequency. Therefore the camera to be used with the illuminator has to be triggered to properly synchronize to pulsating illumination, so to avoid image flickering and intensity changes in the acquired images. A specific camera sync device is therefore included in the prototype system.

The camera for image acquisition is an AVT Guppy F080B.

The potential of the adaptive illuminator has been demonstrated on a washing machine front panel and on a soap dispenser water pipe and clamp.
3.3. Description of self-adaptation

Implementation of self-optimization and self-adaptation are presented hereafter for the two prototypes developed for quality control inspection:

1. robotized vision
2. controllable illumination.

The robotized vision system allows several strategies of adaptation and optimization to increase the inspection confidence:

- For each feature to inspect, the colour of light is chosen in order to optimize the contrast of the image.
- To optimize the speed of the inspection, for each feature the camera exposure time is set to a default value.
- Then the exposure time of the camera is adapted in ‘real time’ to overcome local changes in the light condition of the environment since optimization took place [19]. This exposure time can be used to update the default value to speed up following inspections.
- After that, an image is acquired. The image analysis starts with the recognition of a reference feature, needed to check if the position of the feature under inspection is correct and also to set correctly the regions of interest. If the reference is not found, than the robot adapts the position of the camera and a new image is acquired. Otherwise, if a multi-template strategy is enabled, the inspection software adapts itself by searching with a new template. Both strategies can be enabled simultaneously.

The whole self-adaptation and self-optimization characteristics for the robotized vision system is described in the following block diagram (Figure 21).
Figure 21 Description of the whole self-adaptation and self-optimization for the robotized vision system
The following Figure 22 describes a typical situation in which the robotized vision inspection system is able to behave as a self-adapting system. The objective of the vision test is to detect if the electrical ground wire is correctly inserted in the plastic clamp and connected to its end, as it appears in Figure 22. The image is taken by the camera located at a specific position. Unfortunately, sometimes the spoke of the pulley of the WM can obstruct the vision of the electrical wire (see Figure 23); this may happen randomly during operation of the assembly line. If the camera is fixed, the inspection fails; this is a serious limitation of state-of-art vision inspection systems based on fixed cameras. If the camera is mounted on a robotized vision system, the displacement of the camera to a different location allows for a proper imaging of the electric wire; this strategy is implemented as a self-adapting process in the prototype realized. Being the target object imaged from a different direction, a different template has to be used for image matching; Figure 23 shows the situation.
For the controllable illuminator, the strategies that are implemented in the test bench are described below in the block diagram of Figure 24. They allow to significantly improve image quality. Image quality can be compromised by several causes; external illumination may vary, reflections may occur, etc. Specific image quality estimators are available in literature [20] and the optimization/adaption process can be driven by maximizing one of them, selected a priori. The prototype developed implements a set of algorithms for computing image quality indicators.

- First of all an optimized illumination distribution (optimized off-line from previous calculations) is projected on the target. Then an image is acquired and its quality is computed.

- If the quality of the image is not optimal, the illuminator adapts itself modifying light spatial distribution by using an optimization algorithm (both Nelder-Mead and genetic have been implemented and tested in the prototype). The new illumination is then used to update the default one in order to speed up the whole process.

![Figure 24 Description of the self-adaptation and self-optimization process for the illuminator](image-url)
Figure 25 shows the controllable illuminator prototype at work on a WM part; the part under inspection is the black pipe. The image on the left shows the effect of illuminating the whole area with an intense and uniform illumination; if the controllable illuminator project the lightning pattern represented in the central image, the resulting image is the one on the right, where the pipe is clearly more visible than in the original image.

The effect on image quality of a Self-Adapting behavior of the illumination system can be seen in Figure 26; it is plotted an image quality parameter vs. time. Four different external illumination conditions are represented in a sequence during which disturbing external lighting is affecting image quality. At first the external disturbing light is off and we can see the progress of the image quality indicator towards higher values realized by adjusting the illumination pattern. Then an external disturbing light is switched on; we can see the image quality parameter dropping down due to this disturbance and soon after the illumination system reaction that tends to increase again the quality parameter. Similar behaviour happens when a second disturbing external illumination is added. Finally the external illumination is switched off and the system reacts restoring the initial conditions.

The quality control vision system, implemented as a Quality Control Agent (QCA), exchanges information with the other entities of the MAS. The majority of the tests
performed by vision system are related to manually assembled components. For this reason, there are no large feedback loops for automatic process control that can be closed, however optimization and adaptation can take into account information from other agents. One example of information that can be exchanged between the QCA, the Product Tracking Agent (PTA), the Product Agent (PA), the Independent Meta-Agent (IMA) and the other Resource Agents (RA) is shown in the following Figure 27.

Figure 27 Example of information exchanged between QCA and the other agents.

Possible use of information from the vision inspection system regards statistical analysis, defect classification and optimization of the production process, including optimization of the vision inspection tests.

A not comprehensive list of possible use of information is:

- update default settings for hardware/software
- warning
- pass/fail test, i.e. non-conformity to the given acceptance criterion;
- defect classification, i.e. recognition of the responsible of non-conformity;
- re-planning following tests i.e. to be performed or skipped;
• storage of information for future use in the Moby of the pallet or in Whirlpool databases
• statistical analysis;
• washing machine functionality restore (repair);
• setup parameters for following control stations (if any).

4. Vibration and noise control station

4.1. Purpose

A prototype test station for vibration based quality control has been realised; its core is a non-contact measurement instrument, a scanning Laser Doppler Vibrometry (LDV) []. The system is designed to perform a vibration test on a fully assembled washing machine at the end of the assembly line.

The station was designed to implement hardware and software solutions to support self-adaptation and re-configurability. For the scanning LDV the main hardware that enables such behaviours of the measurement system is the scanning mirrors and a dedicated camera. By these devices the scanning LDV can displace the measurement beam at different locations; this possibility allows to reconfigure the system and to implement adaptivity.

In the prototype realized, self-adaption (achieved by hardware + software) consists in:

• target point selection so to measure vibration at the desired location over the washing machine, by compensating effects of production line inaccuracies in washing machine;
• search for optimal optical signal by slightly displacing laser beam (optical signal amplitude on rough surfaces varies significantly in a quasi-random fashion over the surface – searching for large optical signal is useful in order to keep measurement uncertainty under control) - displacement in sub-millimetric scale

Re-configurability (achieved by hardware + software) will consist in:

• selection of the target point so to measure vibration at the desired location over the washing machine; target point may vary depending on the WM model;
• possibility to move the LDV beam so to measure at single or multiple measurement points (selected depending on production scenarios)
• variable length of time window for data acquisition; it allows averaging the data, thus reducing the effect of random disturbances and reducing measurement uncertainty and increasing resolution in spectral analysis
• possibility to plug-in / plug-out of different post-processing algorithms for deeper analysis of vibration, with consequent change in acquisition parameters
The output information of this quality control station can be used for the simple pass/fail diagnosis and for assembly process control, if proper correlations to other process are known.

4.2. Concept of operation and system lay-out

The vibration station (Figure 28) is a mechatronic unit able to perform the vibration analysis of the appliance.

The prototype vibration measurement system schematically represented in Figure 28 consists of a laser Doppler vibrometer, equipped with scanning mirrors and a smart camera; the measurement instruments are installed on a portal structure below which the WM is placed. The WM is put on its transport pallet.

The laser Doppler vibrometer is measuring on the top of the washing unit; at the end of the assembly line, where the test takes place, the WM is without its top, therefore the WU is optically accessible.
The vibration measurement system is connected to a DAQ device for signal generation (AO) and for acquisition (AI). The DAQ is connected to the PC, which executes the software that manages the measurement process (Figure 29). The acquired signals (AI) from the vibrometer are:

- the velocity vibration of the surface of the washing unit
- the amplitude of the optical beat signal (signal quality - SQ)

Analogue output from the DAQ device (AO) are generated to drive the scanning mirrors for laser beam positioning.

![Diagram of signal acquisition system and DAQ device for signal generation](image)

The camera is mounted next to the scanning mirror and it acquires the image of the washing unit from above; on the image it can be seen the laser beam position and a portion of the WU.

### 4.3. Description of self-adaptation

During the test of each WM on the production line, the relative position between WM and LDV can vary.

One first kind of self-optimization is the repositioning of laser beam at desired measurement set point. This is done by a feed-back loop based on the image. With the camera we can acquire the laser beam position and use these information to move the laser spot using the scanning mirrors. Figure 30 shows the image of a portion of the WU acquired by camera. It is shown the laser beam template and a second template used as reference. Object recognition is performed by pattern matching with reference to templates previously acquired during the learning phase. After pattern matching the distance in pixel between laser beam and its set point can be computed; it is also known the actual beam position in a
reference frame linked to the WU. From these data the system computes necessary displacement for positioning the laser beam at the desired set-point.

![Image](image.png)

*Figure 30 Washing unit acquired by camera, red squared boxes are templates used for pattern matching of WU and laser beam*

The second kind of self-adaptation is performed at a microscopic scale by slightly displacing the laser beam in a narrow region around the desired set-point, in order to increase the amplitude of the optical signal of the vibrometer. Indeed, when a laser beam is shone over a rough surface, optical interference forms a random pattern of dark and bright regions, called speckle pattern. This determines an amplitude modulation of the optical signal of the laser vibrometer, which may cause noise; this noise is called speckle noise and drop-out noise [4], [5], [6], [7], [8]. Processing noisy signals may cause uncertainty in following diagnosis; therefore measurements should be taken with best conditions of the optical signal of the laser Doppler vibrometer [9], [10], [11], [12], [13], [14]. Best measurement conditions are defined in terms of amplitude of the optical signal (signal quality - SQ). In order to decrease the measurement uncertainty it is preferable to have large SQ and to keep it as constant as possible during the acquisition. Automatic search of maximum SQ is performed by the prototype system; a specific implementation of the downhill algorithm drives the sequence of sub-millimetric displacements of the laser beam. In the following Figure 31 it is reported the trend of the SQ versus iteration index during a self-adaptation process.
The whole sequence of steps that the system performs are described in the block diagram of Figure 32, the system performs the following adaptation steps:

a. *acquire environment*: signal quality from the vibrometer is acquired at the desired target point;

b. *adaptation*: the laser beam position is adapted in a narrow area, searching a point of high SQ following a specific optimization algorithm;

c. *stopping criteria*: if signal quality is above a fixed threshold the vibration velocity is acquired and the measurement is performed.

The adaptive behavior implemented in the LDV system is outlined in the Petri net which describes its behavior (Figure 33).
4.4. **Input and output information**

The input information from this quality control system consists in a set of parameters as:

- data acquisition (sampling frequency, number of samples, measurement set-point, camera acquisition parameters)
- stopping criteria (number of acquired iteration for adaptation process, SQ threshold, able/disable convergence to maximum SQ)

The output information consists in:

- vibration signal
- SQ signal

This information is then ready for post processing for product diagnosis. In particular:

- computation of characteristic features for vibration based diagnosis
- pass/fail diagnosis, i.e. non conformity to the given acceptance criterion (this information is used to remove from the production flow defected WM)
• defect classification, i.e. recognition of the cause of non conformity; this may lead to the following actions:
  o repair of the WM by human operators
  o possible feed-back loop to the process originating the defect
  o reprogramming the WM firmware for operation tolerant of the mechanical defect
  o re-planning, or skipped, the tests to be performed.

The output information of this quality control station will also be used for closing control loops to processes operating on the production line.

5. Functional testing

5.1. Purpose

Purpose of the functional testing is to verify that the completely assembled appliance performs correctly. During the functional test, at the end of the production line, the appliance is run to be checked on the base of a standard test cycle. This is done on 100% of the production in order to guarantee the complete and full functionality of each product.

Driven by a Whirlpool proprietary testing system, which is evolving within the GRACE project, standard instrumentation is used to measure electric power consumption, voltage, current and rotational speed of the drum.

Two reasons motivated the interest in further improving this test:
• in order to reduce total time spent in testing and/or to tailor test sequence to a specific need, it would be necessary to adapt the test cycle and design it depending on the production history of each washing machine;
• the output of the functional testing could be useful to modify parameters of the firmware installed on board of each washing machine then to achieve optimal performance of the controller of the washing machine.

The new prototype functional testing has therefore been designed with reference to these requirements. Currently the tests are customized by model, while the GRACE prototype allows for further specification for each washing machine under test, which means they could even be trimmed in some parameters in order to get the maximum performance and reliability on all the production. This means to increase the confidence on what is put on the market, not just to reduce measurement uncertainty, and tailor the test on the specific part.
The system for the Modular Functional Testing has been designed to operate in the Functional Testing area, located at the end of the production line, represented in Figure 34. In order to minimize interference with the production flow of the factory, the prototype system has been developed and realized in the Whirlpool Reliability Testing area (Figure 35). The operation of the prototype is exactly the same as it will be in the functional testing area, even if the mechanical lay-out is different (Figure 36); this will allow to test its full functionality without creating problems to the production flow.
Deliverable D3.2

Self-optimizing/self-adapting quality control systems

Figure 35 – Reliability testing area

Figure 36 Testing area (Reliability) used for GRACE demonstration of functional testing prototype
5.2. Concept of operation and system lay-out

The prototype functional testing system is equipped with an inertial platform where the WM is placed (Figure 36), connected to the electrical and water supplies. Depending on a testing rule, a variety of physical measurements can be taken, one shot or historically traced during the test.

Measurements available are:

- Voltage, Current, Power, Cos φ and Energy are the electrical side,
- Water IN&OUT quantity, and pump activity for the water side,
- two temperatures
- drum speed.

This all is achieved by measurement systems outside the appliance.

Additionally, thanks to the dedicated FW on the WM we can get a variety of status variables of the appliance electronics. Some of them are pure sensor status (pressostat, overflow, acquastop, safety switches and tachometer, motor and pump activity signal) or calculated.

In this special setup that GRACE allows, instead of performing a standard autotest (WM driven and fixed), the load activation sequence, mix and time is completely free. This allows to better exploit potential opportunities.

Innovation consists in making it possible to reconfigure the test sequence depending on information available on the washing machine under test and adjust some parameters.

5.2.1. Test sequence reconfiguration

Within the GRACE project this functional test has become more flexible and adaptable to the needs of the specific part under test and able to trim product system parameters by writing them into the electronic memory of the product.

Therefore a specific testing rule can be created for each machine; Figure 37 describes a testing rule structure.<
The functional test is made of a long list of “elementary action blocks” and the sequence follows Boolean rules conditioned by events like the success or the failure of one test/action contained in a block. For example a failure in a relevant test leads to finish the test (and define a specific error code), thus to jump to the end of the list; otherwise the system continues to decode and execute the following specified “block”. This is a sort of high level language, in which the sequence and jumps can be designed as necessary, from the testing engineer. The jump can be conditioned by a variable defined inside the testing system, so that, if a value coming from external equipment or the WM or from the GRACE system (DB, agents and so on) assigned to a value is inside or outside a boundary, the test can jump on a sequence of blocks instead of others.

Some of the preceding actions, which are feasible, would require an effort beyond GRACE aim to be realized in an automated way. Those actions will be operated manually, only loosing reaction time, not relevant for the aim. Validity of the demonstration data will remain fully safe.

The washing machine in Naples today is tested through a self test run by the machine and the testing system follows and verifies that all the steps are performed in the proper way. The washing machine electronics architecture is based on an internal proprietary communication bus named WIDE (Figure 38).
A first way of optimization can be achieved by exploiting the current appliance control board (standard production). In this case it would be possible to adapt the test choosing properly (in function of MAS directives) one of the standard cycles. Taking internal and external measurements, from the control and from the testing system about different quantities, they can be checked and compared. If necessary it will be possible to enable a following parameter tuning session on the control.
GRACE enabled the **development of a special Firmware** for the washing machine control board (derived from the production one and that could become the production standard). This enhancement allows the product to communicate also externally with the testing machine using the WIDE protocol. This way it will be possible to drive the appliance functions and components as needed and receive the real instantaneous value of the status variables from the washing machine. Figure 39 describes this development achieved.

Currently only external variables were acquired and stored, allowing to plot a trend; GRACE enhancements allows to know the internal ones (the real value of the variable, from appliance control that is the real status that drives the algorithms and loads actuations). Internal and external variables can be stored and compared, value to value in a trend.

At the same time it will be possible to read and write in specific memory area of the appliance control memory, thus, customizing the specific appliance under test.

In order to have the necessary know-how for test reconfiguration and for appliance FW tuning, an **ad-hoc database** has been built, currently collecting data from several places along the line. This huge amount of data is building historical knowledge and will be the base where to find data and perform local and global optimizations. This DB is currently accessible to all the participants to the Grace project in order to allow data analysis on real data coming from the factory.
Technically wise this is an SQL DB, so easily accessible with standard tools, and also by a custom Web application in order to gather data about all the tests. A SW feature is also provided in order to download raw acquired data, normally used to plot the trends on the graphics, in this case useful for data analysis (e.g. to know how much water was inside the washing machine when the resistor was switched on – so, for the WM the “level 1” was reached-).

5.3. Description of self-adaptation

Testing is designed in order to be able to take advantage of the current and historical data collected on the testing station and during all the assembly (thus sharing data with the other control quality agents).

Self optimization consists of an appliance customized test sequence or/and working parameters trimming. Currently they are default values stored onto the electronic memory of the appliance. From now on, they can be adjusted.

Self adaptation can be realized choosing properly from a set of standard test sequences the best fitting to the washing machine under test or having the complete flexibility to generate a custom test sequence, being able to directly drive the loads and read the sensors on the special WM Grace control board.

5.4. Input and output information

The local control station has several inputs:

- The WM comes with an RFID bringing type and serial number. From the type a specific testing rule is selected.
- Testing station receives the measurements performed by the local equipments, outside and inside the appliance (receiving the actual state values of the system).
- Input data are also those coming from the other places (should say “agents”) distributed along the production line and, finally, further input is available from historical database.

Outputs are:

- Detailed test report with measures and trends, which is stored on the testing DB each time a test sequence is performed.
- Output are also the trimming data written on the appliance and the related data in order to guarantee traceability and increase the historical data base.

All this knowledge will be useful for correlations with data about failures coming from the market, in order to highlight further feasible optimizations.
The main part of the information generated inside the control station remains local until it does not change format, this means that the data coming from the communication with the product and the transducers are collected and evaluated through the testing system. The system keeps trace of relevant answers of the sensors and variable trends and a complete report for each testing process is stored within the result of the test itself. This “test result” is the data flow coming out from the measurement system and going to the standard testing DB and also to the GRACE Data Base that builds a historical data repository.

6. References