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Extended summary

Self-Adapting Robot Vision System: Design and Development of a Quality Control Agent for Intelligent Manufacturing Systems

Curriculum: Ingegneria Meccanica e Gestionale

Author

Lorenzo Stroppa

Tutors

Prof. Nicola Paone

Prof. Paulo Leitão

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Abstract. Emerging trends in manufacturing process control are related to the integration of process and quality control in flexible and reconfigurable architectures, as addressed by the EU FP7 research project GRACE where an innovative multi agent system is proposed for production line control at factory level integrating quality control operations.

This thesis addresses an on-line quality control system based on a robot vision system, implementing self-adaptation techniques, that becomes a quality control agent in the GRACE architecture. The work presents its design, conceived as a single mechatronic unit operating within the GRACE multi-agent system.

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The focus of the thesis is on self-adaptation strategies, focused to the improvement of the efficiency of the production line and of the quality of the manufactured items, by customizing the test plan for each single product.

Autonomy, flexibility and reconfigurability of the robot vision system are crucial to enable the complex behaviours typical of a quality control agent, which eventually will lead to improvements in the production line efficiency by customizing each quality control test to each appliance and to the local and global environmental conditions, and manufacturing quality by customizing the test plan and the hardware and software parameters of the robot vision system.

The robot vision system receives information from the agency and from its own sensors and react to expected and unexpected events by adjusting the position of the vision system, the lighting colour and spatial intensity distribution, the camera exposure time, the image pre-processing and analysis and the measurement device to perform different tasks.

The prototype, developed to be integrated on a real test case production line, clearly shows the performance improvement in the inspection confidence level due to the embedded self-adaptation strategies.

Keywords. Self-Adapting Robot Vision System, Quality Control Agent, Multi Agent System, Intelligent Manufacturing Systems, On-Line Quality Inspection.

1 Problem statement and objectives

Modern production systems are acting in a highly competitive, global scale environment. This is leading to rapid changes in process technology required to maintain the competitiveness among the other players of the same market area. In the last decades, traditional centralized, rigid approaches to manufacturing, typical of mass-production scenarios, have proven not to be able to provide the required capabilities of responsiveness, flexibility, robustness and reconfigurability.

For this reason, recently, the production paradigm has shifted to more agile ones, i.e. lean manufacturing [1] and reconfigurable manufacturing [2]. The objective is to identify and reduce waste and increase production efficiency through continuous improvement of the manufacturing process while retaining the ability for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change of its components [3, 4].

The current trend is to build modular, intelligent and distributed control systems that exhibit innovative features, like the agile response to the occurrence of disturbances and the on-the-fly dynamic reconfiguration, i.e. without stopping, re-programming or restarting the process, supporting the flexible and reconfigurable manufacturing paradigms.

Multi-Agent Systems (MAS) are of particular relevance for developing distributed intelligent manufacturing systems [5, 6, 7] and for implementing control at factory level [8, 9] because they allow to achieve modularity, flexibility, adaptation and robustness. MAS allow to design decentralized control systems based on autonomous entities. Each agent responds to changes and adapts to emergent behaviour without external intervention [8].

The GRACE research project (inteGration of pRocess and quAlity Control using multi-agEnt technology; http://www.grace-project.org, [10]) developed within the 7th framework of the European Community (EU FP7) aims to study and develop a MAS for process control in home appliances production lines and particularly washing machines, integrating quality control operations, in order to improve the efficiency of the production line and the quality of the manufactured products. For this purpose, a MAS has been designed [11], considering distributed, intelligent agents representing the manufacturing components, namely products (Product Agents, Product Type Agents) and resources (Resource Agents that specialize in Machine Agents, Transport Agents, Operator Agents and Quality Control Agents).

A big challenge in this approach is the development of quality control stations that embed self-adaptation strategies in order to take part in the agency, becoming Quality Control Agents.

This thesis has been developed within the GRACE project. The scope of this work is therefore the design and development of a flexible machine vision system to be integrated into the GRACE MAS. Flexibility and reconfigurability are two fundamental characteristics of the system that will allow it to become a Quality Control Agent. This will be achieved in two steps:

1. implementing self-adaptation strategies in order to let the system operate autonomously;
2. integrating the system into the agency to take advantage of the shared knowledge to increase the performance of the quality inspection and reduce the cycle time, so

that the efficiency of the production line and the quality of the manufactured goods will be improved.

The concepts designed and developed in this thesis are of general applicability in many research and production environments. But during all the phases of the design and the development, the focus has been kept on the real industrial environment which is the one where the effectiveness of such solutions will be proved and the improvements in the production efficiency and in the manufacturing quality evaluated: the prototype (or at least some parts of it) will be installed in one of the GRACE partners' production line to demonstrate the effectiveness of the proposed solutions in a real test scenario.

2 Research planning and activities

In this work, the possibility of implementing self-adaptation strategies is explored: the objective is therefore to design these strategies and embed them into a QCA in order to exploit the shared knowledge of the MAS to bring self-adaptation strategies to a higher level. This approach should allow autonomy of operations and automatic reconfigurability of the robot vision system in order to react faster to expected and unexpected events in the production, thus improving the reliability of the quality control inspection. Automatic, on-the-fly reconfigurability allows also to customize the test plan for each item, improving the efficiency of the production line while improving also the quality of the products.

The main aim of this thesis is to develop a Quality Control Agent which performs the functions of product testing and quality control that are:

1. measurement of physical quantities through machine vision techniques and particularly part recognition,
2. diagnosis of the quality of the manufactured goods,
3. classification, i.e. defect recognition.

The quality control station will be designed to implement adaptive procedures at the level of measurement system and to be integrated into the multi-agent architecture to support adaptation at the level of manufacturing system. In particular, the following objectives will be achieved:

1. design and development of self-adaptation at the level of QCS to manage quality control activities in order to reduce measurement uncertainty, so to minimize effects of disturbing inputs, and to guarantee the optimal level of confidence of output information;
2. design and development of modularity within the software responsible to manage quality control activities at the level of algorithms for computation of characteristic features and for diagnosis and classification;
3. integrate the QCS into the GRACE MAS to take advantage of the shared knowledge of the agency in order to improve the inspection operations, increasing its level of confidence and eventually increasing the production line efficiency while retaining the same, and possibly higher, quality of the products.

The chosen architecture for the QCA to overcome the limitations of the state of the art vision inspection stations is that of a robotised vision system that implements self-adaptation. The proposed approach uses a six degrees of freedom (DoF) anthropomorphic arm to displace the camera around the object to be inspected, together with a fully controllable industrial level Ethernet camera and a customizable illuminator that can adapt the projected light for each image acquisition in order to optimize the image quality, and with modular analysis software.

Each one of these elements (robot, illuminator, camera, enhanced image processing) improves flexibility of the quality control station and the reliability of the inspection, because each element has dynamically adjustable parameters that the QCA can manage for its adaptation processes.

The test case to evaluate the performances of the system is the inspection of washing units (WU) for washing machines. This scenario presents interesting opportunities for a self-adjusting vision quality inspection because the scene exhibits random variations, which may compromise the diagnosis. Typical situation is that some components can be randomly hidden by other components, because they can assume variable and uncontrolled position relative to each other, due to the manual mounting procedures. An example related to the WU is when one spoke of the pulley hides the grounding wire placed behind it, or when pipes and clamps are mounted with different orientations by different human operators. In all such cases, traditional vision systems with fixed cameras fail in performing the inspection in an efficient way: inspection may be skipped or may provide wrong diagnosis because the parts are not visible or recognized. The solution is in general the use of additional hardware, i.e. using redundant cameras, but in this case no flexibility is allowed, and if the scene variations are complex and random, a constellation of fixed cameras cannot solve all problematic situations which may appear on a real production line. Instead, the six spatial DoF of the robot allow to develop a strategy to search and image the hidden parts by displacing the camera; this behaviour mimics what a human being would do to look for a hidden part. The same test case allows also to demonstrate the effectiveness of controlling light colour and camera exposure for maximizing image quality. Indeed, in a real production environment operating 24 hours per day, the variable lighting conditions between day and night may determine image quality fluctuations which the QCA can compensate.

Therefore the expected contribution of this thesis is to design and develop such a Quality Control Agent to make a further integration step of measurement devices into intelligent manufacturing systems, in order to integrate process control with quality control. The expected performance improvements are on the efficiency of the production line, by optimizing all the steps of the quality inspection, and on the quality of the final product, by improving the level of confidence of the measurements.

3 Analysis and discussion of main results

All the self-adaptation techniques have been implemented on two separate prototypes:

1. the spatially variable illuminator that makes use of a pico-projector;
2. the robot vision system, composed by an anthropomorphic arm in the “eye-in-hand” configuration and an Ethernet camera coupled with a RGB ring illuminator.

For the first prototype, the use of a DLP projector allows for a control of the spatial illumination distribution with a large number of DoF where intensity of the illumination can be changed in different portions of the image.

In order to generate and adapt the illumination distribution, an iterative algorithm of image inversion and processing is developed. In it, the image acquired by the camera is inverted, calibrated, filtered and then back projected on the target surface in order to allow an improved illumination in regions with different optical behaviour (Figure 1).

The procedure is tested with a numerical model and in an experimental test; in all the cases the image quality improves, even if the surface is optically non-cooperative, as a reflecting surface. Table 1 shows the improvements on a test case in terms of local contrast, Tenengrad image quality index (TN) [12, 13] and number of saturated pixels in the Region of Interest (RoI).

Table 1. Comparison between uniform and adapted lighting spatial distribution with the inversion technique for a test scene.

	Uniform illumination	**Adapted Illumination**	**Improvement**
Contrast	149	227	+52%
TN image quality index	7.4E+7	50.2E+7	+578%
Number of saturated pixels	3949	1374	-65%

Similar results can be reported for the heuristic optimization of the spatial light distribution. The technique is based on the active control of the spatial distribution of the light intensity over the target, realized by the same DLP projector and a genetic algorithm to optimize the spatial light distribution to improve image quality. The system is proposed as an intelligent illuminator for on-line quality control, but the solution has a much wider potential for application in other domains. The efficacy of the system is demonstrated with reference to a practical industrial case, namely quality control of presence and correct mounting of parts of appliances on an assembly line, in particular of washing machines (Figure 2).

The system does not need any calibration and automatically adapts to changing conditions according to a given optimization criterion, which may imply a specific image quality index for a specific task. The optimization is robust to local minima and convergence is rather fast, in the order of 40 generations, in particular combining random and greedy search. The system allows also for local actions in the whole field of view of the camera aimed to improve the global quality inside the RoI. Results of experimental tests are reported in Table 2.

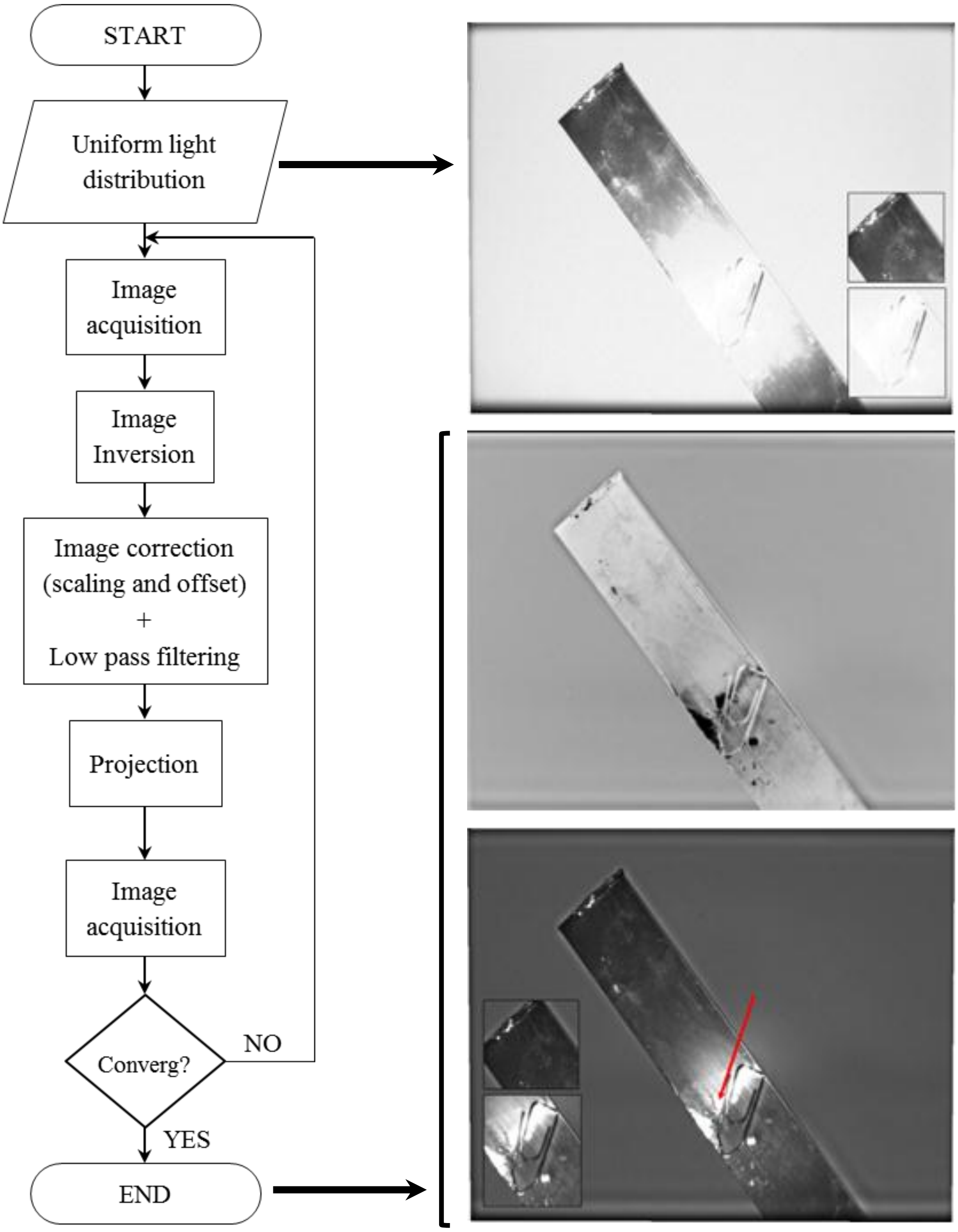

Figure 1. Left: image inversion technique flow diagram. Right, clip visibility test, top to bottom: image acquired under uniform illumination; adapted illumination pattern to be projected to light up the scene; acquired image under adapted illumination.

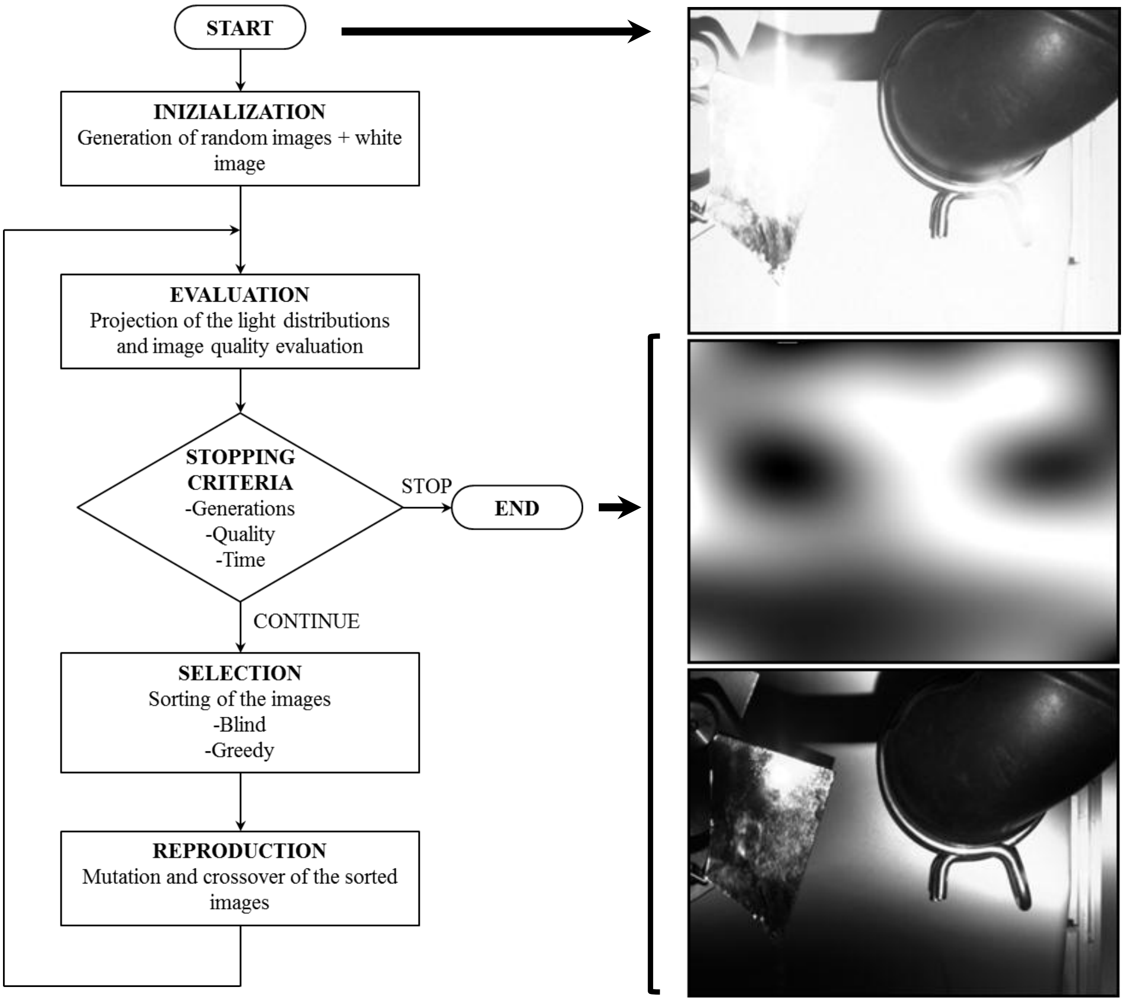

Figure 2. Left: flow diagram of the heuristic optimization through the genetic algorithm. Right, exhaust pipe clamp visibility test, top to bottom: image acquired under uniform illumination; adapted illumination pattern to be projected to light up the scene; acquired image under adapted illumination. The reflection due to the mirror (on the left of the black pipe), which causes blooming over the clamp, i.e., the RoI, is removed by an optimized spatial light distribution which does not project any light on the mirror.

Table 2. Comparison between uniform and adapted lighting spatial distribution with the genetic algorithm on a real test case.

	Uniform illumination	**Adapted Illumination**	**Improvement**
Contrast	208	247	+19%
TN image quality index	6.4E+8	15.4E+8	+141%
Number of saturated pixels	19299	2834	-85%

Concerning the second prototype, the robot vision system, many contributions for the self-adaptation strategies should be considered:

1. robot position adaptation;
2. illuminator adaptation;
3. camera adaptation;
4. pre-processing;
5. software adaptation;
6. MAS integration that gives to the system a higher level of knowledge to allow self-adaptation.

The main contribution of using an anthropomorphic arm to displace the vision system is the adaptation of the line of sight of the vision system when the sight of the component or assembly to be inspected is hidden by other components that have not fixed positions such as the pulley which rotation is not constrained. For this strategy, the system recognizes the obstacle and evaluates the amount of displacement to clear the line of sight (Figure 3).

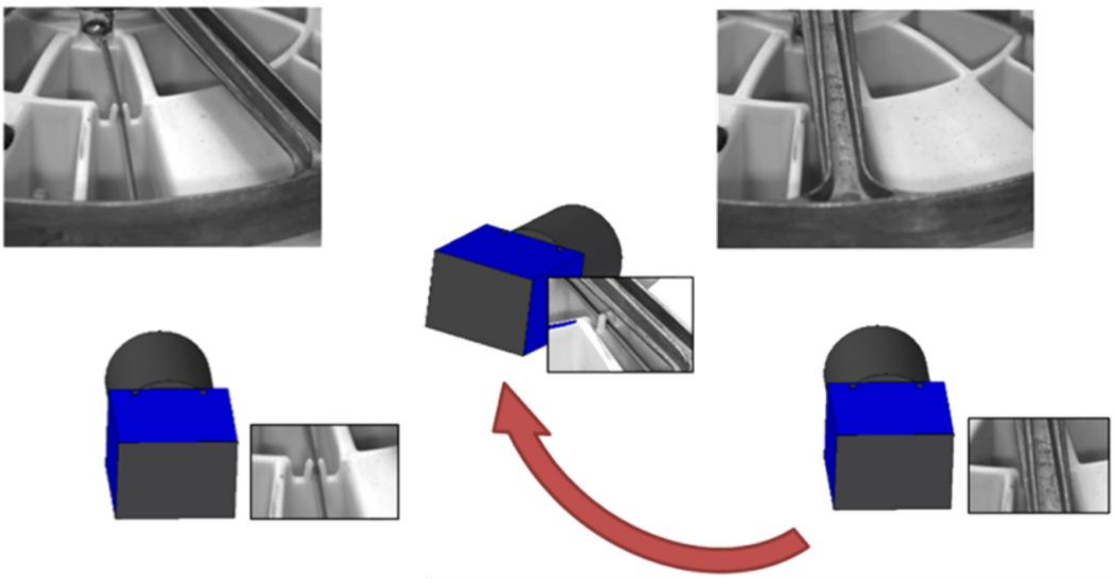

Figure 3. Grounding wire position inspection. Left: the wire is visible by the camera. Right: The wire is hidden by the pulley's spoke. After adapting the position of the vision system the wire becomes visible and the inspection can be performed.

After this step, it acquires a new image, applying a perspective correction procedure estimated by knowing the initial and final robot position and then performs the inspection. Table 3 and Table 4 show the advantages of using such a strategy in conjunction with the perspective strategy to increase the reliability of the inspection: without using the perspective correction, when the adapted position is far from the initial one, many missed recognitions are highly probable. With perspective correction, the number of missed recognitions decreases from 7 to 2.

Table 3. Match score vs. rotation angle WITHOUT perspective correction.

		-Rx			
		0°	**5°**	**10°**	**15°**
	0°	1000	1000	997	984
	15°	995	910	**0**	918
	20°	955	984	973	943
Rz	**25°**	946	918	963	920
	30°	814	729	**0**	783
	35°	729	**0**	690	**0**
	40°	**0**	674	**0**	**0**

Table 4. Match score vs. rotation angle WITH perspective correction.

		-Rx			
		0°	**5°**	**10°**	**15°**
	0°	1000	1000	1000	988
	15°	976	995	985	907
	20°	961	935	968	988
Rz	**25°**	979	944	877	929
	30°	849	808	919	783
	35°	776	868	**0**	**0**
	40°	722	698	642	794

With the RGB illuminator adaptation it is possible to improve local contrast of scenes by choosing the right lighting colour. In fact, using variable light colour to light an object, it is possible to increase the local contrast to have a higher quality image for analysis, as shown in Table 5.

Table 5. Evaluation of the level of confidence of the inspection with different light colours.

	Match Score Mean Value	**Match Score Standard Deviation**	**Confidence Level**
Red	777	211	65.55%
Green	775	242	60.99%
Blue	813	194	73.61%

Concerning the camera exposure time self-adaptation, since image quality is being evaluated through the TN image quality estimator, the exposure time can be optimized to maximize the quality function. The necessity to improve or recover the image quality arises for example when the environmental illumination conditions change or the illuminator has a failure e.g. one or more LEDs are not working. Table 6 shows a comparison between different approaches for setting the exposure time. The proposed strategy of TN maximization gives the best results in terms of improved confidence level of the inspection.

Table 6. Comparison between different camera auto exposure strategies in terms of geometric match score mean value, standard deviation and feature recognition confidence level. Lights on and off are intended as external disturbances.

	Fixed Exposure			**In-Camera Auto Exposure**			**TN Maximization**		
	μ	σ	**Conf. Lev.**	μ	σ	**Conf. Lev.**	μ	σ	**Conf. Lev.**
Lights ON	684	216	**62.49%**	726	299	**59.50%**	711	198	**69.02%**
Lights OFF	668	255	**56.57%**	729	275	**62.16%**	737	167	**78.14%**

Pre-processing is an optional step in the quality evaluation process. Usually hardware self-adaptation is sufficient to provide good quality images. But if, for some unexpected event, the quality of the acquired images is not satisfactory, pre-processing is invoked to try to recover some image quality. Table 7 shows a comparison between the proposed adaptive pre-processing technique and two standard contrast enhancement approaches.

Table 7. Comparison between different pre-processing techniques for image quality improvement in terms of TN values.

Original	**Histogram Equalization**	**Grey Level Grouping**	**Adaptive Pre-Processing**
4.15E+8	8.24E+8	6.73E+8	18.2E+8

Software adaptation is intended both as a modular framework for the inspection, so that the test sequence can be customized by the Product Agent, and as an improved strategy to increase the confidence level of the quality control by using redundant templates.

Modularity is exploited by the integration with the MAS, since the inspection software is divided into smaller sub-programs that can be recalled as needed. The test sequence is sent to the Quality Control Agent (QCA) by the Product Agent (PA), according to the knowledge of the production history of the appliance. The customized sequence is included in the XML files exchanged by the QCA and the Quality Control Station (QCS).

The multi-template technique has been designed to improve the inspection confidence level by optimizing the software of the QCS. By using redundant templates, the confidence level of the inspection is improved, as shown in Table 8.

Table 8. Comparison of single vs. multi-template strategies. Geometric matching algorithm applied to 1380 images, using 4 different templates, namely A, B, C and D.

	Match Score Mean Value	**Match Score Standard Deviation**	**Confidence Level**
Template A	538	437	16.21%
Template B	822	256	36.21%
Template C	725	354	24.36%
Template D	871	188	50.27%
A+B+C+D	930	22	100%

To solve the problem of dimensional measurements for quality control applications on the internal surfaces of cylindrical objects, an omnidirectional vision system has been designed.

The system is based on a standard camera and a catadioptric optics with a conic mirror mounted in axis with the lens (Figure 4).

Self-adaptation strategy is used to centre the catadioptric vision system inside the cylinder in the axial direction in order to correctly image the feature to be inspected.

The achieved results show that the vision system with conic mirror and auto-calibration algorithm can be effectively applied to dimensional measurements in production lines, being faster than alternative techniques, such as scanning profilometry, for full field measurements.

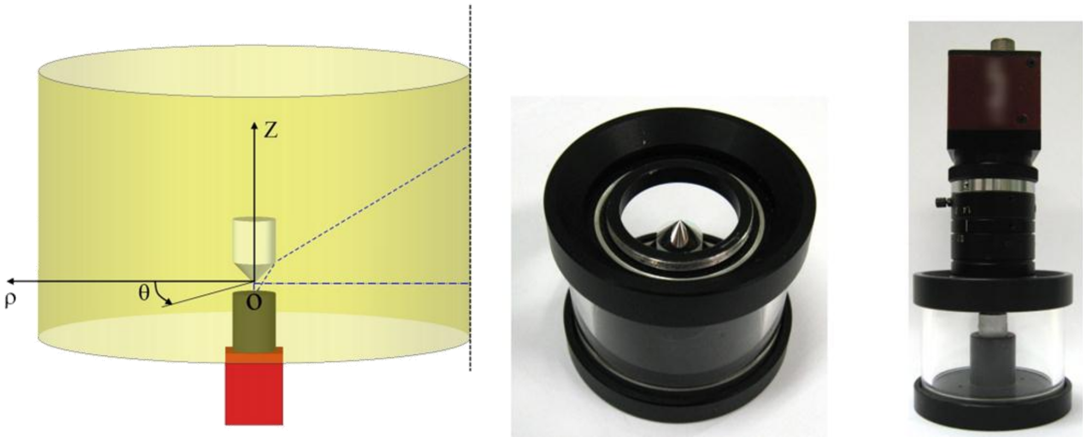

Figure 4. Left: schema of the omnidirectional vision system. Right: catadioptric camera.

4 Conclusion

This thesis addresses a new concept of robot vision system which exploits the advantages of using reconfigurable hardware and software to enable self-adaptation strategies. The complex behaviour that the robot vision system exhibits is suitable for the operations within a multi-agent system, where the proposed system acts as a Quality Control Agent, communicating and exchanging data with the other agents.

The results show that the self-adapting robot vision Quality Control Agent can be realized and it is effective to improve the confidence level of the quality inspections, leading to an increase in the quality of the manufactured goods and in the production line efficiency.

To conclude, the proposed approach of implementing self-adaptation techniques in a robot vision system, designed to be integrated into a multi-agent architecture for intelligent manufacturing systems, is a viable solution for the improvement of production lines efficiency and the products quality. This approach allows autonomy of operations and autonomous reconfigurability of the robot vision system, which is capable of increasing the level of confidence of the quality control tests while optimizing the duration of the inspection by reacting faster to expected and unexpected events in the production environment.

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