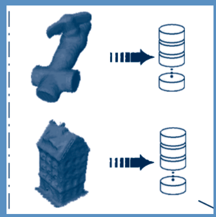
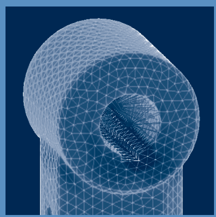
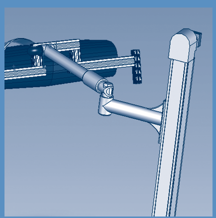
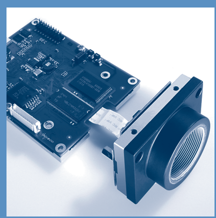
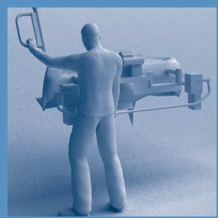


PROJECT 3









IRoPA

INTELLIGENT ROBOTIC PARTNER

IRoPA
Intelligent Robotic Partner

project 3

Development of an innovative robotic architecture to create intelligent partners on production lines

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EXTERNAL INSTITUTIONS

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Maria Elena Innocenti
Physical Engineering

Nicola Rossi
Mechanical Engineering

Cristian Taibi
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Mario Torello
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TEAM B

Iacopo Gambino [Team controller]
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PROJECT DESCRIPTION

The IRoPa project, ordered by the Centro Ricerche Fiat, is dictated by the automotive sector need not only to enhance the flexibility of the production lines but also to allow high product diversification and quick line conversions. The purpose of this project is the implementation of a feasibility analysis – with its relevant preliminary plan – of an "intelligent manipulator" which can comply with these flexibility requirements: in particular, this "intelligent manipulator" has to be able to carry out both the implementation of bodywork (through spot-welding) and the components installation (i.e. dashboard) into the cockpit. The execution of so different tasks requires the design to be significantly modified: in fact, a working cell planned with this method should also allow, with a simple reprogramming, the execution of operations it wasn't initially conceived for.
Firstly, we had to develop an innovative structure, with six degrees of freedom, able to guarantee handling and welding operations to be smoothly completed. Moreover, the robotic partner would have to include also an onboard intelligence system, able to manage moving and positioning stages of the components, employing a vision or sensorial system and optimizing both the operations to be carried out and the path to be followed. Other requirements involve the use of wireless technology, to allow the reduction of both setup costs and reconfiguration time, and an ergonomic analysis of both the current and the future working station, to better understand how the operators' health and the safety conditions could be warranted and observed under any circumstance.

The students' group split into two teams, so as to allocate the individual skills as evenly as possible. This was done mainly to allow each team to be multidisciplinary and able to work independently on almost every aspect of the project. At the same time, however, the teams maintained an overall cooperative approach, to focus on the best solutions and sharing the most complex parts of the work: in particular, team A dealt with the innovative mechanical project of the robot – thanks to a detailed analysis of the existing working cell – while

team B worked on the robot guidance system and the wireless communication setup for data transfer.

Both teams achieved excellent results in their own field of competence, respectively. Their work paved the way to the prototyping of the robot, providing a number of advantages compared to the original, low-tech partner: the automation of the working cell increases productivity and quality by reducing duty cycle and allowing for more repeatability and precision. Further, the new robot not only is more flexible, as it is easily adaptable to different operations or line reconfiguration, but is also compliant with ergonomic principles: the improvement of the working conditions and the reduction of human interventions will surely have a positive impact on the workers both in terms of daily work reduction and job quality enhancement.

project 3A

TeMATIC
Telescopic Manipulator with Automation Technologies and Intelligent Control

_IRoPA_Intelligent Robotic Partner

TASKS & SKILLS

Marco Cavallaro, specialized in technology and factory planning, worked on the ergonomic analysis of the installation operation, both for the current and the advanced solutions, in a digital factory specifically designed for the project.

Davide Devescovi, interested in artificial intelligence and software engineering, worked on the computer vision system controlling the robotic arm movements, focusing on the development of the two different software solutions for position detection.

Maria Elena Innocenti analyzed the ergonomics of the current station, studying its impact on the workers and the available opportunities to increase the level of automation.

Nicola Rossi, specialized in transport systems, worked on the dynamic simulation of the robot, verifying the sizing of the structure and servomotors and analyzing the trajectories of the dashboard insertion.

Cristian Taibi, particularly interested in engines and gears, worked on the innovative robot structure defining servomotors and transmissions and providing a FEM analysis for the most loaded joint.

Mario Torello, interested in digital image processing, dealt with the feasibility study of an advanced computer vision system for the detection of the robot position through an image-to-model mapping system.

ABSTRACT

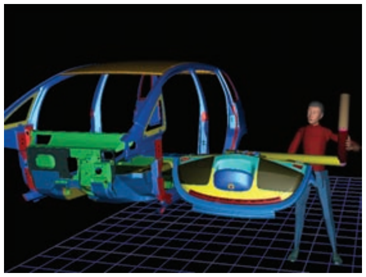
The first task our team accomplished was the ergonomic analysis of the existing, low-tech mechanical partner [fig. **1**] which aids the worker in the dashboard installation process: this study highlighted several problems as ones concerning to inefficiency and the workers' health and safety conditions. We then moved on to the design of an automated solution which could solve these problems. In selecting the structure for the robotic arm, we decided to go for an optimum combination of "tested and tried" and innovative ideas: our robot is basically a standard 6 degrees of freedom arm [fig. **2**], with the innovative addition of a telescopic component, which suits well the insertion operation the robot must perform. Moreover, we studied the interface between the end effector and the interchangeable tools to minimize the set-up time and to comply with the project guidelines requiring not only the robot being able to handle dashboards of different kind and size, but also to carry out welding operations.

The computer vision system, the task of which is monitoring all the operations through a mounted camera, is supposed to be able to detect a generic, textureless, three-dimensional object (i.e., any part of the car body) and calculate its distance from the robotic arm in real-time. As these features are currently the subject of several researches in the computer vision field, it was unlikely that we could reach the prototypal stage. For this reason we decided to work on a feasibility study of an advanced algorithm, simultaneously implementing two simpler yet working solutions, so as to obtain some tangible results. In particular, our first prototype is a simple two-dimensional template matching algorithm, while the second one is able to detect a specific black and white marker in a three dimensional space.

The conclusive stages of our work included an ergonomic study of our new robotic partner to assess the improvements and benefits achieved.

1 *An example of an industrial partner for the dashboard insertion operation*

2 *A sketch showing the concept of our "intelligent manipulator"*



3 *The assessment of ergonomic indices we performed in a virtual digital factory environment*

UNDERSTANDING THE PROBLEM

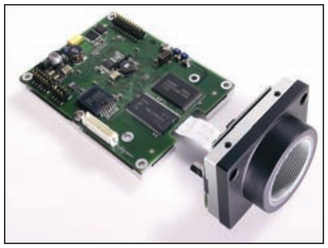
First of all, we had to examine the currently employed mechanical partner, which is manually operated and merely reduces the workers' physical work. According to our analysis, this solution is absolutely inefficient [fig. **3**], because it requires two workers for each mechanical partner and the operation completion is quite slow and error-prone; further, ergonomic principles are not observed, especially in the insertion process, putting the workers' safety at risk.
In order to find a remedy for this situation, we had to design a fully automated robot or, at least, a robotic partner requiring less operations to be performed and easy to manage by the workers, thus increasing productivity while observing ergonomic guidelines. As a result, the two main aspects we had to focus our research on were the definition of the mechanical structure and the development of an intelligent guiding system.

EXPLORING THE OPPORTUNITIES

The first step was to choose the arm structure [fig. **4**]. We thoroughfully studied the state-of-the-art in robot design, so as to understand advantages and drawbacks of the different available options, mainly focusing on the two most commonly used structures: anthropomorphic and Cartesian.

The anthropomorphic structure is characterized by high flexibility – which allows for welding operations but unfortunately also by an insufficient workspace for dashboard insertion process. On the contrary, the Cartesian structure guarantees a wide workspace and a simple control, although its application in an industrial context is rather difficult because of the cumbersome protections required by the safety rules.
Secondarily, we had to select the motors and the reducers to be mounted on the robot. Pneumatic servo-motors aren't widely adopted in robotic applications due to their low accuracy; other options include hydraulic and electric motors, showing comparable performances but also significant differences: the electric motors are usually cheaper and more efficient, while the hydraulic ones don't pose overheating risks and are more capable of handling heavy loads. When we chose the reducers we examined the two most common types. Harmonic reducers are very accurate in positioning and re-

4 *The range of movements our robot is able to perform*



5 *An example of a commercial smart camera, able to carry out onboard processing*

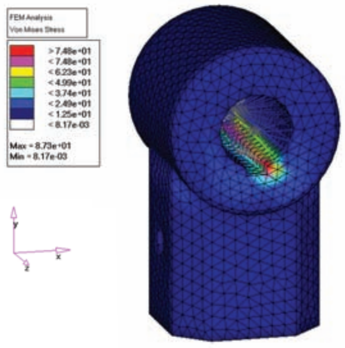
6 *The dashboard insertion step, performed by our robot*

peatability, and can also boast a very low weight; on the contrary, they can cost twice as much and be less efficient than epicyclic reducers.
We had then to evaluate several aspects concerning the intelligence system. First of all we had to choose the best hardware allowing the robot to detect its own position regarding its target. A simple video camera mounted on the arm is generally not sufficient, because it lacks the ability to measure distances and scales; a common solution consists in the employment of a pair of cameras in a *stereoscopic rig* allowing for depth perception, as it happens with human eyes.
Scaling and distance measurements can be obtained using a single camera with some expedients as well. For example, an experimental technique, called 'depth from defocus', is able to estimate the distance of an object from the camera comparing the recorded images as the camera focus varies; alternatively, the camera can be coupled with a laser telemeter which can provide depth data. Other options include the use of *multiview geometry*, a technique which can extrapolate additional information about an object from two or more images taken from different viewpoints, or more advanced 3D shape-based recognition algorithms.
A second aspect we had to consider was the positioning of the processing unit: several commercial solutions adopt a *smart camera* [fig. **5**] approach, where the CPU and the relevant algorithms are all stored in the camera onboard; in this case the camera can be remotely configured and monitored, being able to independently process images and control the robot with no further communication. A more flexible yet complex approach delegates the processing to a remote computer station, connected to the robot both to receive all the recorded images in real time and to send motion commands to the arm.
For what concerns the specific algorithm we should use to detect the object, we reviewed several options, ranging from a simple template matching approach, to a marker detection algorithm, to more complex solutions like main component analysis and surface matching technique.

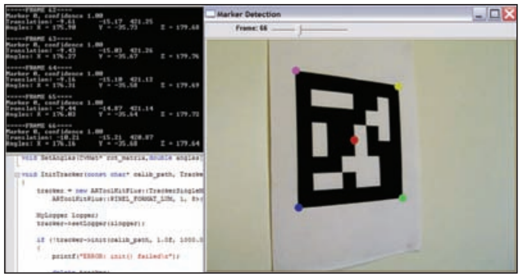
GENERATING A SOLUTION

The final solution [fig. **6**] consisted of a 6 degrees of freedom robot with a telescopic arm connected to the base, able to provide flexibility and a wide workspace while limiting its size. This was possible thanks to the relatively light payload the arm is required to support, also allowing us to conceive a hollow structure: cables can be placed

inside it to increase reliability and reduce operating costs.
We then chose brushless motors, a particular kind of electrical motors often used in robotics because they are easy to control and maintain; the moderate loads our robot will have to hold wouldn't justify the choice of hydraulic motors. We employed harmonic and epicyclic reducers, choosing the most appropriate for each joint of the arm: in this way we managed to reduce the weight resting on the most critical joints [fig. **7**], while holding down the costs by using epicyclic reducers where weight was not a problem.
In order to guide the movements of the robotic arm we adopted a mixed solution. First, a CAD/CAM system pushes the arm relatively near its target; thanks to the knowledge of the car CAD model and the aid of radar sensors, collisions are prevented if the car is not in the expected position. The actual approach and precision positioning are performed by the vision system, for which we decided to adopt a single camera: two cameras, or a single camera coupled with another sensor, didn't yield significant advantages, as some of the advanced algorithms we considered can be as powerful as stereoscopy in terms of collectable information. Moreover, a single camera takes up less room on the arm.
The specific algorithm we focused our feasibility study on, is a surface matching algorithm, which uses *spin images* to perform the match. A spin image is a particular surface transformation that makes the comparison straightforward, reducing the complexity of a surface-to-surface match. Given the 3D models of the objects to be detected, the algorithm can compare the spin images of surfaces in the scene with the stored spin images of models, even in presence of noise or partial occlusions; unfortunately, obtaining real time performances with this method is not easy.
Considering the complexity of the chosen approach, the best way to handle the computation was using a remote PC station; the wireless connection used to make it communicate with the robot was studied by Team B.
Besides the feasibility study of the advanced algorithm undertaken in cooperation with Team B, we coded two much simpler yet working prototypical algorithms. The first one performs a simple template matching operation comparing a known template of an object, on a pixel by pixel basis, with the currently acquired image, detecting the object in the scene; this approach, however, requires a perfectly perpendicular point of view, basically limiting us to a 2D image. The second one [fig. **8**] doesn't show this limit, as it can recognize a specific binary marker from any perspective; unfortunately, this means that the marker has to be accurately placed, can't be occluded by any object and has to be removed afterwards: in our situation, all these conditions weren't easy to comply with.
The final step of our work consisted in the ergonomic analysis of our new "intelligent partner", performed in a virtual, digital factory environment, which allowed a detailed analysis and, in particular, a study of the suggested solution. This study showed that the workers' conditions had dramatically improved for what concerned both safety and health-related factors; moreover, the robot allowed the job to be completed in a faster, more efficient and flexible way.



7 *Tension distribution on the most loaded joint of the structure*



8 *Our marker detection prototype program at work* project 3B

The AntroCart Wireless robot

TASKS & SKILLS

Xenia Fiorentini, specialized in technology and factory planning, dealt with the general cell configuration and the examination ergonomic aspects of the proposed solution.
Lorenzo Guidi, specialized in production and manufacturing processes, worked on the ideation of an innovative structure for the robot and the end-effectors, and performed a preliminary measuring of the arms.
Francesco Monti, specialized in chassis design, performed the simulations needed to size the partner structure and the mechanical components with FEM analysis and dynamic simulations.
Marianna Pepe, particularly interested in source coding and signal elaboration, worked on the wireless communication system and the image compression algorithm.
Federico Sarzotti, specialized in computer graphics, led a feasibility study of an advanced computer vision system for the detection of the robot position in a 3D environment.
Iacopo Gambino, specialized in technology and factory planning, worked with Xenia Fiorentini on the general definition of the system, taking care of the cost-benefits analysis of the project.

ABSTRACT

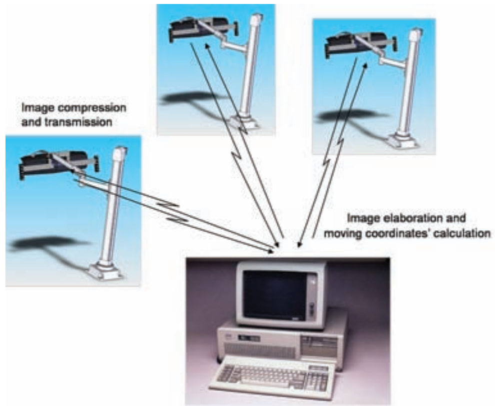
The work-cell currently employed for the dashboard insertion uses a mechanical framework to aid the operator in moving and positioning the components; this solution not only proved to be problematic from an ergonomic point of view, but also offered limited performances. As a result, the idea we developed was the replacement of the current cell with a fully automated robotic partner.
We began our work designing an innovative structure, adopting as guidelines principles the simplicity of the framework, the adaptability to different operations and the least expensive solution. Additional goals were also the small volume for a limited room occupation and a wide workspace at arm reach. We conceived a robot with 6 degrees of freedom, five rotational axes and a translational one, and an equipment designed taking into account the possibility of a line reconfiguration. The feasibility study concluded with an executive project of some elements: a FEM analysis and a dynamic simulation gave us crucial information about the sizing of the critical joints and the best servomotors to choose.
In order to control the movements of the robot we chose a mix of CAD/CAM and a vision system: the robot moves along trajectories previously defined on the base of a CAD scheme; then, once the car door is reached, an accurate positioning can be obtained thanks to a 3D video camera. To complete this operation, the computer system needs to be able to recognize a generic 3D object and to calculate the distance from the robot so that it can identify the arm position in real-time.
The images acquired on board are compressed, using the wavelet transform of the signal, and sent, through a WiFi protocol, to a remote terminal where the current computation occurs. The new cell was designed taking in consideration ergonomic principles to overcome the ergonomic inefficiencies of the previous system. The final solution granted a significant improvement of the work conditions. Furthermore, the decisions regarding materials, configurations and technological solutions were always taken in consideration of the trade off between performances and costs. This approach allowed an easy development of the costs-benefits analysis.

UNDERSTANDING THE PROBLEM

After having analyzed the current work-cell, in which the operator uses a simple mechanical partner, we immediately realized that the dashboard insertion and spot welding processes require lot of efforts by the workers. We decided then to exclude the human operator, who remains only a supervisor, and to create a completely automated work-cell, able to operate with different types of vehicle, automatically recognizing which one is currently being processed. Actually we also took into consideration the possibility of a dashboard model – and maybe also the end-effectors equipment – change, considering a random arrival sequence of vehicles. Throughout the project, our group always adopted a general-purpose approach in facing the problems and considered flexibility as the most important requirement. Finding the most inexpensive solution was the other fundamental goal: as there already existed many different robots on the market, our solution would have to be cheaper but just as effective as those ones.

EXPLORING THE OPPORTUNITIES

The first stage of the project consisted in the analysis of the movements the robot should be able to perform, particularly focusing on two different movements: the handling of the spot welding gun and the insertion of the dashboard in the vehicle. The second movement showed the need for a flexible structure: this compelled us to conceive a solution with six degrees of freedom. We evaluated current commercial products developed by leader companies in this field to find out which positive and negative aspects characterize the most important solutions. The main typologies of six-degree of freedom robot are Cartesian and anthropomorphic robots. The first one presents the advantage of a simple and economic structure, but the floor supports it requires can be quite encumbering. On the contrary, the anthropomorphic solution is very flexible and can reach wide workspaces, although the structure occupies a limited room, but the negative aspect is represented by its more complex structure; the latter solution is the most widespread in the industrial field. Almost all the robots we found showed high performances we judged unnecessary

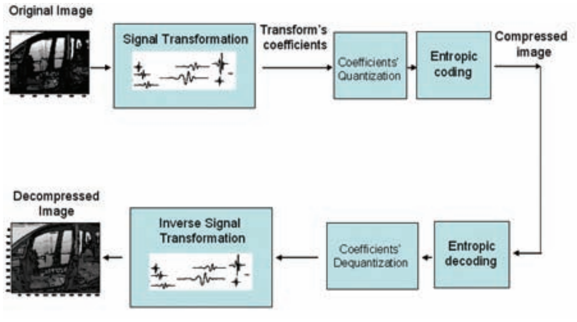


1 *Description of the chosen architecture for the wireless network*

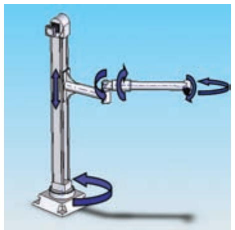
for our application: the reduction of the costs by achieving lower performances was a fundamental assumption in generating the solution. As to the vision system, we noticed that mounting the dashboard on the car is a critical operation, since the algorithm has to recognize an object the image of which, in accordance with the position of the robot arm in the cockpit, could be rotated and translated compared to our model. Therefore we reviewed several possibilities, ranging from a simple template matching approach, to a marker detection algorithm, to more complex solutions using a surface mesh as representation for 3D shapes.

As regards the wireless transmission, we first evaluated the option of an onboard elaboration: in this way only the coordinates obtained from the vision algorithm and those calculated from the cad scheme would need to be transmitted from and to the robot; most important, no image compression would be necessary. However, an elaboration unit near the video camera would be indispensable, but that could hamper the arm movements.

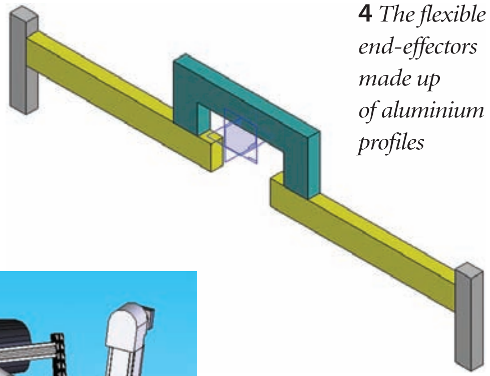
The alternative option was compressing the image and sending it to the remote terminal attending to the elaboration [fig. **1**]. The compression algorithm works through a series of steps: the image is first transformed as the weighted sum of simple waveforms, so that the quantization step can be efficiently implemented, then the quantized weights are codified to reduce source entropy [fig. **2**]. We examined



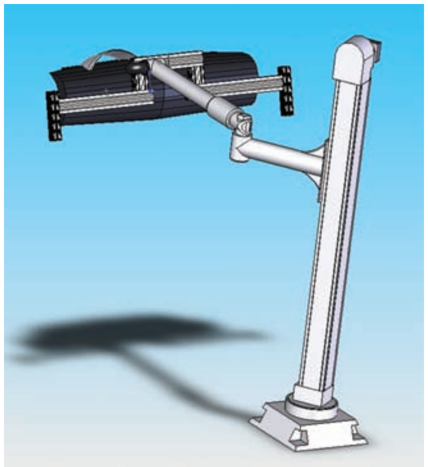
2 *Image compression and decompression scheme*



3 *Robot structure and disposal of the six degrees of freedom*



4 *The flexible end-effectors made up of aluminium profiles*



5 *Manipulation of the dashboard by the robot*

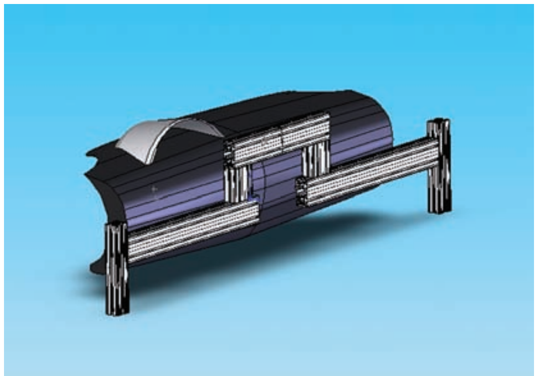
two possible kinds of algorithms: lossless and lossy. The lossless ones give a quite low compression factor, but they definitively succeed in accurately reconstructing the image; lossy algorithms cause a fidelity loss in the decompressed image, but allow for higher compression factors compared to the lossless ones. Two important factors influenced our choice: we used image compression to achieve wireless system better performances, so we looked for a high compressing factor, guaranteed by a lossy algorithm; on the other hand the acknowledgment algorithm had to work also with the decompressed image which, using a lossy technique, is degraded compared to the original one. So the solution had to be a compromise between these two contrasting requirements.

Finally, we considered the wireless communication system: W-PANs (802.15), that have a short-range (about a meter) and can reach a bit rate of 1 Mb/s, and W-LANs (802.11), that reach distances up to 100 meters and allow for a bit rate of 10 Mb/s.

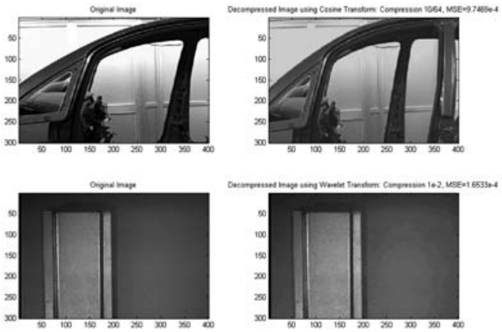
GENERATING A SOLUTION

The solution we put forward is a compromise between a Cartesian and an anthropomorphic structure - that's why we named this robot AntroCart. We adopted a robot with 6 degrees of freedom, 5 rotational axis and 1 vertical translational axis, able to reach a wide workspace occupying limited room in the plant [fig. **3**]. We designed the end-effectors to handle the dashboard and to fix it within the vehicle, adopting a modular structure made up by commercial aluminium profiles allowing the creation of an economical and flexible equipment, able to keep dashboards of different sizes [fig. **4**].

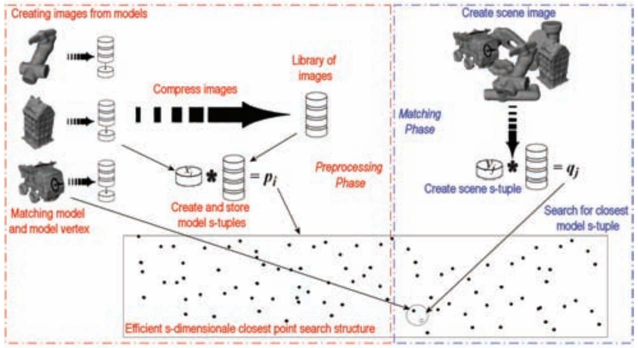
For what concerns the servomotors, we selected electrical brushless motors. Other typologies (pneumatic or hydraulic) weren't suitable for our specific needs: the first doesn't allow an accurate movements control, while the second is usually appropriate for high torque. As to the reducers, however, we chose a harmonic driver transmission because of the operating principle and flexible design that make them perfect for industrial robots. The main qualities of these reducers consist in their compact size and light weight, high reduction ratios in a single stage and high torque capacity with high precision performances. The size of some critical joints was tested out through FEM analysis and, through a dynamic simulation software, we checked the correct performance required by the servomotors [fig. **5**, **6**].



6 *Fixing of the dashboard to the designed end-effectors*



7 *Comparison between the original image and the decompressed one obtained through two different algorithms*



8 *Surface-matching vision algorithm using spin images*

We implemented two different image compression algorithms. They both belong to the lossy class but they use two different transformations. We took two parameters into account: Mean Square Error (MSE) between the original image and the decompressed one, and the ratio between original image size and decompressed image size (compression factor). We chose the algorithm providing the highest compression factor, although it provides also a higher MSE, because it allows the vision algorithm to work correctly [fig. **7**].
The chosen communication protocol is 802.11b. We carried out some tests, but not in an industrial environment: since this system works with a central frequency of 2.4 GHz, which is not licensed and undergo a lot of interferences, its use in complex environments could involve problems we didn't considered in our work.

Both teams studied the 3D vision algorithm in cooperation, carrying out a feasibility study of a surface-matching algorithm. It works by comparing spin images, which are a particular kind of surface representation reducing the complexity of a surface-to-surface comparison [fig. **8**]. When two spin images are highly correlated, a point correspondence between the two surfaces is established. More specifically, before the matching phase, all the spin images from one surface (the model) are constructed and stored in a stack. Then the algorithm selects a random vertex from the other surface (the scene seen by the camera) and computes its spin image. Point correspondences are then established between the selected point and the points with best spin images matching on the other surface. The use of surface mesh as representations for 3D shapes was avoided in the past because of its computational cost: however, nowadays processing power improvements make this technique feasible.
The final result of our activities is a work-cell equipped with a robotic system characterized by high flexibility and reconfigurability, and a distinctive amount of installed intelligence (visors, positions sensors, anti-collision sensors). This goal is achieved with a cell that only employs quite simple and common solutions, allowing a dramatic cost reduction and offering the operators a significant improvement of their working conditions.