Executive summary:

Today's smartest adaptable fixtures have limited adjustment capability, are mostly operated manually, are usually setup off-line with help of external measuring equipment, e.g. laser. Significant increase in effectiveness and decrease in cost may come from on-line fully actuated configuration/ reconfiguration, large adaptability to different shapes and the capability to dynamically concentrate the support in the region where manufacturing is actually performed, doing that on-line and without moving/ removing the part from the fixture. SWARMITFIX develops the new concept of self adaptable swarm fixtures composed of mobile agents that can freely move on a bench and reposition below the supported part behaving as a swarm, all without moving/ removing the part from the fixture.

Each fixture agent is composed of:

-a mobile platform,

-a parallel robot fixed to the mobile platform,

-an adaptable head with phase-change fluid and an adhesion arrangement, to sustain/ clamp the supported part perfectly adapting to the part local geometry.

A hybrid control system is adopted and each robot is treated as an autonomous agent exhibiting its own behaviors. Behavior based trans-location of the robots to destination positions is adopted to reduce planner complexity, with:

-no need to plan exact trajectories and

-no significant increase in complexity when extra units are removed/ added.

The area of manufacturing of thin metal sheets is considered (aircraft and automotive bodies). The project objective is to develop a swarm fixture for a large range of sheet shapes to fully replace the specialized fixtures today used.

The project focuses on the integration of reconfigurable technical systems and processes with combination of technical intelligence from sensors and actuators. SWARMITFIX combines the flexibility given by mobile robotics, adaptability of smart materials and the intelligence of a swarm like behavior. Working in this context and taking advantage of the synergy of these fields, it is possible to develop a fast and intelligent communication between the robots and high adaptability mechanisms based on smart materials. At the same time the use of these advantages will present the challenging part of the project. By successfully integrate the preciously mentioned fields; it is possible to develop a system that automatically and continuously adapts production resources and processes in an optimal

way with respect to business and production objectives. This flexible swarm fixture will increase the competitiveness especially of SME's with small batch sizes by providing an affordable intelligent technology that reduces the time needed for configuration and maintenance and that in this way allows a step forward to an efficient customer-oriented production.

The objectives of the project are to:

-rethink the fixtures as a multiagent swarm system, achieving high online adaptability and reconfigurability with the minimum necessary number of support units.

-The use of swarm single agents, designed as parallel robots (for high stiffness and position accuracy) on a mobile base, being able to freely move on the fixture bench to reach desired support locations, anchor to the bench, accurately position and orient their support heads.

-Introducing the concept of phase-change fluid in the head of each swarm agent in order to get a perfect geometrical adaptation to the local shape of the supported part and at the same time to realize stiff support and clamping.

-Developing an offline simulator to program/ check the fixture configuration for specific CAD sheet geometries and manufacturing cycles.

-Developing an intelligent control system relying on high level intelligent organization and control, and low level behaviors of the agents.

-Developing a virtual environment for the design and digital mock-up of new SWARMITFIX fixtures addressing modularity and standardization issues.

Project Context and Objectives:

The project aims at developing intelligent fixture technology for the manufacturing of components made of thin sheets with 3D geometries processed by different methods and connected together.

While the use of such components is growing in quantity due to current trends towards life cycle design and sustainable production, and in geometrical complexity due to aesthetic and quality issues, the manufacturing equipment is not growing in flexibility in parallel with the same trends.

Minimum use of material, aesthetic and quality issues also have an influence on the manufacturing requirements and processes adopted:

-Continuous welding is replacing spot welding;

-Round holes at precise locations are preferred to slotted holes traditionally used for relative adjustment in assemblies;

-Execution of accurate grooving and windowing operations is increasing;

-Complex surface geometries are adopted to satisfy stiffness requirements as with thicker material.

The demand for flexibility is pushed by short time-to-market, production in small and variable batch and mass customization for some products.

The sheets are first formed, normally by pressing or other forming technologies, and then further processed (deburred, milled, holed, contoured etc.). Fixtures to support and keep the sheets in form are required for the execution of almost all of these secondary manufacturing operations. Currently mold-like fixtures and manual or partially self reconfigurable fixtures are used for this purpose. None of these fixtures offer simultaneously the advantages of short reconfiguration time, easy set-up, adaptability to large shape ranges, minimum complexity and low cost with respect to performances.

Significant increase in effectiveness and decrease in cost may come from on-line fully actuated configuration/reconfiguration, large adaptability to different shapes of the part to support and the capability to dynamically concentrate the support in the region where manufacturing is currently performed, without moving/removing the part from the fixture.

With these aims, we develop the new concept of self adaptable swarm fixtures composed of mobile agents that can freely move on a bench and reposition below the supported part as required, behaving as a swarm, all without moving/removing the part from the fixture. In this view, each swarm agent is composed of:

-A mobile base,

-A parallel robot fixed to the mobile base with at least three degrees of freedom;

-An adaptable head with an adhesion arrangement that comes in contact and sustains the supported part perfectly adapting to the part local geometry.

Once reached the assigned location, the agent anchors to the bench and then adjusts position and shape of the head to the supported part.

Adjustment is carried out at two levels:

-The parallel robot provides fine tuning of the position of the head with resolution higher than that of the mobile platform;

-The head has a fluidly conformable shape and contains a material whose physical phase can be switched from fluid to solid, e.g. electro or magneto-rheological fluid; first the material in the head is fluid to adhere and adapt exactly to the local shape of the part to support; then the material phase switches to solid realizing a stiff support with an adhesion system that locks the part to the head.

The independent mobility of each support unit and the possibility for the agents to group at certain regions where currently required (e.g. regions where at that time some manufacturing operations are being executed) results in higher flexibility with lower number of support units (agents) than even the best of current state of art flexible fixture systems.

The new fixture concept involves several mechatronic and control challenges: Accuracy and reliability, adaptability to part geometry and safe holding, robustness (regardless of possible failures of individual agents), fastness of reconfiguration, locomotion and agent-bench docking systems, control of the agents as a swarm, power and signal transmission.

A hybrid (implicit/explicit) control system is adopted and each robot is treated as an autonomous agent exhibiting its own behavior. The overall task of finding adequate positions for the agents is planned based on part supporting requirements.

Behavior based repositioning of the robots to the goal locations is adopted to reduce planner complexity, with:

-No need to plan exact trajectories and

-No significant increase in complexity when extra units are removed/added.

The project objective is therefore to develop a swarm fixture for a large range of sheet shapes to fully replace the rigid and partially flexible fixtures used today. The focus is on, but not restricted to, the automotive and aerospace sectors. The performance in terms of flexibility, reconfiguration capabilities, leanness and competitive cost of this robotic system will contribute to the enhancement of competitiveness and efficiency of these manufacturing compartments.

Following the motivation to develop a system such like the SWARMITFIX, we strive to go a step beyond flexible/reconfigurable fixtures. With the clear goal to develop a system for higher continuous adaptation of production resources respect to production objectives and technical conditions in the knowledge-based factory is achievable today by synergic convergence of the NMP themes of flexible fixtures, parallel robots and new/smart materials with the ICT themes of robot swarms with networked embedded control. Today's smartest adaptable fixtures have limited adjustment capability, are mostly operated manually, are usually setup off-line with help of external measuring equipment, e.g. laser. Significant increase in effectiveness and decrease in cost may come from on-line fully actuated configuration/reconfiguration, large adaptability to different shapes and the capability to dynamically concentrate the support in the region where manufacturing is actually performed, doing that on-line and without moving/removing the part from the fixture. We propose the new concept of self adaptable swarm fixtures composed of mobile agents that can freely move on a bench and reposition below the supported part behaving as a swarm, all without moving/removing the part from the fixture.

Each fixture agent is composed of:

-A mobile platform,

-a parallel robot fixed to the mobile platform,

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A hybrid control system is adopted and each robot is treated as an autonomous agent exhibiting its own behaviors. Behavior based trans-location of the robots to destination positions is adopted to reduce planner complexity, with:

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The area of manufacturing of thin metal sheets is considered (aircraft and automotive bodies). The project objective is to develop a swarm fixture for a large range of sheet shapes to fully replace the specialized fixtures today used.

The new paradigms of manufacturing refer to High Adding Value, Competition, Sustainability and Innovation for products and processes in a holistic production system. In this framework robotics plays an important role but till now this role has been limited by peripheral robotics, grasping devices and fixturing tools that are mostly dedicated to a single part. The idea is to make these resources more efficient, intelligent and cooperative (high added value), more easy and faster to set-up (competition), more flexible and easy adaptable to different parts so to reduce inventory (sustainability), able to support thin sheets during the manufacturing operations allowing to use less material parts (sustainability) while reducing the mechanical complexity and fixture weight.

With reference to the call the project focuses on integration of reconfigurable technical systems and processes with integration of technical intelligence from sensors and actuators. SWARMITFIX combines the flexibility of a mobile robot, intelligence and reconfigurability of a swarm and the extreme adaptability of smart materials. In this context a fast and intelligent communication between the robots and the highly adaptive mechanism based on smart materials will be the challenging part of the project. This will lead to a system that automatically and continuously adapts production resources and processes in an optimal way with respect to business and production objectives. This flexible swarm fixture will increase the competitiveness especially of SME's with small batch sizes by providing an affordable intelligent technology that reduces the time needed for configuration and maintenance and that in this way allows a step forward to an efficient customer-oriented production.

The project main objectives are:

1. Rethinking the fixture as a multiagent swarm system to achieve high online adaptability and reconfigurability with minimum number of support units.

This is the main objective of the project. It will be achieved through the realization of a physical prototype that will demonstrate the concept soundness and functionalities with reference to the active support of the workpiece during the specified manufacturing operations (mainly drilling and milling). The validation tests will be performed within the Piaggio Aero premises.

2. Using swarm single agents, designed as parallel robots (for high stiffness and position accuracy) on a mobile base, able to freely move on the fixture bench to reach desired support locations, anchor to the bench, accurately position and orient their support heads.

The swarm unit is conceived and designed as an intelligent agent able to work by itself and able to collaborate and co-operate with other similar units.

This will involve:

-The application of advanced methods for the synthesis and optimization of task-oriented parallel robots under workspace, stiffness and accuracy constraints;

-The adoption of design criteria for cost effectiveness, robustness and reliability;

-The selection and development of suitable power transmission between agents and fixture bench and data communication from/to the agents.

A related activity is the development and application of engineering approaches to fulfill in parallel all the requirements including systems modularity, scalability, safety, and the development of criteria for benchmarking these properties.

3. Introducing the concept of phase-change fluid in the head of each swarm agent in order to get a perfect geometrical adaptation to the local shape of the supported part and at the same time to realize stiff support and clamping.

This objective is crucial as it addresses the realization of new supporting/clamping tools that gently adapt to the surface of the thin sheet part and firmly keep it blocked during the operation. It includes the application of know-how in the field of smart materials and their use in robotic systems for the development of the phase-change head, including analysis of local distributions of contact and reshaping pressures at the head-part interface and related influence on the local geometry of the part and on the holding forces during manufacturing.

4. Developing an offline simulator to program/check the fixture configuration for specific CAD sheet geometries and manufacturing cycles.

This will address the generation of the map of support locations by the supervisory controller based on CAD data of the supported sheet and manufacturing process information (NC file of the parts to be supported). The controller will use an internal simulator to determine the minimum of supports and clamps assuring correct overall position and shape of the sheet and will derive and manage in an optimal way the concentration of support agents in the regions under manufacturing. The setup of traditional fixtures is static; the swarm fixture concept implies dynamic setup because number and locations of the supports change during the execution of the manufacturing operations on the workpiece (the fixture continuously adapts to the progression of the manufacturing). The programming interface will make I/O and process easily understandable to the user and will manage the interfacing of the swarm fixture to the manufacturing system.

5. Developing an intelligent control system relying on high level intelligent organization control and low level behaviors of the agents.

A two tiers control system will be employed. One tier will be responsible for finding the optimal distribution of the support points and the other tier will be responsible for moving the robots to their destinations. The latter will be behavior based, thus each robot will be treated as an autonomous agent moving to its destination point, however avoiding collisions on its way. This objective will be achieved by steps. At the first step each robot of the swarm will be behavior based controlled, while the goal (i.e. the location) to reach will be produced by a high level planner. At the second step the complex high-level planning capabilities including all algorithms and methods will be implemented and setup to realize the targeted shape multipoint support.

Measurable and verifiable fixture performance objectives

-Orthogonal stiffness higher than 1 N/um (higher than in best today's Modular Flexible Fixture Systems MFFS)

-Absolute accuracy in all directions at each supporting point lower than 2100um and local deformation caused by head and head-part adhesion system lower than 100 um in all directions (with no external load applied) Repositioning time for each single agent lower than 60 s

-Design of the single support agents to concentrate more than 3 heads in a 200mm side square (estimated feasible for high-speed holing, riveting, etc.)

-Set-up time to reconfigure the fixture to a new part lower than 5 minutes (many hours for traditional aeronautics/ automotive fixtures and comparable to best MFFS and Robotic Fixtureless Assembly RFA)

-Outstanding adaptability compared to the more adaptable fixtures available for 3D thin sheet parts (estimated higher than 70%)

Project Results:

Once the requirements for the system, fundamental ideas and working principles were established and accepted by all the partners, several Scientific and Technical specific results were determined by the consortium. These not only had become the cornerstones for the project objectives to be fulfilled, but represent the way for further exploitation of the results as separate units or as whole. At the same time, these foregrounds represent a clear path to achieve the desired results and to comply with the fixed objectives, which in turn will lead to the innovative fixture system envisioned.

The Science and Technology (S & T) results that had driven the project to a successful were selected in such a way to let each of the partners to be directly responsible of one or more breakthroughs, needless to say with the intervention of other or the consortium as a whole when needed. The division was made according to the partners' expertise and proficiencies; at the same time, these foregrounds share the common principle of the system that is, the integration of different components, in different levels (hardware and software). It is important to stress that the solutions employed were in some cases independent from each other, therefore the exploitation of it can be achieved on their own. However, other solutions were completely dependent on others and the exploitation cannot be measured on their own. On the other hand, in the case were the innovations depend on others, the principles and core ideas of the solutions can be exploited on their own, leaving the physical development on a second plain of importance. This is a clear example of the adaptability and scalability of the system developed in the project.

The specific Science and Technology (S & T) foregrounds results selected by consortium and that have a bigger possibility of exploitation are the following:

1.Single support parallel robot module

2.Adaptable head module: sand head

3.Locker module 138 special

4.Powered bench

5.Swarm control and planning system HMI

6.Integrated SWARMITFIX

7.Adaptable head module 2: MRF

8.Exechon analytical kinematics and singularity/workspace analysis.

An explanation of the aforementioned Science and Technology (S & T) results achieved is given in this section.

1. Single support parallel robot module

The research within Machine Tools has always been driven to combine the flexibility and envelope of the robots with the accuracy and stiffness of traditional Machine Tools. In the last 20 years the focus of this development has been Parallel Kinematics Machines so called PKM. This technology means that the motions in X, Y and Z are performed by three or more parallel axis's that gives an outstanding stiffness and accuracy with a maintained flexibility and envelope. The first machine that actually proved this technology was the Tricept, a PKM machine, developed by Karl-Erik Neumann, that already 1994 performed real work in the industry (taken from http://www.exechon.com online).

The Exechon 5-Axis Parallel Kinematic Machine (PKM) is a successful design created in Sweden and adopted by many producers of machine tools around the world. A new version of the manipulator was developed as a component of the self-reconfigurable fixture system within SWARMITFIX project. The basic Exechon architecture consists of a 3-degree-of-freedom (dof) parallel mechanism (PM) connected in series with a two- or three-dof spherical wrist.

The Tricept developed by Neos Robotics AB, now produced by PKMtricept SL, is a particularly successful example of a tripod for machining applications. A new design, related to the Tricept, is the Exechon tripod, patented in 2006 by Karl Erik Neumann, who had also invented the Tricept in 1985. Unlike the Tricept, the Exechon tripod has no central stabilizing tube (a passive central leg).

PKMs based on several Exechon designs are now produced in China, Taiwan, Korea, and Spain and are commonly used as machine tools taking advantage of their flexibility and 5 axis motion. As said before a new Exechon variant, with smaller dimensions and a 3-dof spherical wrist, has been developed for fixturing applications within the SWARMITFIX project.

A big remaining problem (until now) in the PKM technology has been the fact that all legs and actuators have to be mounted in some kind of platform or structure allowing it to resist the forces from each legs individually and in combination, resulting in a very heavy design preventing it from being agile and mobile.

After almost thirty years since the first PKM machines saw daylight, a new PKM has been developed that can maintain, or even increase, its stiffness and accuracy by totally eliminating the previously mandatory platforms and structures supporting the legs and actuators.

The X150 has solved this problem by connecting the outer gimbals of actuator one and three, eliminating the need of central support of these gimbals and at the same time making it possible to add on extra material in the center, which was impossible in the platform design due to cable issues, resulting in increased stiffness.

This integrated one and three gimbal also prevent actuator one and three from twisting in relation to each other (when a side force is applied) on the machine, resulting in increased stiffness and improved accuracy. Furthermore, the outer gimbal of actuator two has been turned ninety degrees eliminating a center support for actuator two as well. This turned design also puts the holding points of actuator two right on top of the side structure, resulting in increased stiffness.

The new XT-Design makes it possible for an Aerospace manufacturer to pick the optimal size of PKM for every task in his factory optimizing the process and minimizing his investment. The new XT-Design has also made it possible to use various leg lengths on each model and also to mix heads, axis-4 and axis-5, and spindle size, between different modules, giving a variety of machines for a wide range of applications.

This opportunity has already been explored in some applications within Airbus and as it shows the possibility to choose a large range module with a smaller head and smaller spindle further improves the modularity and accessibility in complex parts machining and assembly.

Another difference found in this new design comes from the actuation system used. Since this version of the Exechon PKM is smaller and the relative loads will be carried by a specified number of them, the load capacity was changed. This means that different types of motors were used and a different control system was developed specially for the SWARMITFIX system. This is using smaller motors with Maxon motion controllers which have never been use to control the PKM's. Commonly it is used a CNC controller as the PKM's are normally used, as stated before, as machining tools.

Finally 2 prototypes of the X150 PKM have been manufactured and tested during the integration phase of the system. It has been seen that the envelope the agents can perform is sufficient to sustain and support workpieces with only 2 agents giving enough flexibility and adaptability.

The manufacturing of a future X150doesn't require any special skills or equipment apart from what is needed for manufacturing any high precision machine. The number of parts and the manufacturing and assembly process is well adapted to DMFA (Design For Manufacturing and Assembly) and the only thing that separates the X150from other machines is the specification of the low weight that will require the use of carbon fiber composite in some of the parts such as the legs, gimbals and the carrying structure.

The market potential for the X150will involve some guessing since it's a new way of thinking but it's also easy to imagine the use of two to four X150machines in every wing and fuselage structure made for every plane in the world ending up in hundreds of machines needed worldwide every year. If manufacturing of accessories such as engines, missiles, and other systems are added to the equation the numbers will certainly raise, and if we also look into the automotive industry the numbers of machines manufactured every year can be three digits.

In all modern automated assembly it is essential to be able to accommodate all kind of processes like surface detection, drilling, countersinking, orbital drilling, cleaning, sealing, and assembly, without having to develop special equipment for each and every application, and it is also important that an automated system can be adapted to various shapes and materials on large parts, such as wings and fuselages, as well as smaller parts like flaps and doors.

Historically this type of assembly has always required large, heavy duty, expensive machines designed and built with (and for) high accuracy over the entire work envelope and consequential such large machines been generally very complex and normally financially and physically impossible to build with more than one spindle/assembly tool.

To meet above challenges the aerospace industry must adapt automotive thinking but in contrary to automotive the processes in aerospace are highly accurate and have to be performed in tough materials like composite and titanium.

The future Exechon X150is a standard modular 'machine tool robotics system' combining the flexibility and dynamics of articular arm robots with the accuracy and stiffness of CNC machines. This new patented light design gives these modules extreme mobility and, in combination with adapting technologies such as cross lasers and force sensors, it can perform accurate agile operations over very large areas without the use of accurate large expensive heavy duty structures.

The investment needed to realize a final product of this type of PKM is thought to be of between 200 k Euros and 400 k Euros, which compared to the licensing price of 150 k Euros, is a very good business opportunity. Thanks to this, the market size has been valued of 15 M Euros to 30M Euros.

Regarding the ranking among the market of this type of machine, we can summarize the following:

-Articulate Arm Robots: The first electrical robots was developed in the beginning of 1970 as a technology that should replace human workers in fields of hard monotone and hazardous work like spot welding, arc welding and handling etc. The target was to build a robot with a large work envelope and a great flexibility without any requirement of high accuracy and stability which wasn't required for the applications in question. To achieve these goals the technology used is a so called serial linkage technology meaning that every additional axis is mounted on the previous one. This technology has the advantage of being able to move the mechanics in all directions giving the required flexibility and envelope however without accuracy and stiffness.

-Traditional Machine Tools: It's well known in the industry that all CNC Machine Tools has a very high requirement of accuracy and stiffness to be able to manufacture parts for an industry that requires microns of accuracy in combination with a high chip removal capacity. However, what people normally don't realize is that all traditionally Machine Tools on the market are also based on a serial linkage technology, like the robots, with all the disadvantages in the areas of accuracy and stiffness that comes with it. So, to compensate for this 'bad' technology the Machine Tool manufacturers have to design the machines with massive structures and wide beds to make sure that the serial linkage system maintain the accuracy and stiffness also in the end of the last linkage. However, these massive structures and wide beds totally eliminate the flexibility that is significant for robots.

-Parallel Kinematics Machines: The dream of all developer within Machine Tools has always been to combine the flexibility and envelope of the robots with the accuracy and stiffness of traditional Machine Tools. In the last 20 years the focus of this development has been Parallel Kinematics Machines so called PKM. This technology means that the motions in X, Y and Z are performed by three or more parallel axis's that gives an outstanding stiffness and accuracy with a maintained flexibility and envelope.

-XMIN: The X150developed within SWARMITFIX has managed to combine all above features a package those in a small handle size with a unique performance.

In terms of the competitors it is possible to summarize the following:

-Existing Parallel Kinematics Machines: Parallel Kinematics, as an occurrence, is a number of parallel 'arms' connected to each other in one end and to a base in the other end and by default this design requires joints with multiple Inactive Degrees Of Freedom (IDOF). The number of parallel arms in a Parallel Kinematics Machine (PKM) depends on the design and can vary from three arms up to eight arms but in all cases the target of the design is to combine flexibility and stiffness. Significant for all PKM machines is the problem of the joints, which are complex and difficult to manufacture with high stiffness and backlash free to the right cost. This technology issue limits the number of PKM machines on the market and is also the reason why the most successful designs are the PKMs with less number of joints and IDOFs. The Tricept is today the PKM with fewest number of joints and IDOFs and that's why the Tricept has 70% of the market of PKMs today.

-X150: The new Exechon Concept takes care of all previously described known PKM problems and features all goals for PKM machines such as, high stiffness in combination with extreme flexibility and dynamics. The new Exechon Concept is based on the use of fewer joints with no more than one Degree Of Freedom (1-DOF) and the use of actuators with two Degrees Of Stiffness (2-DOS), linear and bending in one direction. This design forms a solid structure that completely takes care of the bending and torsion forces applied to the machine in all directions.

2. Adaptable head module: sand head

The adaptable head modules developed in this project were separated depending on the working principle of the head. This is, depending on the applications and specially for addressing different industrial interests. This section is devoted to the Sand head module were DIMEC is the lead developer.

The sand head is the name employed to refer to the head module which uses granular material to adapt to the shape of the workpiece. The motivation of developing a support interface between agents and workpiece different from a commercial vacuum cup is; because the simple use of suction vacuum cups do not allow an adequate clamping of the metal sheet during the execution of manufacturing, it was thought then, to combine the action of a suction cup (reproduced in the form of an outer lip) with the action of a membrane containing granular material to increase the contact surface between the head and the sheet.

The principle idea, in which the scientific research and thus, expected results, were driven; was to create a vacuum head based on the principle of hydrostatic segregation and clustering of an incoherent mix of particles: suction of air from the inter-particular space is used to compact the material into a hard state. In a granular material the grains are arranged in space depending by external actions: when submitted to small mean stress the shear strength is very small and the granular material can flow almost like a liquid (i.e. silos); when the mean stress is high the granular material will be able to bear high loading such as in the case of infrastructures.

The final design of the sand head prototype was thought to optimize the operating conditions and reduce the dimensions of the module. It is conceived as a cup, covered by an outer lip that gives the necessary sealing for the vacuum to be produced. The powder is packaged in the center of the cup, held in place at the bottom side by a ring of silencers that conform the filter. At the top side the sand is packaged by a deformable membrane with a lens-like shape so to take advantage from the distribution of the material's stress and increase the stiffness with vacuum. On the bottom side of the cup, after the silencer a second membrane manufactured in rubber is encountered. The rubber membrane permits the repositioning of the powder into the chamber during the positioning of the head under the workpiece (introducing compressed air at the base of the membrane, it expands relocating the powder and filling the whole space of the chamber). The vacuum is given by 4 push-in fittings located at the bottom of the cup.

The prototype is manufactured with 4 plates; forming the powder chamber. In the following each plate is described briefly:

Lower plate: Contains a total of five holes in which 4 push-in fittings are housed to deliver vacuum to the head, 1 more push-in fitting used to pressurize the deformable rubber membrane and a groove which permits the passage of air.

-Collar: This component houses the ring of silences and is the main component if the powder chamber.

-Silencers ring: It is designed with an inclined face that is necessary to create the lens-like shape arc. Each silencer is mounted in a purposely designed hole distributed around it.

-Top flange: It is designed to mechanically lock the external membrane holding the powder at the top side of the module.

The vacuum necessary to harden the powder is produced using a vacuum generator. Between pneumatic connection and vacuum generator a filter is placed, to prevent the passage of grains into the ejector. During the first tests the filter has permitted to control if the particles flowed through the eight mini-silencers. From different types of powder that were tested, the final decision is to use Iron powder, which complies with the requirements of strength provided in the presence of vacuum and the dimensions of the grains of 45-150 µm, can not pass through the filter.

During the research, it was noticed that some amount of powder of certain types of materials were filtering into the vacuum generator, even though their granular size complied with the minimal grain size accepted by the filter; and hence were discarded. This happened because of the presence of funds in the powder. The selected Iron powder, in fact can present smaller dimension as long as it is without funds and a range in size of 10 to 1000µm.

The components of the sand head module prototype above described were purposely selected to achieve the specific results expected. Different options of material and working principles were studied until a decision was made, the components aforesaid play each of them an important role in the functioning of the head module. The most important are the following:

-External membrane: The membrane is a very important component of the smart head. It must be strong enough to resist to the repeating contact with the workpiece, and the sharp powder grains; moreover it must be thin to be well adaptable to the shape of the metallic sheet and easier to fix on the head. Another important requirement is a high friction coefficient to increase the stability of the workpiece. Originally due to concern of wear and tear, a membrane of 0.5mm and 1.0mm was selected. The selection was validated by the non-linear Finite Element Analysis. However, when trying to assemble the prototype, particularly when packaging the membrane and forming the necessary arc, due to the small head size, the membrane could not adapt to the required shape, specially it was impossible to avoid wrinkles in the membrane surface which is unacceptable due to contact surface differences introduced by such wrinkles. For this reason, a much thinner membrane of 0.12mm was used which provided good shape adaptability as well and reasonable wear and tear resistance. The thickness of the membrane was another reason for the selection of the fine powder, which moreover provided good shape adaptability and support.

-Cup shape design: The cup shape of the sand head module was selected mainly for two reasons; it permits to package the sand inside with no loses and can do so in the smallest size possible. At the bottom of the cup the necessary pneumatic connections are located an only simple interface between the robot's flange and the head is needed. Furthermore, thanks to the circular shape the manufacturing of all components present less complexity as well as the decreased complexity shown for the controller and planning modules. Thanks to the cup shape the controller does not need to control the orientation of the heads decreasing the number of degrees of freedom. Of course, this comes with a compromise. Given the shape of the cup and the workspace of the PKM, the distance between heads can not be as close to each other as wanted, however given the stronger and stiffer support given it is thought that the distance presented should be enough to avoid vibrations in the workpiece while manufactured.

The sand head module is assembled as said before, directly on the PKM's 6 DoF flange. This permit to fully take advantage of the high stiffness of the parallel machine, however due to the size of the mobile base the distance between each head of the two agents is greater than expected.

Finally, the research has been carried out in order to fulfill not only the project specific results but to give an extra option to the industry in the search of grippers or support components. The industry can benefit from a dedicated adaptable peripherals for all handling and supporting operations. The industries in mind are the aerospace, automotive white goods and all sectors that manufacture goods with large thin panels made of metal, composite and plastics. It is important to consider how the result achieved will rank against the already commercial components, in this case the sand head module is a component that proves to cost-effective with functional characteristics higher than suction cups especially regarding stiffness.

The closest competitors are: Manufacturers of vacuum peripherals and robot grippers. The closest product on the market is metal plate based vacuum cups for metal sheets but they are not adaptable to shapes different from flat.

At the end of the project the sand head module has been tested and the functionality proven, however in order to have a commercial component further tests are need and specially industrialization of the component has to be improved, specially since the manufacturing and assembly steps are not so easy if the module has to be mass produced. The time to market is considered to be of 2 years from the end of the project with an average investment of 50 k Euros. The market size is difficult to calculate at this stage, specially since it will depend on the acceptance by the industry, however each module or licensee to produce is though to be in the order of 5 to 15 k Euros, giving real possibilities to become a commercial product.

3. Mobile base and locker module VERO-S NSE plus 138 special

The purpose of this subsystem is to realize the motion of the agents on the bench. In principle, translational horizontal displacements realized only with motions in two perpendicular directions (x and y motions) is sufficient. However, it is increasingly desirable to have less strict non-holonomic constraints, i.e., to have the ability for the agent base to move in one or more diagonal directions. The main reason is the need for fast repositioning during milling, which may be impossible if the required displacement must be realized by two separate motions with a necessary full stop between them.

During the initial steps of the research carried out to define the best and more reliable motion operation of the mobile base, several locomotion principles were developed and studied to finally choose the one with the best performance. The various studied principles are: sliding, rolling in grooves, rolling with tracks, rolling directly on the bench, and swinging around a vertical axis. The later, the swing locomotion principle was selected in order to realize the mobile base. The mobile base or platform gives the first position tuning of the system, using the swing locomotion method and a 3 legged base with modified commercial Schunk lockers for the docking mechanism. The three legs are inserted alternatively in the bench. The base rotates about one inserted leg while the other two are pulled up; it then rotates at an angle and stops with the unused legs above free bench pins. Then, one of the latter legs slides in, while the former is pulled out keeping the third leg pulled up. The presence of one leg always inserted in the bench guarantees the equilibrium of the agent; and the special gear transmission provides the necessary torque for the agent to rotate orienting at the same time the retracted legs thanks to the two spur gears in each leg. Furthermore, the legs are equipped with the electrical female connectors providing electric power to the whole agent and the capability to transmit air from the bench to the on-board tank. Since the rotation is about a single leg the locking force has to be greater than 10 kN. This force is provided by the Schunk components that together provide:

- holding force of 75kN;

-draw in force of 18kN;

-repeated accuracy less than 0.005mm.

To actuate the legs of the mobile base assuring the complete detachment from the electrical connectors a maximum stroke of 45mm is needed, this is done by pneumatic cylinders capable of carrying out this operation in less than 0.5s in either direction. Thanks to the design of the mobile base, together with the docking and locomotion principles selected and developed, the swarm fixture demonstrator is capable of supporting the workpiece with only two agents, with the help of 4 passive supports. The fixturing can be done in any of the 3 conceived configurations of the system, vertical bottom-up (from the floor), vertical top-down (from the ceiling) and horizontal (attached bench to a wall).

DIMEC in conjunction with SCHUNK GmbH & Co, a third party supplier, had developed the locker module used in the agent's mobile base. The locker module is a spin off from the standard from the shelf component from Schunk that has been modified to adjust to the requirements needed in the project.

The locker is a patented product from Schunk and part of their 'Quick-change-pallet-system'. Together with DIMEC the necessary modifications in design were made. The changes were developed by the technical engineering department of Schunk always taking into account DIMEC interests.

The quick change pallet system from Schunk is a method of reducing set-up time that ensures higher machine running times and a more rational production from batch size 1. Especially in small batch quantities and a comprehensive range of workpieces, very significant cost advantages can be achieved with the VERO-S system. SCHUNK thus supports the trend toward greater production variability.

In order to increase life span and process reliability further, the base body and all functional components such as clamping pins and clamping slides are made of hardened stainless steel. Hermetically sealed against dirt, chips and coolant, the modules are completely maintenance-free.

The clamping slides are closed via spring force and self-lock the clamping pins. The turbo function provides as standard uses compressed air to increase the force in the spring packages and also at the piston surface. This increases the pull-in forces by up to 300%. Compressed air at a pressure of 6 bar is sufficient for opening the modules. When the module is deaerated, the spring packages lock the module automatically.

This module is used normally for retooling operations in the manufacture industry as well as positioning of the workpiece to be milled. However, in the SWARMITFIX project a different application has been envisioned and well accepted by Schunk. In the case of the SWARMITFIX project, the Schunk Vero-S system is used not for retooling but to lock the swarm agents to the working bench. In simple words, the lockers are used as feet for the agents so it can 'walk' over the workbench to the desired locations and then dock itself in the final assuring stiffness with the clamping force of 9 kN.

As described before, the agents utilize the swing method in their mobile base to reposition themselves bellow the workpiece. Thanks to the design of both the locker and the clamping pin (also used in the project), the reposition of mobile base can be done in a fast a safe manner. The entry radii of the pin permits joining even with a tilting angle or eccentricity. This is a major advantage since the control system does not have to worry of perfectly locating the pin above the locker with a certain tolerance. Of course, a close enough approximation is necessary to dock but by removing tolerances in the positioning certain parameters of calibration can be omitted.

As said before some modifications were developed to completely comply with the requirements of the project. These modifications were established by DIMEC and developed in conjunction with Schunk. The modification did not change the functioning principles and were not envisioned to improve the capabilities in terms of strength of the module. Principally, the modifications were introduced in the outside area of the locker.

The following is the description of said modifications:

-Air supply: In order to let the air supply be carried from the work bench to the whole agent, the locker had to be able to let the air pass through it. A special component was introduced. A small whole to house a coupling was introduced. Couplings are used to prevent leakage when transmitting liquid or gaseous mediums. The coupling elements are special mounting parts, which are built directly into accommodation housing. The system seal (axial seal) between coupling mechanism and coupling nipple acts axially and is placed in the coupling mechanism. The coupling nipple is located in the bench and when interfaced with the coupling mechanism inserted in the locker the air is permitted to free pass through. This modification is of the out-most importance given that without it a pipe less functioning of the agents would not be possible.

-Anti-rotation pin: Also in the circumference generated by the mounting screws an 8 mm diameter whole was introduced, this is to permit the anti rotation pin located in the bench to be inserted. At the same time this pin gives the orientation of the locker in the bench. The whole is made with H7 tolerance and it is the principle centering component on the locker. If this pin is not correctly aligned with the respective whole introduced in the locker the locker can not be clamped. At the same time, this pin lets the agent rotate about the clamped leg.

-Central removable plug: The central removable plug located in the locker is a standard feature of the component; however in this project the use has been little modified. The whole is envisioned to provide a blow-out function which in some way is used. However the major interest of having through whole in the middle of the locker was to provide a place in which electrical connectors could be placed and at the same time use the blow-out function to blow compressed air as part as the cleaning system describe before. The electrical connectors embedded then in the locker permit the agent to take the necessary electricity directly from the bench. The same way as for the air supply, this lets the agent to work wireless, thus without introducing constrains in its operation due to wires hanging around the mobile base.

-Clamping Schunk pin: This is a necessary accessory also from Schunk in order to use the locker; this will be addressed in the section Powered bench.

It is easy to see the enormous usage the modified Schunk locker component can have and the good acceptance in the market, every manufacturing sector where holding of workpieces were high accuracy and stiffness are required and at the same time electric power has to be provided will be a direct beneficiary of the research benefiting from the standard capabilities of the module plus the added value that supplying electric power generates.

At this stage there is no direct system that can give a robust quick change pallet system that comprises in the same solution the capabilities of electric power distribution. Manufacturers of equipment for manual and partly automated fixturing especially in the area of manufacturing will be competitors after they develop a system with the same characteristics.

Taking advantage of the fact that the standard is already developed and has great acceptance, it is thought that the component can represent a big opportunity for Schunk. The market size calculated is in order of one to five M Euros with an initial investment to fine tune the modifications and improve the electrical connector of 10 to 50 k Euros and a relatively short time to market in the company decides to pursue this opportunity.

4. Powered bench

The work bench is one of the most important results obtained during the project, without disregarding the importance of the whole project of course. However without the working bench the locomotion and hence the functioning of the agents would be impossible. Furthermore, the bench can be on its own and important commercial component for every system using the quick change pallet system from Schunk and in need of pneumatic and power supply. As already established, we have used commercial docks provided by the Schunk comprising a female and a male unit. One of the two units is a simple and passive mechanical interface while the unit with opposite gender is equipped with the mechanisms for the generation of the locking force. The units in the bench, which are numerous, are the passive ones while the units in the agent are the ones equipped with the locking equipment in order to minimize the cost of the system.

Initially research was made considering a type of unit with simple female and male unit with locking mechanisms. A design of the agent has been completed with these units and static and structural analyses have been carried out on the mock-up of the system. The locomotion of the agent on walls and upside-down was possible with limitations in the load and velocity of repositioning so a decision was made to change to a different model of locker with passive male and higher load capacity and stiffness. This final locking system comprises equipment for the feeding of compressed air to the agent, electrical power to the agent and equipment for blowing out the swarf and cleaning the surface before locking.

The bench design was done taking into account the presence of a big amount of swarf generated by the manufacturing process. The agent cleans its path blowing the chips before every relocking. The passive males of the lockers, distributed on the bench, are placed on tall cylinders in order to create canyons where the chips are collected and blown down into holes.

The electrical power is transmitted to the agent through special electrical connectors located in both docking units, male and female. The male unit is equipped with the male connector and takes the electricity from the power generator. The female unit, when docking aligns and inserts the connectors to receive the electricity. During the assembly of the electrical connectors, these must be aligned so the connection is always assured. At the same time, when the agent is rotating, the electric supply is assured and when completely docked the three legs are receiving electricity.

The bench comprises a structural (base) layer made of steel, the Schunk clamping pins assemblies and electrical and pneumatic supply located at the bottom of it. It is a planar design with 52 pin modules in which the agent can dock.

The 52 clamping pin modules are spread out in the bench in such a way to permit the agents swing motion to be realized at intervals of 60 degrees rotations. This, at the same time assures the correct positioning of the agents throughout the whole bench and assures any position under the workpiece to be possible by the agents.

The pin modules are made of 5 components, the steel column which is the main component housing all pneumatic, electric and mechanical components needed, a sub assembly module in which the Schunk pin is screwed, the alignment pin, Schunk pin and electrical male connector. The Schunk clamping pin has also been modified from its standard version in order to let it house the electrical male connector. The standard version of the Schunk locker accessory, cab be fixed nominally by a separate screw from the top side, so the used thread is located in the housing of the pin; or also from the bottom side with a bigger screw utilizing then the thread located in the pin. For the SWARMITFIX system a modification was implemented so to be able to pass the cables and locate the male electrical connector in the middle of the clamping pin. The inside thread of the pin disappeared and a bigger through whole and neck were placed. The only way to install the modified clamping pin is now by a purposely created thread on the new neck design.

In the bottom of the bench, as said before, the necessary pneumatic and electrical components are located, each of the 52 modules receive electrical power and compressed air from the main power source and air compressor respectively. The power generation is controlled by a relay system which means the bench has 52 relays and a Maxon controller connected to an I/O card installed in the controlling PC. The air supply to the agents is passively controlled by the couplings located in the both the mobile base that has already been described and in the clamping module, simply when the agent is docked to a column the couplings permit the pass of air filling constantly the on-board tank. For the cleaning system to be controlled, the bench is fitted with a Festo valve block controlled directly through the HMI.

The cleaning system is divided in two parts:

-Cleaning system in the bench by blowing air directly from the pin modules;

-Cleaning system on-board the mobile base, blowing air to the bench surface.

With the selected design the swarf is blown purposely in the correct direction away from the module's surface and directly to the base legs surface assuring a proper contact between the two. In the bottom part of the workbench electrical and pneumatic connections are housed, the rows of clamping modules are supplied by rows of connections forming a fork like system underneath the bench. The pneumatic and electrical components rows of the fork like housing system utilized, are intercalated between them, making easy to recognize which is row is for electrical components and which one is for pneumatic components. To level the bench, protect the connections and fix it a frame was created. It also gives the capability for the bench and hence the whole system to be mounted in different positions increasing the modularity and customization of the fixture system.

The work bench represents innovation in the form of a unique modular bench supporting continuous reconfiguration in presence of large amount of swarf, guaranteeing accuracies comparable to manual reconfigurable benches. Its robustness contributes to a continuously increasing accuracy needed in the manufacturing industry. Once the technology is proven different sizes can be created depending on the specific end user application.

During the trials in Piaggio Aero premises, the bench has been tested and has successfully proven its capabilities. The pneumatic and electrical characteristics are enough to power in both ways the agents, electrically and pneumatically. The blowing of swarf has been tested as well with satisfactory results, however a problem in the Schunk clamping pins prevented for further trials that remained pending, such as installation in vertical configuration and on the ceiling, however it is safe to assume that once the third party component problem is solved there are no clear evidence it should work in a different way than it has been performing.

Companies manufacturing large workpieces with strict accuracy requirements and high flexibility needed will be directly benefited by this innovation. At the same time, with the functioning principle developed in SWARMITFIX, different work bench sizes and even shapes can be developed. The final customer will benefit of a workbench easy to install with low setup time, full online reconfigurability with stiffness and accuracy performance typical of traditional reconfigurable fixtures.

In terms of market there is a very viable business future for such a innovation, even with the elevated cost ranging from 200 to 400 k Euros depending on size and architecture the market opportunities and size round the Million Euros if well accepted in the market and replacing in use systems like gantry positioners for machining units and reconfigurable fixtures. At this moment there is no such a commercial system that gives the benefits of the SWARMITFIX workbench that can be characterized by a cost per unit area of bench, high and constant accuracy in every location competing in applications were flexibility is a must.

Since the core ideas are patented, and the fact that active repositioning on a bench accurate and robust to swarf is not easy to realize it is expected a relatively long time before competitors propose alternative solutions.

5. Swarm control and planning system HMI

The control system has been designed following a formal approach based on the definition of the system structure in terms of agents and transition function definition of its behavior. Thus, a modular system has resulted enabling software parametrization. This facilitated introduction of changes is brought about by testing different variants of the mechanical structure of the system. A novel approach to task planning for a self adaptable and reconfigurable fixture system has been developed as well. The solution for task planning is based on constraint satisfaction problem approach. The planner takes into account physical, geometrical, and time-related constraints.

An off-line program, on the basis of CAD geometric data about the panel, representing its state before and after machining, generates the plan of relocation of the mobile supports and the parallel manipulators. Some optimization techniques will be used for that purpose. The panels will be subjected to the following machining operations:

-Drilling: in this case the support locations depend on the form of the material. One static configuration of several manipulators will serve the drilling of a number of holes,

-Milling: which is a continuous process requires the manipulators to relocate during milling. This has to be done fast enough so that the current milling speed will not be affected

The supervisory controller uses the plan produced off-line to control the manipulators during machining. The manipulators have to relocate themselves during machining. The off-line program will find the optimal locations for the supporting heads and the trajectories of the mobile bases of the swarm agents. This will be based on geometrical data. The supervisor will produce the desired time-dependent trajectories for the p-agents.

For the purpose of the considered project, physical agents (or in short p-agents) are composed of the mobile base with Schunk lockers, the manipulator and the supporting head, i.e., the mechanical components. However, for the purpose of the design of the control system each such agent will be decomposed into smaller entities, each composed of a single effector. This effector together with its control equipment and software implementing the control algorithms will be termed a software agent (or in short s-agents). S-agents are distinguished in such a way that the control system software assumes adequate modularity. Thus one p-agent can be decomposed into several s-agents.

The p-agents relocate themselves over the workbench, which contains the docking elements forming a mesh of equilateral triangles. The mobile base of the p-agent, when supporting the machined plate, is docked to three docking elements. During transfer to another location it detaches from two of the docking elements and rotates itself around the one that remains attached to the base plate. There are six docking elements it can reach in one step, thus it can rotate through intervals of 60°, i.e. 0°, 60°, 120°, 180°, 240° and 300°. The p-agent draws energy from the powered bench using the modified Schunk lockers embedded with the necessary electrical connectors. A high capacity capacitor is used to control the electrical current discharge when the relocation has finished and the 2 legs are inserted back to the work bench.

Once the mobile base is securely locked to the bench the manipulator (the parallel kinematic machine - PKM) rises the supporting head to the prescribed location, thus providing support to the machined plate. Initially the head is soft, but once it has reached the prescribed location it is solidified.

An embodied agent is comprised both of the hardware and the software components. The hardware components (effector and receptors) are equivalent to the p-agent and the control subsystem of an embodied agent (the software component) is equivalent to an s-agent.

For the final user to be able to use the system without having to invest much time in understanding the control system itself, a user interface has been developed. The interface is done in a simple way so it is easy to use and self explanatory. With this interface the user can command all the parts of the prototype, bench, mobile base, pkm and head, all at the same time or each separately. The control of the complete agent, can be done in teach or jog mode which means the user can bring the agent to the desired position and save that configuration in order to create a new plan.

On the other hand, a plan coming directly from the planner software can be executed just by launching the specific task. A complete plan can be, at the same time, executed in automatic mode; in which the agents will go to the locations until they reach the final location; and in step by step mode in which the user commands the different movements of each agent and if needed can skip one step. The step by step mode can be used firstly to corroborate the positions of the agents and also to realize fine tuning.

The interface is designed in a way that the different components of the system are named as robots; this means there are, in this first prototype, 7 robots (sbench, smb1, smb2, spkm1, spm2, shead1, shead2). Once the interface is launched the effector driver process (EDP) of each robot has to be loaded, or in turn only the EDP of the desired robot. When the EDP has been loaded for the first time after turning the power on, synchronization for all robots launched, but the sbench, is needed. Once all robots are correctly synchronized the master process (MP) can be launched and a plan can be either generated or run.

Finally, although the module is not used in the interface it is intrinsically embedded as well. It creates an XML file with all the locations of the agents, the file path is set in the configuration file and thus read once the interface is open. Each item of the XML file represents one location or configuration of the agents, it can be exported into the interface so the user can see that specific position and tune it if needed. Also, when in jog mode, the configuration can be saved directly into an XML file. If a manual plan is being created this is the easiest way to do it.

6. Integrated SWARMITFIX

With the SWARMITFIX fixture an RFA (robotic fixturless assembly) system has been developed at a higher level of modularity and flexibility. It merges the advantages of RFAs with those of MFFSs (modular flexible fixture systems), namely: the ability to distribute the support action; adaptability to workpiece shapes in a larger range; and stiffness of the provided support.

The swarm fixture agents have to satisfy requirements analogous to the ones of multi-posts fixtures in terms of adaptability of workspace of positioning of the heads, head adaptability, force of adhesion and stiffness.

A critical characteristic of the fixturing system is the size of an individual agent. It is higher than post units due to the embedded actuators, sensors and docking-locking devices. This gives some limitations in the number of agents that can concentrate in a region and has influenced the choice of the degrees of freedom of the head positioning mechanism.

After the integration phase of the SWARMITFIX project that had taken place in Piaggio Aero premises in Finale Ligure, Italy; can be concluded that the first industrial-level swarm fixture ever realized is a success up to some extent. As any new system developed nowadays in the world a very extensive trial phase has to be made in order to really have a commercial product. However, after the evidence provided during the integration and trial phase it is safe to assure, that although improvements can be made, the system complies at the very least with the aforementioned minimum requirements specified by the consortium of the project.

It is known by all the partners that industrialized activities are needed in order to be able to enter the fixturing market with a commercial product; of course, commercializing this system is an immediate spin-off from the project. At this stage, we have created only the first prototype that will serve for trial purposes as well as for engineering and industrializing activities of the system. It is thought that between 3 to 5 years are needed to really be able to offer a proven product to the industry.

It is important to stress that the project has come to a successful ending, having the demonstrator to realize manufacturing operations with no constraints other than the velocity in repositioning of the agents. These constraints have been inserted only for precaution and in the near future will be removed.

The prototype was completely integrated for the first time in Piaggio Aero and consists of:

-Fully functional workbench, air and electric supply embedded.

-2 fully functional agents consisting of mobile base, pkm and MRF head

-4 passive supports with adjustable height to hold the workpiece in place on the periphery with vacuum cups and dismountable joints for precise location of the workpiece.

The prototype was mounted as said before in Piaggio Aero premises in Finale Ligure under the 5 axis vertical machining center from Jobs S.p.a., Jomach 032; and manufacturing operation trials were realized utilizing thin aluminum sheets of 1.2mm thickness, the operations were mainly those of drilling 5mm wholes and milling of a prescribed shape with an 8mm mill tip.

The physical demonstrator is installed in a very simple way; the major issue encountered within the installation point of view is weight of the workbench, that being nearly 6 tons, makes difficult the first positioning or at least special movable crane equipment is needed. The workbench was stabilized and balanced to assure a perfectly horizontal plane of the support columns in which the agents clamp.

Another issue encountered is the total height of the demonstrator, although this issue is easily avoided and can be seen only as a partial problem, completely depending on the installation site and the end user manufacturing capabilities. The first solution for the height issues can be simply avoided by installing the bench in a purposely made whole in which all the connections needed can be previously installed, this, in fact represents the final installation intended by the project consortium, however it was not possible to change the installation site inside Piaggio Aero premises due to their constant production. The second solution is as simple as using a bigger CNC center in which the Z axis gives more space or even a gantry machining center used throughout the manufacture industry.

After the integration, clear indications of the modularity and scalability of the system are appreciated, being this the first prototype it was developed only a certain type of bench, base and heads, however the main idea is to be able to, given the geometry of a family of workpieces, select the size and geometry of the bench, as well as the number and types of agents. Individual agents can have different heads, varying in size, adaptability, stiffness, and adhesion principle. This is clearly accomplished even though is not possible to be shown with the demonstrator. Only the two types of head are present and depending on the operation, characteristics of the workpiece and end user specifications one can choose which head to use. Following the design requirements and the prototype developed if it is needed different sizes and types of agents can easily be developed.

At the end of the integration phase and after the agents functioning was thoroughly tested and assured, manufacturing operations were carried out. Utilizing the control HMI, a plan created by the offline planner module was loaded. Given the differences of the virtual plane in particular the differences inserted by the curvature of the metal sheet the generated plan was fine tuned in order to achieve good support contact throughout the whole agent configurations.

As this was the first trials, the machined part consisted of a rectangular shape to be milled and a set of drilled wholes inserted. The different positions o the heads are selected by the planner in order to assure correct support when the CNC machine is in the vicinity of the heads, or better said the heads had achieve their final position and exert the prescribed suction force at a correct position and orientation to assure the support of the metal sheet. It is important to remind that the time the 2 heads are supporting the workpiece is very short, since with this prototype while one agent supports the other relocates. At the same time by letting the heads apply vacuum at the same time, even for a very short period of time, we can assure the second head will be in contact with the workpiece.

The created HMI as mentioned before in its own section has proven to be very robust and easy to use. It is self explanatory in the most cases and just minimal information is needed to anyone that would like to use. The plan can be generated as well, by using the interface and deciding each location by the end user instead by the planner. In a final product version of the system, this could be helpful is small simple parts are needed to be manufacture or if just certain extra operations are needed. For example, nowadays if the new drilled whole is needed due to an improvement in design, the metal sheet has to be fixed to the support fixtures and in many cases even the fixture has to be improved to follow the new design. With SWARMITFIX fixture system is only a matter of seconds to mount the workpiece in the peripheral passive supports, and just a couple of minutes to locate the supporting agents in the desired locations. This operation mode although not recommended is possible and gives new possibilities to the manufacturing industry.

The relocation time of the agents during an automated plan execution at this stage is around 4 seconds depending on the amount of dof that need to be moved. It is important to stress that the slowest movement at this stage is that of the mobile base that has been constrained for safety, this means the relocations or in other words the walking of the agents can be done much faster.

The SWARMITFIX project has always been intended to be a solution for the manufacturing of large thin metal aluminum panels; this means that the focal point of interest within the industry is that of the aerospace, however, also automotive industry in particular bus and truck manufacturers as well as train industry can benefit from the system. In particular the final customer of the system can be benefited from an unachieved flexibility so far, constant accuracy over any extension and full compatibility with the manufacturing environment in presence of swarf and cooling liquids.

From this point forward, in order to arrive to a fully commercial product investment is needed, however it is difficult to establish the amount, this is because it depends on how well accepted within the industry the system is. An important point is that after the first developed prototype an approximate price can be speculated rounding the 1 M Euros for a system comprising 4 intelligent fixture agents, a 10m x 5m bench and a set of passive auxiliary supports to hold the workpiece in the periphery. Furthermore, again stating from a good acceptance pf the system and the new trend being developed for the manufacture industry the market size over a single year can be estimated to be around the 10 M Euros.

The acceptance and thus the market opportunity comes as well form the fact that at this moment the system cost is proportional to the scale and constant performance, competing with other products for similar use on large sizes and with high flexibility needed. Furthermore there is no direct competitor that can provide the same characteristics embedded in a single product, the closer competitors are producers of reconfigurable fixtures and rigs with partial adaptability embedded, multipoint adaptable fixtures and at some extent manual reconfigurable fixtures producers. The growth of swarm fixture in the market is based at least for the first years on improvements of in use technology.

7. Adaptable head module 2: MRF Head

As already mentioned, two adaptable head modules were developed during the SWARMITFIX project. The MRF head module utilizes special material to conform to the wide range of panels having different surface curvatures. In simpler words, the head needs to adapt and adhere to the local geometry of the surface were the machining operation is been carried out. Following this particular characteristics the MRF head module was designed to comply with the following requirements:

-Enough yield stiffness to hold the panel and withstand the machining forces

-Rigid adhesion to the sheet keeping constant contact during milling and drilling operations

-Self adaptability to the workpiece

-Fast operation time

-Insensible to thermal changes

A comprehensive study was carried out in order to select the material that could comply in the best possible way with the different requirements. The study involved memory metals and phase change materials such as; thermoplastic materials, fusible alloy, electro-rheological and magneto rheological fluids. And the magneto-theological fluid was selected.

Magneto-rheological fluids are stable suspensions of magnetically polarizable micron sized particles suspended in a low volatility carrier fluid, usually a synthetic hydrocarbon. The fluid used in the final prototype of the MRF head module has characteristics of low off-state viscosity and fast response time. These characteristics helped to allow easy and quick adaptations to the surface contour of the workpiece.

The MRF head module adaptation to the workpiece is in principle more complex than that of the sand head module, in particular because of the necessary internal changes needed to change the material phase from fluid to solid. The adaptation is at two levels: the head is mounted on a joint and it rotates matching the (approximate) orientation of the part surface (initial adaptation); after this initial rigid-body adaptation, the head body is pushed against the workpiece using also the adhesion system embedded in the head which generates an internal force between head body and workpiece (secondary adaptation). The adhesion system for the MRF module is also vacuum making the exchangeability between the two head modules to be easier and decreasing complexity to the control system. The head body, at this stage, is compliant-plastic and it deforms matching the local geometry of the workpiece surface.

The final design was developed once all the functioning principles were selected. This was needed in order to decide the final shape and packaging of the module as well as the actuation principle employed. A brief description of the individual components that made the MRF head module is given.

The triangular shape is needed in order to guarantee an optimal support during milling and drilling. At the same time, the triangular shape permits a shorter distance between the border of the head and the tool. It is composed of 4 major components: triangular base, guidance, pistons with O-rings and rubber cover.

-Triangular base: It is the lower part of the triangular head and is made of T 300 Series Stainless Steel austenitic. The material was chosen to guarantee the effect of the magnetic field on the MR fluid. Presents the channels in which the magneto-rheological fluid is introduced. Each channel is designed to lead the MR fluid from the central collector to two of the holes of the guidance, whereas the channels at the edge of the triangle lead the fluid to three holes. All the channels are connected to the central collector, so all the 27 holes of the guidance are in order to allow all the movements needed by the pistons to adapt correctly to the surface of the workpiece. It also presents the necessary holes to insert the vacuum connector and the proximity sensor.

-Guidance: The upper part is made by aluminum, to prevent the magnetization of the sheet during processing. Since the part is the guidance for the 27 small pistons necessary to support the workpiece, to minimize corrosion and wear of the guide holes it was chosen as material Al 6082, a medium strength alloy with excellent corrosion resistance.

-Pistons and O-rings: The small pistons are 25 mm long and have a diameter of 6 mm. To guarantee the contact with the surface, the pistons have a circular head. In order to reduce the friction between the pistons and the guidance the selected material for the final prototype is Delrin. To prevent the loss of magneto-rheological fluid the pins present two seats for o-rings, endless round sealing rings of circular sections. An O-Ring seal is a means for closing passageway preventing an unwanted escape or loss of fluid.

-Rubber cover: It is located at the top of the guidance and glued to a purposely designed protrusion. The material used is a vulcanizable at room temperature silicon by means of a polyaddition reaction.

The triangular head of the MRF module is the core of the development attempting to introduce a new kind of adaptable fixture that can replace the vacuum cups or commonly used grippers. However, a means for activating the phase-change material is needed as well as an actuator to rotate to the proper orientation the head. These can be seen as the core body of the module and are the pneumatic cylinder, servomotor and bracket used to connect the head module to the PKM.

-Pneumatic cylinder: The pneumatic cylinder is needed only to move the neodymium magnet located inside it to supply the magnetic field needed to increase the viscosity of the magneto-rheological fluid. In this way once the small pistons have adapted to the workpiece shape, the cylinder is actuated sending the magnet close to the fluid collector and solidifying it. The cylinder is divided in two parts, the upper part holds the magnet while the lower one is connected to the air supply and holds the necessary seals to prevent air flowing away from it. On the outside part of the lower section of the cylinder, two bearings are located interfacing the bracket; these are needed to let the module rotate in order to achieve proper orientation. At the bottom of the lower section a cap is screwed to hold the servomotor.

-Servo motor: The selected actuator is a Harmonic Drive hollow shaft servo motor capable of rotating the head module to the desired orientation according to the workpiece shape.

-Bracket: The bracket is used to interface the module to the PKM and locate the necessary bearing that will let the module to rotate achieving the orientation needed. The cylinder is inserted in the bracket and secured by screwing the motor to it as well. On the other hand, the bracket is also screwed to the extension arm that comes from the PKM 6 dof flange. This, although decrease the stiffness of the parallel machine, is needed to let the plan calculate feasible locations of the heads.

The physical prototype of the head was tested during the integration phase of the complete system in Piaggio Aero. The MRF modules were assembled to the swarm agents by the connection arm. At the same time, this arm not only actuates as the interface between head module and PKM, but it gives the necessary space to install the different components needed to actuate the MRF module. These are the vacuum generator, 2 pneumatic electro valves controlling the cylinder and vacuum generator, the signal processing unit for the proximity sensor and the Maxon motion controller for the servo motor. One of the most complex issues of installing the head module in the agents is the need to rout pneumatic pipes and cables form the mobile base all the way to the connection arm.

During the trials the MRF modules were utilize for supporting an aluminum sheet of 1.2mm in thickness while milling and drilling operation were carried out. There is enough evidence at a first glance to prove the working principle. It was clear, that when the CNC machine was realizing the operation, either milling or drilling, in the vicinity of a supporting head the vibrations decrease. For an MRF to be in supporting mode, several things are needed, first the PKM realizes and initial approach, second the harmonic drive installed in MRF module rotates the triangular shape accordingly to the shape of the desired workpiece, then a final approach is realized where the vacuum is activated and hence the head comes to contact the workpiece. Finally, once the head is in complete contact with the workpiece, the pneumatic cylinder is activated to fix the position of the 27 pistons that have adapted to the local geometrical surface.

8. Exechon analytical kinematics and singularity/workspace analysis

The equations used to describe the kinimatics of the PKM are better seen in the attached PDF which presents a synthesis of the whole development of the kinematic analysis reported in the scientific article (Zoppi, M.; Zlatanov, D.; Molfino, R. 'Kinematics analysis of the Exechon tripod'. Proceedings of the ASME 2010 International Design Engineering Technical Conferences and Computers, August 18th 2010.)

For the single support parallel robot module (Exechon X150 PKM, described in section 3.1) to be controlled, the kinematic analysis was needed. It is common to solve this paradigm numerically; however strong computational capabilities are needed and the operation time is increased not to mention the needed space to install a robust enough computer on board the agent. In order to optimize the performance of the system, in both operation time and space, the analytical analysis and solution was developed.

The PM has three legs herein labelled A, B, C. Two of them are identical 4-dof RRPR chains A, C, that ignoring actuation, each of the A or C legs, as well as the two legs combined constrain the end-effector of the PM as an RE chain, a revolute followed by a planar joint, with the R axis perpendicular to the normal of the E joint. The remaining leg, labeled B, is a 5-dof SPR serial chain. Its last joint axis, the revolute fixed in the platform is parallel to the planes of planar motion of legs A and C. Furthermore, the direction of the prismatic joint is parallel to the normal from the center of the spherical joint to the revolute axis.

The end-effector has three degrees of freedom which means that its feasible poses form a three-dimensional subspace of SE(3). Indeed legs A and C constrain the platform to perform planar motion in a rotating plane, i.e. into a four-dimensional sub-manifold of SE(3). The third leg is with 5 dof, therefore the platform must have at least 3 dof. However, it is clear that not all of the four freedoms permitted by the RE legs are possible, as the 5-dof leg allows translational motion only in directions parallel to the plane which contains the center of the spherical joint and is perpendicular to the platform revolute axis. Thus, not all translations parallel to the plane Pi alpha, allowed by the RE legs A and C are allowed by leg B. Therefore, only a three dimensional space is the intersection of the motion end-effector motion patterns allowed by the legs.

This means that locally the motion can be described by three parameters. In general, this does not imply that there is a global choice of the three parameters, which will describe the pose in a non-singular manner. However, this is possible for this mechanism. A non-singular representation is e=(alpha,beta,h) . The angle alpha describes the rotation of Pi alpha, the rotating plane of planar motion of legs A and C. The angle beta is the planar orientation of the platform in Pi alpha. The third parameter, h, measures how far the platform is translated from the projection of the projection of the spherical joint, onto Pi alpha. The triple e describes the pose of the PM platform unequivocally for any geometry and configuration.

There is a simple linkage that reproduces exactly the motion pattern of the PM. It can be described as a serial chain with three joints, with its first joint realized by a 1-dof 2-RP planar parallel mechanism, while the second and third joints are a revolute and prismatic joint.

Inverse position kinematics

In practice the PM is used as a regional manipulator, a 3-dof positioning device, with a typically spherical wrist attached to the end-effector at point S. This results in a combined hybrid manipulator, like the 5-dof Exechon PKM and the 6-dof fixture agent X 150. The end-effector of this hybrid chain is denoted by ee.

We have assumed that we have a 6-dof mechanism with a spherical wrist, centered at S. When solving the inverse kinematics of the hybrid tripod the first (easy) step is to obtain the coordinates of point S, which is a known point in the body ee whose location is given.

From this, one proceeds to solve the inverse kinematics of the 3-dof parallel tripod, from a given point S of the 3-dof platform. The result is the three input parameters, for example, the joint variables of the prismatic joints. To complete the inverse kinematics of the 6-dof hybrid manipulator, it remains to obtain the joint variables of the three actuated joints in the serial spherical wrist. This is obtained from the relative orientation of the hybrid chain end-effector, ee, and the PM platform, e, by means of a standard Euler-angle calculation.

The overall process for obtaining the inverse kinematics will not reported in these lines, due to the large amount of equations.

This analytical solution of the inverse kinematics of the PKM is used by the control system to move to the desired position the PKM. It basically solves analytically the configuration and returns the necessary Euler angles of each joint. The controller user interface is capable of exporting the current configuration Euler angles into a separate file and thus create a manual plan from them. On the other hand, if one wants to drive the PKM to a desired location and knows the Euler angle of such location, it is possible for the user to import these angles as XML to the interface and execute the motion.

Potential Impact:

Being the goal of the SWARMITFIX project to create and original autonomously reconfigurable fixture system; there is a lack of familiarity surrounding the novelty of the concept and technology in both industry and research centers. At the same time the novelty of the concept and system developed give place, according to the consortium, to an important economical impact especially in the fixture and manufacture industries.

The impact on 'New generation of products helping European instrument manufacturers and machine builders to stay ahead of the competition' is achieved through the following recalled objectives. These intelligent devices solve a problem of growing importance for aircraft and automotive industries where the amount of material is reduced for costs and life cycle Eco-consistency reasons. These sectors represent in Europe more than 450 billion Euros (ACEA 2001 and EADS 2007 data). Near future applications are also foreseen in the railway, metal construction and furniture, white industry and ship building sectors.

Furthermore the project strongly impacts the MANUFUTURE 2007 rationale: leadership in sustainable development: environmental friendly processes, low energy and materials consumption, safeguard of manufacturing employment in Europe.

Potential expected impact

The SWARMITFIX project specific objectives have been outlined in a way that obtaining such results the impact in both industrial and socioeconomic level will be maximized. According to each attained objective expected potential impact can be achieved. A relationship between the expected impact and the specific objective that will help to achieve the said impact is given as follows:

<u>Adaptive production systems</u>

The project will contribute to the development of new manufacturing systems that adapt to flexible, small or even single batch oriented production. Today, adaptability of production systems relies on available robotics and it is limited by the devices that interface directly the pieces to be manufactured like fixtures and grippers. The problem of modular and adaptive fixtures has been considered by different research actors but no solution till now satisfies completely the requirements on agility and adaptability addressed by the work programme.

<u>Rapidly configurable machines, self-adaptive machine structures, self-optimization. reduction of time needed for reconfiguration and maintenance</u>

The swarm fixture developed, with simple robots reconfiguring in real time to adapt to different thin sheet shapes, will substitute sets of complex specific devices purposely designed for a very limited range of pieces. This results in savings in cost and reduction in fixturing and set up time. Modularity of the homogeneous robots swarm guarantees fast maintenance and scalability. Furthermore the new hybrid control approach will optimize reconfigurability against every operation phase in the manufacturing cycle. In this way the new fixturing system impacts perfectly the work programme issues. Impact will be both at manufacturing shop floor level up to production planning and logistics levels with improved productivity along all the chain.

<u>Control system architectures for mechatronic knowledge-based systems</u>

The new generation of fixtures adopts a set of behavior based mechatronic agents. The control architecture relies both on implicit, stigmergy based, and explicit communication. This innovative architecture together with the intrinsic high stability of the agent mechatronic design produces robustness and stiffness to the overall system. Reconfiguration planning goal and logic's are based on the knowledge of the behaviors of single and multiple cooperating agents that adapt in real time to the specific manufacturing task. The swarm fixture concept involves problems of seamless connectivity and inter-working of scalable embedded systems in the manufacturing domain. The fixture agents cooperate in spatial proximity to jointly realize the common workpiece support task and together represent a small-scale complex distributed system expressing a reactive, but also efficient, robust, predictable, safe behavior.

More efficient, flexible, secure, easier to maintain and more productive (large infrastructure) manufacturing plants

The new fixture is a distributed system that requires a new engineering approach ensuring efficient, adaptable, safe and secure behavior for the manufacturing process. The self adaptability of the fixture improves the flexibility towards customized production, reduces human presence and work in the production environment rising safety and security, avoids re-fixturing tasks, and reduces fixturing setup time improving plant productivity. The modular distributed system makes maintenance interventions easier and faster. While the fixture can be considered a 'small scale' distributed system, the control methodology developed for the dynamic fast reconfiguring architecture can be applied to more complex, large scale distributed systems.

Quantification of economical impact

The new generation of fixtures will open significant gain perspectives to their builders and suppliers and will allow to their users, mainly to manufacturers in aerospace and automotive sectors but not limited to, to produce their products at shorter time to market, improved quality, lower cost and reduced resources consumption, thus allowing them to stay ahead of the global competition. Using as few as only two intelligent advanced Exechon PKM Agents to machine a complete panel will not only reduce the cost of the fixture dramatically, but also increase the accessibility and the up-time in production, and the same Agents can be moved between several flat tables and reduce the need of dedicated fixtures substantially.

A rough but conservative estimation of the quantification of these impacts follows:

Fixture storage and management costs are reduced of more than 400% with no need to store, maintain and manage trimming tools. Furthermore the high re-configurability allows the machining of left and right part kits in the same space. It also allows older parts to be machined without storing conventional tools for years.

If compared to traditional methods adopted for limp sheet manufacturing the adoption of the new highly reconfigurable fixtures, whose set-up time is in the range of minutes and may be performed in hidden time, will allow to cut the re-tooling times, which for complex and delicate thin sheets are in the range of hours. For thin sheet manufacturing cycle of about 10 operations the expected reduction of the producing time is 90%.

Re-fixturing operations require an attentive and very accurate manual re-positioning of the thin sheet on the fixture for next operation; the re-positioning errors are the main cause of defects. The use of the new fixture will avoid many manual re-positioning steps because it is the fixture itself that is programmed to adapt the supporting points to the different sequential operations and the re-positioning program, before the actuation, is checked through simulation.

An estimate of main savings offered by one SWARMITFIX installation in the aerospace manufacturing sector as perceived by end-users themselves as follows:

Taking the conventional fixtures costs of manufacture and re-tooling, the use of the SWARMITFIX system in which only one time investment and no re-tooling is needed the savings can sum up to 2M Euros, this is mainly, because with conventional fixtures there is one purposely fixture for each manufactured part and the cost of each fixtures is very elevated. On the other hand, for any minor redesign of the part, relevant changes in the fixture are in order (re-tooling); finally if the redesign is big, a completely new fixture maybe needed increasing even more the costs. Again, with to store several dedicated fixtures the maintenance and storage savings are expected to be of around 100 k Euros / year X 5 years. Given the high adaptability, re-configurability and autonomy of the system the set-up time can be reduced by 95% meaning a saving of nearly 720 k Euros / year X 5 years. The set up time reduction and the characteristics of the system represent a lower time cycles for manufacturing the workpieces, in terms of time cycle it is considered to be a reduction of 975 h / year of manufacturing operation that equals to an approximate of 78 k Euros / year X 5 years. Finally the estimated expected savings during the first 5 years, considering the above mentioned aspects can amount to 6,490,000 Euros.

Savings in the automotive sector per each SWARMITFIX installation are expected to be comparable. Hereafter the main savings offered by the SWARMITFIX, as perceived by the automotive/vehicle end-users, are accounted for. The feasibility of the data is lower compared with the previous one referred to the aerospace sector because the use of thin sheets in this domain is not yet completely achieved and statistically reliable reference data are not yet available.

However estimated savings can be approximated as follows:

In the automotive sector the replacement of conventional fixtures cannot be completely done, this means the system cannot be used for all the parts comprised in an automobile given the size of them. However, the replacement of the fixtures when possible means an estimated saving of 840 k Euros. At the same the storage and management of fixtures is decreased even more than for the aerospace, this is because in this sector more dedicated fixtures are used meaning that when replacing them with the SWARMITFIX system more fixtures disappear form storage, this can amount to 115 k Euros / year X 5 years. The set-up time reduction is less given the lower amount of fixtures that can b replace, in any case the reduction is expected to be of 75% meaning a saving of 600 k Euros / year X 5 years. In terms of time cycle reduction, in the automotive sector it is foreseen that using the SWARMITFIX system less repositioning of parts are possible, less manufacturing operations to adapt the support device to the part local shape are achieved, it is important to stress these manufacturing operations are of no added value to the final product and only increase the total manufacturing costs. The total time saved is considered to sum up to 1200 h / year and giving an estimated saving of 98.500 k Euros / year X 5 years. Finally the estimated expected savings during the first 5 years, considering the above mentioned aspects in the automotive sector can amount to 4,907,500 Euros.

Scope of the dissemination activities

Several dissemination activities have been done during the life of the project, others are still ongoing or will be done to further exploit the results and bring to the industry the development done.

The scope of the project cannot be addressed at a national level. First of all, the competence centers and research institutions in the various disciplines involved (end-users profiling, mechatronic design methodologies, information technology) are spread in different countries. Then, in relation to manufacturers of products made of thin sheets, even though some European countries (such as Germany, Italy, France, UK, Sweden) exhibit the highest concentration of big companies, smaller producers are based in almost every European nation. Hence a project like SWARMITFIX aiming at a general solution of a manufacturing problem common to different manufacturing sectors can only be conceived at a European level. This is also true when one considers the need of gathering around such an important objective the necessary critical mass in terms of transectorial know how and financial resources to sustain the research. It was then deemed impossible to initiate such a wide scope and ambitious research at private or national level. The project is an opportunity for the partners to establish a transnational cooperation. The complementary expertise will guarantee effective problem solving and accurate definition of application requirements. Impact will be greater and cost-effective higher than that which would come from several smaller national projects as a large market platform will push and support SWARMITFIX.

In order to achieve all the above mentioned goals, a consortium of industrial companies, end users and academic research bodies was formed; great attention has therefore been paid at the structuring of the consortium so to emphasize its European added value, complementarity and transnationality which include University departments expert in mechatronic design and control and communications; high tech SMEs; end-users at the levels of fixture suppliers and fixtures users. The goal appeared achievable from the beginning of the project and a momentous change possible in the manufacturing of thin sheets products and beyond. About 50% of the budget was allocated to the industrial partners to achieve a system design with straight industrial performance and interest.

<u>Promotional, dissemination and marketing activities</u>

Dissemination activities have been done during the project and will continue in order to share the knowledge to the industry. This, as envisioned by the consortium is needed in order to obtain not only the necessary feedback by the end-users that drove the research done, but to obtain at the end a real commercial product that will be of interest to the same end-users.

The biggest challenge for putting a new product on the market is to find an established channel of distribution. This challenge is even bigger when the product in question has a high level of innovation in it. Through the network of Exechon we have now found what we consider a perfect partner for the first real market introduction, Delfoi in Sweden. Delfoi's business idea is to deliver a super modular manual fixturing for the Aerospace and Automotive industry using a flexible box system combining various modular profiles with manual adjustable parallel kinematics holders. This solution is perfect for one-off prototype manufacturing but in combination with SWARMITFIX Agents it would also attract the volume manufacturing industry. Exechon, Delfoi and Airbus are currently discussing a live project in this direction. During 2010 extensive discussion has taken place between Airbus, Delfoi, and Exechon regarding the use of SWARMITFIX Agents in combination with the Delfoi Boxjoint system to be able to supply Airbus with a semi automated and flexible fixturing system.

The described Airbus system will be a real in-production reference system Exechon has been forced to productify the existing SWARMITFIX Agents up to a level accepted by Airbus for full production. The Airbus project must be seen as the first step to the commercialization of the SWARMITFIX Agent and has therefore become a very high priority to Exechon. For the same reason the specification of the Agent has to change to fulfill Airbus requirements.

Some samples of the specification for the Airbus Agents are:

-500mm stroke

-10 micrometer positioning accuracy

-5 micrometer repeatability

-10 N/micrometer stiffness

-KUKA KRC4 Controller

For the dissemination activities in general there was no strict deadline, it has been ongoing and will continue even after the project has ended, several publication in scientific journals and conferences have been realized as well as industrial seminars and university courses and involvement in different associations. An overview of the activities is presented bellow.

Involvement in robotics associations

Dissemination and innovation promotion in the field is greatly facilitated by the help of robotics industrial and academic associations. These organizations have strong ties with their national and regional industries and research communities.

The following institutions were involved:

-SIRI, The Italian Association of Robotics and Automation, http://www.robosiri.it

-VDMA Robotics + Automation in Germany, http://www.vdma.org

-EURON EUropean RObotics research Network, http://www.euron.org

-UCIMU-SISTEMI PER PRODURRE, http://www.ucimu.it

After gathering the results form the system trials, different associations will be involved.

Website

The website of the project has been designed and activated: http://www.SWARMITFIX.eu

It is used by the partners both as a repository of documents and to disseminate knowledge to relevant target manufacturing sectors: automotive, aeronautics, trains, shipbuilding. Links to MANU-FUTURE and EUROP are included and new links will be added upon request from the interested institutions. It was decided that each WP leader will have full access to the relevant area and will be responsible for the related content within the website. PMARlab-DIMEC will be responsible for the overall administration of the website, and will oversee and maintain the contents. A 'restricted area' for the exchange of confidential material and material under development has been created and has proven to be a useful tool for the exchange of ideas between partners.

Poster presentation and flyer distribution

Information about SWARMITFIX has features prominently on the PMARlab-DIMEC poster created in 2008. The poster and the project have been presented at multiple meetings and events:

The SWARMITFIX concept was presented at the following meetings and conventions:

-ISICT course on Robotics, Genoa 31 January 2009-10-02

-ISR 2009, Barcelona 10-12 March 2009

-IFR meeting Barcelona, 13 March 2009

-IMB 2009, Köln, 21-24 April 2009

-Alumotive 2009, Montichiari, 2-3 April 2009

-EWF, EUROJOIN 7 / GNS5, Venice, 21-22 May 2009

-Training Course SIRI, Comau, June 21 2009

-Strategic Research Agenda for robotics in Europe, Brussels, 7 July 2009

-Summer Schools on Screws Theory, Genoa 22-30 August 2009

-CLAWAR'09, Istanbul, 9-11 September 2009

-ATA Conference on Vehicles architectures, Florence 25 September 2009International Conference on Reconfigurable Mechanisms and Robots, REMAR'09, held in London, 22-24 June, 2009

-Manufacture 2009 Conference - Implementation of a sustainable European Manufacturing Industry, Gothenburg, 30 November - 1 December 2009

-Reconfigurable Exechon Parallel Kinematics, Simplified Machining and Assembly, Karl-Erik Neumann, Al Bolen, Exechon AB - Aero Tech Congress and Exhibition, Seattle, WA, USA, 10-12 November 2009.

-Presentation by Karl-Erik Neumann, 1st Advanced Manufacturing Technology Forum, Filton, UK, 20-22 October 2009, Aero Tech, Seattle, USA, November 10-12 2009.

-Presentation by Karl-Erik Neumann, Manufuture 2009, the European Manufacturing Conference, 30 November - 1 December 2009, Gothenburg, Sweden.

-SWARMITFIX presentation, Ladislav Vargovcik, EURON-EUROP Annual Meeting, 10-12 March, 2010, San Sebastian, Spain.

-ALUMOTIVE, Montichiari, 2-4 Aprile 2009

-R. M. Molfino, Swarm Fixturing of Aircraft Body Components and Fixturing of car Body Assemblies, Automate 2011, Chicago, March 21-24, CD Conference Proceedings.

Other presentations on various aspects of the project were prepared and scheduled These include talks at the following conventions: LAMIERA, 14 May, Bologna, Italy; ISR-Robotic, the Joint 41st International Symposium on Robotics and 6th German Conference on Robotics, 7-9 June, and Automatica, the 4th International Trade Fair for Automation and Mechatronics, 8-11 June, both held in Munich, Germany; ROBTEP 2010, 7-9 June, Bardejov, Slovakia; CCMMS, the Chinese Conference on Mechanism and Machine Science, 20-25 July, Shanghai, China; as well as the ASME 2010 International Design Engineering Technical Conferences (IDETC), 15-18 August, Montreal, Canada.

After presenting thorough the concept, main ideas and conceptual design, presentation of the posters were stopped in order to fully develop the system. This, does not meat no further dissemination activities were done. Continuously, the partners have prepared and submitted scientific articles to renowned journals and conferences.

A flyer promoting the project has been prepared. It is distributed by the partners to their business and academic contacts as well as at conferences, exhibitions, and other events.

Publications

A list of publications regarding the achievements of the project is given below; it is important to stress these publications let the scientific and industrial community to understand not only the importance of the system but the details of design, manufacture and specific characteristics achieved.

Newspaper articles on the project appeared in the Mediaplanet Automation supplement of the Italian national daily business newspaper Il Sole 24 Ore, as well as in the daily Italia Oggi.

-SWARMITFIX un'attrezzatura intelligente, Rezia Molfino, Matteo Zoppi, MEDIA-PLANET AUTOMATION, Il sole 24 ore, 17 November 2009 200.000 copies

-The same on Italia Oggi, 16 November 2009 100.000 copies

Research papers on different components developed within the project have been accepted for publication in the proceedings of several conferences: ISR-Robotic, the Joint 41st International Symposium on Robotics and 6th German Conference on Robotics, 7-9 June 2010, CCMMS, the Chinese Conference on Mechanism and Machine Science, 20-25 July, 2010, Shanghai, China, the ASME 2010 International Design Engineering Technical Conferences (IDETC), 15-18 August, Montreal, Canada. Two papers have been submitted for presentation at the 11th Polish National Robotics Conference, 9-12 September, Karpacz, Poland and one to Frontiers of Mechanical Engineering in China.

-R. Molfino, M. Zoppi, and D. Zlatanov. Reconfigurable swarm fixtures. In Reconfigurable Mechanisms and Robots Proc. of the Int. Conf. REMAR 2009, volume IEEEcn:CFP0943G-PRT, pages 696{701. KC, London, UK, Jul. 22-24 2009.

-R. Molfino, M. Zoppi, Attrezzature robotiche per manipolazione e supporto di stampati, ALUMOTIVE, Montichiari, 2-4 Aprile 2009

-Xiong Li, Aamir Khan, Roberto Avventenente, Matteo Zoppi, Dimilter Zalanov, Rezia Molfino, Development and Analysis of Shape Conformable Support of Self-reconfigurable Intelligent Swarm Fixture, ISR 2010, Munich, June 7-9, 2010

-C. Zieliński, T. Winiarski, P. Trojanek, T. Kornuta: 'Multi-agent control system specification of a robot based reconfigurable fixture', 11th National Robotics Conference, Karpacz, Poland, 9 - 12 September 2010.

-W. Szynkiewicz, W. Kasprzak, T. Zielińska, D. Zlatanov: 'Planowanie rozmieszczenia ruchomych podpór przy obróbce przedmiotów o dużych rozmiarach' (Planning of the

distribution of mobile supports for large objects subjected to machinning), 11th National Robotics Conference, Karpacz, Poland, 9 - 12 September 2010.

-W. Szynkiewicz, T. Zielińska, W. Kasprzak: 'Robotized machining of big work pieces: localization of supporting heads', Frontiers of Mechanical Engineering in China.

-Summary of the project in Institute of Control and Computation Engineering 2009 Annual Report, pg.60, also: http://www.ia.pw.edu.pl/download/Annual09.pdf

-Robot Control and Pattern Recognition Group's web page mentions the project at: http://robotics.ia.pw.edu.pl/twiki/bin/view/Grants/GSWARMITFIXFP7-214678

-R. Molfino, M. Zoppi. ''SWARMITFIX un'attrezzatura intelligente'', Italia Oggi, Class Editori.
R. Molfino, M. Zoppi. ''SWARMITFIX un'attrezzatura intelligente'', Media-Planet Automation, Il Sole 24 ore.

-Zoppi, M.; Zlatanov, D.; Molfino, R. ''Kinematics analysis of the Exechon tripod''. Proceedings of the ASME 2010 International Design Engineering Technical Conferences and Computers, August 18th 2010.

-Zielinski C., Kornuta T., Trojanek P., Winiarski T., Walecki M. ''Specification of a Multi-Agent Robot-Based Reconfigurable Fixture Control System''. 8th International Workshop on Robot Motion and Control, RoMoCo'11.

-Zielinski C., Kornuta T. ''Generation of Linear Cartesian Trajectories for Robots Using Industrial Motion-Controllers'', 16th International Conference on Methods and Models in Automation and Robotics, MMAR'2011.

-Molfino, Rezia; Zoppi, Matteo, ''The robotic swarm concept in fixtures for transport industry''. The 7th International ASME/IEEE Conference on Mechatronics and Embedded Systems and Applications.

-L. Xiong, M. Zoppi, R. Molfino, Reducing Computation Time In Optimization Procedure For Fixture Layout Based On SWARMITFIX, 5th International Conference on Integrated Modeling and Analysis in Applied Control and Automation IMAACA 2011, Rome, 12-14 September 2011, CD Proceedings

-Li, X.; Zoppi, M.; Molfino, R.; de Leonardo, L. ''Design of a mobile base for a self-reconfigurable intelligent swarm fixture system". The 14th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines, CLAWAR 2011.

-de Leonardo, L.; Zoppi, M.; Li, X.; Gagliardi, S.; Molfino, R. ''Developing a new concept of Self Reconfigurable Intelligent Swarm Fixtures''. Proc. of the Int. Conf In Reconfigurable Mechanisms and Robots. REMAR 2012

Educational activities

Two Ph.D candidates, at the University of Genoa and the Warsaw University of Technology, are basing their research on the project. Students in the EMARO (European Master in Robotics) Erasmus Mundus programme have been exposed and have contributed to aspects of SWARMITFIX.

Ph. D research theses:

-Li Xiong- Università di Genova (DIMEC)

-Piotr Trojanek - WUT - work on his Ph.D. on multi-robot coordination.

M. Sc Thesis

-Serena Gagliardi - Università di Genova (DIMEC)

-Luis de Leonardo (EMARO) - Università di Genova (DIMEC) Laboratory work

Laboratory work

-Flexible Automation students - Università di Genova

-Robot mechanics students - Università di Genova

-EMARO (European Master on Advanced Robotics) students - DIMEC-UNIGE, WUT

As a part of a joint exchange program and of an Erasmus Mundus action, DIMEC will continue its collaboration with the Department of Mechanical Engineering of the Shanghai Jiaotong University, and through them possibly expand contacts with the new company started in Shanghai for the development of the first Chinese civil aircraft. The aim of this initiative is to prepare a potential future market for the technology in China.

Of particular interest is the international Master-level programme EMARO (European Master in Advanced Robotics), an Erasmus Mundus project, that has been operative since 2008.

The following courses will include materials and offer projects related to SWARMITFIX:

-Robot Mechanics

-Flexible Automation

-Control of Mechatronic Systems

-Industrial and Service Robotics

-Robot Programming Methods

-Mechanical Design Methods in Robotics

-Mobile Robots

Direct contact with potential users

In the course of their business contacts the SWARMITFIX participants are familiarizing their partners with its concepts and emerging technology. The following major companies have been contacted and had been exposed to the ideas and results of the project:

-A branch of Kuka working on aerospace manufacturing systems. The SWARMITFIX concept has been introduced in discussions with DIMEC and PAI.

-AMS, Ace Manufacturing Systems, India. The company is an Exechon licensee. SWARMITFIX was introduced by Exechon, further presentations are planned.

-TAL Manufacturing Solutions, India, the makers of the TATA car. The company is an Exechon licensee. SWARMITFIX was introduced by Exechon CEO Kalle Neumann; follow-up presentations are planned. (See Appendix C.)

-BFW, Bharat Fritz Werner, India. The company is an Exechon licensee. SWARMITFIX was introduced by Exechon CEO Kalle Neumann; follow-up presentations are planned.

-Premier, India. The company is an Exechon licensee. SWARMITFIX was introduced by Exechon CEO Kalle Neumann; follow-up presentations are planned.

-Shanghai Jiaotong University, Shanghai, China, September 2009. Swarm fixturing technology was presented to invited participants to a special event purposely organized.

List of Websites:

http://www.swarmitfix.eu

http://www.youtube.com/user/LMdeLeonardo?feature=mhee