Handling carbon fiber fabric in agile manufacturing cells

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Abstract: - The paper addresses the design of agile cells for manufacturing low volume aircraft sub-assemblies and focuses on the problem of robust grasping and handling carbon fiber fabric. The difficulty of the manufacturing task is faced equipping the cell with two cooperative robots. Both robots use purposely developed. The paper presents in detail the adaptive end-effectors purposely developed like robotic hands following the approach of multi point grasping technology and the design of some alternative picking modules that can be used at the robotic hands fingertips.

Key-Words: - Flexible manufacturing cell, Dexterous handling, Soft material, Carbon fiber fabric, Robotics, Mechatronic design (6 - 10 words)

1 Introduction

Modern production systems have to be flexible to adapt quickly to an increasing number and variety of products and fluctuating demands. In this highly volatile and dynamic environment, reconfigurable and flexible production systems have been suggested and partially realized during the last decade for industrial environments working on stiff, well defined shape parts and components. Indeed the level of flexibility of these systems has to be improved so that they should be able to adapt in real time to different changing scenarios and needs. The few dedicated systems that are available have high tool recovery cost and increased tool needs. On the other hand, the automation of processes dealing with limp, soft, porous material, such as carbon fiber, leather, fabric, and technical tissues, not only requires the development of a suitable reliable robotic device, but also of a highly flexible handling system for such difficult materials.

The paper deals with a new hyper-flexible cell for handling carbon fiber preforms, served by two cooperating robots, endowed with plug & produce capabilities, able to pick parts with different geometries from a cutting table and to place them on moulds with different 3D shapes (e.g. calotte, tail, fuselage). Both arms are endowed with a new smart modular hand/gripper adaptable to the handling of different carbon fiber textures in single and multi layers.

The manipulation of non stiff materials like carbon fiber fabric open the doors to new automation and robotization processes in other manufacturing sectors working on limp thin sheets like automotive, leather, textile/clothing, medical

Eco-sustainability issues call for the design and manufacturing of less mass and more energy efficient products so, in the near future, wider and wider use of limp lightweight sheets will be applied not only in the transport sector but also in many other industrial sectors. The robotic manipulation of thin, near 2D, limp non-homogeneous and permeable parts is very difficult. Only a few dedicated and conventional systems, with a complex and time-consuming configuration and setup process, are available. For this reason, the handling operations today are made manually or, sometimes, by dedicated automated cells. Up to now viable robust, cost efficient, flexible robotic handling solutions are not yet working in industry.

2 State of the art

When talking about flexible manufacturing and assembly cells, the central issue of an advanced robotic manipulation has recently been and is being extensively addressed and this offers advantages to many industrial sectors as demonstrated by the 4-year initiative to develop a robotic autonomous manipulator (ARM) that mimics the human hand and is able to handle flexible material fabric. “ARM

Industry Day" was organized by DARPA in Arlington (US) on February 18 2010 to launch this initiative. In the last 30 years some researchers faced the problem and prototyped few reliable handling systems most of which very expensive and narrowly oriented to specific tasks (see pioneering work done within Hull University, The Charles Stark Draper Laboratory, Textile/Clothing Technology Corporation, MITI and WO/1984/000949, WO/1995/024974).

Basic research activities, in the context of fabric handling, were performed on the physical principles for adhesion of the gripper to the material at the areas of interaction for their manipulation. The leading work of Seliger on the analysis of the performance of different gripping methods was summarized in [1]. A radial outflow gripper developed at the University of Salford [2] was able to handle low permeability materials but it is unsuitable for porous materials. New interesting gripping principles, adaptable to a wide range of materials, were developed and patented like Coanda effect ejector [3] and dynamic fan originally proposed by researchers at DIMEC [4] and demonstrated on porous materials in different versions within the European projects EuroShoE (2006) [5] and Leapfrog IP (2009). The results of the latest activities in LeapFrog IP [6] and study of the prototype definitely indicates the need to channelize efforts for developing new miniaturized solutions based on the same adhesion principles.

Development of innovative handling mechanisms has significantly complemented the above activities. Tsourveloudis [7], Acaccia and Molfino [8] developed modular and multi-fingers grasping devices with planar workspace. Dougeri and Fahantidis [9] demonstrated a soft finger gripper that grips limp materials but this device does not preserve the pinched part shape. In 1982 Salisbury and Craig [10] anticipated the use of sensors like tactile and vision to achieve intrinsic grasping robustness in uncertain environment but no effective industrial development followed. The European Project ROBOTEX BRE20958 used vision sensors to achieve the correct presentation of the material to a standard sewing-head. The European Project CR117391/BRE20643 developed sensing mechanisms which allow quantitative monitoring of the processes associated with the spreading operation. These projects faced a real problem with technologies available at that time but now it could be possible to achieve more reliable and cheaper solutions based on up-dated technologies.

The above activities are of significant interest for the aerospace industry, more so, in the context of manufacturing costs and complexity. Hence, flexibility and short ramp-up time are the important factors to be focused to alleviate the existing burdens without compromising on quality.

In the aerospace industry, Sarhadi [11] attempted to define basic concepts of developing a sensor-based robotic lay-up cell for dry carbon fibre. A cell was subsequently developed to handle aero-engine blade preforms from dry fabrics. Later, an improved prototype-manufacturing cell with integrated electrostatic gripping device with a vision system was developed, capable of rapid lay-up of carbon composites based on CAD design data [12]. This work presented the requirements of handling varieties of ply sizes and material types for laying up dry carbon fiber besides a novel folding device to integrate a material delivery system into a robotic cell for manufacturing dry fibre composite components. Prior to this work, Newell and Khodabandehloo [13] defined and simplified a mathematical model using finite element analysis in order to predict the shape of a prepreg. This approach was used to assist in controlling the handling trajectories of an automated composite manufacturing facility. Though, these research works were carried out in the field of composite structures, they are by far very few in case of the 3D-manipulation of near 2D- limp material.

During the last few years there has been a renewed and increased efforts for developing a cost-effective automated process chain and workflow for composite structure manufacturing. The German Federal Ministry of Education and Research (BMBF) recently funded research activity in this field; "REDUX" (BMVIT) [14] has provided an initiative in establishing a basic flexible process chain for the composite structure fabrication (CAD design to production). New techniques in Flexible 3D Robotic sewing, Resin Transfer moulding were introduced for a modular process workflow. A prototype Robotic cell Demonstrator was setup at EADS-D in Ottobrunn to study and analyze the feasibility of a cost-effective production process flow. Though, the demonstration of this activity has to an extent, succeeded in providing a production workflow for simple composite structure lightweight assemblies, there still exists a need for a flexible handling system for pre-forming i.e. draping or wrapping of cut part geometries for a diverse selection of moulds.

The recent "CFK-Tex" project aims to address this scenario by creating a prototype end-effector for the automated sorting of cut parts from the cutting table to the stockyard which offers great flexibility regarding different contours and materials by an automated reconfiguration. However, the automation of the performing process with the defined placing, draping and crabbing of a single carbon fiber textile on special 3D-moulds is the main objective of the project. The above single process steps were examined separately and proper strategies and principles were analyzed.

The current State-of-the art concerns the development of handling systems that could handle fabrics, but with a little flexibility and modularity for customising the system according to operative changing needs. Though advancements in context of fabric handling are being made, still there is a lack of universally accepted reference models, standards, methodologies and software tools for the development of adaptive automation control systems for soft permeable items handling.

The paper addresses the above issues by presenting the design of a flexible cell for draping and wrapping of carbon fiber on different types of mould without any tool change [15]. The outcome of the work aims to address the following industry relevant issues:

- Short cell ramp-up time and easy re-configurability
- Step towards a standardization of handling systems with easy adaptability and integration in manufacturing systems
- Hyper-flexibility towards varied products handling
- Introduction of new technologies (VSA) for a cost-effective solution
- Modular software and hardware architectures

The proposed 3D handling cell consists of a cooperative robotic system equipped with reconfigurable gripper endowed with new eco-efficient picking modules, able to grasp carbon-fiber fabrics. The grippers are capable of adapting the positions of picking modules to the part geometry and stiffness.

Given the large size of the fabrics to be handled accurately, cooperating robots provide a greater flexibility in handling compared to a large single tool. The main advantage of this system, in comparison to a single handling unit, is that it enables to save workspace, tool manufacturing cost and the subsequent return of investment, besides the reusability of the system (robot and grasping device) with minimal or practically no reconfiguration for other customized application. Also, the ability to handle the part simultaneously in a geometrically coordinate fashion forms a significant feature and advantage of the cooperating system.

A lesson learnt from the current state of the art is that a balanced interaction between the information flow and the material flow have always determined the efficiency of a system.

In the proposed scenario, the reconfigurable grasping device with the picking modules has a simple design with augmented control strategies for real time adaptation. The grasping device is endowed with a variable stiffness actuation, in order to have a "natural" soft interaction between the grasping device and the mould. This makes the device better adaptable to geometric features of the parts and the mould, such as curved surfaces, as well as the properties and requirements of the materials to be handled. The picking points, which depend on the part geometry, the mould type, and the material properties of the fabric, are transferred to the robot controller via a TCP/IP interface in order to inform the grasping device together with the robot system on the requested self-adapting needs.

3 Cell layout

The handling cell layout is sketched in the Fig. 1. The task of the cell is to unload carbon fiber cut parts from a cutting table and to place them on different type of moulds through a cooperative handling system without tool changes and re-setup [16]. The two grasping devices mounted on to each system have an ability to adapt the picking modules positions to the geometry and properties of the actual part to pick.

The two robots are fixed on to a beam sliding on an overhead linear rail. Both arms are equipped with identical handling devices performing the draping/wrapping operation in cooperation. Another cell of the family, able to handle big carbon fiber parts, could include robots mounted on mobile platforms.

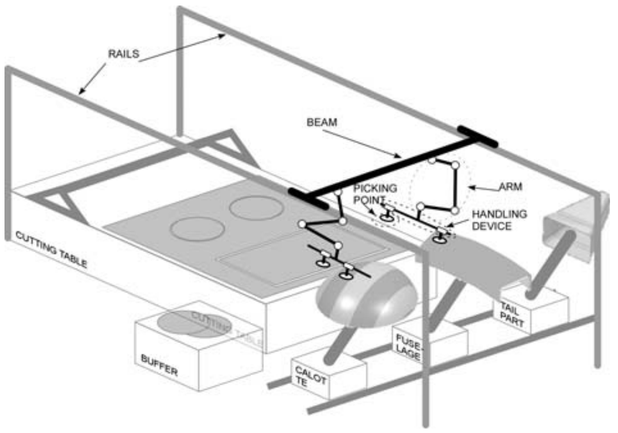


Fig.1 Sketch of the manufacturing cell

3.1 Handling strategy

The main workflow of the task is as follows:

- The two robots synchronously reach the part on the cutting table and move the grasping devices in order to position the picking modules on the prescribed picking points;
- The picking modules are actuated and the part is lifted up through a collaborative synchronized task of the two robots.
- The part is then transferred to the placing reference position on the mould through a collaborative task, by reducing a little bit the distance between the two TCPs (Tool Center Points) during the transport in order to avoid to introduce unwanted stresses into the carbon fiber tissue (see Fig. 2)
- The part is then operated taking into account the shape of the mould, the wrap up rate and needs (see Fig. 2)
- The part is then released onto the mould with VSA small modifications.

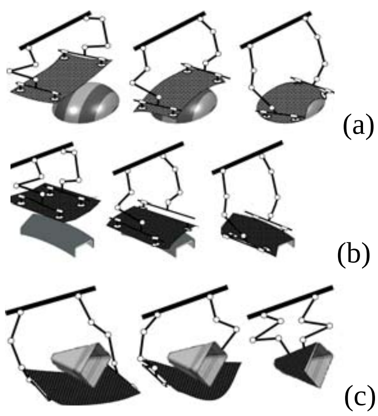


Fig.2 Work sequence in mould draping and wrapping tasks of carbon fibre preforms on different moulds: calotte (a), fuselage (b), tail part (c).

During the above operations, an optical sensor (3D Laser Measurement Scanner) is used to identify the mould and activate the suitable placing tasks. The image processing in 3D is used to identify position and orientation of each handling device for achieving the different picking points. An algorithm determines optimal picking points and control strategies to drive the item on the mould, the points data are transferred to the robot.

3.2 The cell control

The different components of the automation hardware are connected via adequate interfaces, standard if possible or purposely developed.
Fig. 3 presents a sketch of the physical layout of the cell together with the information control flow architecture.

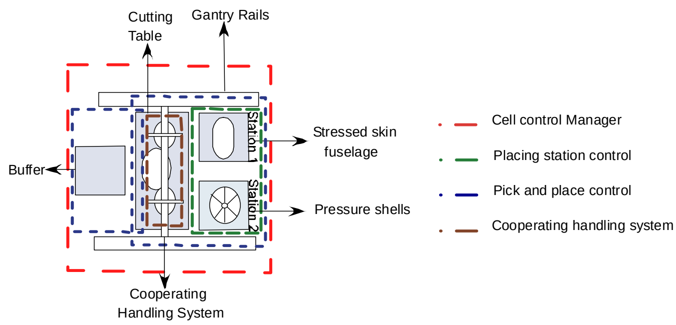


Fig.3 Sketch of the architecture of the cell layout information flow

Simple picking (from a table) and placing stations (moulds for open carbon fiber components or for close wrapped components) are arranged within the cell mimicking the work done in the aerospace industry. The cell logistics and programming are defined and implemented, including the development of the human friendly interfaces and the criteria for the efficient management of the cell also against unexpected events.
A suitable Product Data Base includes Product Description and CAD files of the carbon fiber parts and moulds. Besides the logics for the cooperative tasks with mutual interaction and force exchange between the robots/part/mould, the real time adaptation procedures at cell level are studied also with the aim of the possibility of 'auditing' the reconfigurations with regards to parts handled in the aerospace manufacturing environment. In fact, in aerospace, on one hand, reconfiguration of the production occurs very often due to product variants and volume changes while, on the other hand, it is common practice (also because of safety regulations) to keep track of the production layout/cycle used for the manufacturing of each part. 'Auditing' of adaptation changes can be done automatically as cell operations monitoring. The "configuration snapshots" of the cell will be further

used as knowledge for suggesting autonomous adaptation in more complex handling cells of the same family.

Modular cooperative adaptive control architecture have been considered for the handling system [17]. The two arms have to really cooperate during the carbon fiber preform handling [18]. In fact during this task the two kinematic chains (robot + gripper) close on the limp preform while exchanging generalized forces and the handling trajectories needs to perfectly comply with difficult tasks like mould wrapping [19].

Real time control logics [20] are defined and corresponding algorithms written for placing strategies and picking strategies enhancing the capability of the cell to quickly and robustly adapt to different carbon fiber aerospace components manufacturing.

The framework is expected to enable real time awareness of system status and reconfiguration potential so that the most appropriate adjustment of operating parameters can take place. The control logics ensure that all possible adaptation actions are accounted for at all handling task levels and therefore all flexibility/performance potential of the system can be assessed.

4 The handling device

The multi points grasping philosophy, already successfully adopted for fabric handling in Leapfrog IP [4], has been adopted taking into account the lesson learnt in the previous research work. This approach allows developing a handling device working with near 2D limp porous parts with different shapes, sizes and materials, usable for different handling tasks and manufacturing environments. Taking into account the cooperative work of the two robots, the handling device is embedded with a suitable minimum number of picking modules and it will be able to reconfigure adapting the picking positions to the lifting-up/handling needs of the actual parts/tasks.

The proposed philosophy allows decoupling the adaptation to the part layers/material, in charge of the picking module, from the adaptation to the shape and size of the part to be handled, in charge of the hand architecture. In effect the picking modules guarantee the picking robustness versus material and surface properties and the handling system architecture, made by two handling devices, guarantees the re-configurability range complying with the parts different sizes and shapes while the cooperation of the two robots guarantee the adaptation of the grasped fabric to the mould shape.

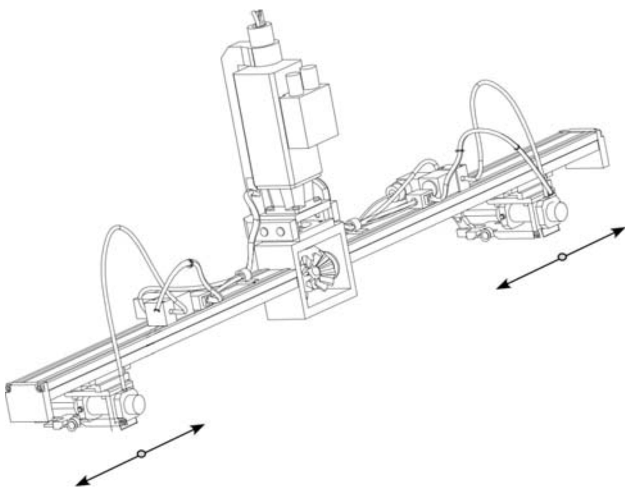


Fig. 4 Digital mock-up of the grasping device.

The grasping device works with two picking points whose distance is adapted on the fly to the item to pick. The degree of freedom number is minimum and the orientation is demanded to the wrist of the robot.

An electrical motor, through a bevel gear mechanism, drives two in line ball screw linear tracks whose slides carry the two grasping modules, see Fig. 4.

Picking modules have been designed mainly based on the previous experience and tests made on different physical picking principles.

To obtain an efficient grasping the distance between the two modules is adapted to the item edge size and the technologies of sucking need to be coordinated from the control system that drives the task. The grasping steps are: regulating the distance between the grasping modules while approaching to the item laid down on a flat surface; sucking the item near to the ends of the selected edge; lifting of the gripper.

The approaching step is guided by the world coordinates of the two points of the item to be grasped; when the gripper is above the item it goes down slowly till to touch upon, then the vacuum is actuated and sucks the item edges. The lifting step is superimposed to the sucking step These steps have to last a minimum time in order to prevent the detachment of the items more porous and permeable to the air.

The pneumatic circuit was designed to guarantee a prompt sucking function by limiting the fluid inertia and losses. It foresees small air breaths to facilitate the item detachment.

The handling mechanism has been designed, realized and integrated with the picking modules, sensors, variable impedance actuation and motion control for re-configurability.

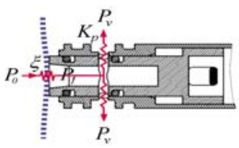
Two generation of picking modules have been designed. They are presented in the following sections.

4.1 Pneumatic picking module: first solution

The working principle, referring to the schema of Fig. 5 is the following: the internal cylindrical hollow cursor presents holes on its wall that coincide with the holes of the external envelope only when the cursor is on the lower position (grasping position). In this position the vacuum is supplied. The cursor ascent stops the vacuum supply because the internal and external holes are no more coincident. The separation of the template is guaranteed by the cursor ascent.

Fig. 5. The picking module in open and closed positions and a physical prototype

The pneumatic circuit approximate model is hereafter presented. The hardest problem that has been faced is the carbon fiber fabric modelling taking onto account the air permeability due to the lack of technical data.
The first model is the following where the pressure drops on the fabric and valve are considered lumped and the drop on tubes has been neglected, the fluid has been considered not compressible. Fig. 6 refers to the simplified model of the device. porous materials, the holding force depends on the ratio: (drop through porous material)/(overall circuit drop).



$$F_g = A_p \Delta P_f = A_p \frac{\xi}{K_p + \xi}(P_0 - P_v)$$

Fig. 6. Simplified model

The innovative picking module has been developed to be small, reliable and low cost. It is modular and can be integrated in the design of the handling device.
Fig. 7 shows the digital mock-up, main components of the device and a physical prototype; a functional block diagram is also given. A cursor slides into the hollow external envelope (orange in Fig. 7) between a lower configuration (*on-state configuration*) and an upper configuration (*off-state configuration*). A mini electrical motor within the cover rotates a small block that can lock the cursor in the upper configuration. While the motor sets the picking module on/off, the actuation force is obtained by compressed air, which moves down the cursor like the piston of a pneumatic cylinder. During the release phase, the release of the template is guaranteed by the cursor ascent.

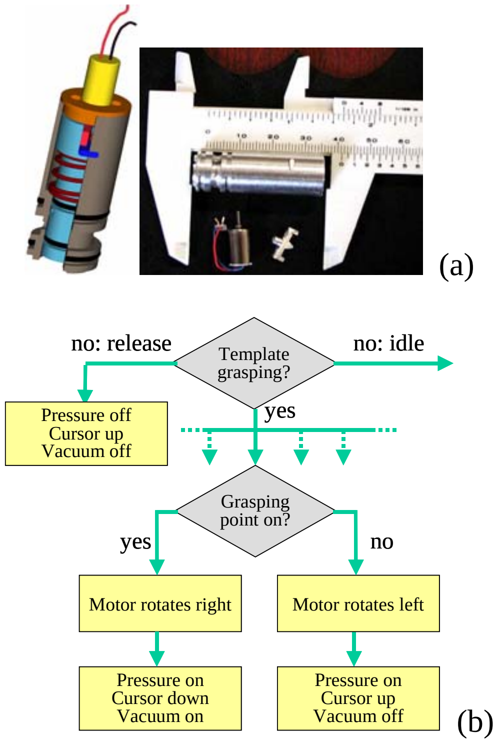


Fig. 7. Picking module: digital mock-up, physical components (a) and functional block diagram (b).

The working feasibility of the innovative, patented, picking module has been validated, first, by means of virtual tests on a specific digital mock-up, then on the physical prototype. One important point is that the suction force wasn't convenient compared to the energy consumed
Due to the small lifting forces registered during the tests, these picking modules need to be grouped in small arrays in the handling device.

4.2 Pneumatic picking module: final solution

The goal is to develop a cost effective gripper, able to generate high lifting forces, to be used in different industrial applications for pick and place of delicate materials such as carbon fiber fabric. Vacuum can be generated with vacuum generators of various types. The three basic types are: ejector, vacuum pump, vacuum blowe. Each type has its own specific advantages, but they have one thing in common: a high suction capacity at a high vacuum

always means high power consumption and high operating costs.
From a comparison to the other devices vacuum pump resulted the compromise in term of requirements: high suction capacity, suitable suction pressure for the application, variety of work pieces.
In the market there is no vacuum pump that suits the approach of the research because either, the size is large, or no ready to use product and the price is high compared to the application.
The authors decided to use a radial compressor with the aim of improving the efficiency of the device. Although some radial micro compressors can be found in the market, the price is relatively high compared to the application and integration wouldn't be easy. For that reasons was designed a low cost effective compressor that, compared to the other devices vacuum pump is a good compromise of the recalled requirements.
The compressor was designed to follow a high efficient state-of-the-art characteristic curve.
A small size and cost effective brushless motor with 62000 rpm was used. For 62000 rpm from the curve the maximum pressure ratio is 1.12 for a mass flow of 0.012 kg/s.
Getting this data from the characteristic curve it was used as input data for CFturbo software to generate the shape of the blades, see Fig. 8

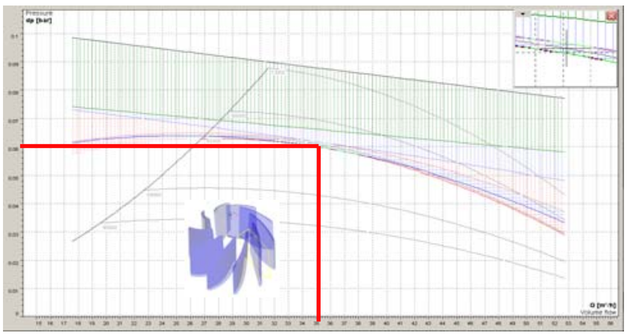
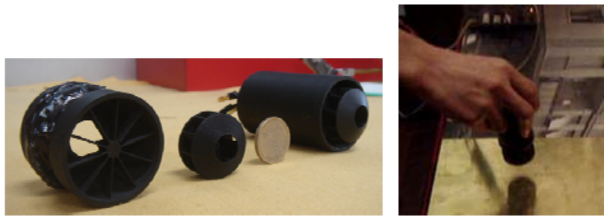


Fig. 8 Compressor design chart.

At the final stage of the design the compressor hub diameter is 5 mm, suction diameter 14 mm, impeller diameter 29 mm, outlet width 9 mm and number of blades 10 with leading angle of 20 degree.
The envelope and the cap, designed to fit in the gripper, are shown in Fig. 9

Fig. 9 Compressor, Cap, Assembly

The prototype samples were manufactured using laser sintering, see Fig. 10. In the future for mass production other manufacturing process will be investigated. A summary of the picking module design, more details are in [21]



(a) (b)
Fig. 10 Prototype parts (a) and early test (b)

5 Experiments

One of the most critical design activity is the design of the new eco-efficient picking module able to robust handling of carbon fiber fabric performs.
A test bench was purposely implemented and used at the PMAR laboratory with the purpose: - to evaluate the final picking module performances; - to obtain the mass flow rate/pressure curve for different materials; - to compare the results to the mass flow rate/pressure expected performance graph; - to modify the compressor according to the results and in general develop the design of the picking module and to set its parameters. The test bench is shown in Fig. 11. Fig. 12 shows the arrangement used during the experiments.

Fig.11 Test bench used in the early experiments

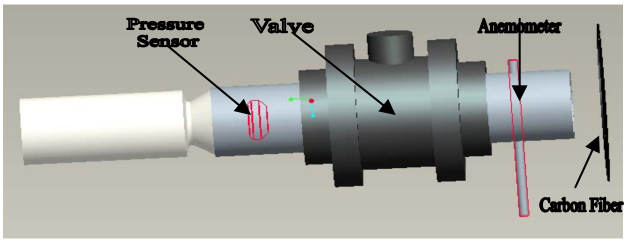


Fig.12 Test arrangement

The experiment procedure is articulated in the following steps:

- Record the speed of the air using the Anemometer.
- Calculate the mass flow rate,
- Record the suction pressure, calculate the suction force.
- Change the position of the valve, and repeat the first three steps.
- From this data draw the mass flow rate/pressure curve for different types of material according to the permeability of each.

The early experiments and demonstration have been done with reference to the following ranges:

- carbon fiber materials (not restricted to): T700SC 12K 50C, 6K HR, HTA 5131 6K
- geometry/size: from 100x500mm to 500x1800mm
- layers number: 1-2
- mould shape: see Figure 2

Many data were collected and results achieved during the experiment tests. As example are here reported some results on the behaviour of the new picking module used to handle samples of carbon fiber, see Table 1 and Fig. 13, 14.

Table 1 Comparative results on the picking module parameters

	Actuator: 16V, 2.6A Diameter: 36mm		Actuator: 20V, 3,4A Diameter: 63.5mm	
	Pressure [mbar]	Suction force [N]	Pressure [mbar]	Suction force [N]
Max	21.7	2.2	17	5.3
Min	17.6	1.7	14.5	4.2
Mean	19.6	1.9	15.5	4.9

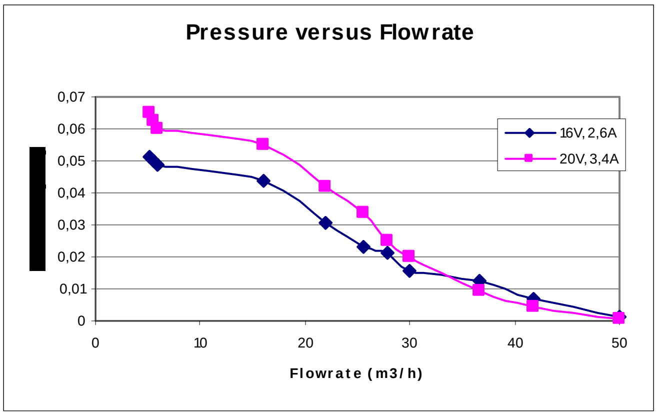


Fig. 13 Characteristic curve for carbon fiber from experiments on the test bench

Fig. 14 reports the differences between measured pressure and expected pressure as from the computational model.

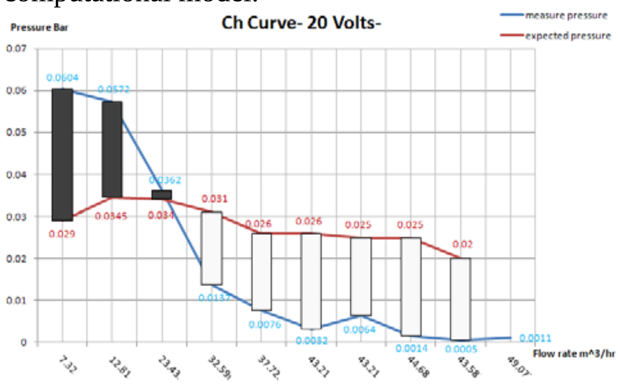


Fig. 14 Measured pressure compared with computed one.

6 Conclusions

The main result in these scenarios is to successfully enable the robotic handling of difficult material that, till now, is mainly performed by human hands.

The new metamorphic hyper-redundant handling system with its 14 mobilities, equipped with the new picking modules and with the proprioceptive and exteroceptive sensors is able to adapt real time to different kind of carbon fiber materials, different geometry of the cut parts, different number of layers and different placing mould shapes.

Besides the hyper flexible cell here addressed, more sophisticated cells of the same family will allow handling largest parts, see Fig. 15.

The hyper flexible intelligent cell will contribute to reduce the time to market for mass customized aircraft components.

A great added value is associated to the high level of flexibility of the cell. Carbon fiber components are used mainly in transport green production: in aerospace, automotive, bicycle. But new applications are foreseen in electronics (cases), in medical products, civil engineering, military, motorsports and other new sectors are showing interest day by day

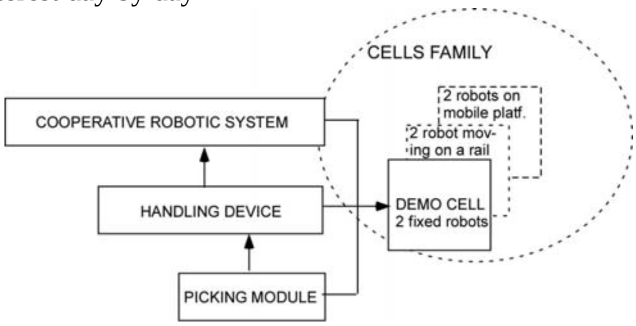


Fig. 15 Vision of the proposed cell family

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References

[1] Seliger G., F. Szimmat, J. Niemeyer and J. Stephan, "Automated Handling of Non-rigid Parts", Annals of the CIRP 52/1 (2003), pp. 21–24

[2] Ozcelik Babur, Fehmi Erzincanli, "A non-contact end-effector for the handling of garments", Robotica, Vol. 20, pp. 447-450, 2002

[3] Lien T. K., Davis P. G. G. "A novel gripper for limp materials based on lateral Coanda ejectors", Annals of the CIRP 2008, vol. 57, no 1 pp. 33-36

[4] Molfino Rezia, Matteo Zoppi, Enrico Carca, "Robotic soft Material Handling", in: Transforming Clothing Production into a Demand-Driven, Knowledge-Based, High-Tech Industry, The Leapfrog Paradigm Editor(s) name(s): Lutz Walter, George-Alexander Kartsounis, Stefano Carosio, Springer, 200

[5] Molfino R.M. and M. Zoppi. "Mass-customized shoe production: A highly reconfigurable robotic device for handling limp material". Int. J. IEEE Robotics&Automation Magazine, 12(2):66{76, 2006.

[6] R. Molfino, "Robotic handling of limp soft near 2D material", Schunk International Expert Days, Hausen, February 24-25 2010

[7] Tsourveloudis N, Valavanis K, Kolluru R et al. "Position and Suction Control of a Recon-figurable Robotic Gripper". Machine Intelligence and Robotic Control, 1999, 11(2):53-62

[8] Acaccia G., L. Bruzzone, R. Molfino, M. Zoppi, "Modular SMA-based matrix gripper for grasping and handling of limp materials", Int. Conf. on Intelligent Manipulation and Grasping IMG04, Genova, Italy, 2004, pp.266-269

[9] Dougeri Z. and N. Fahantidis, "Picking up Flexible Pieces out of a Bundle", IEEE Robotics and Automation Magazine, vol. 9/2 (2002), pp. 9–19

[10] Salisbury J K, Craig J (1982) "Articulated Hands: Forces Control and Kinematic Issues". The Int. J. of Robotics Research 1(1):4-17

[11] Sarhadi, M.: "Robotic handling and lay-up of advanced composite materials, an overview", in Taylor, P.M. (Ed.), Nato ASI Series, Sensory Robotics for the Handling of Limp Materials(1990), Vol. F64, Springer-Verlag, Berlin, pp. 34-49

[12] Chestney, J.A. and Sarhadi, M., `"Control and integration techniques in a fully automated manufacturing cell for carbon composites" (1996), IEE Proc. Control Theory and Applications, Vol. 143 No. 2, pp. 159-63

[13] Newell, G.C. and Khodabandehloo, K., "Modeling flexible sheets for automatic handling and lay-up of composite components" (1995), Proceedings of Institute of Mechanical Engineers, Vol. 209, pp. 423-32

[14] BMVIT, Take off – First Aerospace Research Results, Bundesministerium für Verkehr, Innovation und Technologie : Journal (2007), pp. 20

[15] Gunther R., Straßer G. and Ehinger C., "Highly Flexible Automated Manufacturing of Composite Structures Consisting of Limp Carbon Fibre Textiles", SAE Int. J. of Aerospace, Volume 2, Issue 1, pp. 181-187

[16] Edi P., Yusuf K., Radzi A. Ghani A., H. S.S. Aljibori. "The Design of Light Jet Aircraft". WSEAS Transactions on Applied and Theoritical Mechanics, Issue 2, Vol.4, April 2009

[17] Discenzo, F.M., Maturana, F.P., Staron, R.J., et.al.; "Prognostics and Control Integration With Dynamic Reconfigurable Agents", 1st WSEAS International Conference on Electroscience and Technology for Naval Engineering and All-electric Ship, 12-13 July 2004, Voliagmeni, Athens, Greece, 2004

[18] Mills, A.: "Automation of carbon fibre preform manufacture for affordable aerospace applications. Composites Part A" Applied Science and Manufacturing 32 (2001) 7, S. 955–962

[19] Roebrock, P., Boehnke, K. Offline Path Correction System for Industrial Robots. WSEAS International Conference on Automatic Control, Modeling & Simulation, pp. 276-280, 2007

[20] Taylor P.M., "The Automated Handling of Limp Materials, in Theory and Practice of Control and Systems," Edit. A. Tornambe, G. Conte, A.M. Perdon, World Scientific Press, (1999)

[21] Yousef J, Zoppi M, Molfino R, "Pick and Place Vacuum Robotic Gripper for Flexible Material Manipulation", 1st International Conference on Applied Bionics and Biomechanics: ICABB 2010, 14-16 October, Venice, Italy

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