Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 38 (2019) 1276–1283

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

29th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2019), June 24-28, 2019, Limerick, Ireland.

Automated Handling of Auxiliary Materials using a Multi-Kinematic Gripping System

Michael Vistein*, Jan Faber, Clemens Schmidt-Eisenlohr, Daniel Reiter

Institute for Structures and Design, German Aerospace Center (DLR), Am Technologiezentrum 4, 86159 Augsburg

Abstract

Using a special, multi-kinematic gripping system, the vacuum bagging process in the manufacturing of carbon-fibre reinforced plastics (CFRP) can be automated. Using the example of a parabolic rear pressure bulkhead, the flexibility of the multi-kinematic system is used to handle largely different sized cut-pieces of auxiliary materials. Avoiding the need for special gripping systems for each part greatly reduces the cost for automation because it allows using a single system for a broad variety of different tasks. With a genetic algorithm for optimization, the high redundancy created by using several robots with each 6 or 7 degrees of freedom can be solved. The overall process is simulated using a 3D visualization environment and therefore can be programmed completely offline before being executed with real robot hardware

© 2019 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the scientific committee of the Flexible Automation and Intelligent Manufacturing 2019 (FAIM 2019)

Keywords: manufacturing; robotics; simulation; composites

1. Introduction

The vacuum bagging process during the manufacturing of lightweight airplane structures is usually performed manually. However, rising part sizes have an influence on the reachability during manual handling steps and therefore lead to a decrease in positioning accuracy and reproducibility.

* Corresponding author. Tel.: +49 821 319874 1078
E-mail address: michael.vistein@dlr.de

2351-9789 © 2019 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the scientific committee of the Flexible Automation and Intelligent Manufacturing 2019 (FAIM 2019)
10.1016/j.promfg.2020.01.220

In a current case study, a full-scale demonstrator of a parabolic pressure bulkhead (diameter ≈ 4 m) is manufactured using robotic handling systems. The manufacturing process is based on an out-of-autoclave Vacuum Assisted Process (VAP). The layup consists of a dry carbon fibre preform with eight stringers. The preform must be entirely covered by multiple cut-pieces of vacuum bagging materials. The thin, flexible materials have to be handled carefully and positioned within a tolerance of ±5 mm. Since the preform top surface is geometrically complex, a variety of geometrically differing cut-pieces has to be stacked. In our case study 24 packages consisting of four characteristic shape designs have to be placed. A robotic pick and place system therefore must be highly adaptable to allow the handling of all packages with a single gripper.

To achieve this goal, a flexible, multi-kinematic gripping system has been developed. It consists of three small-size robotic arms (two 6-DoF IGUS robolink W, one 7-DoF KUKA LWR) attached to a large industrial robot (with 6 DoF). For the current use-case, only two of the small robots are used. Therefore, in total the system has 19 controllable joints.

The gripper consists of three kinematic chains with 12 and 13 degrees of freedom respectively, which introduces high redundancy. To solve this, a genetic algorithm has been used. While the positions of the final gripping points in the tooling are provided by construction, the position of the large industrial robot (and therefore the poses of the small-size robots) is variable. The fitness function used for optimizing the position of the large robot is a key factor in the path planning process, and has to deal with restricted joint limits and singularities. Using this optimization approach, it is not only possible to place all 24 differently sized packages, but there is still enough workspace left to drape the auxiliary materials over stringers or the edge of the mould as required.

Vacuum bagging is rarely addressed in automation projects for the production of CFRP parts. In [6] and [11] some automated vacuum bagging is performed, however both systems are optimized to one specific geometry and cannot be easily adapted to other geometries. For the automated layup of a CFRP preform, several end-effectors have been created. To adjust a gripper to curved surfaces and thus to enable the production of different sized and shaped parts with a single end-effector, different approaches have been used. Kordi et al.[10] and Jiménez et al.[9] both use additional driven degrees of freedom at the gripper. Brecher et al.[3] use a self-adapting arm based on the fin-ray principle. Using a reconfigurable, multi-kinematic system has already been proposed by Müller et al.[12] for flexible production of large, rigid aircraft parts. This paper extends these approaches by using small-sized off-the-shelf robot systems which offer very high flexibility, but require a high level of path planning due to the high level of redundancy. Some preliminary work is published in [4] and an overview of pick-and-place systems including vacuum bagging is provided in [2].

Section 2 describes the process that is necessary for robotic vacuum bagging with the specific design of packages of vacuum bagging materials (section 2.1), the generation of grip-points for the robots (section 2.2), the design of the multi-kinematic gripper (section 2.3) and finally the draping process (section 2.4). Section 3 describes the program generation for the multi-kinematic gripper including the optimization algorithm used for positioning the multi-kinematic gripper and the overall path planning. Section 4 provides an overview of the systems required for the simulation and execution of the planned trajectories. Finally, the results are summed up and an outlook is given in section 5.

2. Robotic vacuum bagging

Traditionally, vacuum bagging is performed manually. To allow an automated process, several steps are required: The vacuum bagging materials must be split into several manageable cut-pieces, a draping process must be developed which places the materials without wrinkles on the preform, and grip-points for the robotic end-effectors have to be defined.

2.1. Package design

The application scenario is based on the geometric design of pre-tailored near net-shape auxiliary material packages. These packages consist of thin layers of wovens, films and knitted fabrics such as peel ply, release film and flow media. The design of auxiliary material packages has been described in [5]. Prior to the automated handling, all packages are prepared manually. First, single layers of auxiliary materials are cut. In the second step those layers are joined to each other using an ultrasonic welding device.

The auxiliary materials have to cover the entire surface of the composite preform. Referring to the resin flow, locally different stacking sequences, meaning varying material combinations in the packages, are used. In order to define the near net-shape cutpiece contour of each package the surface is segmented driven by geometric characteristics, in particular by eight radial oriented stringers. As mentioned, the cutpiece design is additionally affected by the material stacking as we aim for a uniform stacking within each cutpiece. For all packages, manufacturing tolerances for gaps and overlaps of ±5 mm have to be considered.

With these requirements, 24 geometrically different three-dimensional (3D) packages are generated for the use case. Although all packages differ from each other, they can be classified by their basic outer contour. Figure 1a) displays the 3 basic package designs and the required grip-points in 2D.

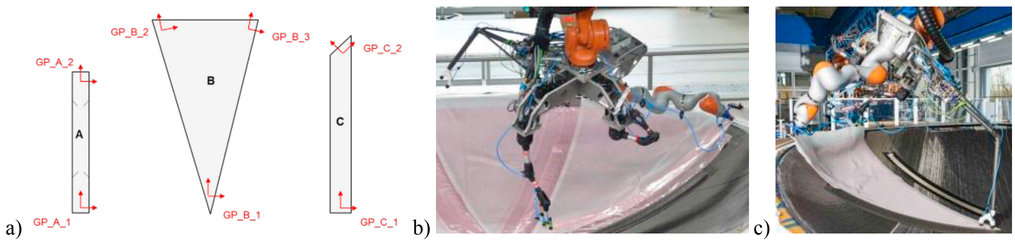

Figure 1: 2D-Classification of the packages in three basic contours (a), pieces A and B attached to gripper (b and c)

- Package A consists of peel ply and release film and is placed on top of the stringers. It is similar to a rectangle with two gripping positions.
- Package B consists of peel ply, release film and flow media. It is similar to a triangle with three gripping positions and is placed lateral to one stringer.
- Package C consists of peel ply and release film. It is similar to a sloped rectangle with two gripping positions and is placed between the stringer and cutpiece B.

2.2. Generation of relevant grip-point data

The grip points are constructed at the corners of the packages with an offset of 30 mm from the edges. This offset is reasoned by the bending stiffness of the auxiliary materials, so that a bend down of the edges during handling is avoided. An automated routine exports the coordinates for each grip-point on each package and saves the grip point data in a CSV-file which for further processing by the robotic path planning.

2.3. Gripper design

The main goal for the construction of the multi-kinematic gripper was to create a universal manipulation system which can be used for a broad variety of different tasks, mainly driven by the packages used for vacuum bagging described in section 2.1. To achieve this flexibility, three small sized 6-DoF robots are mounted to a gripper, which itself is mounted on a large size industrial robot. For the current use-case, a portal robot with three linear joints and three rotatory joints (forming a spherical wrist) has been used. The portal kinematics allows unobstructed accessibility of the mould from the top with a very large, uniform workspace. The current design of the multi-kinematic gripper is based on an earlier version which has been published in [13]. Based on results of previous full-scale production experiments as well as on simulation experiments, several design aspects have been optimized. The current design can be seen in figures 1b and 1c.

The multi-kinematic gripper consists of two igus robolink W robots and one KUKA LBR iiwa 820 robot, each equipped with two vacuum suction caps for material handling. Additionally, two further vacuum suction caps are mounted on a fixed cantilever beam. Packages A and C can be handled using the LBR iiwa and one igus robolink, while package B due to its large size is handled by the LWR iiwa, one igus robolink and the fixed cantilever end-effector. The second igus robolink robot currently is not used for packages A to C but is necessary for very small semi-circular packages which are not covered in this work. Instead of the fixed cantilever beam, an additional robot could be used. However, adding weight far from the flange of the porting industrial robot is not desired. Furthermore, an additional robot does not add much flexibility, since the large industrial robot itself already has 6 degrees of freedom.

The sensitivity of the LBR iiwa can be used for additional tasks where force feedback is needed. In the current use-case, the iiwa has also been used for pressing the vacuum bagging materials into the radii of the eight stringers with a defined force. This process step avoids air entrapment during the resin infusion.

The proportions of the gripper have been mainly influenced by the packages as defined in section 2.1. Using the offline-programming, optimization and simulation environment described in this paper, the gripper could be tested extensively during each step of the iterative construction process, and thus far before any part of real hardware was built. Furthermore, the automated optimization approach has been used to determine some properties of the gripper, such as the length and orientation of the static end-effector.

2.4. Draping process

Before the vacuum bagging materials are placed on top of the preform, resin is sprayed on several points to “glue” the materials on the preform. Without gluing, in particular the smaller packages A and C tend to slide downwards to the centre of the mould due to gravity.

The handling and deposition process of the packages is initialized by attaching them to the multi-kinematic-gripper. In an industrialized production, auxiliary material packages could be delivered to the work station being folded in boxes. This seems realistic due to the varying contours of each 3D package as described in section 2.1. Another advantage of the manual attachment to the gripper is the flexibility of the workman. Because of the three-dimensional shape of the packages, a pick-up from a plane surface is much more complex compared to flat carbon fibre layers used in dry fibre preforming processes. Preliminary tests have shown that the precision of a robotic pick-up with the multi-kinematic gripper is less precise than the manual attachment. Furthermore, the time required to place the packages precisely on a pick-up table is longer than the time required attaching them to the gripper. After manual attachment, the robotic system transfers the package to the mould. In particular for depositing, robots offer benefits such as reachability and reproducibility that significantly increases the process stability and the quality of the part.

To avoid wrinkles during depositing, a specific movement of the gripper system has been implemented. First, the packages need to be placed with the grip-point near the centre of the mould. In a second step, the outer grip-point(s) can be placed.

For packages A and C, two small robots are used for manipulation on each of the two grip-points. While the robot handling the grip-point near the centre of the mould can remain static, the other robot has to perform a draping motion to place the outer grip-point from a pre-position over the mould to the final position. The pre-position has been determined experimentally in a way the cut-piece is placed smoothly.

Due to their increased size, packages of type B require three grip-points. The central grip-point (marked as GP_B_1 in figure 1) is manipulated by the fixed end-effector on the cantilever beam; the outer grip-points (GP_B_2 and GP_B_3) are attached to the small robots. The outer grip-points must be moved from the pre-position in a straight line to the final drop-position on a vertical plane which is defined by the outer drop-point and the central drop-point. This guarantees a constant overlap of package B with the neighbouring packages A and C. Due to the different sizes of the packages of type B and the limited workspace of the small robot, this draping motion is not possible with the fixed end-effector remaining on the central drop-position. Therefore, a multi-step draping process has been developed:

1. The fixed end-effector is positioned as the inner drop-point by means of moving only the large robot. The small robots are already positioned on the pre-position above the mould.
2. The gripper is repositioned closer to the edge of the mould to provide enough workspace for the small robots. The end-effectors of the small robots must not move with respect to the mould.
3. The small robots are used to drape the packages over the edge of the mould onto the final drop-points.

The repositioning of the gripper in step 2 provides additional workspace for the small robots and is dependent on the size of the packages. This step requires advanced robot control, because all three robots must move simultaneously (i.e. the small robots must compensate the motion of the large robot) to achieve a constant position of the end-effectors.

3. Program generation

Traditional robot programming by manually moving the robot to the desired position and saving the posture (often referred to as "teaching") is a cumbersome job even for traditional tasks, where only a single robot is involved. With a gripping system consisting of several robots that introduces a high level of redundancy, manually teaching the robots is hardly feasible and would likely lead to poor results. In order to achieve good results while reducing the manual effort necessary, we use an offline-programming approach combined with an automated optimization strategy and a simulation environment for validation of the calculated results.

3.1. Optimizing robot positions

The position and orientation of the gripper have a direct impact on the further flexibility of the small robots. Both small robots used have a rather limited motion range for many joints (LWR ±180∘, Igus ±90∘). Positions of the gripper where the small robots are required to use joint angles close to the limits severely reduce the work space available for manipulation. Furthermore, positions close to a singular position (e.g. joint 5 of a robot with a spherical wrist set to 0∘) must also be avoided. Since the motion of the gripper always influences all robots, this poses a multi-objective optimization problem. For optimization purposes, the gripper is assumed to be free to move without any further constraints. In our demonstration setup, this is achieved by being mounted to a large industrial gantry system, consisting of three linear and three rotatory joints therefore covering a very large workspace with only one singular joint configuration that can be ignored.

As described in section 2.4, it is often necessary to specify more than one position for each end-effector to allow draping motions. Therefore, the available workspace of each robot should be used efficiently. Exploring the whole workspace of the large industrial robot for optimal positions of the gripper would be extremely time consuming due to the size and the six degrees of freedom that are available. Therefore, a heuristics based approach using a genetic algorithm has been chosen. This approach is not guaranteed to provide an optimal solution, however, usually a solution very close to the optimum is found. The implementation has been done using the Java programming language and is based on the libraries Jenes[8] and Jenetics[15]. For a genetic algorithm, two key items must be defined: the *genotype* and the *fitness function*. While the genotype is a representation of a solution candidate (*individual*), the fitness function determines the value of an individual.

3.1.1. Genotype

The genotype consists of several *chromosomes*, which themselves can contain multiple *genes*. Each gene represents a single piece of information, such as a single bit or a number. For the optimization of position and orientation of the multi-kinematic gripper, an initial start position needs to be determined (e.g. positioned in the middle of the cut-piece with a certain distance above the mould). The algorithm then has to find a transformation to another position and orientation which puts the gripper in to an optimal position. The transformation τ can be represented using six numeric values, three for translation and three for rotation (cf. *Euler angles*):

$$\tau = (x, y, z, \theta, \phi, \psi)$$

By limiting the value range of each component allowed within the optimization process, some constraints can be placed upon the final position of the gripper (e.g. to avoid collisions between the gripper and the mould).

The lightweight robot is equipped with 7 joints and therefore has built-in redundancy. In order to calculate the inverse kinematics function for this type of robot, additional information is required to solve the redundancy. In case of the LWR, an angle α can be specified which describes the angle between a plane formed by the base, the elbow and the wrist of the robot to a vertical plane. Since the position of the elbow has an impact on all joints, an optimized α value helps to avoid joint limits.

The genotype G consists of the transformation τ and redundancy value α. Each numeric value is represented as its own chromosome, each chromosome containing only a single gene:

$$G = (x, y, z, \theta, \phi, \psi, \alpha)^{\top}$$

During evolution, new individuals are created by *mutation* and *recombination*. By mutation, each component is slightly modified, thereby exploring the solution space. With recombination, the chromosomes of different individuals are combined. Only matching chromosomes are exchanged, e.g. the *x* coordinate from one individual is exchanged with the *x* coordinate of another individual. The combination of mutation and recombination provides a good, directed exploration of the solution space without getting caught in local maxima.

3.1.2. Fitness function

The fitness function is used to assign a numeric value to each individual created during the evolution process, which describes how "good" an individual is. For the multi-kinematic gripper, the fitness function F consists of several parts. For each small robot r at each position i, a pose-based fitness $R_{r,i}$ is defined:

$$R_{r,j} = \sum_{j=0}^{j_r} s_{r,i,j}$$

$$s_{r,i,j} = \begin{cases} \left(\frac{x_{r,i.j}}{\varepsilon}\right)^2, & if\ j \in J_r \wedge |x_{r,i,j}| < \varepsilon \\ 1 - x_{r,i,j}^8, & else \end{cases}$$

The value $s_{r,i,j}$ describes a fitness value for robot r (with j_r joints) at position i and for joint j. The value $x_{r,i.j}$ is the joint position, normalized to the interval [-1 ,1]. For most joints, an inverted higher parabola is used, which heavily penalizes normalized joint positions close to -1 and 1. For some joints $j \in J_r$, a piecewise defined function is used which also penalizes values between [-ε,ε]. This is necessary e.g. for joint 5 to prevent positions near singularities. An example of such fitness function with ε = 0.2 can be seen in figure 2.

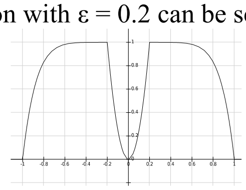

Figure 2: Piecewise defined function for fitness of single normalized joint position

Besides the function $R_{r,i}$ also a path-based function $P_{r,i}$ is defined which values the path of the robot from position i to position $i + 1$. For the vacuum bagging task, those motions usually need to be linear motions, thus large variation of joint angles (such as created due to switching between different configurations of the robot) must be avoided. Therefore, the function $P_{r,i}$ takes the path travelled by each joint into account.

$$P_{r,i} = \sum_{j=0}^{j_r} |x_{r,i+1,j} - x_{r,i,j}|$$

The overall fitness function F is defined as follows:

$$F = r \cdot \sum_{i=0}^{n_i} \sum_{r=0}^{n_r} \left(r_r \cdot \frac{R_{r,i}}{j_r}\right) + p \cdot \sum_{i=0}^{n_i - 1} \sum_{r=0}^{n_r} \left(p_r \cdot \frac{P_{r,i}}{j_r}\right)$$

Both $R_{r,i}$ and $P_{r,i}$ are normalized using the joint count j_r to compensate for the lightweight robot having 7 joints while the igus robot only has 6 joints. n_i is the total number of positions, and n_r the total number of robots. The weight factors r_r and p_r allow the prioritisation of the small robots, while the factors r and p decide whether the pose based or the path based optimization criteria is prioritised. The selection of the weight factors is highly dependent on the desired task.

3.2. Path planning

The optimization process described in section 3.1 yields a position for the gripper which efficiently uses the workspace available to the small robots. The draping motions of the small robots are performed as linear motions. Usually, these motions are possible and singularities are avoided due to the definition of the fitness function (cf. section 3.1.2). For step 2 of the draping process for packages type B, the large industrial robot also has to move. The initial position is provided by the fixed end-effector placing the package; the second position is calculated by the genetic algorithm to provide workspace to the small robots for the draping motion. Between these two positions, an intermediate position slightly above is calculated to avoid contact of the static end-effector with the mould. All three positions are then connected with linear motions of the industrial robot. No paths are planned for the small robots in this step; the path is implicitly generated by inverting the path of the portal robot.

Besides the draping motions, not further motions of the small robots are required. All other transfer movements can be performed purely with the portal robot. The position for pick-up is defined by the user, and the transfer motions to the form can be calculated using the coordinates of the drop-points in the mould. Transfer between both positions is done using linear motions with intermediate points high enough to prevent collisions of the gripper and the mould.

4. Robot control

Three different robots are used in the multi-kinematic gripping system, each robot has its own control hard- and software. The large industrial robot uses a KUKA KRC-4 robot control, which can be programmed using the KRL programming language. The iiwa robot is equipped with a KUKA sunrise controller, which uses the Java programming language. Finally, the igus robot does not provide any robot controller out-of-the-box. The stepper motors are driven using motor controllers mcDSA-S65 from miControl which are connected to a PC using the EtherCAT fieldbus and can be controlled using the DS-402 protocol.

The standard controller software of the robots provide no easy way for the synchronization of multiple different types of robots. Using a fieldbus for simple synchronization of motion start times is not sufficient. For the draping of package B, a motion of all robots is necessary which must be exactly synchronized not only at the start, but during the whole duration of the draping motion. Therefore, an alternative control approach was necessary.

The real-time synchronization of multiple robots is achieved using the Robot Control Core (RCC)[14], which runs on a standard x86 PC using Linux with Xenomai[7] real-time extensions. Programming is done using the Robotics API[1] which is a Java based framework for robot programming. Both RCC and Robotics API have been developed at the Institute for Software and Systems Engineering (ISSE) at Augsburg University. The Robotics API also provides a 3D visualization environment which is backed by a simulated version of the RCC, thus all programmed motions can be previewed and optimized offline, while still using the exact same path-planning algorithms as with real robot hardware.

The Robotics API uses a sophisticated world model that forms a graph of frames of all relevant objects in the application. This model also allows attaching robots to other robots, thus forming arbitrary kinematic chains. Such robot chains can either be controlled independently (the target frames are specified relative to the robot's base frame) or combined (the target frames are relative to the world coordinate system). In the latter case, the second robots (in case of the multi-kinematic gripper the small robots) are automatically compensating motions of the first robot to reach the specified target. For the draping motion of package type B, the small robots are "locked" onto their current position relative to the mould and thus compensate any motion of the large industrial robot (within the bounds of possibility).

5. Conclusion and outlook

Using the gripper hardware and methodology presented in this paper, we have been able to place all 24 cut-pieces of inner vacuum bagging materials on top of a preform using robots. The required positioning quality (±5 mm) could be achieved for almost all cut-pieces, only in two cases slight manual adjustments had been necessary. Placing all cut-pieces took only about 60 min, and no performance optimizations have been done so far. Therefore, the tooling time was strongly reduced compared to the manual process and the reproducibility increased. Additionally, any (accidental) manual impact to the preform is avoided with the automation system.

The absolute accuracy of the end-effectors is not optimal, mainly due to low-cost materials (plastics and Bowden cables for the IGUS robots) and generally limited stiffness of the materials. The reseat accuracy however is good enough that slight manual adjustments to calculated positions can be used for the production of many identical parts.

The optimisation approach finds suitable positions of the gripper for each package usually within a few seconds, and the evolution takes less than 60 s on current hardware to find a near-optimal solution. Sometimes, "unintuitive" positions are found which provide a much better workspace, but would not necessarily come to mind when the user tries to position the gripper manually. Therefore, the use of optimisation technology proved very useful for a highly actuated system. A very important step in the process is the definition of optimisation parameters (such as weight factors) which heavily influence the resulting gripper positions. The integrated simulation environment greatly helped for a quick finding and testing of those parameters. Since the genetic algorithm is based on randomness, it is very probable that two subsequent runs for the same package do not yield the same result. Therefore, a path for each package has been generated using the algorithm and validated using the simulation environment. If the solution was suitable (in particular: collision-free), it was saved. During production, all paths are pre-planned and deterministic.

Improvements can be made in several areas. Using more precise small robots and a stiffer gripper construction will certainly reduce the number of points that need manual adjustments, but will also increase the cost of the end-effector. The time needed for vacuum bagging can also be reduced further by optimizing the transfer motions from the pick-up station to the mould. Some limits to the velocity however exist since the packages act like a sail.

References

[1] Angerer, A., Hoffmann, A., Schierl, A., Vistein, M., Reif, W., 2010. The Robotics API: An object-oriented framework for modeling industrial robotics applications, in: 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4036–4041. doi:10.1109/IROS.2010.5649098.

[2] Björnsson, A., Jonsson, M., Johansen, K., 2018. Automated material handling in composite manufacturing using pick-and-place systems–a review. Robotics and Computer-Integrated Manufacturing 51, 222–229.

[3] Brecher, C., Emonts, M., Ozolin, B., Schares, R., 2013. Handling of preforms and prepregs for mass production of composites, in: 19 th International Conference on Composite Materials.

[4] Faber, J., Schmidt-Eisenlohr, C., 2017. Automated handling of auxiliary materials for vacuum bagging in CFRP fuselage production, in: ECCM17 European Conference on Composite Materials, Munich, Germany.

[5] Faber, J., Schmidt-Eisenlohr, C., 2018. Concept study on optimized auxiliary material designs and application techniques for vacuum bagging of full-scale CFRP rocket booster, in: ECCM18 European Conference on Composite Materials, Munich, Germany.

[6] Filsinger, J., 2013. New variant of VAP (vacuum assisted process) to enable an automated process setup, in: International SAMPE Technical Conference, pp. 1444–1449.

[7] Gerum, P., 2004. Xenomai-implementing a rtos emulation framework on gnu/linux. White Paper, Xenomai .

[8] Intelligentia s.r.l., . Jenes. URL: http://jenes.intelligentia.it/.

[9] Jiménez, V.C., ZUBIRI, O.B., Lasarte, R.M., ASTIGARRAGA, F.J.E., Martinez, J.R.G., MORENO, M.S., ARREGUI, X.I., 2015. Gripping device for manipulating flexible elements. US Patent 8,944,481.

[10] Kordi, M.T., Husing, M., Corves, B., 2007. Development of a multifunctional robot end-effector system for automated manufacture of textile preforms, in: Advanced intelligent mechatronics, 2007 IEEE/ASME international conference on, IEEE. pp. 1–6.

[11] Meiners, D., 2007. Beitrag zur Stabilität und Automatisierung von CFK-Produktionsprozessen. Universitätsbibliothek Clausthal.

[12] Müller, R., Esser, M., Vette, M., 2013. Reconfigurable handling systems as an enabler for large components in mass customized production. Journal of Intelligent Manufacturing 24, 977–990. doi:10.1007/s10845-012-0624-y.

[13] Schmidt-Eisenlohr, C., Vistein, M., Brandt, L., 2017. Introduction of a multi kinematic gripping system for the vacuum bagging process of complex shaped aerospace composite structures, in: Automated Composites Manufacturing-Third International Symposium.

[14] Vistein, M., Angerer, A., Hoffmann, A., Schierl, A., Reif, W., 2014. Flexible and continuous execution of real-time critical robotic tasks. International Journal of Mechatronics and Automation 4, 27–38.

[15] Wilhelmstötter, F., . Jenetics. URL: http://jenetics.io/.