Enhancement of an Optical Cut-Piece Detection System for Pick and Place Use Cases

Christoph Frommel*
German Aerospace Center (DLR e.V.)
Augsburg, Germany
christoph.frommel@dlr.de
*Corresponding author

Alfons Schuster
German Aerospace Center (DLR e.V.)
Augsburg, Germany
alfons.schuster@dlr.de

Marcin Malecha
German Aerospace Center (DLR e.V.)
Augsburg, Germany
marcin.malecha@dlr.de

***Abstract*—The usage of fibre reinforced parts (FRP) in aerospace industry is state of the art due to their high mechanical properties and low weight. Due to the rising amount of possibilities on how to use and manufacture FRPs other fields like automotive and maritime are increasing the usage. Dependent on the parts size and geometrical complexity the manufacturing processes range from solely manual to highly automated. For example, fibre placement with mechanically guided tape laying machines is used to manufacture large component preforms fully automated. Fibre placement for thermoset parts is using prepreg tapes that get cured in the autoclave or thermoplastic tapes with in-situ consolidation which lead to fully cured parts after deposition. On the other hand preforming with patches of unidirectional, non crimp fabrics or weaves is done mainly by hand. However, for smaller companies the investment to automate these manufacturing processes inherits high risks.**

A solution to this problem is the combination of robotically guided patches that are draped manually by skilled workers, which is developed in the European Union's founded project DrapeBot. With the help of the robot and low cost end-effectors, highly flexible manufacturing scenarios with low investment can be achieved. A crucial step in this process is the material logistics to ensure correct material handling and also high quality of the part. In previous researches a camera based system to detect dry carbon fibre as well as thermoplastic patches was developed [1]–[3]. In this work the existing system was further developed to fulfil the needs for a co-operating patch preforming system in the project DrapeBot. Three use-cases from aerospace, automotive and maritime are presented describing the different requirements for the preforming processes and how the system had to be adjusted to fulfil them.

***Index Terms*—computer vision, patch preforming, automated manufacturing**

I. Introduction

A standard approach in aviation industry to save weight of primary structures is to use fibre reinforced parts (FRP) with a focus on carbon fibres (CFRP). The manufacturing processes for the preforms of these structures varies from manual lay up (e.g. A320 rear pressure bulkhead) up to fully automated tape laying (e.g. A350 side shell). One approach to automate various manual processes is the automated pick and place process. The pick and place process grips cut-pieces with mechanically (industrial robots and portal devices) guided end-effectors and places them on a stack or on the mould. In previous projects, an autonomous manufacturing system was developed that focuses on pick and place of dry carbon fibre cut-pieces and thermoplastic organo-sheets.

The system includes a manufacturing execution system that controls the preforming sequence. An optical camera system detects the shape and location of cut-pieces on a material carrier, to ensure repeatability and accuracy of the gripping, since cut-pieces can move during transport from cutting to the preform station. The camera uses several filters and a red flash to get rid of most of the ambient light to ensure high quality pictures for detection. After detection, the system uses industrial robots to automatically grip the piece and place it on the target position and repeats with the next until preforming is finished. For simple robot paths manually programmed movements can be used. Complex movements with high risk of collision or during cooperating movements in-line path planing is used to generate the paths.

The software was written in C++ and is divided in independent classes, which are instantiated in two main modules. The first module is the cut-piece detection module, which holds all the camera and geometry related information, e.g. image acquisition or undistortion. The second module is the main module, that is responsible for process execution, robot positioning and user interaction. Both modules can be configured independently, at startup the main module instantiates as many cut-piece detection modules as there are cameras connected. While one camera can handle the detection for several robots, multiple camera results can be combined for one or more robots, see figure 1.

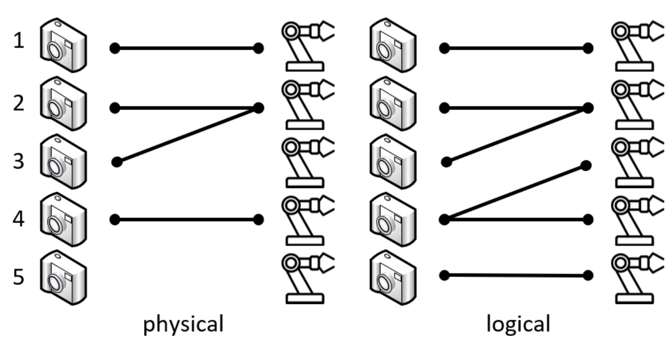

Fig. 1. Example of camera to robot connections

With the help of this system several full size parts as well as research demonstrators were produced. One was a A350 size rear pressure bulkhead with one robot for patches and two cooperating robots for long structural plies. The camera during image acquisition with active flash and detected cut-piece from the rear pressure bulkhead can be seen in figure 2 [4] [5]. This enabled pick and place processes with high repeatability and in cases of large parts getting rid of highly unergonomically positions of workers during preforming. Another use case was the autonomous preforming and fixation of thermoplastic cut-pieces for an A350 size window skin section.

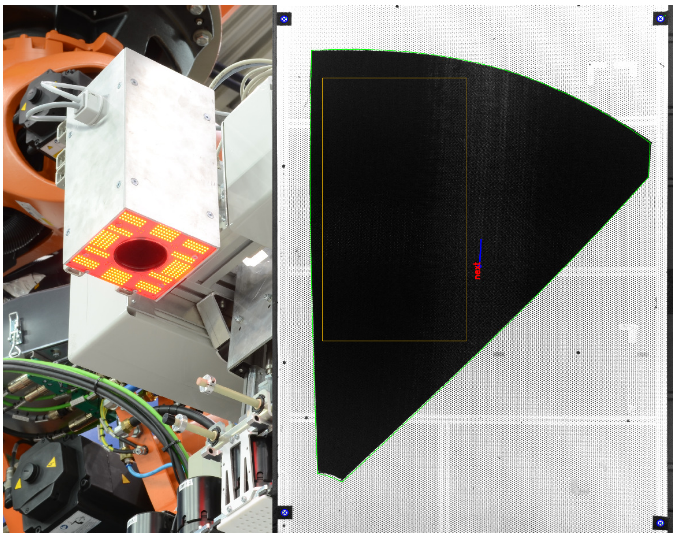

Fig. 2. Camera-system during image acquisition and detected cut-piece

This system was specifically designed to fulfil the needs for aviation production scenarios. However, other fields like automotive and maritime applications are also increasing in the usage of FRPs. Their part dimensions and materials differ and also the investment risks for smaller companies compared to large aviation companies require other solutions.

II. Use cases and hardware determination

The European Union funded project DrapeBot combines the automated pick and place approach with highly trained workers for the draping process. Three use cases from aviation, automotive and maritime were chosen to develop a cooperating robot cell, were the industrial robots support the worker. The aviation scenario uses the "Technology Evaluation Cell" (TEZ) at the German Aerospace Center (DLR e.V.) Center for Lightweight Production Technology in Augsburg, which is equipped with two KUKA robots on one linear axis. Automotive and maritime use cases share a robot cell with one ABB robot. The goal is to relieve the worker from simple, time consuming and ergonomically challenging tasks like holding a ply, fixation or taking a picture for quality assurance. Also, the ergonomic aspect when transporting large plies and place them accurately, in order to start the draping process, is solved by a cooperating handling. Either the robot with the worker transport plies or two robots are transporting which ensures fibre correct handling and higher repeatability. To manage all these production scenarios, a manufacturing execution system is developed by IT+Robotics, which coordinates all of the process steps [6]. The so-called central node manages the process using MQTT as network protocol. Since common cobots load capacity is to low it is necessary to use industrial robots thus makes additional safety features necessary. Voice and gestures to control the process as well as augmented reality are implemented to help the worker in its task. The shared goal of all use cases is to set up a scenario that allows the highly skilled workers to work in a robot cell together with large industrial robots. This approach enables the development of these human machine cooperating robot cells with almost no invest for the aviation scenario, since the robot cell already exists, and low investments for automotive and maritime shared robot cells, which could be the key to bring automation in these manufacturing fields. In the following, three use cases will be described to highlight the individual requirements of each use case and how the camera setup was determined.

A. *Aircraft frame*

For the aviation use case, draping of a structural frame for an A350 sized shell is developed [7]. The frame is generic in size and ply-book but follows industrial design guidelines. A total of 28 plies of dry carbon fibre non crimp fabrics are used. Cut-piece sizes are approx. 200x330 mm², 1300x330 mm² and up to 4100x330 mm². Therefore, pick and place by one robot as well as cooperating transport with two robots is applied. Patches up to 1500 mm length are transported with the help of an automated guided vehicle (AGV) from the cutter to the robot cell. Plies over 2 m length are transported on rolls and are unrolled on a table in the robot cell. Figure 3 shows the TEZ with patches on AGV, long plies on table, mould, robots in park and detection position as well as safety equipment.

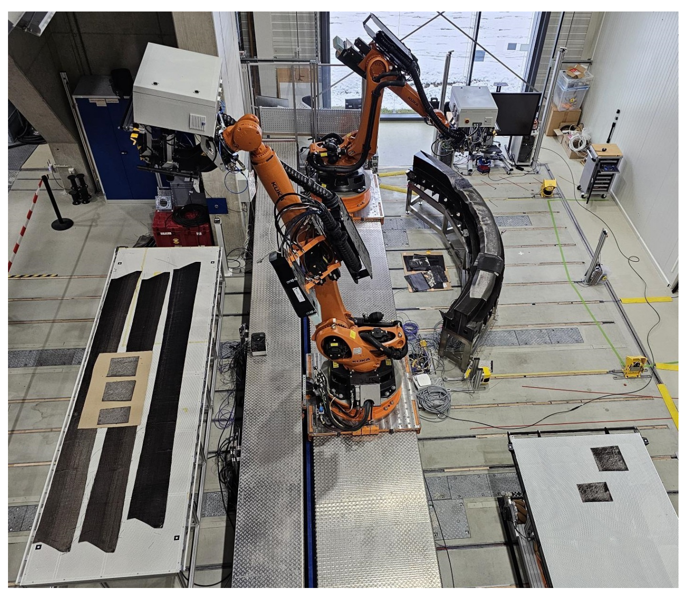

Fig. 3. Robot cell TEZ in DrapeBot configuration

Compared to earlier preforming scenarios, there are two material carriers in the robot cell. Both carriers need to be calibrated to the the robots as well as to the camera system. Since the distance to the table and the AGV is different during image acquisition, there are two major problems to be addressed. Geometric dependencies in the calibration need to change on the fly for the respective material carrier. If patches are picked from the AGV, only one robot needs to be addressed, otherwise both robots need coordinates to pick the plies. To be compliant with the MQTT network protocol, an interface to the software needs to be implemented.

B. Car hood

The first use case for the DrapeCell is to aid in the manufacturing of a sports car hood by Dallara. For the hood, several tailored cut-pieces of prepreg material are used. The prepreg has protective films on both sides and areas where the protective film is removed to measure the fibre angles during transport and draping. Figure 4 shows the setup for the manufacturing of the hood, with the robotically guided end-effector carrying a patch from a table to the mould.

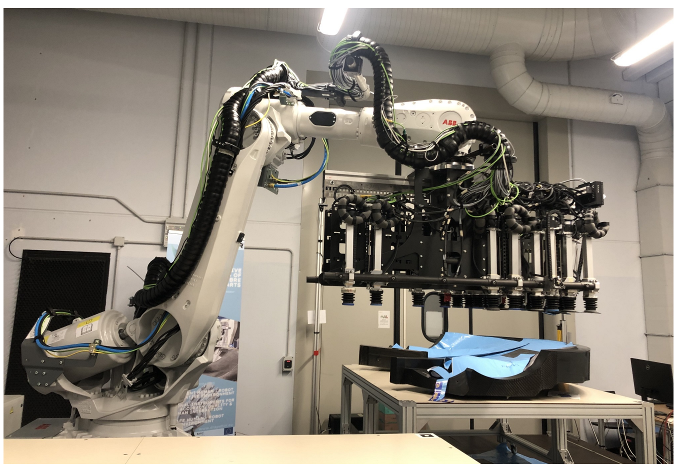

Fig. 4. DrapeCell during patch transport at Dallara

The main difference, compared to the aviation use case, is the fixed mounting of the camera below the ceiling of the robot cell. Due to the single robot as well as cooperating handling with the worker, only one robot is needed. Since the system was initially designed to detect carbon fibre patches, the highest contrast could be achieved with a white material carrier. The protective films on the prepreg can change dependant on the manufacturer and even the batch of material. Therefore, the colour of the material carrier has to be different from the protective films to ensure enough contrast.

C. Ship propeller blade

The DrapeCell is also used for the third use case to help a worker in preforming and will be finished end of 2024. The structure for the maritime part is the blade of a propeller made by BaltiCo. It consists of roughly 200 plies varying in shape and material. Dry carbon fibre as well as dry glass fibre fabrics will be used. Figure 5 shows a demonstrator blade of the propeller.

Fig. 5. BaltiCo manufactured propeller blade demonstrator

Similar to the car use case, smaller plies will be transported to the mould with only the robot. Cooperative transport between the robot and worker will be done with larger plies. Main difference between the use cases is the material that has to be detected. Also, the camera will be mounted stationary above the material carrier that has to differ in colour from the material.

D. Camera selection experiments

For the aviation use case it was possible to use the existing camera setup with an industrial camera, combined with a flash housed as one unit. However, due to the detection of larger cut-pieces, a camera with higher resolution was chosen. This leads to higher accuracy in the detection since more pixel per mm are present. In this case the Allied Vision Alvium G1-2040M-CH-C with a FUJINON CF8ZA-1S lens was used.

Due to the different materials used in the automotive and maritime use cases, a pre-trial to select the best camera system had to be done. During these tests a monochrome as well as colour camera were used. The optics for both were determined using a CAD environment and the ply book to ensure that all sizes of cut-pieces can be detected by one optic. Since the camera will be mounted stationary above of the material carrier, the camera needs to be further away to avoid the robot colliding with the camera during gripping. During the pre-trial, all materials used in the use cases were photographed with both cameras and different lighting scenarios. Ceiling mounted neon lamps for room lighting as well as environmental light from ceiling and wall windows were used. LED panels were used to improve lighting from the sides as well as the red flash for the monochrome camera. In total eight different materials with five different combinations of lighting on two different coloured material carriers were photographed to evaluate which camera system would be chosen.

The larger distance between camera and table needs a brighter flash due to inverse-square law, which can cause a problem for workers in the robot cell. The different materials and changes in colour for the protection film on prepreg materials has led to the decision to use a colour camera. A selection of materials and shapes, used in the use cases, can be seen in figure 6.

Fig. 6. Snippet of materials and shapes used for DrapeCell use cases, prepreg top, dry carbon fibre middle, dry glass fibre bottom

Due to the DrapeCell being operated at different locations during the project, Profactor, Dallara and BaltiCo, it was decided to only use room lighting in addition to the random environmental lighting. Additional lighting from LED panels resulted in reflections which could hinder correct detection. Overall, the colour camera in combination with room lighting was the most flexible combination to handle possible problems. To reduce the complexity, the same camera model just in colour with a 12mm optic was chosen as final camera setup.

Besides of the camera setup, first impressions of the used materials were made. The dry carbon fibres behaved similarly to materials used in previous projects. Glass fibres showed higher reflective behaviour but overall homogeneous properties. However, the prepreg materials, with their different protection films and stiffness, tend to show inhomogeneity especially at wrinkles, which can be seen in figure 6 with the upper cut-piece.

III. Enhancement of existing camera system

After specification of the process properties of material and lighting as well as definition of the camera system, the up to now used cut-piece detection software could be further developed to meet the project requirements. Besides the implementation of MQTT as network protocol, the cut-piece detection module was extracted from the encapsulated overlaying software. Additionally, the fixed cameras above the material carriers need additional perspective corrections. Major part of the aviation use case was to add multiple material carriers, that respectively change the positioning of the camera.

Since there is a demand to use cut-piece detection on a couple of different robot systems, both available programming language and communication interfaces are of particular importance. To separate this from the detection part, the cut-piece detection class was encapsulated in a Windows-DLL. Any C++ or C-# framework can access the functionality by instantiating the necessary number of detector objects by calling the detector factory method. The class interface is pure virtual, in order to reduce interdependency, and only basic data types are used for compatibility. The class covers image acquisition, image evaluation, cut-piece position determination in camera or table coordinates and additionally an interface to the CAD-related data, mostly to obtain the cut-piece contours for the detection. The process related grip–, drop- and tool centre points (TCPs) as well as layup information can also be obtained if needed. Grip-points define where the TCP is placed on the detected cut-piece, whereas the drop-point defines where the cut-piece will be placed in the mould. The layup information contains the ID and shape of the cut-piece that needs to be detected.

To implement the MQTT network protocol two options were discussed: Adding the MQTT protocol to the C++ code or use existing libraries from other languages (e.g. Python) and bind the DLL to be operable from the Python environment. Since there were already existing modules that implemented MQTT to other software parts in the project, and also to make the cut-piece detection more viable for future projects, it was decided to bind the Windows-DLL for python usage. A python binding was created by using pybind11 to allow usage of the C++ implementation additionally from python. Every C++ method is exposed after a detector object is created by a call of the detector factory. This allows usage of the detection with any interface that is needed. This leads to using the cut-piece detection software for the DrapeBot project solely in Python.

The paho-mqtt library was used to implement the MQTT protocol in the code. After initialisation of the camera with camera settings and calibrations the MQTT loop is started and waits for changes in the subscribed topics. The topics are changed by the central node to control the process behaviour. After the cut-piece position was determined, the grip-points are calculated by transforming the contour data to the found ply contour. The maritime and automotive use case, as well as the detection from the AGV in the aerospace use case, publish one calculated KUKA frame (yaw-pitch-roll annotation) to the respective topic in the network. Afterwards, the central node uses this information to grip the piece and transport it to the mould by a path planner from IT+Robotics and motion execution developed by the Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing of the National Research Council of Italy. To correctly grip the long plies with cooperating robots, there are two frames published for each robot. The first set of grip-points define where each robot has to grip the ply from the table. The second set are position dependent frames to bring the cut-piece in a fibre friendly position, similar to a catenate, above the table until it isn't touching the table. This ensures that the cut-piece doesn't shear during the transport from the table to the mould by false handling.

To toggle between the camera settings for the AGV and long table, a new initialization step before each image acquisition is done. After receiving the ply ID from the central node, to determine which cut-piece needs to be gripped, the respective camera calibration is loaded. This changes the main parameters for calculation like pixels per mm and the dependencies between camera to robot cell calibration.

Lastly, the geometrical calibration, for the stationary cameras, for the maritime and automotive use cases were solved. Since the system was initially designed to be mounted on a robot, one could easily adjust the detection position and orientation of the camera, in order to make the camera plane parallel to the gripping table. This is not easy to achieve with a ceiling-mounted camera, since the smallest changes in camera position result in high deviations in the picture due to the high distance to the table. The camera was shimmed and oriented as precise as possible but still showed a small tilt regarding to the table plane. To solve this issue, the calibration targets, that are needed for the robot calibration, for an initial perspective transformation to the table coordinate system were used. This rectifies the image and takes out the perspective distortion, a technique of widespread use in cellular phone scanners nowadays [8]. Figure 7 shows the table before and after perspective correction for the automotive use case, both red rectangles have the same size and shape.

The upper image shows high deviations on the right side, whereas the lower image shows that the table is very precisely aligned to the red rectangle with 90 degree edges. This ensures that the contours that are used to find the cut-piece in the image are comparable, since they are extracted in two dimensional coordinates without any perspective. The same procedure will be done for the maritime use case.

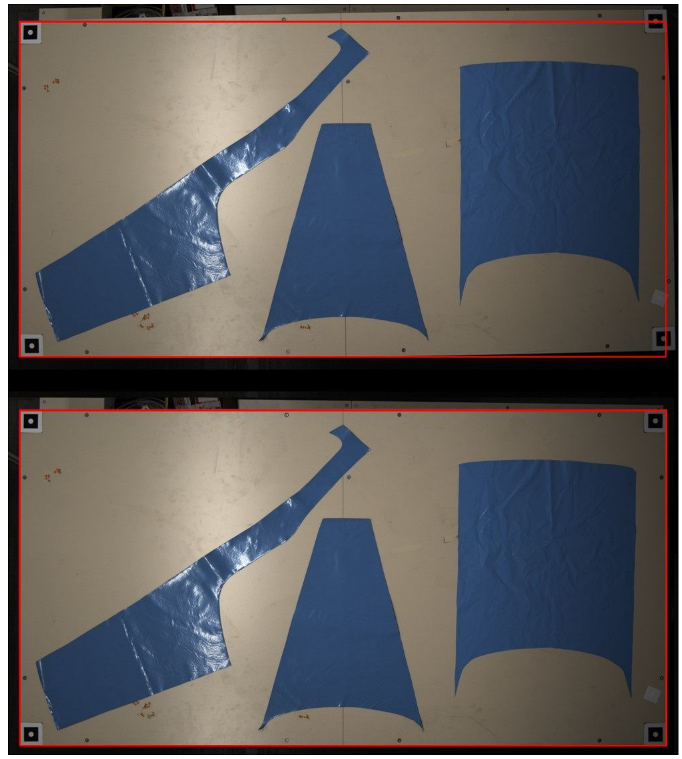

Fig. 7. Perspective transformation - red rectangles have the same shape

IV. Results

At the state of development for the aviation use case it was possible to detect patches from the AGV as well as long plies from the table. The plies that are gripped cooperatively from the AGV are currently under development. For all detections, the software was running in the MQTT loop and were triggered by the central node, which also moved the robot equipped with the camera to the respective detection position. With help of the ID of the ply, together with the execution command from the central node, the correct calibration was loaded and the detection was triggered. Figure 8 shows the detection of a patch on the AGV with another patch that will be gripped later on in the process.

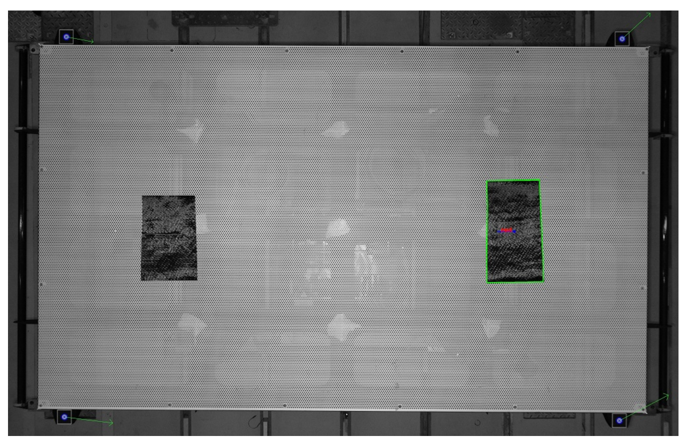

Fig. 8. Detection of reinforcement patch on AGV

The green border shows the contour that was used to find the cut-piece on the table and the final position it was placed. If there are multiple solutions found by the algorithm, the one with the highest matching factor, that results from the template matching, is used. Afterwards, the frame was published to corresponding topic and the central node gripped the ply with the second robot and transported it to the mould were the worker could drape the cut-piece. Figure 9 shows the detected cut-piece placed on the mould before the gripper holds it in place to help the worker draping it to its final shape.

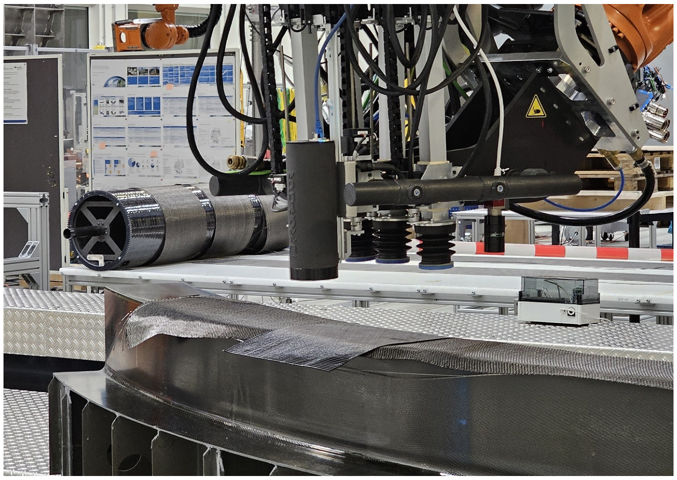

Fig. 9. Detected cut-piece automatically placed on mould

In this early stage of the project, accuracy of deposition is not the first priority. However, with help of markings on the tooling the position could be determined to be within the set tolerance. This shows that the accuracy through calibration and control of the process chain of detection, gripping, transport and placement is already approaching manufacturing tolerances. The cut-piece was detected and transported several times and visually showed high repeatability of the process. Currently under development is the transport for the long plies. To achieve perfect fibre friendly transport, a catenary should be applied between the to end-effectors. Since the implementation of this behaviour is more complex to achieve, a circular orientation determined from CAD environment is used to approximate the catenary. Figure 10 shows the detection of a long ply on the table.

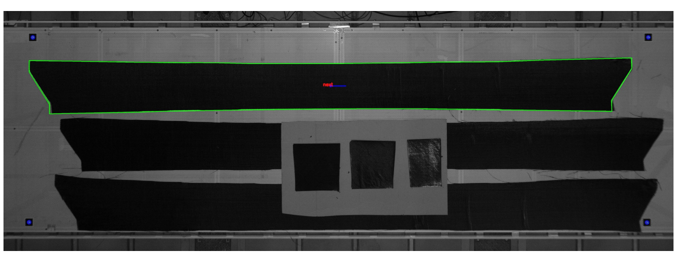

Fig. 10. Detection of structural ply on table

As described in III the first set of calculated grip-points is how the robot picks the ply. A second set of coordinates is published in reference to the detected position that brings the ply in the circular position above the table until it loses contact. This ensures a safe starting position for the cooperating transport without damaging the ply. Afterwards the ply will be transported in a synchronous and fibre friendly motion to the mould were the worker can start the draping process from the middle of the ply to one of the sides. The robot will then move according to worker position until it reaches the final position, repeating on the other side. With this behaviour the cut-piece detection software could handle all requirements that were set for the functionality of the system in the aviation use case. Parallel to the aviation use case the automotive use case at Dallara was finished. In total five cut-pieces were used in this process. Two of them were transported only with the robot, the other three were in cooperation with the worker that drapes the plies Figure 11 shows one of the cooperating plies on the left that was detected by the system.

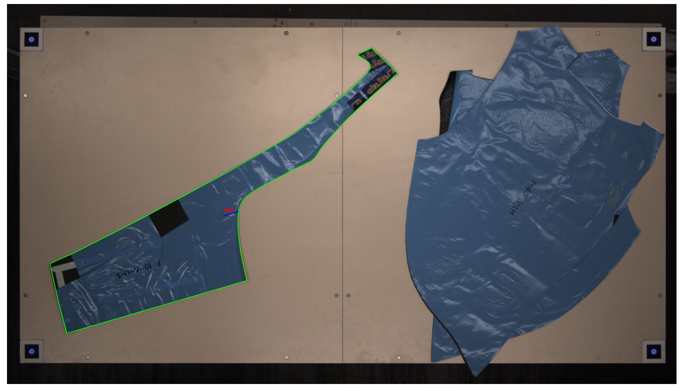

Fig. 11. Perspective transformation - red rectangles have the same shape

As seen in figure 11 the cut-piece has no homogeneous surface. The wrinkles as well as cut outs of the protective film, to enable fibre angle measurements during transport, interfere with the detection. However, the template matcher had no problem in detecting the plies. All five plies could be detected by the system and published the central node where to grip them.

Usually, a border detection is used to further increase detection accuracy. The border detection interpolates points along the contour and calculates the distance from the found contour to the given contour. Aviation parts, especially fuselage parts, usually consist of rather big and easy to describe geometries, whereas the tailored cut-pieces for the car hood have varying shape size and radii. Especially the long thin part of the cut-piece in figure 11 on the left side, led to a lot of false detections due to its slender shape. Since the small part can easily deviate from the original geometry, due to transport forces, the deviation from the border detection is to high for a correct detection with this algorithm. Even though the border detection was not possible to use, the accuracy of the detection was sufficient with only the template matching factor.

Currently, the maritime use case at BaltiCo is prepared and set up to be finished in 2024. With the current development of the system, the detection of cut-pieces for both the aviation and automotive use case could be established. For both use cases it was shown that the detection lead to correct gripping and finally correct placement of the cut-pieces.

V. Outlook

After the system was established in the use cases, further points of improvement could be determined. During the experiments for the aviation use case, reflections in the material could be seen. The filters in the camera system need to be further optimized or supplemented with additional to get rid of them. If the reflections are present on the border of the cut-piece the border detection would also lead to false negative detections. Also, the border detection method itself needs to be improved to handle more complex shapes. One solution could be to implement an adaptive border detection threshold that is linked to the shape of the geometry.

To further increase the automation of the process chain, automated initialization and error handling need to be implemented in the system. For example, if somehow connection or power supply to the camera is interrupted, the system should initialize again if possible or give the central node the status of the system to enable a worker to get the system back up running. The final state of the system should be that it handles all initialization, error handling and calculations on its own as soon as the general python code is started, which could also be done by the central node to fully automate the system except of physical hardware errors.

Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101006732, "DrapeBot – collaborative draping of carbon fibre parts". We would also like to thank Dallara S.l.r. and BaltiCo GmbH for the great collaboration and contribution to the success of the project.

References

[1] A. Schuster, "Autonomes System zur Herstellung von Organoblechen und Preforms", Dissertation, University Augsburg, 2015

[2] M. Kühnel, A. Schuster, C. Rähtz, S. Schneyer, R. Glück, M. Beyrle, M. Kupke, "Flexible and Automated Thermoplastic Preforming Process in Aerospace" CAMX – The Composites and Advanced Materials Expo 2017, 12.-14. Dec. 2017, Orlando, USA, 2017

[3] C. Frommel, M. Körber, M. Mayer, A. Schuster, M. Malecha,L. Larsen, (2019) "Autonomous preforming system: automated and sensor-aided handling of dry carbon fibre textiles" 29th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2019), 24.-28. June 2019, Limerick, Ireland, doi:10.1016/j.promfg.2020.01.004 ¡https://doi.org/10.1016/j.promfg.2020.01.004¿, ISSN 2351-9789

[4] D. Deden, C. Frommel, R. Glück, L. Larsen, M. Malecha, A. Schuster, "Towards a fully automated process chain for the lay-up of large carbon dry-fibre cut-pieces using cooperating robots", In: SAMPE Europe 2019. SAMPE Europe Conference 2019, 17.-19.09.2019, Nantes, France, 2019

[5] C. Frommel, F. Krebs, T. Haase, M. Vistein, A. Schuster, L. Larsen, M. Körber, M. Malecha, M. Kupke, "Automated manufacturing of large composites utilizing a process orchestration system", In: 30th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM 2021, 30th International Conference on Flexible Automation and Intelligent Manufacturing, 15.-18. June 2021, Athens, Greek. doi:10.1016/j.promfg.2020.10.066 ¡https://doi.org/10.1016/j.promfg.2020.10.066¿, ISSN 2351-9789

[6] A. Gottardi, M. Terreran, C. Frommel, M. Schönheits, N. Castaman, S. Ghidoni, E. Menegatti, "Dynamic Human-Aware Task Planner for Human-Robot Collaboration in Industrial Scenario", European Conference on Mobile Robots, ECMR 2023, Coimbra, Portugal, September 4-7, 2023, https://doi.org/10.1109/ECMR59166.2023.10256268

[7] M. Malecha, G. Nehls, "DLR develops safe and flexible workspaces for robot assisted manual draping", Composites World, Gardner Business Media, Inc.. ISSN 2376-5232, 2023

[8] G. Bradski, "The OpenCV Library", Dr Dobb's Journal of Software Tools, 2000