SYSTEM CONCEPT FOR HUMAN-ROBOT COLLABORATIVE DRAPING

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ABSTRACT

Draping is a technically complicated process as it involves the placing of a flat piece of carbon fiber fabric in a 3D mold, without creating wrinkles, maintaining an accurate position and ensuring correct fiber orientation. Currently, this process is either done fully manually or – in simpler cases – fully automatically through robots or application-specific handling devices. In this paper a system concept is proposed that allows human-robot collaborative draping. Based on typical use cases from the aerospace, boat-building and automotive industry various interaction modes are identified, including the joint transport of large patches of material, the placing of the material and the draping of areas of low and high curvature. The analysis is presented in the form of a prototypical robotic work-cell including the sensor systems as well as the real-time software architecture to allow a smooth and efficient interaction between the human and the robot.

1. INTRODUCTION

1.1 Industrial draping and human robot collaboration

Draping is the process of placing soft and flexible patches of textile material (in the applications considered in this papers it is carbon or glass fiber fabric) on a 3D shape during the manufacturing of carbon fiber composite parts. Draping remains very important as an alternative to automated fiber placement and tape laying due to its flexibility and its compatibility with a wide variety of fabric materials. As a result, 30% of aerospace composite parts [1] are still produced through draping, while many automotive and almost all marine structures are made this way. At present, most draping is done manually, with only 5% of aerospace composite parts using some automated draping process.

The automation of draping processes often uses specifically designed handling systems that pick up a patch of material and either place it directly on the mold or in a frame that holds the patch in place while it is lowered on the mold [2]. Sometimes the edges of these frames are modified to change friction and to better control the draping process. Robotic draping has been investigated in [3]. The main challenge is to deform the flat material into a 3D shape that resembles the shape of the mold. Various kinematic structures with a varying degree of flexibility have been introduced [4], but there are often limitations in terms of curvature that can be achieved. The draping of tight corners, flanges or U-shaped structures is difficult with such flexible gripper systems, unless application- and geometry-specific designs are made.

In order to obtain a higher degree of automation, a combination of human and robotic capabilities will be a solution that combines the dexterity of humans, when draping small, high curvature areas and the precision and higher reach of robots when draping the larger, less curved areas. To enable an efficient collaboration process, human and robotic capabilities need to be tightly and seamlessly integrated. This is a substantial extension over situations, where a human and a robot are just operating within the same workspace, but on independent tasks. Also, trust [5] needs to be investigated, as – due to the typical size of the parts – the robot will inevitably have a significant size and payload.

1.2 Typical requirements in boat-building, automotive and aerospace applications

The degree of automation varies in the different industries, and directly correlates with the manufacturing volume. In the automotive industry RTM (Resin Transfer Molding) processes are most common and parts are of medium size with up to 2m along the major dimension. The range of materials is increasing, often dry material in combination with infusion processes is used. For large production numbers the draping process is automated, with specifically designed equipment. For smaller and medium size batches, such as in sports car, the draping is done manually and also includes e.g. prepreg material. In the aerospace industry manual draping is used for medium size parts, especially for spars, ribs and similar parts with high local curvature. Manual work is often supported by projection systems to help with the positioning of the single patches. In boat-building the draping is a purely manual process, with two or three persons involved when draping larger patches of material, e.g. during the construction of a boat hull. Materials include glass fiber for the leisure craft and carbon fiber for racing equipment.

Independent of the particular materials and processes used, requirements for draping processes always include the accurate placement of the material and controlling the distortion and re-orientation of the fibers when the material adapts to the 3D shape. The main defects that are found during draping include wrinkles, bridging and foreign objects.

1.3 Challenges for human-robot collaboration

Combining the skills of humans and robots in draping processes creates several challenges that need to be addressed when designing such systems.

The robots used for draping will be full scale, non-compliant robots due to their size and due to the payload required to carry the - often heavy - grippers. Collaboration can thus be ‘scary’ for the human operator and aside from setting up appropriate safety devices also a certain level of trust is needed to enable the collaboration. The main challenge is to find a balance between efficiency and safety.

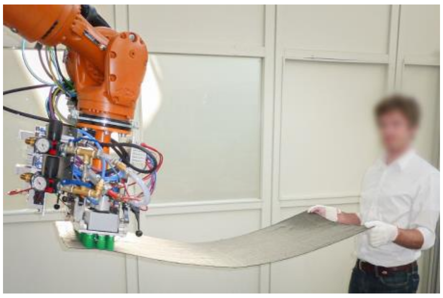

Fig. 1 Collaborative handling of a patch of material.

Collaborative draping also includes situations, where the robot and the human are in direct collaboration and need to jointly complete the task, such as transporting a large patch of material (Fig. 1). This leads to hard real-time constraints as the robot needs to react immediately to the actions of the human. Also, there must be a common, high-level understanding of the task to enable a seamless interaction. Using specific gestures of the human to signal e.g. the completion of a process step to the robot is not an option as this would substantially reduce the efficiency.

In situations where the robot is holding the material in place, while the human is draping nearby areas of high curvature, the human will be very close to the robot. This might also happen during the placement operation while the robot is still in motion. At that point the robot cannot take any ‘avoiding action’ when it is operating close to a human. More intelligent modes of interaction are required than just keeping a certain minimum distance or blocking certain areas around the robot.

In the following section a concept for human-robot collaborative draping is described that takes the requirements of different domains into account, by analyzing human-robot interaction modes and proposing a concept at hardware and software level. In section 3 a particular instance of this concept is provided.

2. SYSTEM CONCEPT FOR COLLABORATIVE DRAPING

2.1 Human-robot interaction modes

Based on the analysis of typical application scenarios in the aerospace, boat-building and automotive domain, a set of human-robot interaction modes have been identified. It has been found that in addition to human-robot collaborative tasks, there are also robot-only tasks, which will be included in the discussion below, and possibly human-only tasks, which are not included. The following interactions have been identified:

(1) Two Robots transport a large patch to the mold and pre-drape it into the initial shape.
This is a robot-only operation mode that is suitable when the patches are large and the area on which they are to be draped does not have high curvature. This requires the coordinated planning of the robot trajectories, including a good model of the behavior of the material that is handled between the robots, but the task as such is fully predictable.

(2) The robot and the human transport a large patch from the delivery table to the mold.
This is the most difficult interaction scenario, because it requires the robot to follow the human in order to avoid over-tensioning the sensitive material, but on the other hand it needs to be placed in the correct position. The robot obviously has a higher capability of locating the position with high accuracy and thus needs to guide the human to this location.

(3) The robot transports a patch and drapes it.
This operating mode is a simplified variant of mode (1). In this case the patch of material is small enough to be handled by a single robot and the curvature of the part allows fully automatic draping. Standard motion planning can be used to generate a trajectory and – due to the absence of human interaction – there is not much variability involved.

(4) The robot does initial draping and holds the patch in place, while the human is draping.
This interaction methods poses challenges in terms of trust. The human possibly needs to work close to the robot. Sensor systems need to provide accurate feedback to avoid that the robot unexpectedly starts to move in the wrong direction.

(5) The robot work-cell assists the human by delivering material or projecting information.
In these interaction modes the robot provides assistance, e.g. by delivering auxiliary materials that need to be placed or by projecting position information during manual draping. The main difference to other collaborative scenarios is that the task is completed by the human and the

robot does not directly react to human. The scenario, however, requires at least an understanding about the state of the process.

2.2 Hardware level and collaborative draping process

Human robot interaction will be realized in industrial robot cells including one or more robots. Large cut pieces and molds make it necessary to use an additional linear axis for the robots. Due to the weight of the grippers, robots with respectively high payload capacities are needed. The robots also have to provide the infrastructure for the features of the gripper such as compressed air, electricity and network technology. The gripper uses several features to handle the collaborative draping process. First the gripper needs modules to pick up the material and hold them in place but also needs adjustable gripping force to allow slipping when required. Generating defined slippage is realized by friction-control modules which support during draping but also during holding of material on the tooling. The fixation of draped plies is carried out by tacking modules which melt thermoplastic binder in the material. To automatically drape certain cut pieces the gripper needs to be flexible and deformable to the desired geometry. With a deformable gripper the position of the cut piece on the gripper needs to be detected by position measurement modules to ensure precise placement. Finally, sensor modules which detect fiber angles and movement of cut pieces finish the requirements needed to perform the precise draping of fabrics in a human robot collaborative scenario. The cut pieces are usually provided by industrial cutting machines. If the cutter is not located in the robot cell the cut pieces are delivered to the robot on material carriers which have to be calibrated to the cell. To precisely grip the cut pieces computer vision will be used to detect the location on the material carrier.

Since the worker is within the reach of multiple robots, special safety features have to be implemented for worker detection. Combinations of laser systems and camera-based detection will be used. To enable communication between the worker and the robot cell augmented reality devices like a HoloLens are an option. This enables voice and gesture-based interaction between worker and robots. The overall task execution will be controlled by a high-level Manufacturing Execution System (MES). The MES needs to communicate with every participant in the system via several network technologies. Processes like cutting are defined tasks which only need triggering when needed. However, the robots need to react in real-time to worker movements which are provided by external systems. Therefore, the robot controls need to be accessible by the MES to change robot paths on the fly.

2.3 Software structure for real-time interaction

The control architecture of a workcell for collaborative draping needs to handle two different working modes: robot-only tasks where the robot(s) work(s) without interaction with the operator and human-robot collaborative tasks.

A standard control architecture for industrial robotic cells is shown in Figure 2. The core of the system is the PLC that acts as a central node able to run a predefined finite state machine, to communicate with the factory automation through a fieldbus, to control the workcell actuators and to acquire workcell sensory data. The robot starts and stops the execution of predefined programs under the supervision of the PLC. This architecture is simple and effective but is not flexible enough for a collaborative scenario.

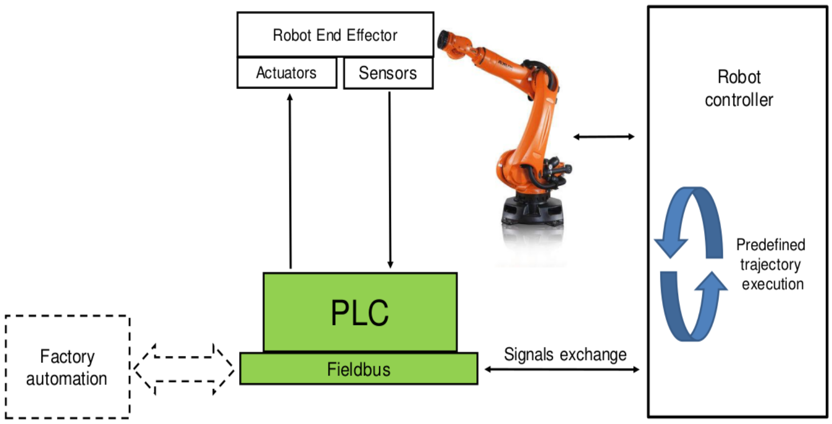

Fig. 2. Standard control architecture for robotic work-cells.

To improve flexibility and to enable the collaboration the scheme presented in Figure 3 needs to be evolved with the integration of smart sensors able to track the presence of the human operator(s) in the robot workspace, and possibly providing information at a higher level about human actions and intentions. In case of a cooperative task, the goal is to use sensory information to adjust online the robot nominal (i.e. planned offline) trajectory to deal with operator feedback (i.e. operator experience in draping process) and operator movements (i.e. uncertainties of the movements). The trajectory adjustments should prevent damage to the manipulated materials but at the same time they should be constrained within predefined ranges. Tracking the operator in combination with safety sensors, is also fundamental for safety monitoring to prevent dangerous working conditions.

An intelligent perception system is a key component of a modern workcell [6], [7]. Therefore, the draping cell is equipped with a perception system that exploits multiple technologies such as 3D cameras, which provide RGB and depth images, and inertial sensors attached to the human workers operating in the cell, that are the main target of the perception system. Indeed, rich information about humans (as in [8]) is essential to achieve an efficient human-robot collaboration. The vision sensors are organized in a camera network in order to provide an overall map of the workcell. An additional force/torque sensor is integrated between the robot flange and the robot gripper to measure the force/torque exchanged between human and robot during the collaborative material manipulation.

The measurements provided by the different sensors are fused together to generate unique information able to provide feedback on the operator position and movements. The fusion module is capable of providing reliable and stable information, and to overcome the limitations of a single sensor: for example, a camera network with a proper sensor placement can overcome occlusions that are very likely to occur in a human-robot cooperative application.

The signals provided by the sensor fusion module feed a Model Predictive Controller (MPC) able to work as an active filter to generate a deformation of the nominal trajectory executed by the robot if the operator movements and intentions differ from the expected one. As a primary task the MPC acts as a target tracker, while as a secondary task manages the exploitation of functional redundancies (when available), and scaling the velocity according to the human level of interaction and the robot constraints. The MPC, therefore, is a module that, based on the actual scene information (humans, robots and sensors), modifies the pre-planned trajectory. The generation of the deformation is based on a bounded model of the integration of impedance-based algorithms in MPC as an extension of [9] for dynamic applications with time-varying boundaries. The MPC, therefore, extends the approach to the control of a trajectory, and at the same time allows the integration of dynamic filter – such as impedance-filters – to modify smoothly the trajectory according to the human intention. The methodology allows to modify the velocities in order to fulfill ISO/TS 15066:2016, the dynamics of the robots, and exploiting the information coming from the camera to enable a safe online continuous re-planning.

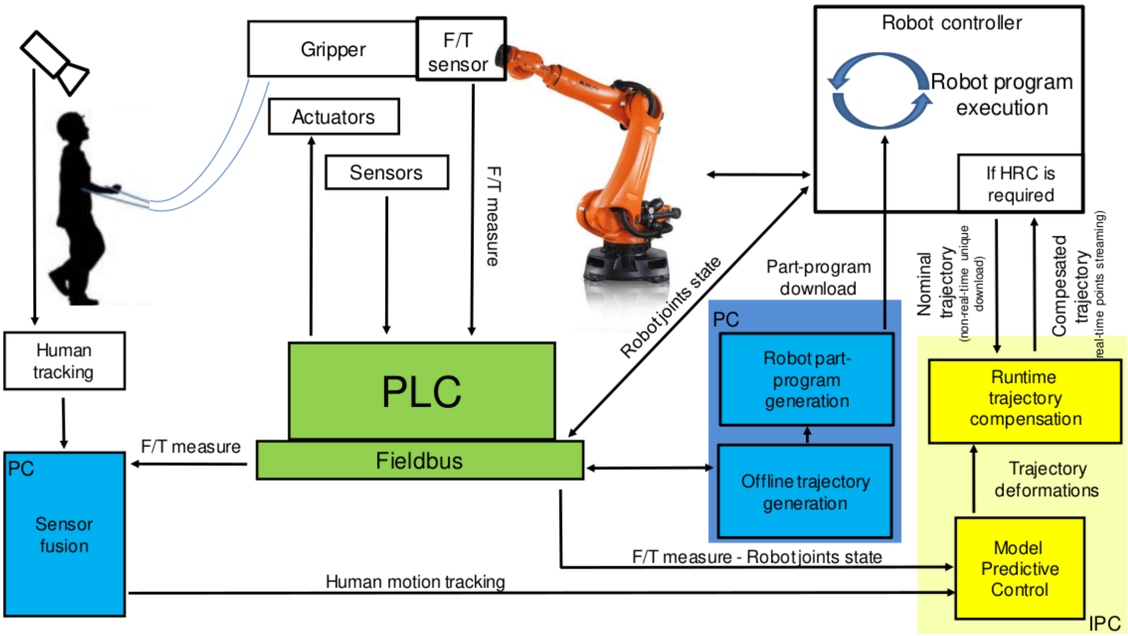

Fig. 3 Control scheme of work-cell for collaborative draping.

The MPC runs on an Industrial PC (IPC) and can be developed through soft PLC with the IEC-61131-3 automation languages, to keep the application as close as possible to industrial practice (see also [10]). The MPC is triggered only during the collaboration, in all the other cases the robotics workcell acts as a standard application with the execution of predefined programs. The adjusted trajectory is sent from the IPC to the robot controller through the so-called real-time open channel, provided as a software option by several robot manufacturers.

3. IMPLEMENTATION EXAMPLE

A CFRP frame is designed by general design guidelines for fiber reinforced layups [3,11] and would be used in the door surrounding of a single-aisle airplane. Features of the frame are the length of approximately 4 meters, local reinforcements which are generating slopes, double curvature in the radius of web to flange and the resulting 90 degrees between draping planes of web to flange. The cut piece spectrum of the lay-up consists of several plies, all of them have approximately 400mm in width but differ highly in length. This spectrum of cut pieces requires several combinations of human-robot collaboration modes as stated in section 2.1.

An industrial robot cell with two robots on a linear axis will be used for the preforming process. Also located in the robot cell will be the tooling on a fixed position as well as material carriers. For the patches and short cut pieces an autonomous driving table can be used. The long cut pieces are delivered to the robot cell and are placed on a long table. Both carriers are calibrated to the robot cell for possible cut piece detection via machine vision. Finally, a worker is located in the robot cell which makes it necessary to enhance the cell with additional safety features for safe human robot collaboration. In conventional robot cells, guards like safety fences are common, which basically prevent access to the cell while robots are moving automatically. To facilitate the presence of the worker in the cell, a hierarchical concept is proposed. In order to generally control the entry into the cell while maintaining accessibility, light curtains are used (Fig. 4, red border). This allows traditional safety features to be implemented like ensuring a safe position of the robots or triggering an emergency stop on entry.

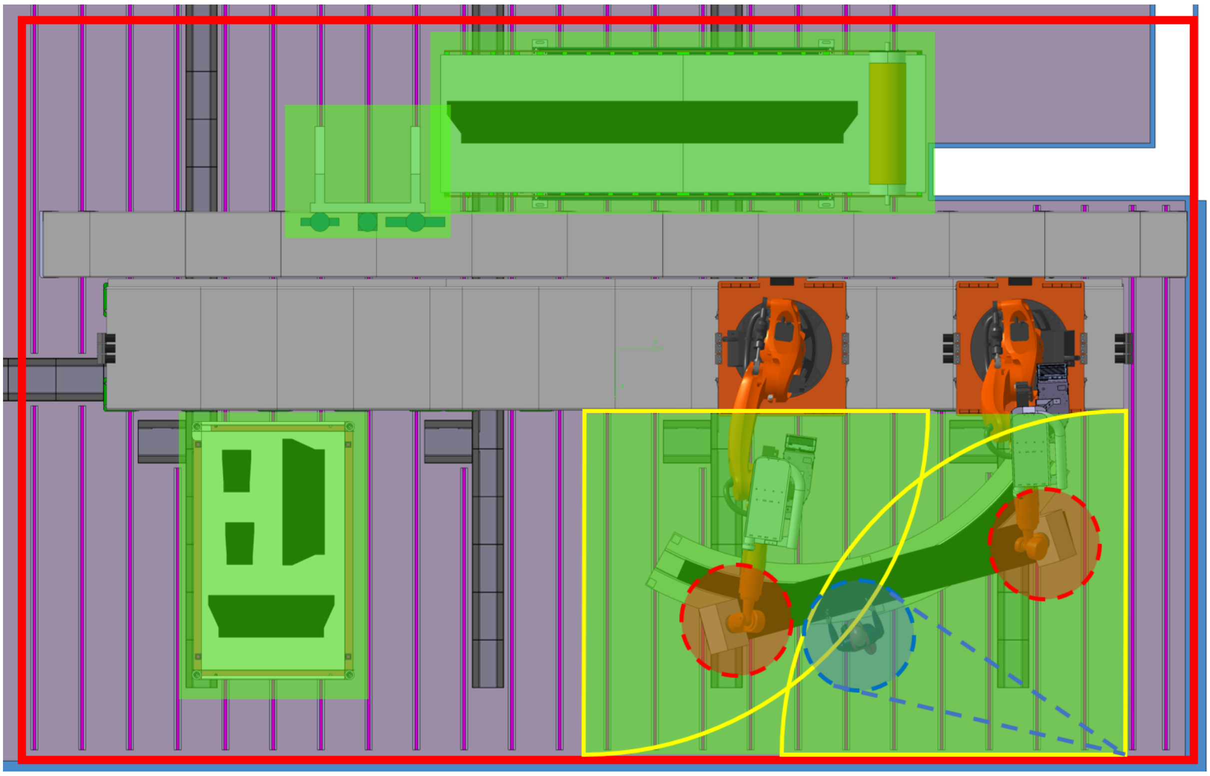

Fig. 4 Collaborative draping cell with safety features: light curtains (red border), interaction zones (green area), position tracking (yellow view fields), safe tools (red circles) and skeleton tracking (blue circle)

Additionally, within the cell, there are one or more designated "interaction zones" (green areas), which have a fixed position and size. The safety control will be implemented in a way that the robots are only allowed to move when the worker is within an interaction zone. This requires the accurate detection of humans in the work-cell. For this purpose, the perception system will be used, which can be enhanced by safety equipment such as laser scanners (yellow view fields). The robot needs to be able to enter the interaction zone as well. Since this needs to happen in a safe and controlled way, an additional package for the robot controller will be used (e.g. "SafeRobot" for KUKA), which provides comprehensive features such as the definition of safety zones, safe tools (red circles) and reduced speed. To enable sophisticated interaction with the robot, this basic safety equipment will be extended with multi-modal sensing such as camera-based skeleton tracking (blue circle and view field), speech recognition and gesture detection. This will increase the intelligence of the work-cell and enable a safe and efficient collaboration.

4. CONCLUSIONS

Collaborative draping poses several challenges when setting up a robotic work-cell. At the highest level, a suitable balance needs to be found between safety and efficiency. This will require more intelligent behavior of the robots that goes beyond just stopping or slowing down in the presence of a human. At the control level, the interaction needs to resolve contradictions such a placing the material in the right location while properly reacting to the variability of human motion. This requires developments in perception and real-time control. Due to the size of the robots also trust between the human and robot is an important factor to be taken into account.

5. REFERENCES

1. S. Das, J. Warren, D. West, S. M. Schexnayder, Global Carbon Fiber Composites Supply Chain Competitiveness Analysis, CEMAC technical report, May 2016
2. M. Elkington, C. Ward, A. Sarkytbayev, Automated composite draping, SAMPE 2017. SAMPE North America, (2017).
3. C. Frommel, M. Körber, M. Mayer, A. Schuster, M. Malecha, L. Larsen, 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
4. T. Gerngross, D. Nieberl, Automated manufacturing of large, three-dimensional CFRP parts from dry textiles, CEAS Aeronautical Journal, 2014
5. K. E. Schaefer, Measuring Trust in Human Robot Interactions: Development of the "Trust Perception Scale-HRI", pages 191–218. Springer US, Boston, MA, 2016.
6. M. Faroni, M. Beschi, N. Pedrocchi, Inverse Kinematics of Redundant Manipulators with Dynamic Bounds on Joint Movements, IEEE Robotics and Automation Letters, (2020) 5(4).
7. S. Ghidoni, M. Munaro, A multi-viewpoint feature-based re-identification system driven by skeleton keypoints. Robotics and Autonomous Systems, (2017) 90, pp.45-54.
8. M. Terreran, M. Antonello, S. Ghidoni, Boat hunting with semantic segmentation for flexible and autonomous manufacturing. In 2019 European Conference on Mobile Robots (ECMR) (2019), pp. 1-8.
9. A. Dalla Libera, N. Castaman , S. Ghidoni, R. Carli, Autonomous Learning of the Robot Kinematic Model. IEEE Transactions on Robotics (2020).
10. A. Rendiniello et al., "A Flexible Software Architecture for Robotic Industrial Applications," 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), (2020), pp. 1273-1276.
11. D. Deden, C. Frommel, R. Glück, L. Larsen, M. Malecha, A. Schuster, (2019) Towards a fully automated process chain for the lay-up of large carbon dry-fibre cut pieces using cooperating robots. SAMPE Europe 2019. SAMPE Europe Conference 2019, 17.-19.09.2019, Nantes, France.