A SMART ROBOTIC CELL FOR AUTOMATING COMPOSITE PREPREG LAYUP

Rishi K. Malhan[1], Aniruddha V. Shembekar[1], Rex Jomy Joseph[1], Ariyan M. Kabir[1], Prahar M. Bhatt[1], Brual Shah[1], Wenping Zhao[2], Steven Nutt[3], and Satyandra K. Gupta[1]

[1]Center for Advanced Manufacturing, University of Southern California
[2]Raytheon Technologies Research Center (legacy- United Technologies Research Center)
[3]M.C. Gill Composites Center, University of Southern California

ABSTRACT

Hand layup is a commonly used process for making composite structures from several plies of carbon-fiber prepreg. The process involves multiple human operators manipulating and conforming layers of prepreg to a mold. The manual layup process is ergonomically challenging, tedious, and limits throughput. Moreover, different operators may perform the process differently and hence introduce inconsistency. We have developed a smart robotic cell to automate the prepreg sheet layup process. The cell uses multiple robots to manipulate and drape sheets over a tool. A human expert provides a sequence to conform the ply and types of end-effectors to be used as input to the system. The system automatically generates trajectories for the robots that can achieve the specified layup. This paper describes a systematic approach for selecting and placing robots in the cell and description of tools and end effectors needed for utilizing the cell. We also describe planning algorithms for (a) generating plans to grasp and manipulate the ply and (b) generating feasible robot trajectories. Our system can generate plans in a computationally efficient manner for complex parts. We demonstrate the automated layup by conducting physical experiments on an industry-inspired mold using the generated plans. Our system can perform sheet layup at speed comparable to human operators.

1. INTRODUCTION

Composites are engineered materials most often consisting of continuous aligned carbon fibers embedded within an engineered polymer matrix. High-performance composites are frequently produced from prepregs, or fiber beds pre-impregnated with a catalyzed but uncured polymer resin [1]. Composites enable production of lightweight structures with high specific mechanical properties, tailored anisotropic structural response, and high durability. For these reasons, they are enabling technologies for multiple sectors of national importance, including aerospace, defense, clean energy, and ground transportation. The U.S. composites industry is growing at an annual rate of 5% and was valued at $7.5 billion in 2015, with 62% of this value located in manufacturing-intensive sectors. The Federal Government has identified lightweight, high-strength, and high-stiffness composites as a critical technology for the Department of Defense, as well as an essential cross-cutting technology for U.S. manufacturing, with applications in transportation (aerospace, automotive), efficient power generation, and infrastructure.

High-performance composites are often produced by laying down prepreg material on a contoured tool in a specific orientation. The layup (or material placement) step is critical to both part

Copyright 2020. Used by the Society of the Advancement of Material and Process Engineering with permission.

quality and productivity [3]. After a layup, the resulting laminate is cured using heat and pressure to develop the desired material properties. Successful layup is critical because the ply stacking sequence governs mechanical response and because defects caused by improper layup (e.g., wrinkles, ply bridging at corners, air gaps, porosity [2]) can lead to part rejection or rework.

Prepregs are available in narrow forms (fiber tows or tapes measuring 3 - 300 mm wide) or wide woven roll sheet stock, for example, 1200 mm wide. Tows and tapes are unidirectional, lightweight, compliant, and compatible with automated fiber placement (AFP) or automated tape layup (ATL), processes that consist of laying down material using a placement head attached to a robot (gantry or arm) [4-5]. However, AFP and ATL are incompatible with small or medium-sized parts whose complex features or production characteristics pose capability, accessibility, size, or cost challenges. Recently, the use of composites in the automotive industry has led to the development of high-rate production methods for vehicle parts using liquid molding. However, such methods require substantial infrastructure investments. For these reasons, most small and medium-sized complex-shaped parts are currently produced by hand layup.

Hand layup is time-consuming and slow, expensive (due to labor costs), and can result in part-to-part variability because of human factors that are difficult to control (e.g., operator experience and dexterity). Thus, there are substantial technical and economic incentives for replacing hand layup with an automated process that can (1) improve productivity and reduce the risk of operator injury due to repetitive motion injuries, and other ergonomically challenging tasks, (2) provide consistent layup quality through a formalized and optimized process, reducing the risk of human-induced defects, and (3) increase throughput and reduce overall costs. The hand layup process was studied by Elkington et al. [6,7] and Prabhu et al. [8] to identify methods used for deforming and draping prepreg to a complex-shaped tool surface. Such et al. [9] investigated the use of tracking and projection technologies to assist human operators during layup. Ward et al. [10] developed a system for automated removal of backing paper, applicable to both hand layup and future automated solutions. Buckingham et al. and Molfino et al. [11] proposed approaches for automating the manufacturing of composite broad goods. However, the systems prioritized sheet translation rather than accurate draping (deformation and conformation) to the tool. Elkington et al. [12], building on prior work at the University of Bristol, demonstrated an automated prepreg sheet layup process, which our work leverages and expands upon. The approach utilizes a six-axis industrial robot and tailored end effectors to conform prepreg sheets to a tool. Recently, Elkington et al. [13] reviewed prior literature on automated prepreg draping. Furthermore, human-robot collaboration techniques have also been developed for the manipulation of flexible materials [14]. Here, we build upon prior work by developing a conceptual framework that leverages advances in prepreg processing and collaborative robotics [14-16], and focuses on draping without pre-shearing. Das and Nilankan [17] designed an optimization-based motion planner to solve the problem of deformable object manipulation by utilizing a controller that accounts for modeling uncertainty associated with shape changes.

Our goal is to develop a robotic cell using robots to reduce manual labor in the composite layup. The human-robot interaction is necessary for risk-averse sectors such as aerospace, where efficient production is critical, but full automation is unlikely if the risk of process-induced defects exists. This paper describes a systematic approach for selecting and placing robots in the cell and description of tools and end effectors needed for utilizing the cell. We also describe planning algorithms for (a) generating plans to grasp and manipulate the ply and (b) generating feasible ro-

bot trajectories. Our system can generate plans in a computationally efficient manner for complex parts. We demonstrate the automated layup by conducting physical experiments on an industry-inspired mold using the generated plans.

2. SYSTEM DESIGN

Recent advances in robotics are attractive for composite manufacturing. Modern robots are highly repeatable and can potentially be used for the layup on complex tools. On-line planning capabilities are providing foundations for automatically generating plans and eliminating the need for manually writing programs. There are new on-line sensing modalities such as 3D vision that can be used for real-time process monitoring, defect detection, and repair plan generation. The concept of a hybrid robotic cell enables accepting appropriate interventions from human operators when robots cannot resolve problems on their own.



Figure 1: Tool Changing Mechanism for End Effector

We have created a robotic cell that supports collaboration among three robots. Two or more robots collaborate to manipulate the material and place it on the tool. This requires performing sheet stretching, shearing, and compaction operations. One robot manipulates the tool to ensure that other agents can access necessary regions. A human operator (with assistance from robots) performs inspection, repair, and material placement tasks deemed too difficult for robots. The human operator also troubleshoots problems and modifies automatically generated plans. Finally, the cell includes a centralized planner to coordinate the motions of all the robots.

We have conducted preliminary tests by 3D printing molds that have concave and convex regions. Based on these preliminary tests, we have developed requirements for the automated robot instruction generation system [18-19]. The automated robotic instruction generation system will need to compute both draping and grasping robot trajectories over the mold. Following are the key instruction generation system requirements:

1. Users should be able to guide draping paths based on this previous experience and draping simulation. This requires development of a user-friendly GUI.

2. When human experts perform the layup process, they know exactly where to start the layup process and how layup should progress so that there will be no wrinkle formation. For automated robot instruction generation, the planner will identify the priority sequence of layup regions for the mold and appropriately generate the robot motion plans.

3. Draping robot motions need to be computed based on the user-defined path. A planner will be required to generate robot joint angles for tool motion that will take into account the process and robot constraints.

4. A grasp planner will be needed to compute the grasping locations of robots, which will enable robots to hold the sheet and exert the necessary force to stretch the sheet, so that wrinkle formation is avoided.

5. When robot trajectories are discontinuous, point to point trajectory planner will be required to generate collision-free repositioning robot motions.

6. Robot trajectories will be generated in the form of a series of locations for robot end effectors to travel. For accurate layup, robots need to go to the exact location specified by the planner, for which a higher degree of accuracy in part placement is needed. Hence an accurate part registration planner is required.

7. The motion between the draping robot and the grasping robots will need to be synchronized to avoid any possibility of collision.

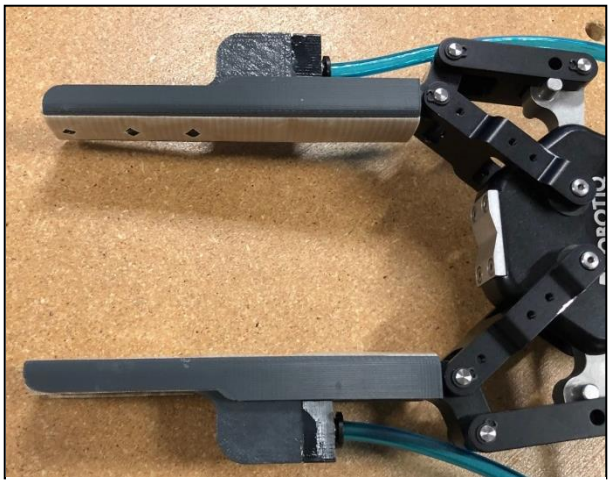


Figure 2: Preliminary Design of Sheet Grasping Fingers

8. A simple tool changing mechanism will need to be incorporated to incorporate different sized rollers and dibbers. Figure 1 shows the 3-D printed tool holder mounted on the KUKA iiwa LBR 7 robotic manipulator and the roller that can be attached to the holder by simply pushing and rotating. The planner will need to specify a tool change command to utilize the appropriate tool.

9. The grasping robots will need to frequently change their grasping locations and continuously need to handle the sticky composite sheet. To effectively release the sheet without it being stuck to the gripper finger, a new grasping end effector will be needed. For this, we will need to make use of the custom grippers with the air pressure to release the sheet. Figure 2 shows a preliminary prototype of custom gripper fingers that perform satisfactorily during the preliminary test. The grasp planner needs to compute a set of feasible grasping location so that grasp-ing locations can be changed to avoid defect formation.

The draping robots need to conform to the surface of the mold during the layup as well as apply enough force to adhere to the prepregs on mold surface. Thus, we require a robot that operates under force control and provide enough compliance. The grasping robots are required to maintain a certain amount of tension while grasping the prepreg sheet to avoid dropping. Moreover, the grasping robots also needs to be compliant

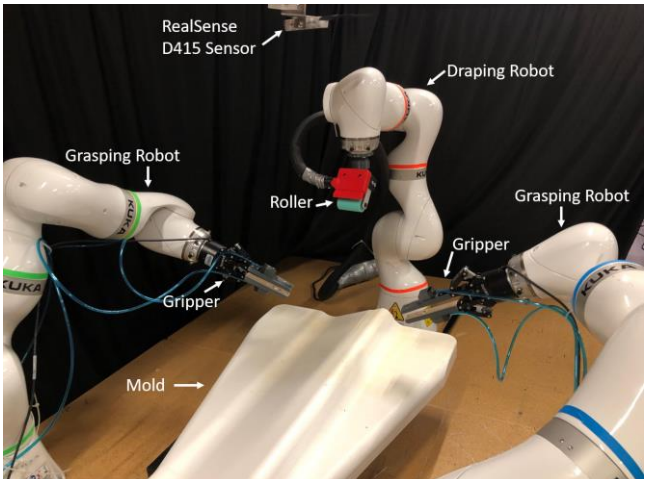


Figure 3: Designed Composite Sheet Layup Work Cell

to draping robot's actions and provide enough slack during the layup operation. Thus, the robots selected will need to have force control. Considering the reachability requirements for the test molds, we have selected one KUKA LBR iiwa 14 R820 robotic manipulators for draping and two KUKA LBR iiwa 7 800 robotic manipulators for grasping the sheet. These manipulators have in-built force sensing and force control technology that will provide aid to the layup process.

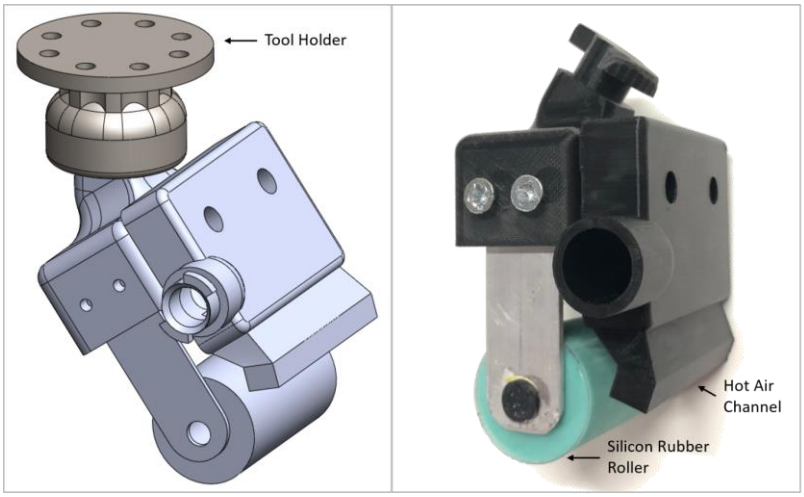


Figure 4: Flat Roller End Effector

Robotic manipulators should be placed in the work cell in such a way that their configuration space overlap should be as minimum as possible to avoid collisions, but on the other hand, they should cover as much mold region as possible to ensure smooth trajectories and avoid singularities. The robot-tool layout was determined using a combination of sampling, optimization, and search-based algorithms [20-21], utilizing knowledge of kinematic constraints to minimize the chance of collisions [22]. The mold placement planner generates the position and orientation for the mold to be placed in the robotic work cell, where it ensures the maximum reachability of the draping robot over the mold surface. Figure 3 shows the 3-robots work cell for the automated sheet layup process.

For the process monitoring and intervention control, perception technology is needed. We have added the RealSense D-415 RGB-D sensor in the work cell, which will continuously monitor the composite sheet being draped over the mold. This sensor will allow the intervention controller to track the sheet in real-time and provide necessary actions to robots' controllers in case of any issues.



Figure 5: Conical Roller End Effector

2.1 Draping robot end effectors

The primary requirements for draping robot end-effector are to maintain a draping force, provide a compliant contact with the sheet, and avoid damage during layup. Considering the above constraints, we have designed the different sized roller end effectors for draping robots. Figure 4 shows the CAD model and the physical roller end effector. The head of the end effector is designed in such a way that it can be easily inserted into or removed from the tool holder (which is fixed to the robot wrist) without any mechanism.

The main body which holds the rubber roller and the air channel is 3D printed with ABS to reduce the overall weight of the end effector. The metal plates are used to connect the rubber roller to the body to support the force exerted by the robot. The silicon rubber is made of Smooth-On Mold Max with a shore hardness of A40. This rubber roller provides the necessary cushioning between robot and sheet to prevent any possible damage in the layup process. The sheet is slightly heated with hot air passing through channels which activates the resin and improves the adhesion to maintain the tackiness of the resin on the composite sheet.

In some mold surface geometries, sharp corners are present in the mold. If the corner radius is too small, roller cannot access the surface near a corner, and ply bridging can occur. To avoid that, we have designed the conical roller. Figure 5 shows the CAD model and the physical design of the conical roller. With such shape of the roller, ply is draped appropriately over sharp corners of the mold. The main body and the hot air channel of the conical roller are the same as the flat cylindrical roller. For small concave/convex corners where rolling motion is difficult to perform, specialized dibbers can be used.

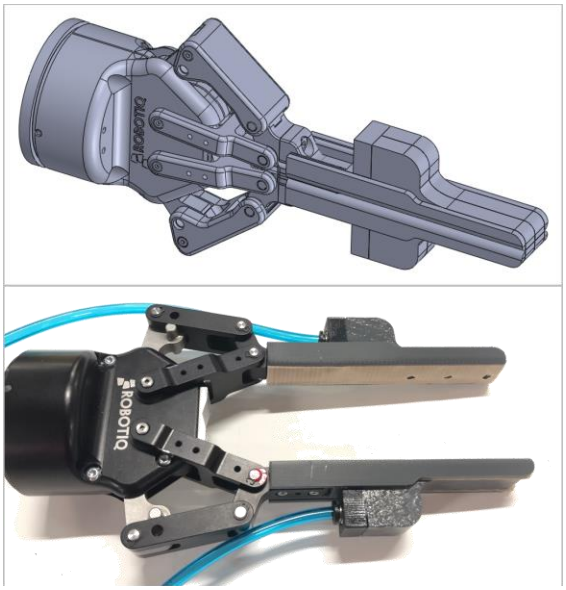


Figure 6: Grasping Robot End Effector

2.2 Grasping robot end effectors

To provide the necessary force and for the ease of gripping, we have used the Robotiq 2F-85 gripper. This gripper allows us to control the gripping force and easily manipulate the sheet. As the gripper is holding the sheet with a certain force, opening the gripper does not release the sheet completely due to the stickiness of resin. Hence, we have designed the custom gripping fingers which have PTFE tape on the contact side of the fingers. PTFE is not affected by the stickiness of the resin and releases the sheet as soon as the gripper is opened. We also have added the pneumatic control for pressurized air release from the inner side of the finger. This will ensure the sheet release completely when the gripper is opened. Figure 6 shows the grasping robot end effector for the layup process.

2.3 User interface

The main requirements for the user interface are to:

1. Select the mold and the tool for draping
2. Generate the tool path over the mold for draping robot using geodesic curves.
3. Generate automated instructions for robot motion
4. Control robot motions
5. Simulate the layup process

We have developed the user interface for the composite sheet layup process using the ROS 3D visualizer package RVIZ. RVIZ lets you add, and control visualize mesh models, point clouds,

etc. We have also added the control panel buttons, which will enable the user to handle the complete layup process flexibly. Figure 7 shows the user interface for the layup process.

There are seven main components of the user interface:

a. Notification Bar: Notification bar shows the information regarding process steps to be followed by the user, the existing process going on in the simulator, as well as errors and warnings whenever required.

b. Mold and Tool Selection: The first thing for the user to do is to select the appropriate mold for the layup from the drop-down menu. Users can select one or many tools from the drop-down menu to generate the appropriate draping trajectories.

c. Toolpath Generation: Once the draping sequence generation button is clicked, a new window will pop up with the only mold where the user can generate the toolpath by drawing trajectories for a layup. Users will also have the option of selecting the existing toolpaths from the system. Once the toolpath is generated, the user can either determine the mold placement location or choose to select the existing mold location for a layup.

d. Mold registration: Mold localization with respect to the reference frame (draping robot base frame in this case) is performed in two stages - (i) vision-based registration and (ii) contact-based registration. If the user chooses to select the existing mold location, then the vision-based registration step will be eliminated, and the user will perform the contact-based registration. In contact-based registration, another window will pop up, which will prompt the user to generate the probing trajectories for contact-based registration. Users can simulate the probing trajectories to ensure correct robot motion over the mold. Once contact-based registration is performed, the part will be localized with respect to the reference frame with submillimeter accuracy.

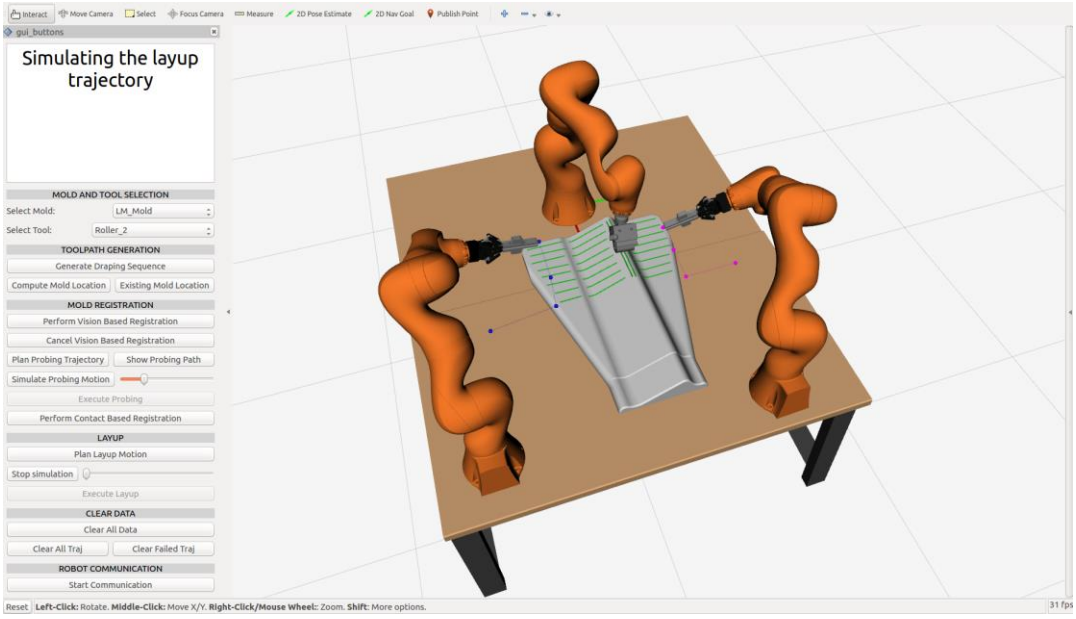


Figure 7: User Interface for Robotic Layup Process

e. Layup process: Once the user presses the plan layup button, the robot motion sequence is generated. Both draping and grasping robot trajectories will appear on the screen. Successful draping trajectories will appear as green, while failed trajectories will appear as red. If there are any failed trajectories, the user can regenerate the draping sequence and re-localize the mold. Users can simulate the robot motion to ensure correctness.

f. Clear data: Users can clear all data and start the complete process again with either the same or the different mold. Users can also clear the failed trajectories from the window to visualize the feasible robot motion for the layup

g. Robot Communication: Users can control the actual robot motion for the layup from this inter-face. Once the communication is established with robots, the user can track the real-time motion of the robots, and, also start or stop the layup motion.

3. ROBOT INSTRUCTION GENERATION

3.1.1 Draping robot motion

Depending upon the mold shape and layup area, the skilled operator generates the toolpaths for the draping robot motion using GUI. Each toolpath is a series of waypoints over which robot end effector needs to travel. We can always make use of these waypoints directly to generate the robot motion, but the path executed by the robot may not satisfy motion constraints, like continuity constraint, velocity constraint, collision constraint, etc. For reliable layup, all the motion constraints need to be evaluated during the trajectory computation phase. Hence, a low-level constrained trajectory generator is used to compute the robot joint angles for tool motion. The input to this draping trajectory generator module is sequence waypoints with respect to the robot frame and the robot tool center point (TCP). The output of this planner, set of joint angles for motion, is sent to the robot controller for motion execution.

3.1.2 Grasping robot motion

Based on the toolpaths for layup, mold geometry, and the mold location, grasp locations in the cartesian frame are computed using a grasp planner. These grasp locations are then converted into configuration space using grasp robot path generation module and sent to the respective grasping robots' controllers for motion execution. If a modification to the grasp plan is required by the process, we use machine learning techniques to refine the plan online [23].

3.1.3 Point-to-point trajectory motion

In the case of a draping robot path, a motion plan is generated only for robot travel along toolpath. This trajectory generator module does not consider the motion between the two successive toolpaths. If the toolpaths are not continuous, then the draping robot needs to readjust its position and orientation for the start of every new path. The same problem appears in the grasp plan generation as it is not concerned with the robot motion during the regrasp. Point-to-point (PTP) trajectory planner is used in these cases for generation motion execution instructions doing the intermediate phases. This PTP planner takes the start and end joint angles configurations, and locations and sizes of environmental objects as inputs and compute the path for robot motion, which

is collision-free. Therefore, for the layup execution, constrained trajectory motion, combined with PTP motion instructions, are sent to robot controllers.

3.1.4 Intervention controller robot instructions:

The intervention controller motion execution plans are generated during the online process monitoring when the actual layup is started. Based on the regrasping positions to avoid any drooping or to eliminate wrinkles, robot motion is computed in joint configuration space and sent to the robot controller as an interruption signal.

3.1.5 Robots communication and synchronization

The robot instructions are transferred to robot controllers using TCP/IP protocols. Low-level socket programming is implemented for a secure connection and data transfer between multiple robots with PC. Each robot, as a server, has a one-to-one communication line with PC, which acts as the client. The robots' synchronization is handled by the PC, which sequentially sends the motion instructions to robot controllers for layup execution. Robot controllers also have separate communication lines for handling interrupt signals given by the intervention controller. These intervention signals are given priority, and regrasp motion is executed first before resuming the layup.

3.2.1 Path Constrained Trajectory Planner

Finding an exact solution involves solving a non-linear optimization problem in the configuration space for every waypoint in a path. We propose a path-constrained trajectory planner that will evaluate reachability over the paths by enforcing the constraints. All the waypoints are transformed with respect to the base of the robot. An optimization problem is solved to find the joint configuration. Constraints involved in this optimization routine are:

- Configuration Space Constraints: The joint angles, joint velocities, and joint torques of the robot are limited within the upper and lower bounds.

- Instantaneous Velocity Constraint: We need to ensure that the robot must meet the minimum desired velocity while executing the paths. For a waypoint, we can apply a rigid body transformation to find the corresponding robot flange pose. An instantaneous velocity vector can be defined. This vector is comprised of position and orientation velocities. A Jacobian matrix J is used to express the differential kinematics of the robot.

- Transition Velocity Constraint: Instantaneous velocity constraint does not ensure if the joint velocity is sufficient to transition. We introduce a transition constraint for this purpose.

- Continuity Constraint: We need to avoid any large joint angle changes while executing the paths. The Jacobian matrix can be used for two close configurations are similar. We use Pearson's correlation coefficient between the Jacobian matrices at consecutive configurations to enforce the continuity constraint.

- Force Constraint: The robot must apply the desired force on the path which is being executed. The Jacobian matrix establishes the relationship between the joint torque vector and the force

moment vector at the end-effector. Assuming the inertial effects to be negligible under constant velocity, we use the Jacobian matrix to enforce the constraint on the joint configuration of the robot.

- Collision Constraint: We model the robot and the roller tool using a set of spheres. We compute a (Euclidean Distance Transform) EDT map for the environment for faster collision detection.

- Singularity: Manipulability index is used to keep the robot away from singularities. We can analytically compute this index at any given configuration.

A solution, if exists, may not be found by the optimization algorithm if all the constraints are enforced at once. In our approach, we apply the position, orientation, and continuity constraint first to guide the end-effector in the region where position and orientation constraint is guaranteed to be satisfied. Continuity constraint is more relaxed as it directs the algorithm to find a solution in position and orientation regions, which is closer to the previous solution. Singularity constraint, on the other hand, will truncate the region to avoid singular solutions. So, continuity and singularity constraints are applied along with position and orientation. We then apply velocity and force constraints. The constraint which imposes the most restrictions is the collision constraint.

Due to complex geometries, the tool is likely to collide with the mold. So, we enforce the collision constraint in the end, which will have the smallest feasible region. However, even after using a successive application of constraints strategy, it is not guaranteed to find a solution if it exists. It is highly dependent on the initial guess used in the optimization algorithm. If the initial guess is closer to a region where all the constraints except one are being satisfied, the algorithm can get stuck in the local minima.

3.2.2 Grasp Planner

Our algorithm is an any-time state-space search algorithm. It generates a grasp plan and then updates it further to reduce the cost. The algorithm can be terminated if a time limit is reached, the cost cannot be decreased any further, or all the nodes have been evaluated. Our goal is to use domain-dependent heuristics to generate a low-cost initial plan and obtain an optimal resolution solution in a computationally tractable time. We use an ordering heuristic that prioritizes the nodes in every stage. The ordering heuristic first explores the state space to prioritize the nodes (grasp points), which are promising. We begin by exploring a small number of grasp locations for every node. We evaluate two grasp locations, which are equally spaced between the mold surface and a maximum height above the mold. We pick the location with a lower cost and assign its grasp location to the corresponding grasp point. All the grasp points in a stage are then ordered based on the respective assigned costs. We then use the generated lower cost grasp locations as an initial guess for the gradient descent step used in local assignment search. The heuristic significantly reduces the computational cost. It allows us to generate good initial guess for the gradient descent search during the location assignment. A minimum cost solution is then found with fewer iterations as opposed to exploring the entire search space for the optimal solution. Additionally, prioritizing nodes helps us evaluate the grasp points, which can have a lower cost at the beginning of the algorithm. Therefore, our algorithm generates grasp plans with a low initial effort com-pared to randomly selecting nodes.

This algorithm is used to find solutions for the grasp plans in each of the two-state spaces corresponding to each robot separately in our case. Consider the mold A shown in Figure 8 as an illustration. The two independent solutions are found for robot-1 (RB1) and robot-2 (RB2). The first two images show that only the unconformed particles in a robot's virtual partition are considered during evaluation. The unconformed particles in the other robot's partition are considered to be fixed at their draped position during the simulation. The third image in the sequence shows the combined solution, which is generated from the nominal grasp locations. We can see that the ply collides with the mold. We use a state-space search to reposition the grippers of both the robots in order to minimize the cost. We use gradient descent to adjust for the grasp locations, which gives us a solution shown in the fourth image.

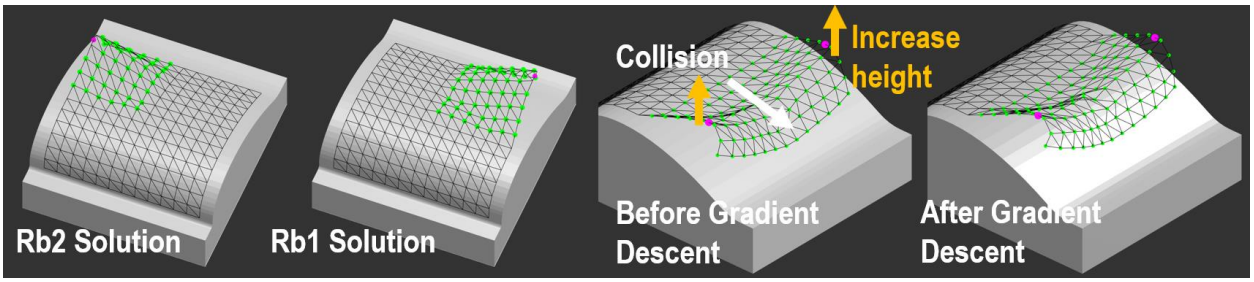


Figure 8: (Left to Right) Independent solutions obtained for robot-1 (RB1) and robot-2 (RB2), ply state simulated for combined solution obtained from the nominal grasp locations, solution improved using a state space search using the nominal grasp locations

3.3.1 Intervention Control

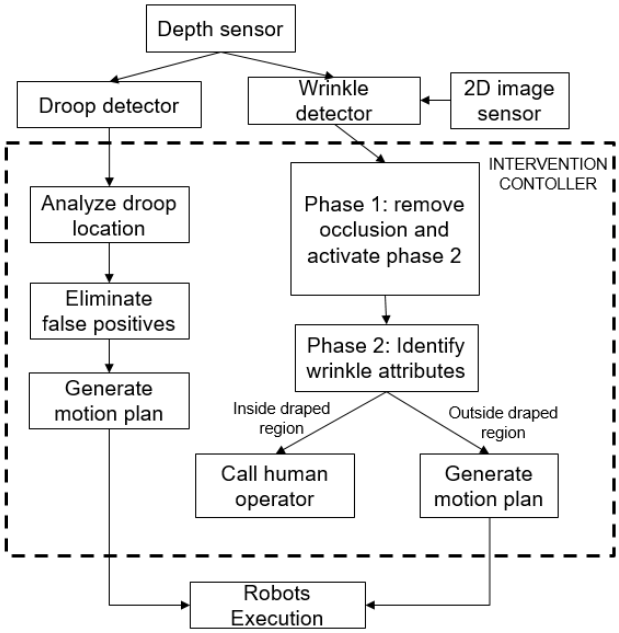


Figure 9: Intervention Control Architecture

This controller takes direct control of robotic arms to prevent collisions. Figure 9 illustrates the defect analysis and corrective action flow of the intervention controller. The intervention controller simultaneously processes the signals received from both the droop detection module and the wrinkle detection module. Appropriate grasp plans are computed based on the drooping or wrinkles attributes and sent to the robot controller for motion execution.

The online monitoring of ply (sheet) requires us to constantly monitor the ply state during the motion execution. If there is only one camera in the cell, then in some cases, either draping or grasping robots can cast occlusions to the ply view. Therefore, we have implemented the intervention control in 2-stages with four cameras. The first stage of intervention control includes the detection of ply using depth sensors from different angles, while the second stage includes ply capture and analysis from the more accurate 2D camera.

3.3.2 Droop Avoidance

Drooping location signals are analyzed based on their distance from the draped region. The undraped region surrounding the draped region is not categorized as drooping, as ply in this region will be closer to the mold. For generating the motion plan, higher weight is given to the drooping locations which are away from the draped region (see Figure 10).

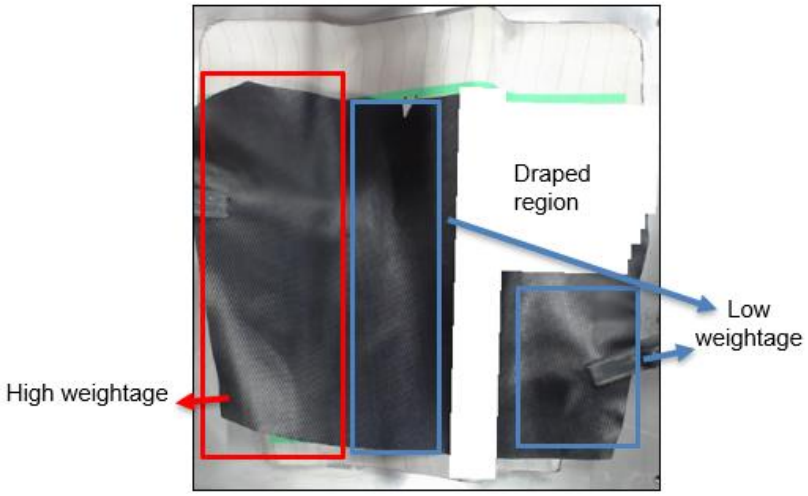


Figure 10: Assigning weightage for undraped region

Using the droop location and the weight metric, the nearest grasping robot is identified. The current grasp pose of that robot is altered in both translation and orientation. The orientation component is important to avoid any possible bending of the ply at the grasping point when the sheet is lifted. The new robot pose is obtained by moving along the curve whose center lies on the nearest point in the draped region.

3.3.3 Wrinkle Elimination

Phase 1: getting wrinkle locations using depth sensors - Due to the inaccuracy of depth sensors, data may contain both false positives (not detecting wrinkles even when it exists) and false negatives (detecting wrinkles even if there isn't any). Hence, when the callback for phase 1 is activated, the draping robot halts the motion and goes to the home position. This eliminates ply occlusion due to the robot and activates the more-accurate image-based wrinkle detection module.

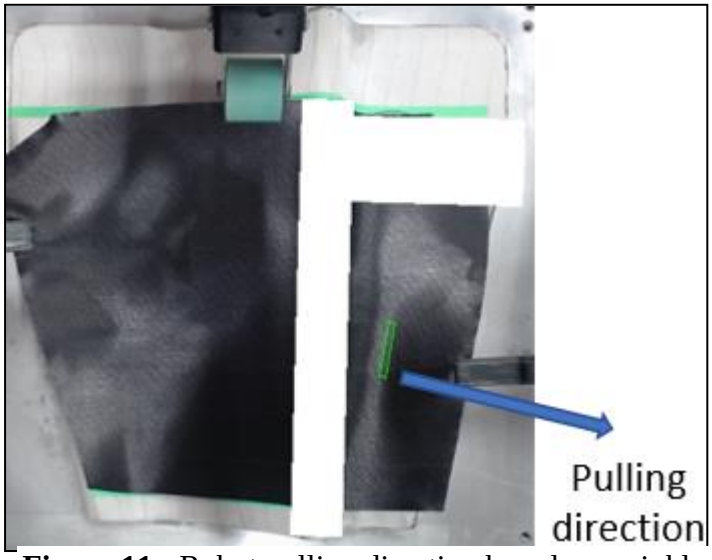


Figure 11: Robot pulling direction based on wrinkle orientation

Phase 2: analyzing wrinkle attributes to generate a corrective motion plan - Image-based wrinkle detection correctly identifies and eliminates false negatives and false positives. From the remaining wrinkles, preference is given to the wrinkles identified inside the draped region as they cannot be easily rectified by robots. Hence, in that case, the system will call the operator to come and rectify the wrinkle. Other wrinkles are sorted based on their sizes and priority given to more prominent wrinkles. Wrinkles appearing inside already fixed regions are ignored. Using the wrinkle attributes (wrin-

kle centroid, bounding box encircling the wrinkle, bounding box orientation, etc.), the direction of wrinkle is analyzed, and the grasp plan is generated to traverse along the perpendicular direction of wrinkle. Figure 11 shows the direction of grasping robot motion to pull the wrinkle out.

4. Results

We tested the system with a complex industry part. Figure 12 shows steps of the robotic layup process for this part. The mold dimensions are 711 x 558 x 76 mm. It took 7 minutes to layup one sheet using the robots. The ply tolerance was within +/- 2.54 mm and +/- 10^{o}. Process is repeatable within 500 microns through thickness. Conformity and compaction were achieved within tolerances. No visible damage such as wrinkles, voids, or bridging was observed. Quality was comparable to hand layup operation. 92% reduction in human labor was achieved.

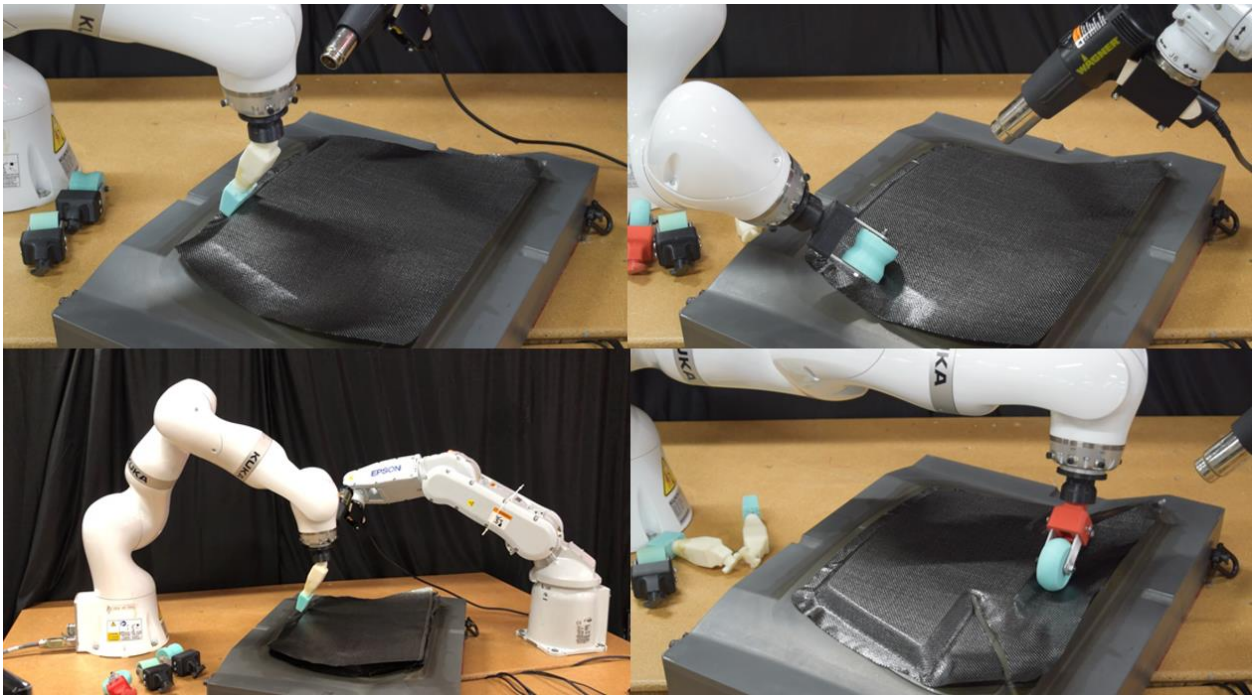


Figure 12: Layup over an industrial test case

5. Conclusions and Future Works

This paper describes an approach for automated prepreg sheet layup using a robotic cell. Conceptually, the method relies on development of a manufacturing cell comprising multiple robots, whose task execution is based on automated instruction generation and aided by process simulations and input from human experts at key stages. Aspects of the approach were implemented within a lab-scale test cell, and an experimental investigation was performed to assess viability, evaluate technical challenges, and identify areas where R&D efforts should be focused. Results show that automated prepreg sheet layup is viable, and potentially competitive with hand layup even for complex-shaped parts but may require human input at key stages. This work also showed that Robot instructions can be generated automatically without any need for robot pro-

gramming. We also illustrated that layup process can be monitored, and interventions can be performed to prevent defect formation. The future directions for work include the following:

- We need to standardize the robot end-effectors' design.
- For appropriate adhesion between the mold and the ply, controlling ambient temperature is critical. We need to integrate a thermal management system with the cell.
- Significant variability in sheet behavior was observed. This may due to different types of woven carbon fiber, change in ambient temperatures, different refrigeration conditions, etc. This will require on-line adaptation of plans based on observed performance.
- Fast automated tool change is needed, as multiple tools are swapped during the process.

6. Acknowledgements

This work was supported in part by Subaward No. ARM-17-01-F-20 from the Advanced Robotics for Manufacturing ("ARM") under Agreement Number W911NF-17-3-0004 sponsored by the Office of the Secretary of Defense. ARM Project Management was provided by Matthew S. Fischer. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of either ARM or the Office of the Secretary of Defense of the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein.

REFERENCES

[1] Campbell, F.C. "Chapter 1 – Introduction to Composite Materials and Processes: Unique Materials that Require Unique Processes". *Manufacturing Processes for Advanced Composites*. Elsevier, 2004.
[2] Campbell, F.C., Mallow, A.R., and Browning, C.E. "Porosity in Carbon Fiber Composites: An Overview of Causes." *Journal of Advanced Materials* 26(4) (1995): 18–33.
[3] Campbell, F.C. "Chapter 5 – Ply Collation: A Major Cost Driver". *Manufacturing Processes for Advanced Composites*. Elsevier, 2004.
[4] Manson, J.-A.E., Wakeman, M.D., and Bernet, N. "Composite Processing and Manufacturing - An Overview." In A. Kelly and C. Zweben, eds., *Comprehensive Composite Materials*. Elsevier Science Ltd., 2000.
[5] Lukaszewicz, D.H.J.A., Ward, C., and Potter, K.D. "The engineering aspects of automated prepreg layup: History, present and future." *Composites Part B: Engineering* 43(3) (2012): 997–1009.
[6] Elkington, M., Bloom, D., Ward, C., Chatzimichali, A., and Potter, K. "Hand layup: understanding the manual process." *Advanced Manufacturing: Polymer & Composites Science* 1(3) (2015): 138–151.
[7] Elkington, M., Ward, C., Chatzimichali, A., and Potter, K. "Studying effects of preshearing on hand layup." *Advanced Manufacturing: Polymer & Composites Science* 1(2) (2015): 80–93.
[8] Prabhu, V.A., Elkington, M., Crowley, D., Tiwari, A., and Ward, C. "Digitisation of manual composite layup task knowledge using gaming technology." *Composites Part B: Engineering* 112 (2017): 314–326.
[9] Such, M., Ward, C., Hutabarat, W., and Tiwari, A. "Intelligent composite layup by the application of low cost tracking and Projection technologies." *Procedia CIRP* 25(C) (2014):

122–131.
[10] Ward, C., Bhatnagar, V., and Potter, K. "Developing an Automated System for the Removal of Protective Films From Pre-Preg Material, To Remove a Manufacturing Bottleneck in Terms of Pick and Place Automation." *Proceedings of the SAMPE SETEC 13 Conference*, 2013.
[11] Molfino, R., Zoppi, M., Cepolina, F., Yousef, J., and Cepolina, E.E. "Design of a Hyper-flexible cell for handling 3D Carbon fiber fabric." *Recent Advances in Mechanical Engineering and Mechanics* (2014): 165–170.
[12] Elkington, M., Ward, C., and Potter, K. "Automated layup of sheet prepregs on complex moulds." *Journal of Advanced Materials* (2016): 70–84.
[13] Elkington, M., Sarkytbayev, A., and Ward. "Automated Composite Draping: A Review." *Proceedings of the SAMPE 2017 Technical Conference*. Society for the Advancement of Material and Process Engineering (2017).
[14] Kruse D., Radke R., and Wen J. "Collaborative human-robot manipulation of highly deformable materials." *Proceedings of the 2015 IEEE International Conference on Robotics and Automation (ICRA)*. Institute of Electrical and Electronics Engineers. (2015): 3782-3787.
[15] Peng. Z and Li Y. "Position/force control of two manipulators handling a flexible payload based on finite-element model." *Proceedings of the 2007 IEEE International Conference on Robotics and Biomimetics (ROBIO).* Institute of Electrical and Electronics Engineers. (2007): 2178-2182.
[16] Zhang P., and Li Y. "Simulations and trajectory tracking of two manipulators manipulating a flexible payload." *Proceedings of the 2008 IEEE Conference on Robotics, Automation and Mechatronics.* Institute of Electrical and Electronics Engineers. (2008): 72-77.
[17] Das J., and Nilanjan S. "Autonomous shape control of a deformable object by multiple manipulators." *Journal of Intelligent & Robotic Systems* 62(1) (2011): 3-27.
[18] Malhan R.K., Kabir A.M., Shembekar A.V., Shah B., Centea T., and Gupta S.K. "Hybrid Cells for Multi-Layer Prepreg Composite Sheet Layup". *IEEE International Conference on Automation Science and Engineering (CASE)*, Munich, Germany, August 2018,pp:1466-1472.
[19] Malhan R.K., Kabir A.M., Shah B., Centea T., and Gupta S.K. "Automated prepreg sheet placement using collaborative robotics". *In: Society for the Advancement of Material and Process Engineering (SAMPE) Technical Conference and Exhibition*, 2018.
[20] Malhan R.K., Kabir A.M., Shah B., and Gupta S.K. "Identifying Feasible Workpiece Placement with Respect to Redundant Manipulator for Complex Manufacturing Tasks". *IEEE International Conference on Robotics and Automation (ICRA 2019)*, Montreal, Canada, May 20 – May 24, 2019.
[21] Malhan R.K., Kabir A.M., Shah B., Centea T., and Gupta S. K. "Determining Feasible Robot Placements in Robotic Cells for Composite Prepreg Sheet Layup". *ASME Manufacturing Science and Engineering Conference*, Erie, PA, June 2019.
[22] Pan J., Chitta S., and Manocha D. "FCL: A general purpose library for collision and proximity queries". *Proceedings of the 2012 IEEE International Conference on Robotics and Automation*. (2012): 3859–3866.
[23] Malhan R.K., Joseph R.J., Shembekar A.V., Kabir A.M., Bhatt P.M., and Gupta S.K. "Online Grasp Plan Refinement for Reducing Defects During Robotic Layup of Composite Prepreg Sheets." *IEEE International Conference on Robotics and Automation (ICRA)*, Paris, France, May 31-June 4, 2020.