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Smart Robotic Assistants for Composite Prepreg Sheet Layup

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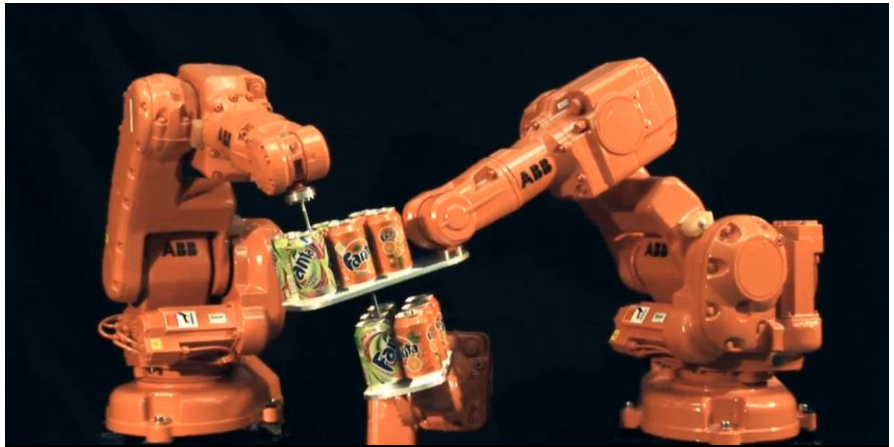
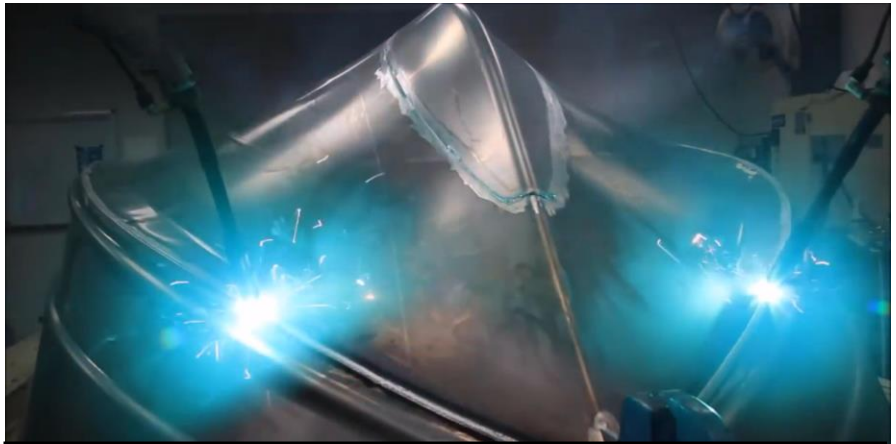
Today's Industrial Robots

Source: https://www.youtube.com/watch?v=8_lfxPI5ObM



Source: https://www.youtube.com/watch?v=SOESSCXGhFo

Source: https://www.youtube.com/watch?v=NAqm5_jk2ws

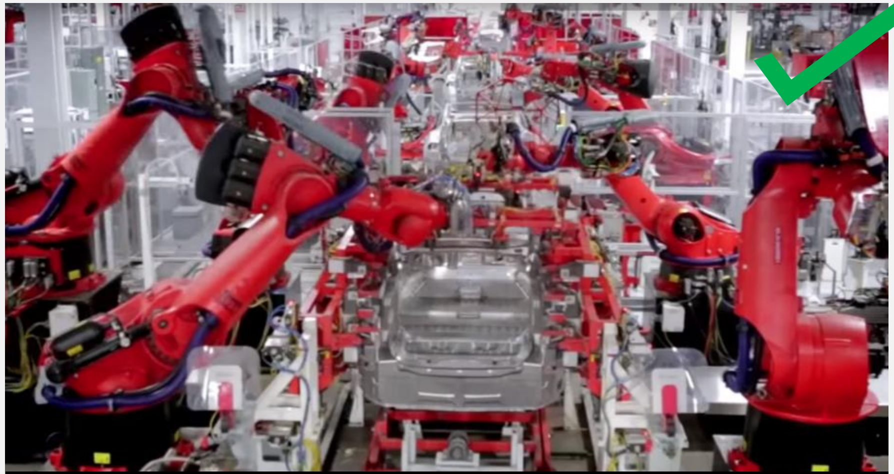


Source: https://www.youtube.com/watch?v=CigVLW4M4-I

Robots are physically capable of performing highly complex tasks

Where are Robots used in Manufacturing?

Mass Production



Source: https://www.youtube.com/watch?v=8_lfxPI5ObM

Source: https://qz.com/431747/us-fashion-companies-are-starting-to-look-beyond-china-for-sourcing-apparel/

High Mix Applications

Source: https://www.windpowerengineering.com/ge-completes-hiring-goal-for-lm-wind-powers-wind-turbine-blade-plant/

Source: GrayMatter Robotics

Humans are still doing these tasks


Source: SnugTop


Source: https://www.peritusfoam.com/open-cell-spray-foam/


Source: Fiberglass Part Manufacturer

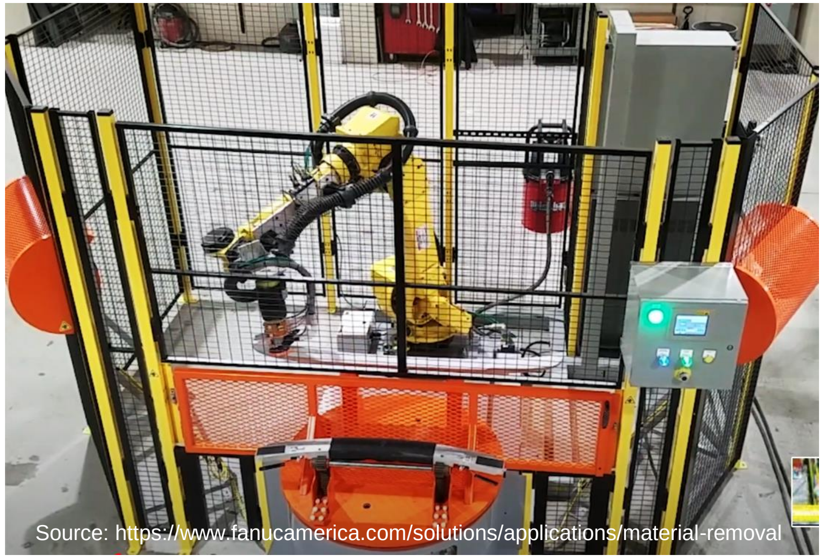

Source: https://www.familyhandyman.com/project/drywall-sanding-tips-and-techniques/

Source: https://www.aviano.af.mil/News/Articles/News-Display/Article/280626/aviano-unveils-first-locally-painted-f-16/


Source: https://www.wvnews.com/news/wvnews/wind-energy-has-potential-to-propel-wv-forward/article_c39d6cd5-6ea1-581d-ba3b-ef92203c4278.html

Limitations of Industrial Robots in Manufacturing

- Configuring a robotic cell for a new task takes significant time and effort
- Need human experts to program robots
- Robots repeat preprogrammed motions and cannot automatically adapt to changes in the workspace or tasks
- Recovering from errors requires significant downtime and can be very expensive



Robots are largely used in mass production applications.

Less than 2.5 robots for every 100 manufacturing workers in US.

Challenges Faced by Manufactures

- High labor churn in tedious and ergonomically challenging jobs
- Many unfilled jobs
- Traditional industrial robots cannot be used in high mix applications

Growth in robotics deployment will mainly come from high mix applications

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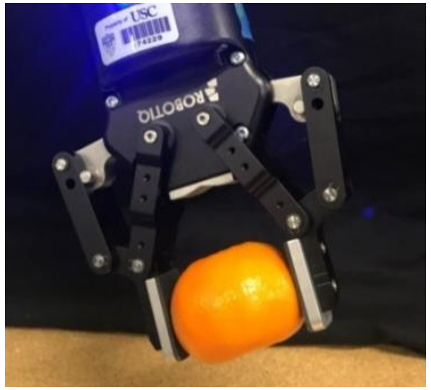
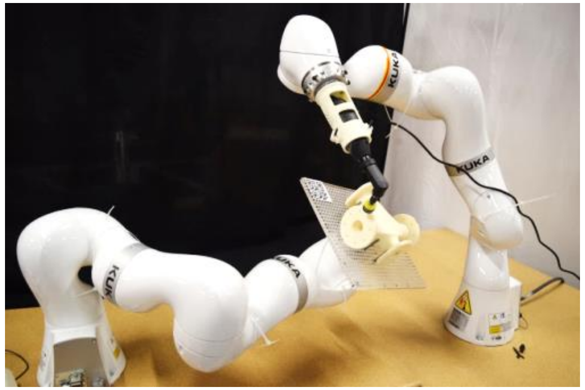
Recent Advances in Robotics

Stereo Vision
Force Sensing
Tactile Sensing



Impedance Control
Visual Servo
Shape Control



Multi-Arm
Manipulation

Mobile
Manipulation

Collaborative
Robots

Relying on humans to program robots is not a viable option as robotic cells get more complex in high mix applications

Our Goal

Develop robotic assistants for
high mix manufacturing applications to
increase human productivity and reduce health risks

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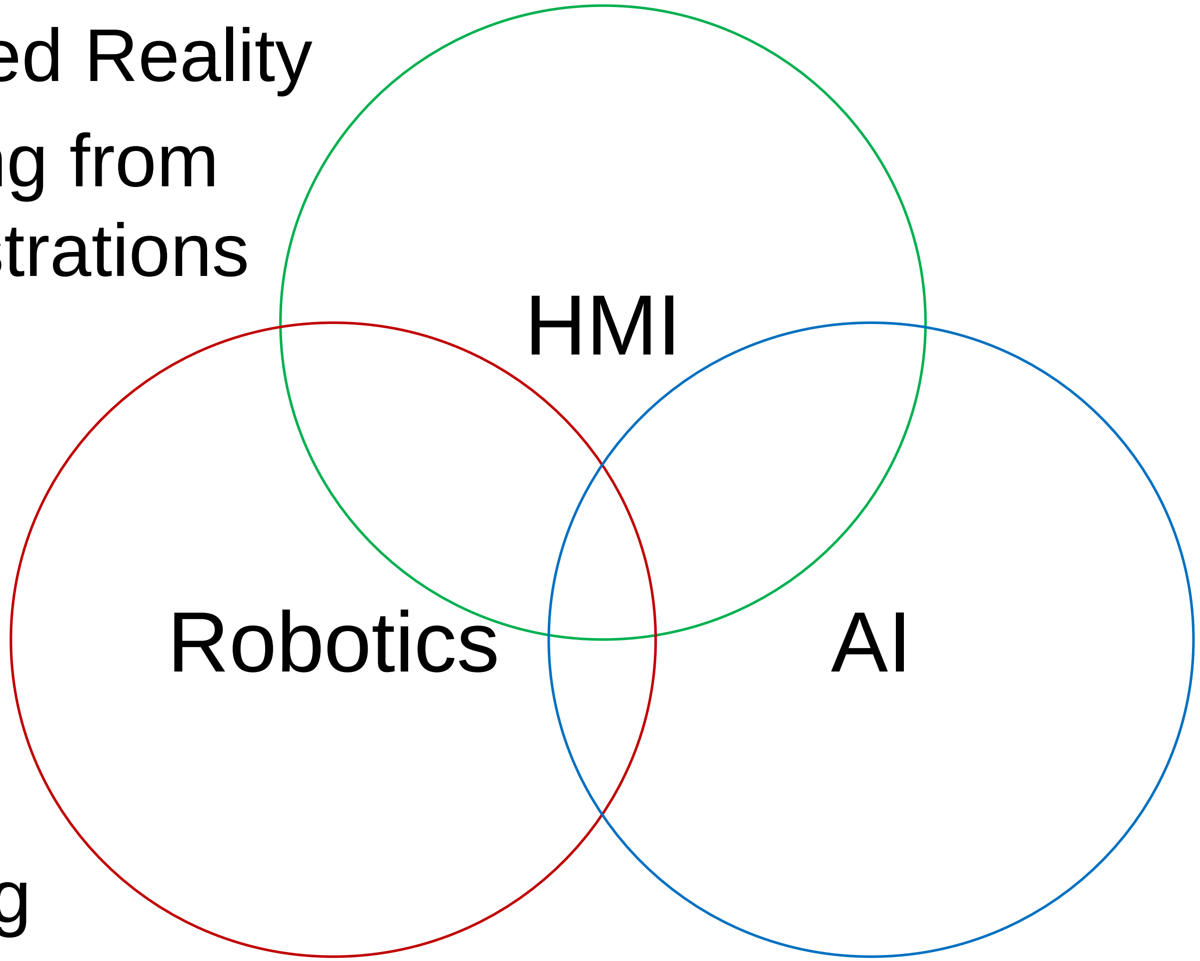
Our Focus: Smart Robotic Assistants

Augmented Reality

Learning from Demonstrations



Novel Platforms
Control
Advanced Sensing
Grippers

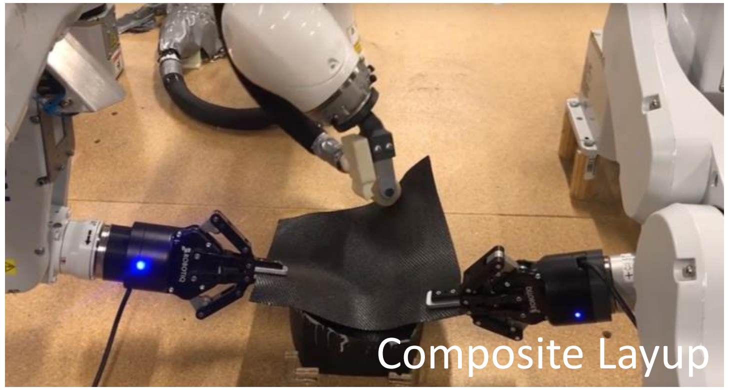
Perception
Planning
Reasoning
Learning

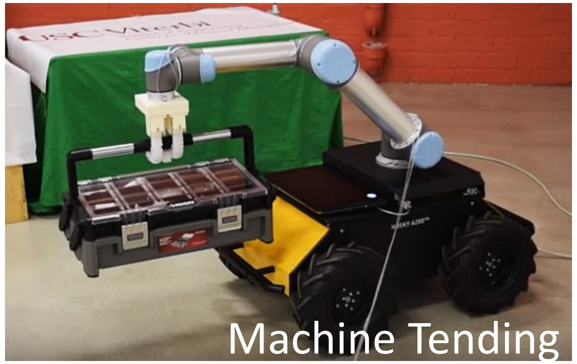
Manufacturing Applications


Bin Picking and Kitting


Finishing


Collaborative Assembly


Composite Layup


Machine Tending


Additive Manufacturing

Inspection

Current Automation in Composites

- Current automation techniques are focused on tape layup and fiber placement
- These processes are used to manufacture large part with simpler geometries
- More complex and smaller parts are manufactured using prepreg composite layup

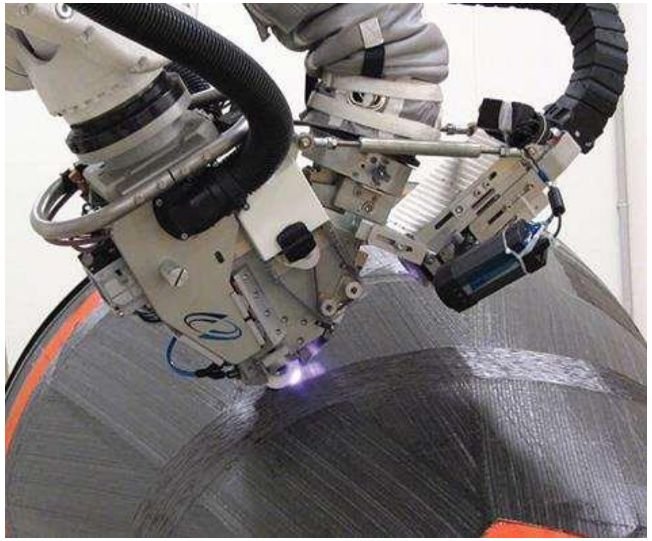


Image Source: https://www.researchgate.net/profile/Russell-Wanhill/publication/309962841/figure/fig6/AS:781657061736450@1563372974811/Automated-tape-laying-CFRP-tape-layers-being-placed-on-the-lay-up-tool-for-an-Airbus.jpg

Motivation

- Prepreg layup process is manual and skill dependent
- A typical part consists large number of sheets being stacked on top of each other making the process cumbersome
- Manual process is susceptible to defects and rework
- Carbon fiber prepregs are difficult to recycle and have an adverse effect on the environment, hence reducing rework and waste is important for sustainability

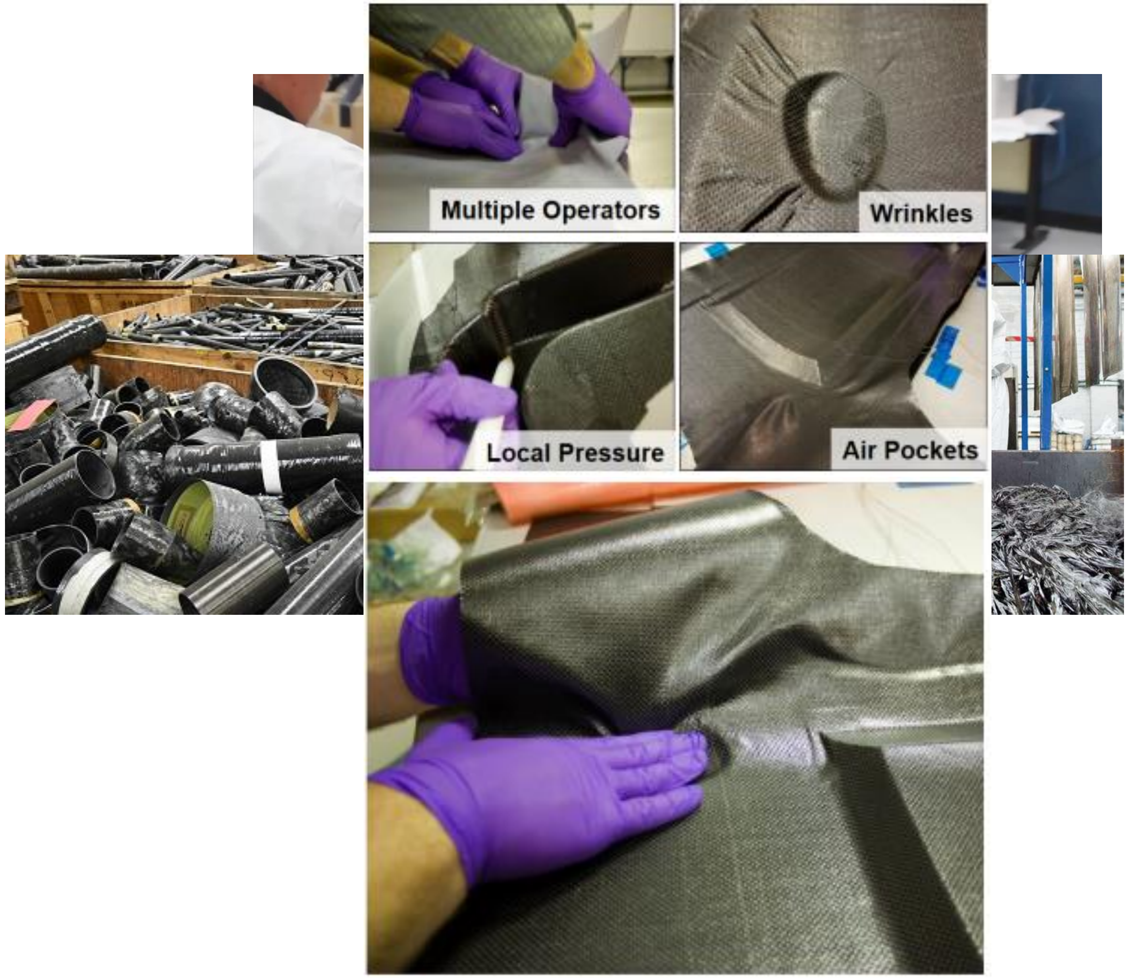
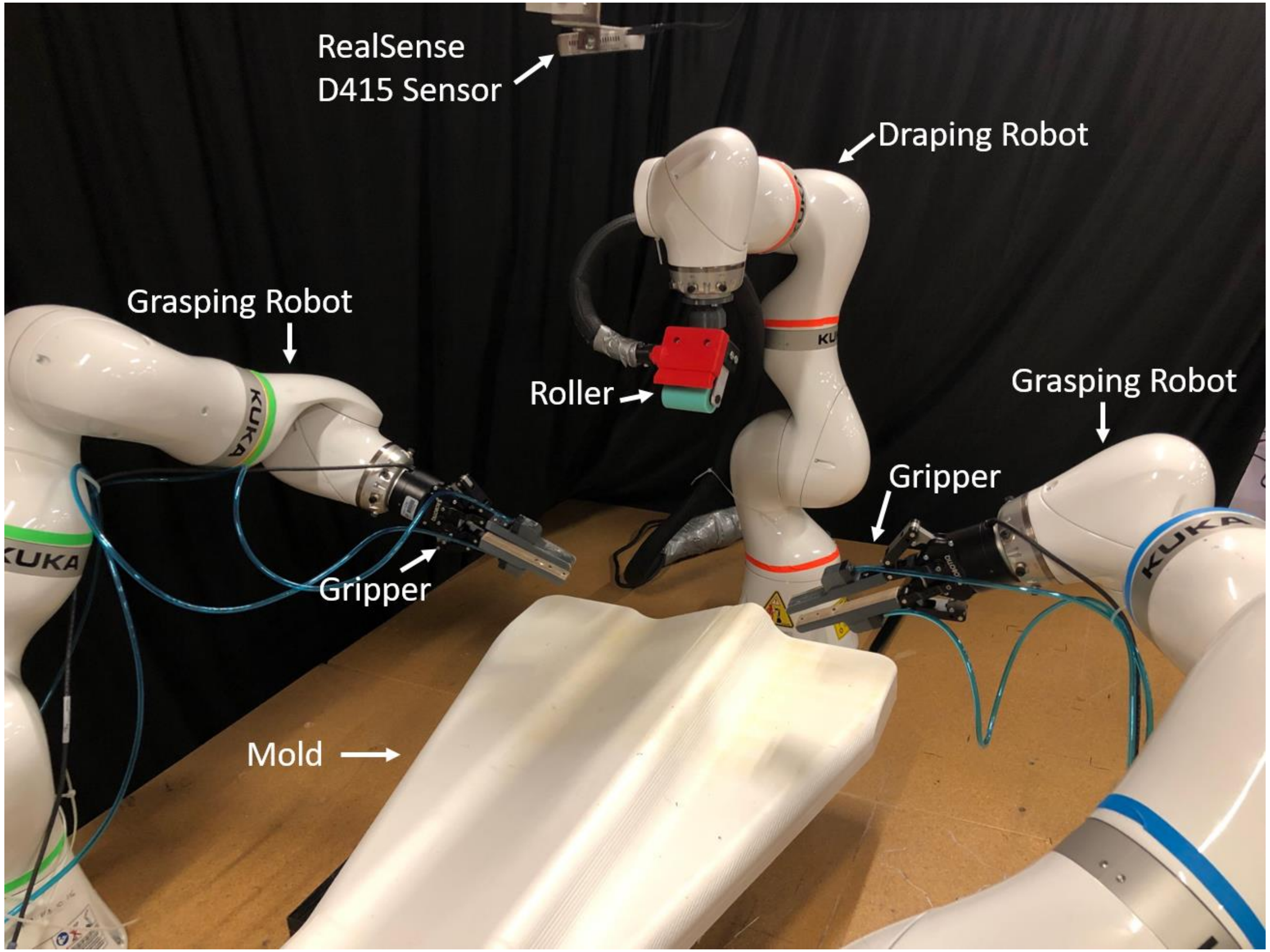
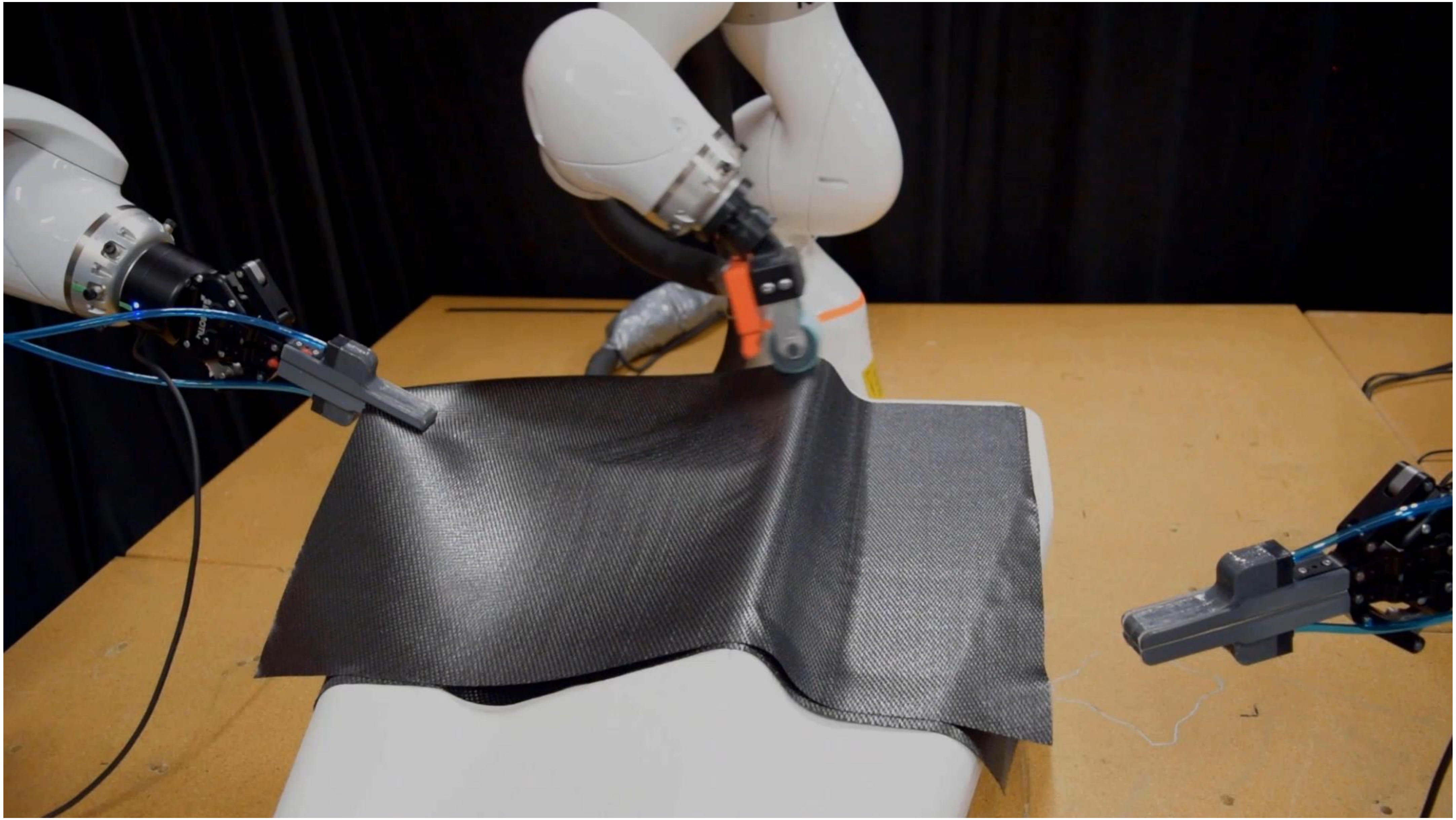


Image Source:
https://d2n4wb9orp1vta.cloudfront.net/cms/brand/CW/2017-CW/0817CW_Recycle_ELG_EG416_5281.jpg;width=550;quality=60
https://www.innovationintextiles.com/next-step-in-recycling-carbon-thermosets/

Robotic Cell for Small Part Layup



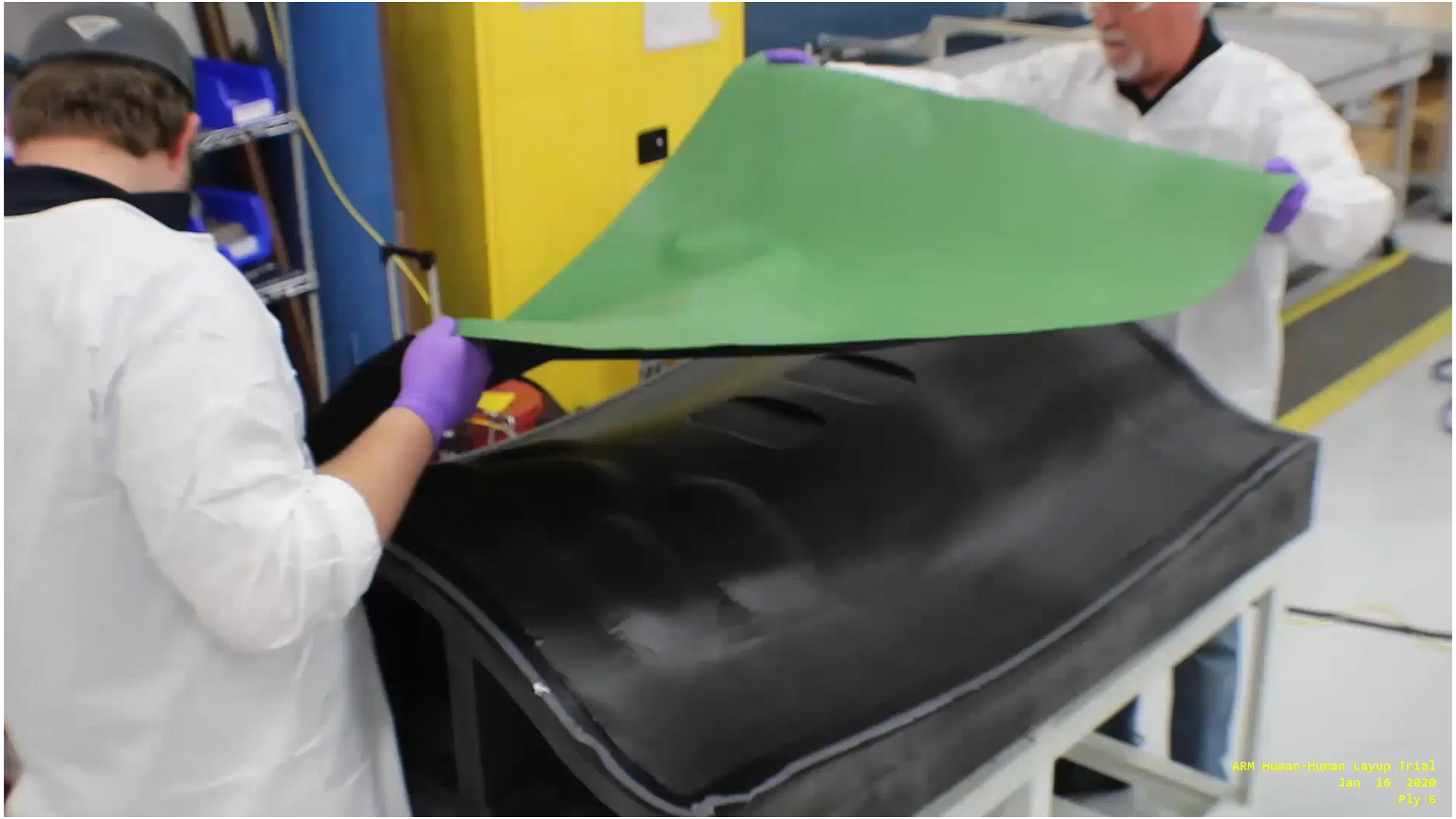


Results

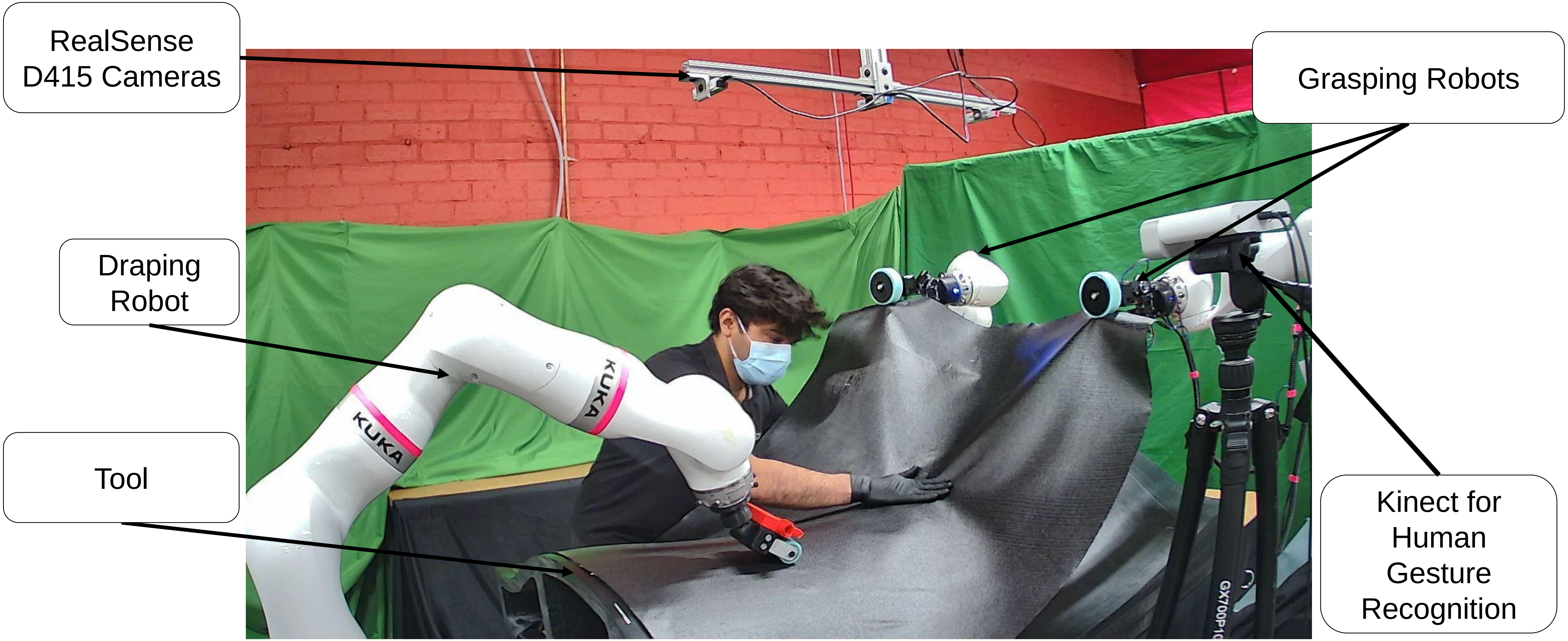
- Sheet layup operation can be automated using a robotic cell
- Human competitive layup speeds can be achieved
- Robot instructions can be generated automatically without any need for robot programming
- Layup process can be monitored, and interventions can be performed to prevent defect formation

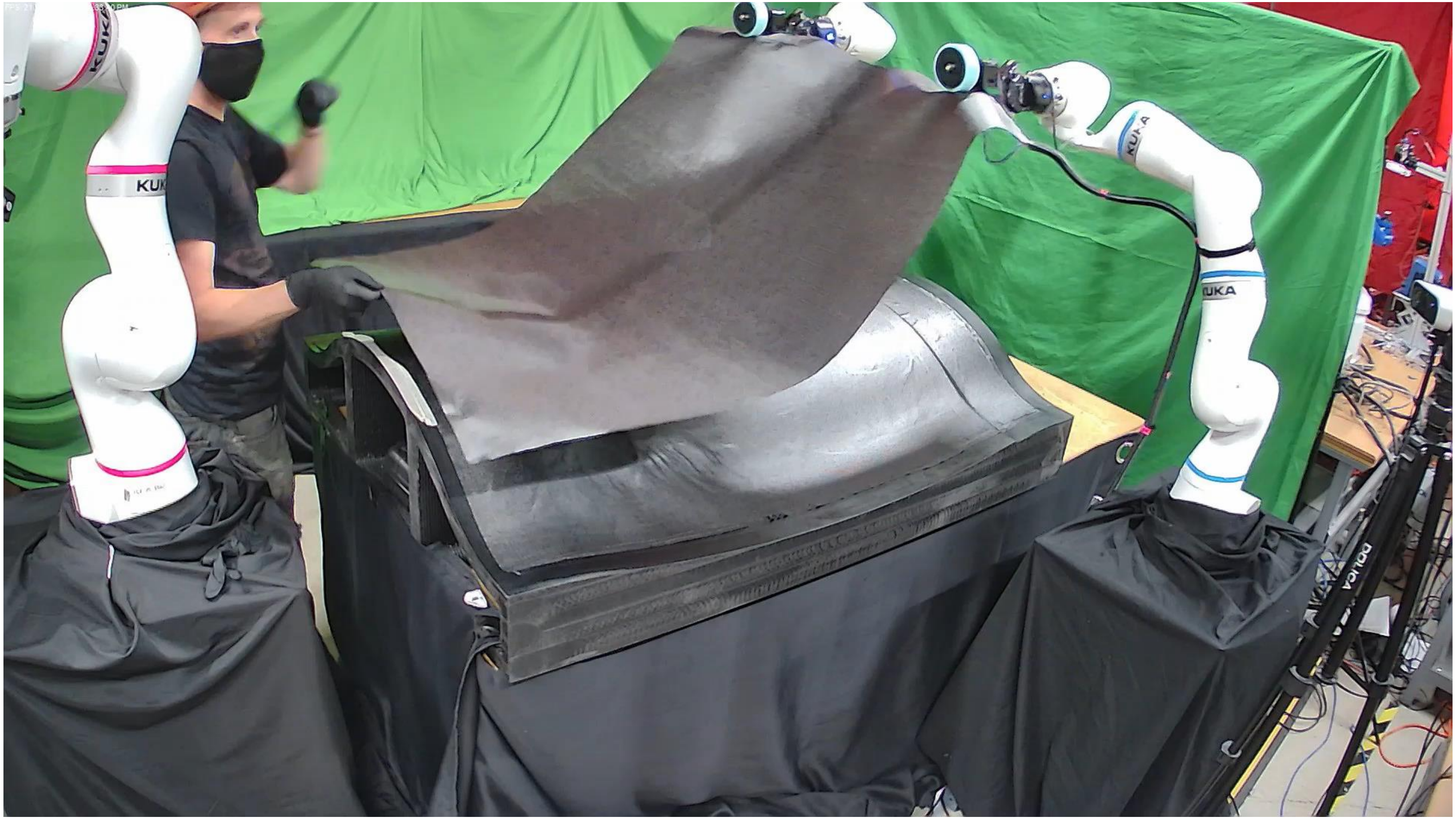
Total Number of Layers 15
Large ply layup time (9 plies): 12 min/ply
Small ply layup time (6 plies): 6 min/ply
Total time: 144 min

Manual Operation Showing Large Part Layup

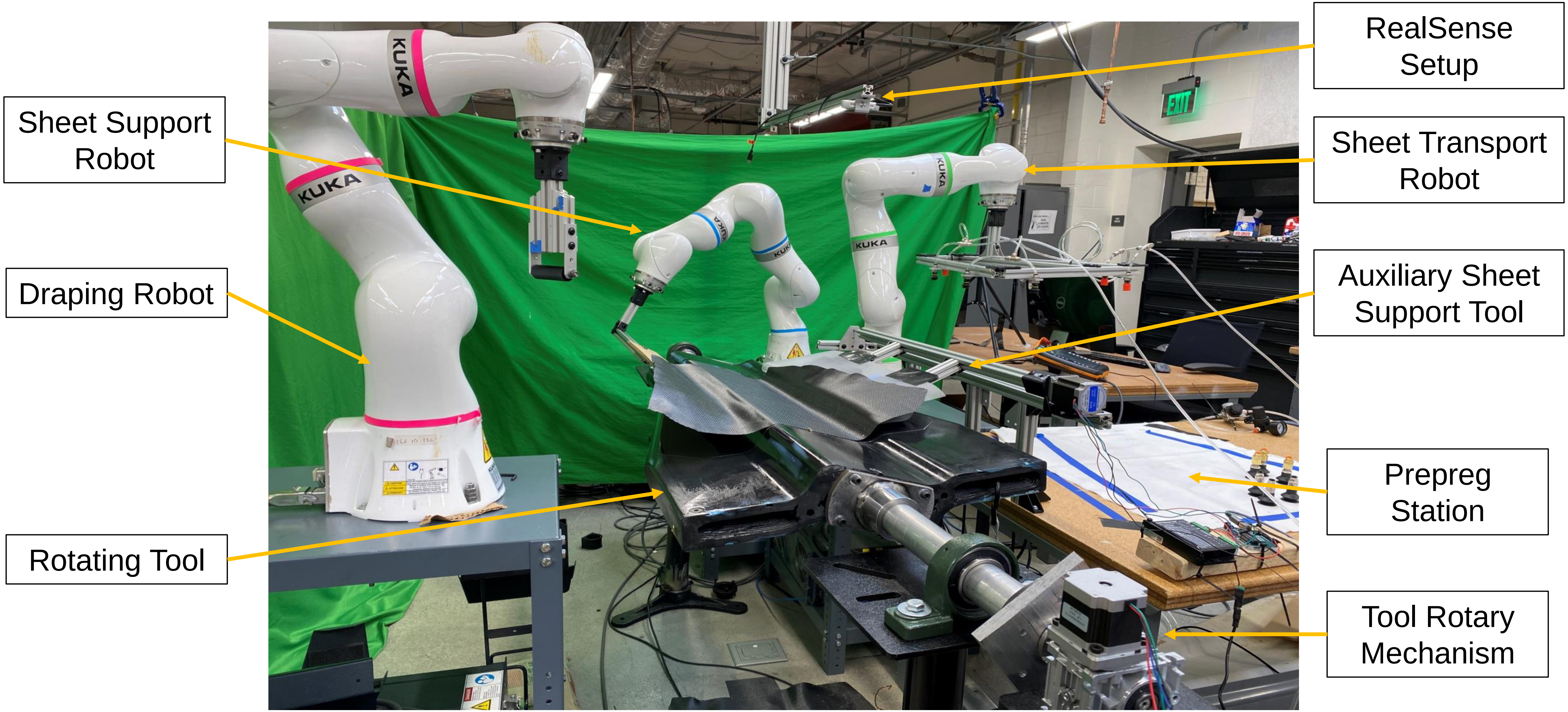


Hybrid Cell for Large Part Layup




KUKA
DOLICA

Layup on Complex Rotating Tools



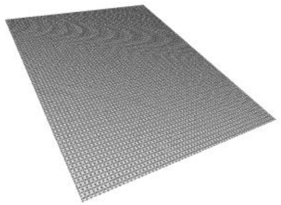
Key Technologies

- Digital Twins
- Robot Trajectory Planning
- Deep Learning Based Defect Detection
- Visual Servo for Sheet Transport

Creating Digital Twin for Prepreg Sheet Handling

Sheet Simulation

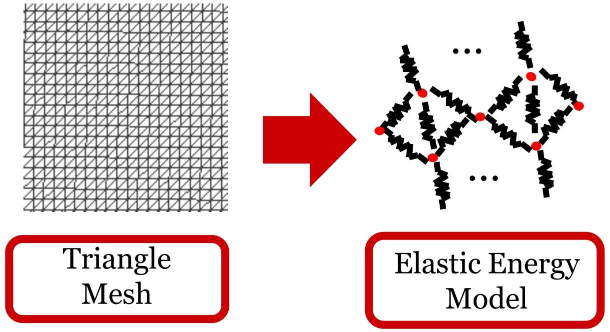
Initial Mesh



Material Parameter

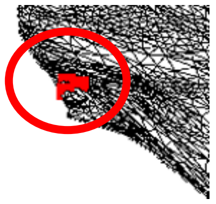
- Surface Density
- Tensile Stiffness
- Shear Stiffness
- Bending Stiffness
- Damping Stiffness

Sheet Model Generator



- Construct Mass Matrix
- Compute Internal Elastic Forces
- Construct Force Model

Constraints



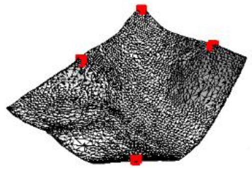
External Forces

- Gravity
- Wind
- Contact
- User Forces

Numerical Integrator

- Solves differential equations for deformation models using Mass Matrix, Damping Matrix, Force Matrix, External Forces and External Constraints

Predicted Deformation



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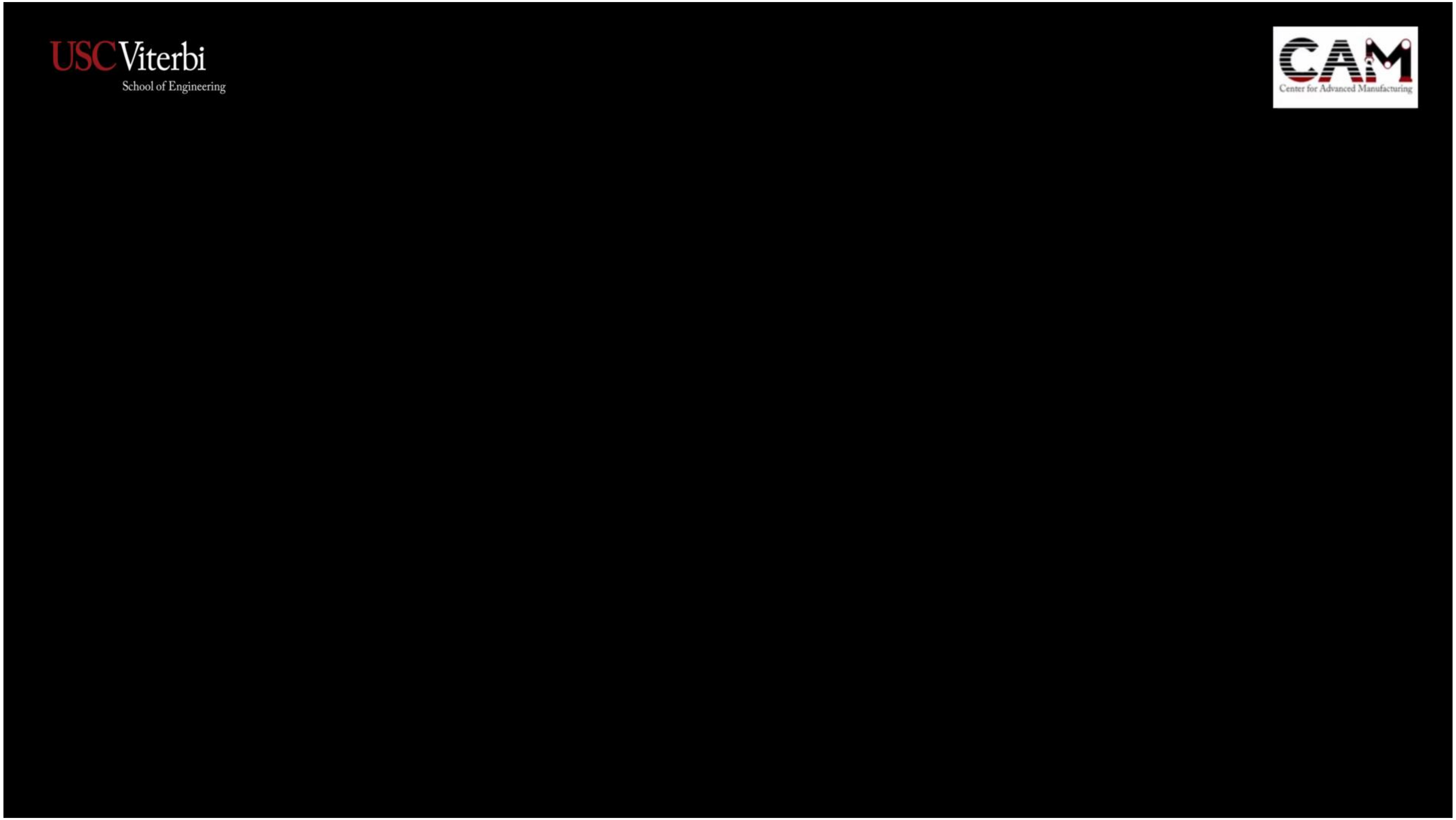
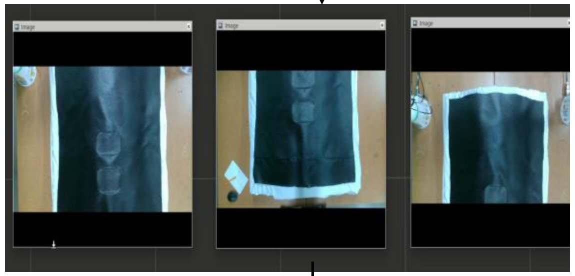
Sheet Simulation Demonstration

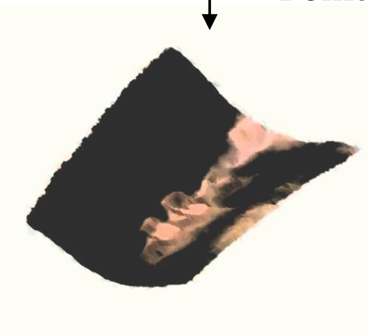


Real-Time Sheet Tracking

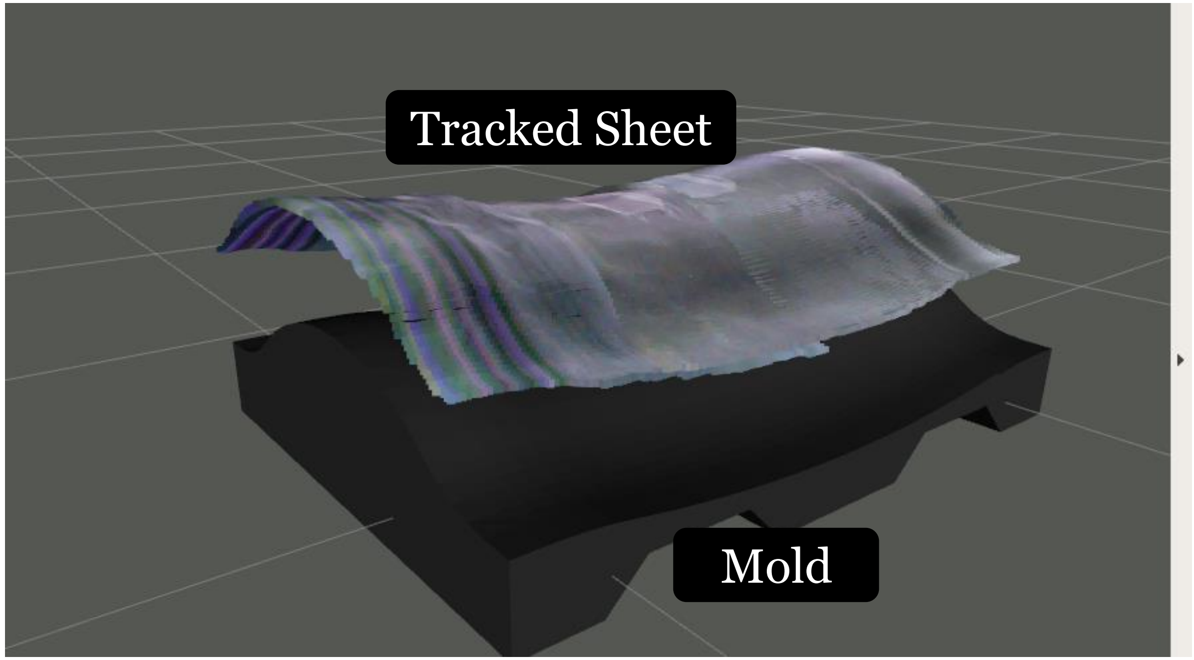
Depth Image Feed from RealSense



Merged Pointcloud



Tracked Data of the Composite Sheet in RVIZ Over Mold



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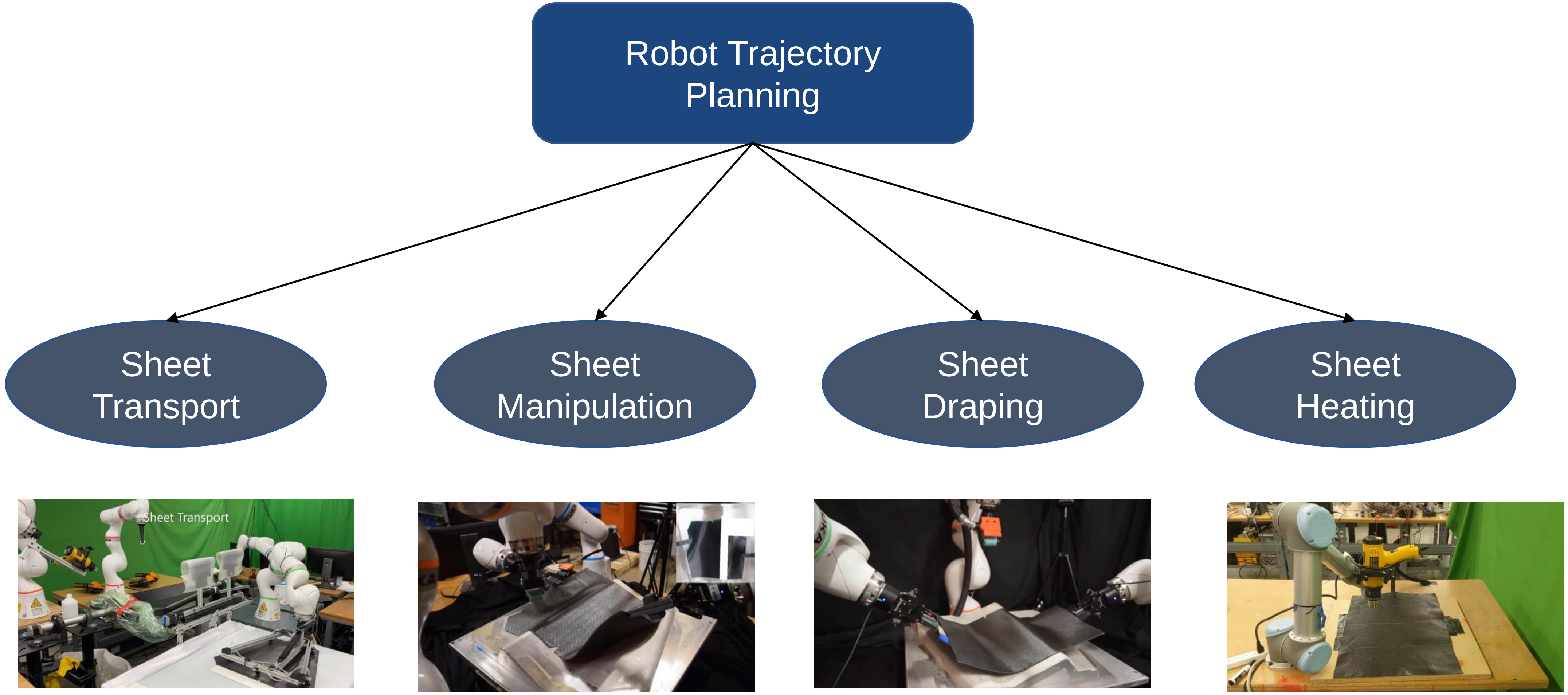
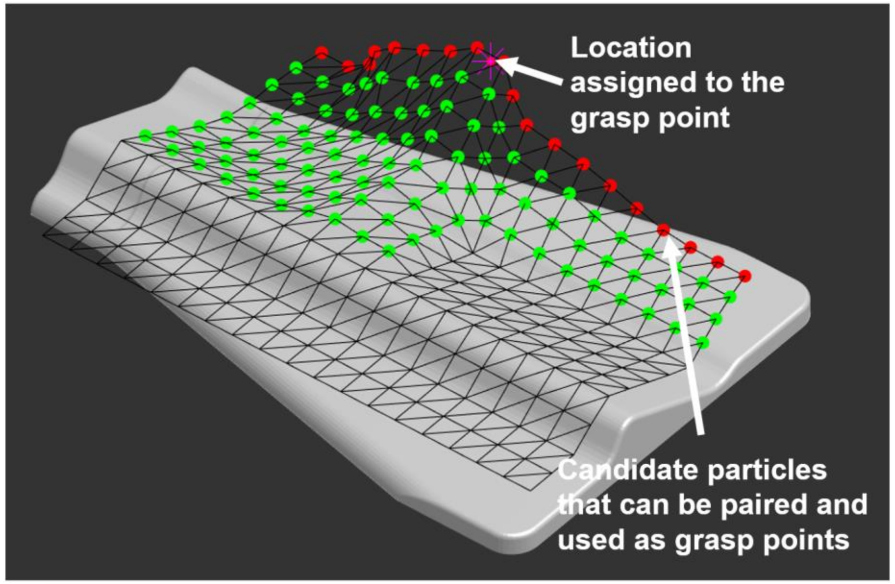
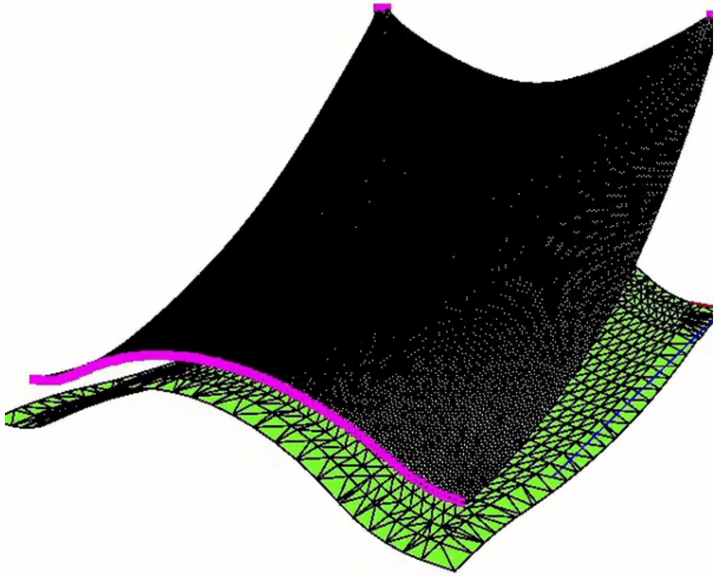
AI Enabled Robot Trajectory Planning


Robot Trajectory Planning
Sheet Transport
Sheet Manipulation
Sheet Draping
Sheet Heating
Sheet Transport

Grasp Planning

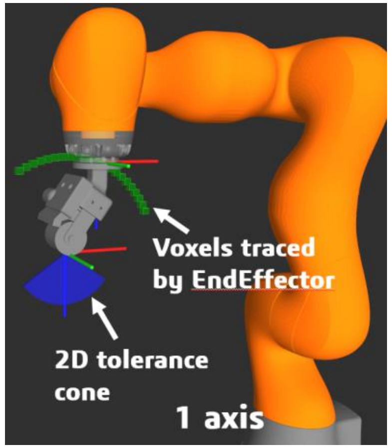
- Prepreg sheet is approximated by a mesh defined by position of vertices
- Vertices shown in green are the free points on the undraped sheet
- Vertices shown in red are grasping points
- The robot uses a pair of consecutive grasp points to move the sheet
- This planner implements a heuristic-based searching approach to find grasping locations that meet the criteria
- These simulated locations are subjected to certain process constraints to generate which is further optimized for shortest time path

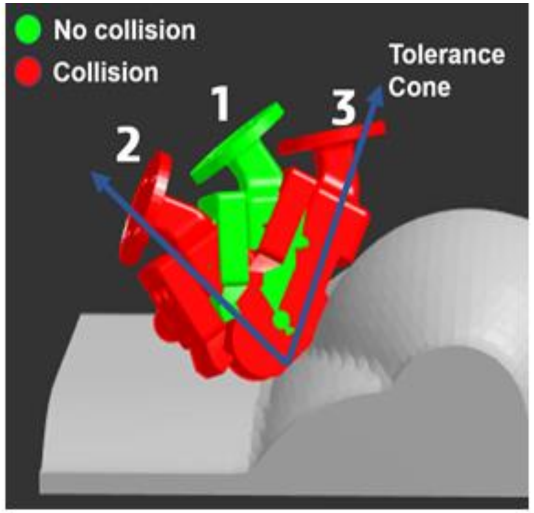




Sheet Draping Planning

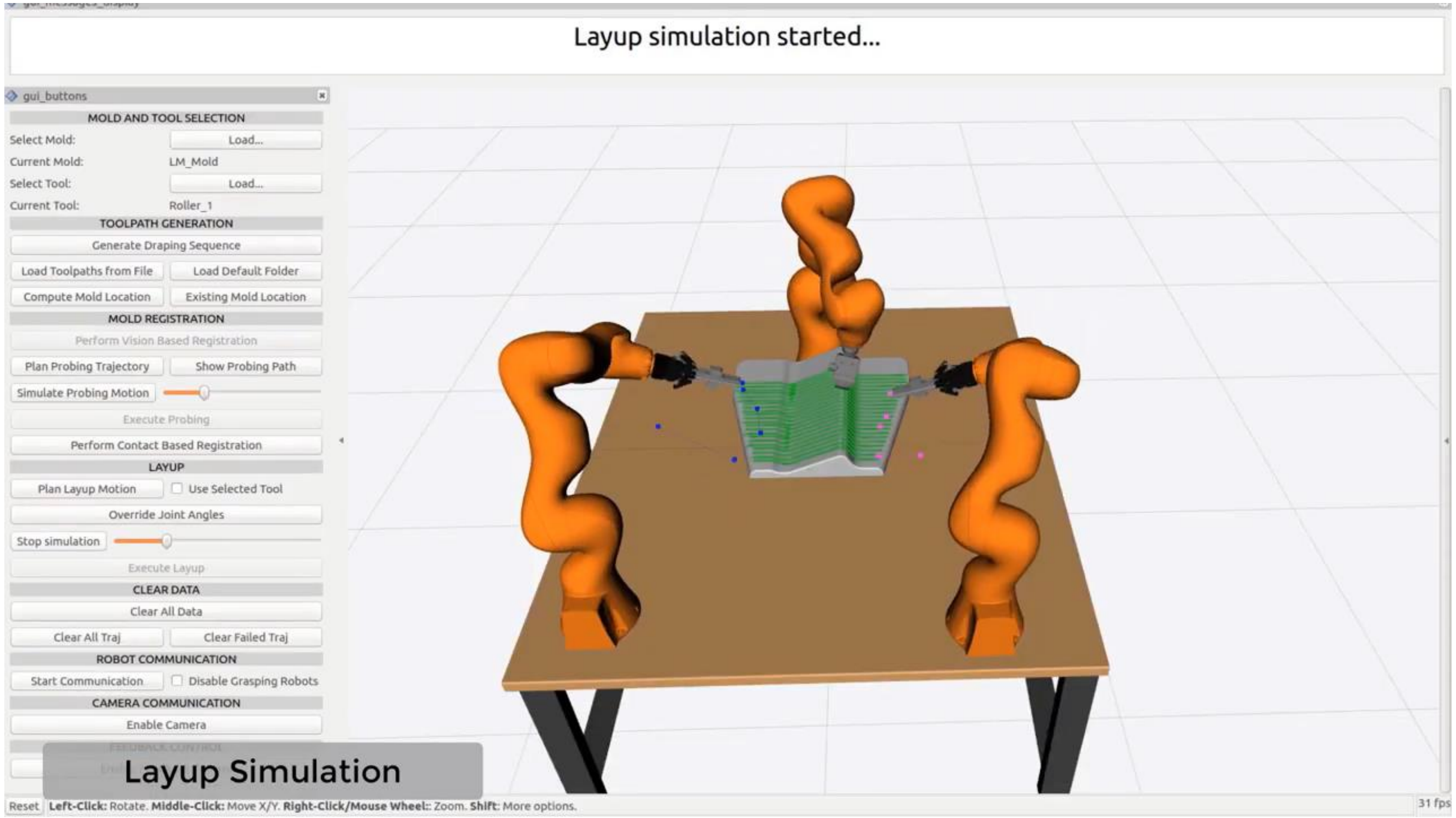
- Human operators provides the draping paths over the mold by interacting with the User Interface
- These paths need to be used to compute robot trajectories, such that the process constraints are met
- Process constrains involve
  - Continuity constraints while executing each path
  - End-effector velocity constraints
  - Force constraints
  - Collision constraint between draping and grasping robots as well as the human
- Generate variable density waypoints by using surface normal information to increase the time of compaction at high curvature surfaces





Three orientations illustrated in the tolerance cone

Sheet Draping Planning

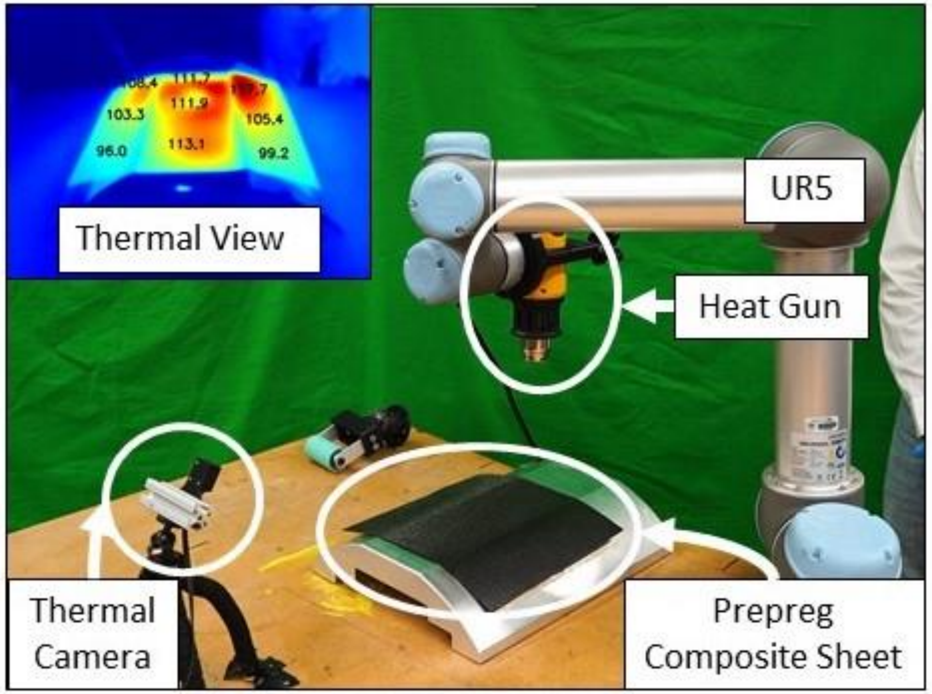


Sheet Heating Planning

Objective: Maintain the temperature of the prepreg sheet within a desirable range conducive for draping without thermally damaging the prepreg

Challenges:

- Important to account for thermal characteristics of the sheet for robot planning
- Improper heating can exacerbate defect formation



Solution:

- Learn a temperature evolution model for the sheet
- Look-ahead search to find feasible state transitions for robot to maintain temperature constraints
- Use sensors to monitor the sheet state and achieve adaptive control

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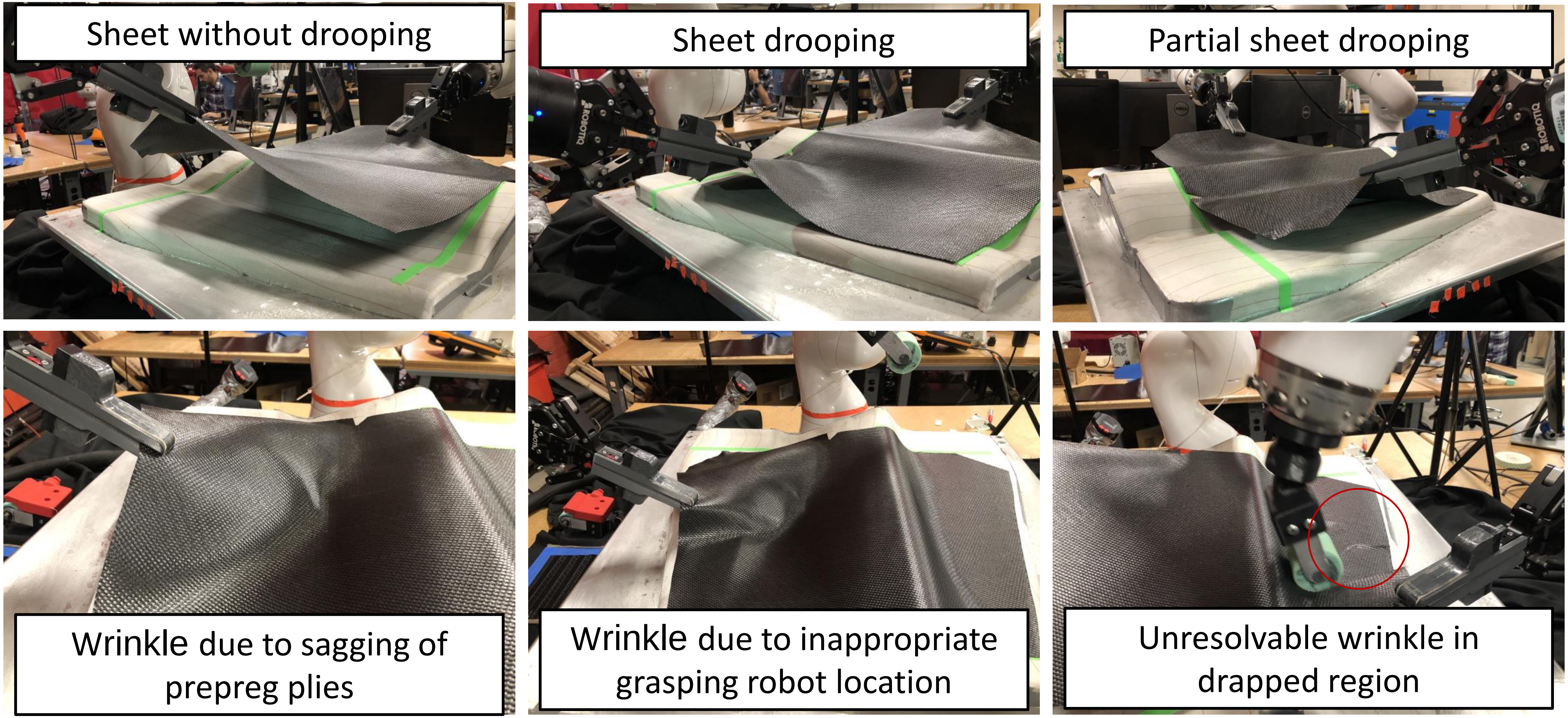
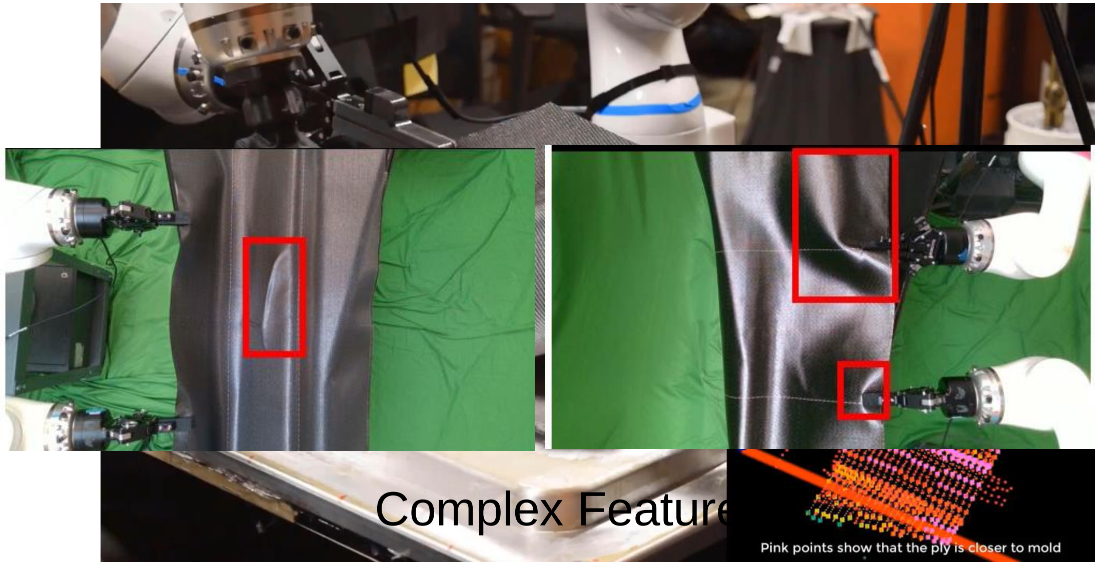
Deep Learning Based Defect Detection

Common Defects: Drooping and Wrinkles



Deep Learning Based Defect Detection

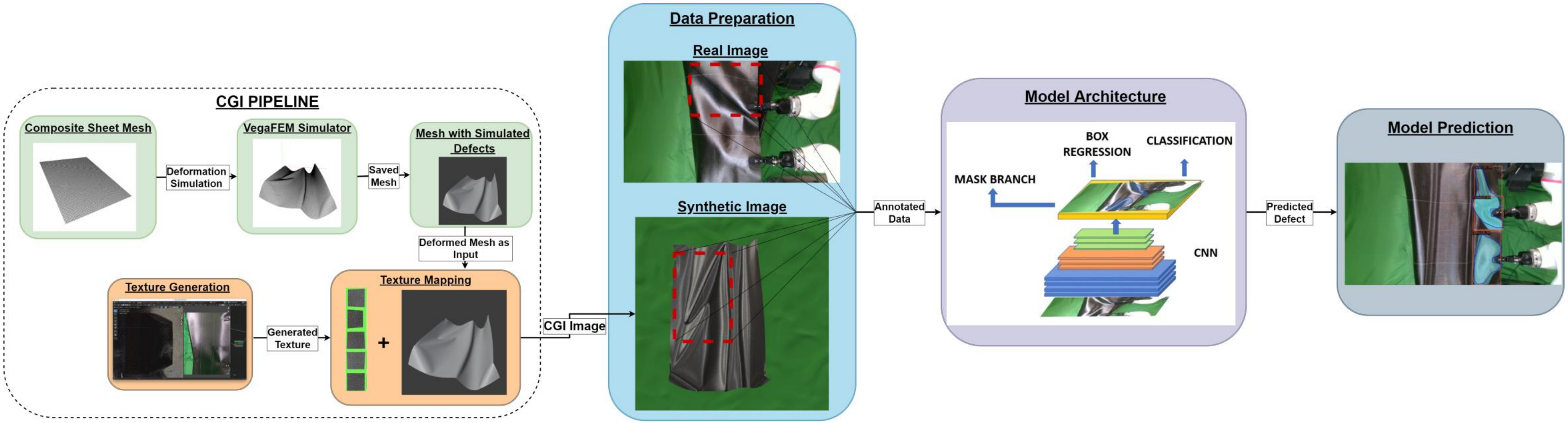
- Open loop execution of the robot motion plans can lead to poor quality and defect formation
- Detecting anomalous configurations and defects in-process is an important feature for any smart robotic cell
- Defects in a composite prepreg have complex features making them difficult to detect using traditional vision method
- Deep learning methods are more robust but pose the challenge of collecting large amounts of data



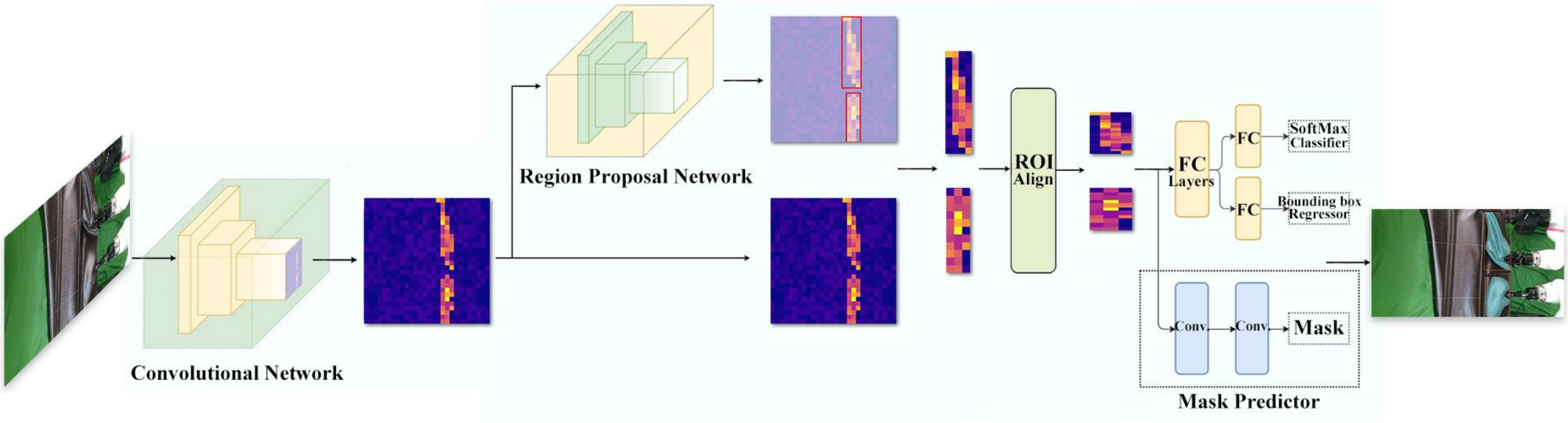
Solution: Physics Aware Synthetic Image Assisted Defect Detection

Deep Learning Based Defect Detection

Objective: Use the digital twin of the sheet combined with advanced CGI textures to generate feature aware synthetic images to train a deep learning model for defect detection

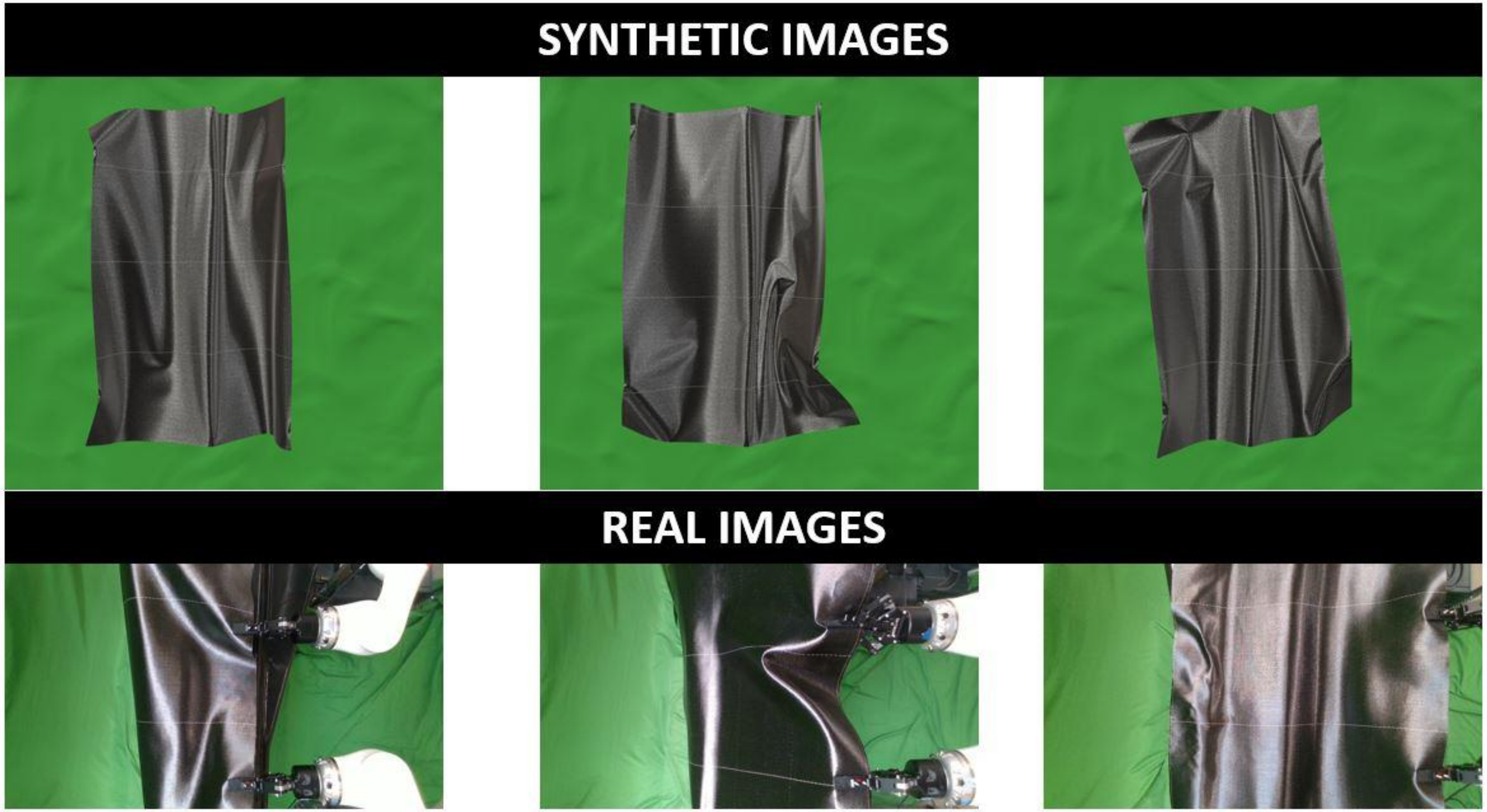


Deep Learning Network Architecture

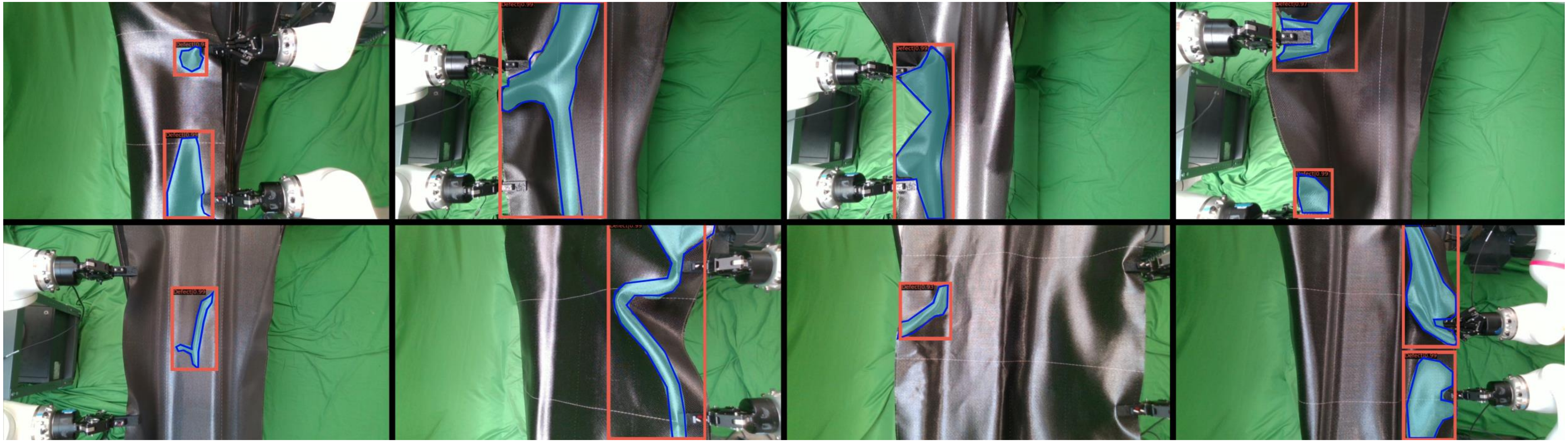


- We use 2-Stage training for the network
- Mask-RCNN architecture is used
- On performing ablation studies, ResNet-50 is used as the backbone

Deep Learning Based Defect Detection



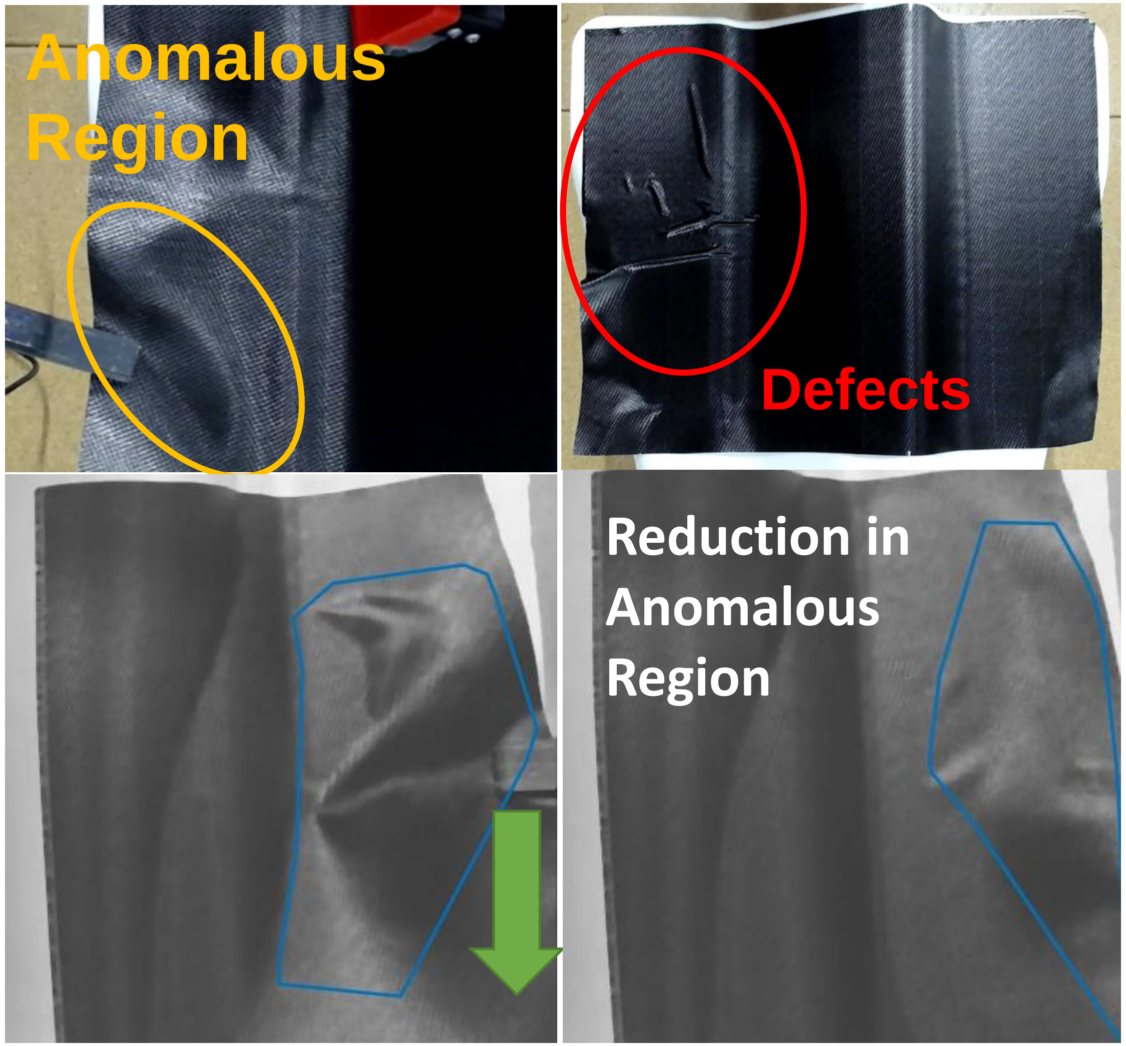
Results



- The deep learning-based defect detection system can detect wrinkle-based defects with 0.98 mean average precision (mAP)

Preventing Defect Formation

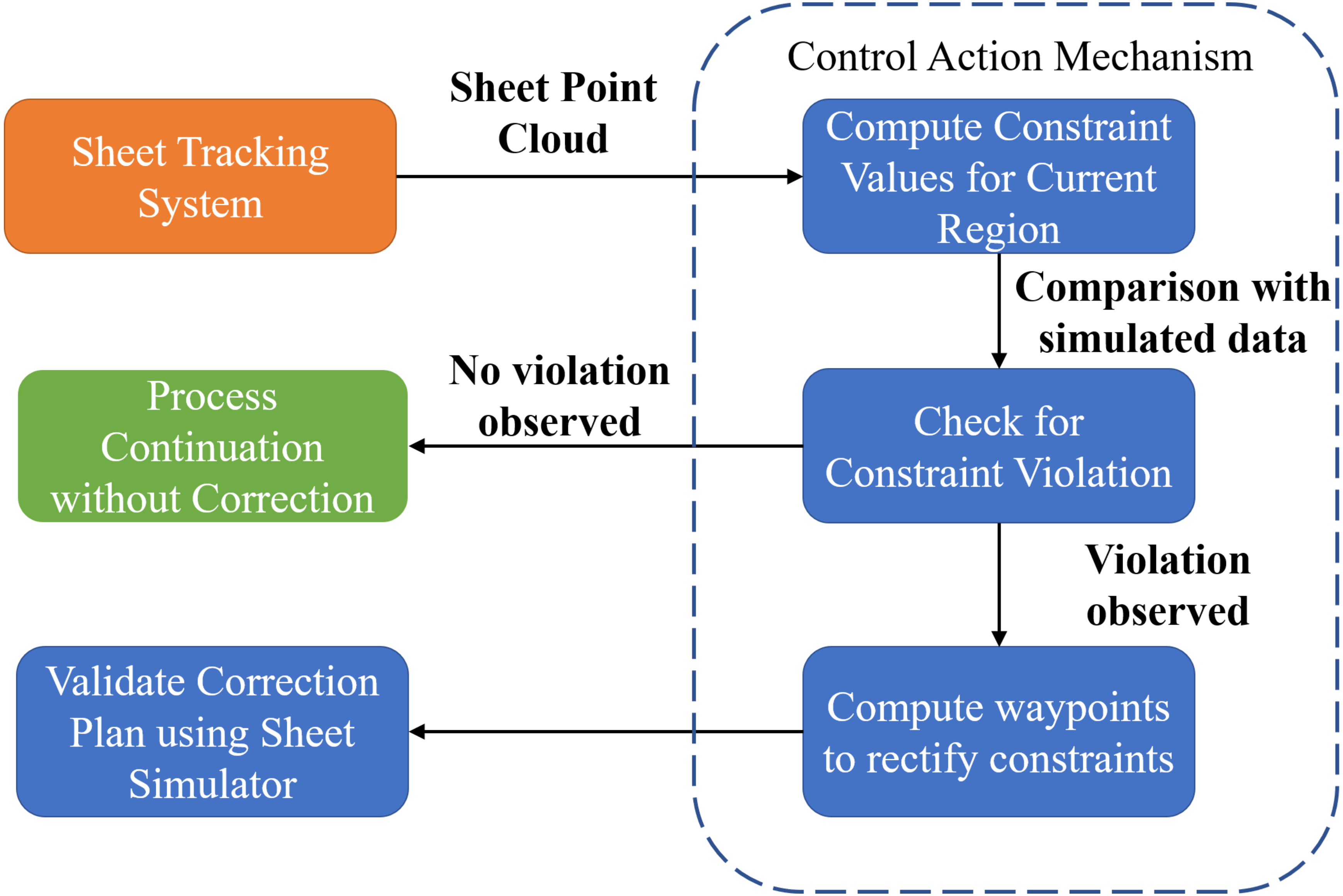
- Uncertainties in simulation model used for generating grasp plans can cause defects during robotic layup
- System uses multi-modal sensing based on vision and force feedback for on-line process monitoring
- AI based algorithms use the feedback to identify risky anomalous regions which can generate defects
- Analogous to hand layup, a pulling motion at the gripper reduces such anomalous regions



Intervention Controller

- Grasp plans may showcase some deviations from ideal scenario.
- Grasp planning system has inherent dependence on material model which maybe erroneous
- This entails for a need of an intervention system that can detect anomalous behavior and take appropriate action
- We utilize the sheet tracking system to evaluate grasping locations in real-time and take corrective actions

Intervention Controller: Basic Idea



Results

	Case 1	Case 2 A	Case 2 B	Case 3
Sheet Tracking				
Actual Sheet Configuration				
	No Deviation	Minor Deviation		Major Deviation

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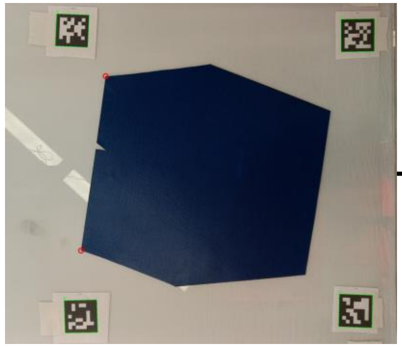
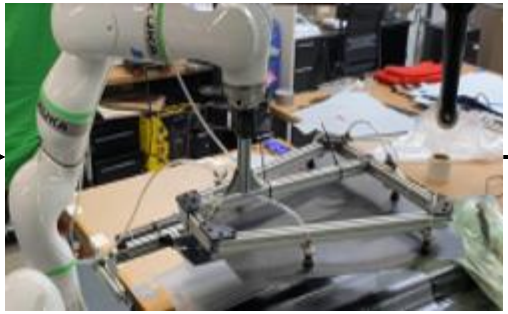
Visual Servo Based Sheet Transport

Sheet Transport in Prepreg Composite Layup

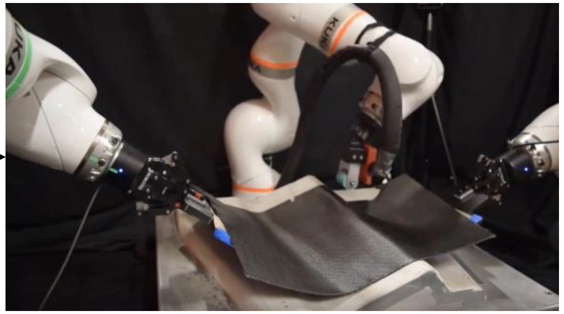


Sheet Loading Station



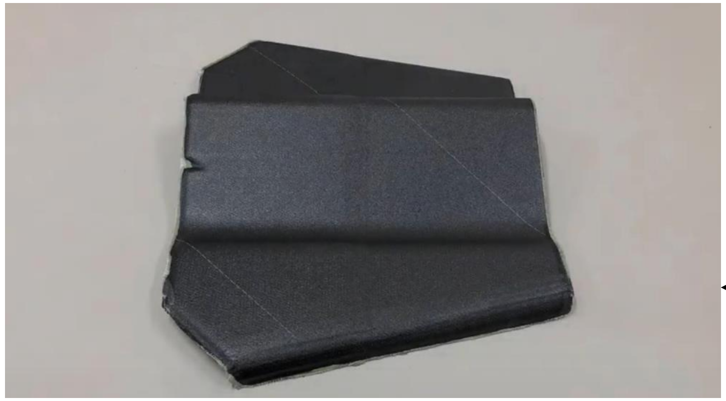
Sheet Pick and Place Robot

Sheet Placed at the Desired Location



Sheet Draping with Appropriate Grasping

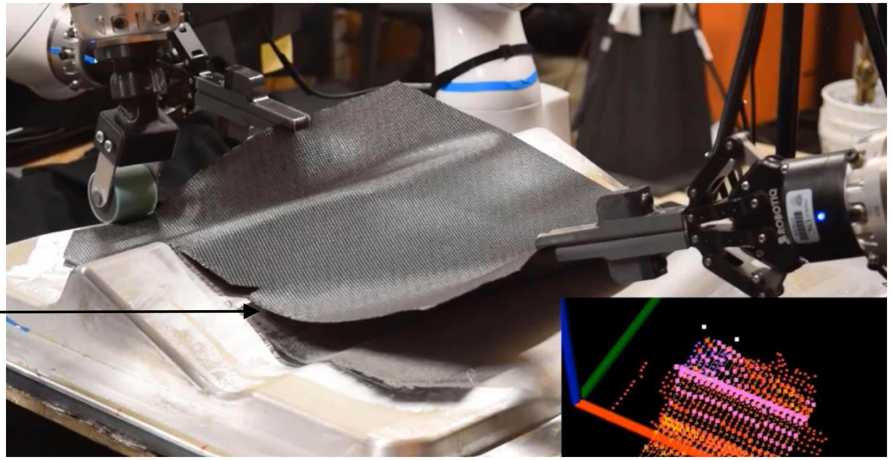
Final Cured Part



Challenges with Sheet Transport

- Deformable nature of the sheet can cause the sheet to assume different shape under suction-based grasping
- Deformable features are difficult to align with classical methods

Misalignment while using classical open loop vision-based techniques



Deformable features more difficult to align

Visual Servo a Potential Solution

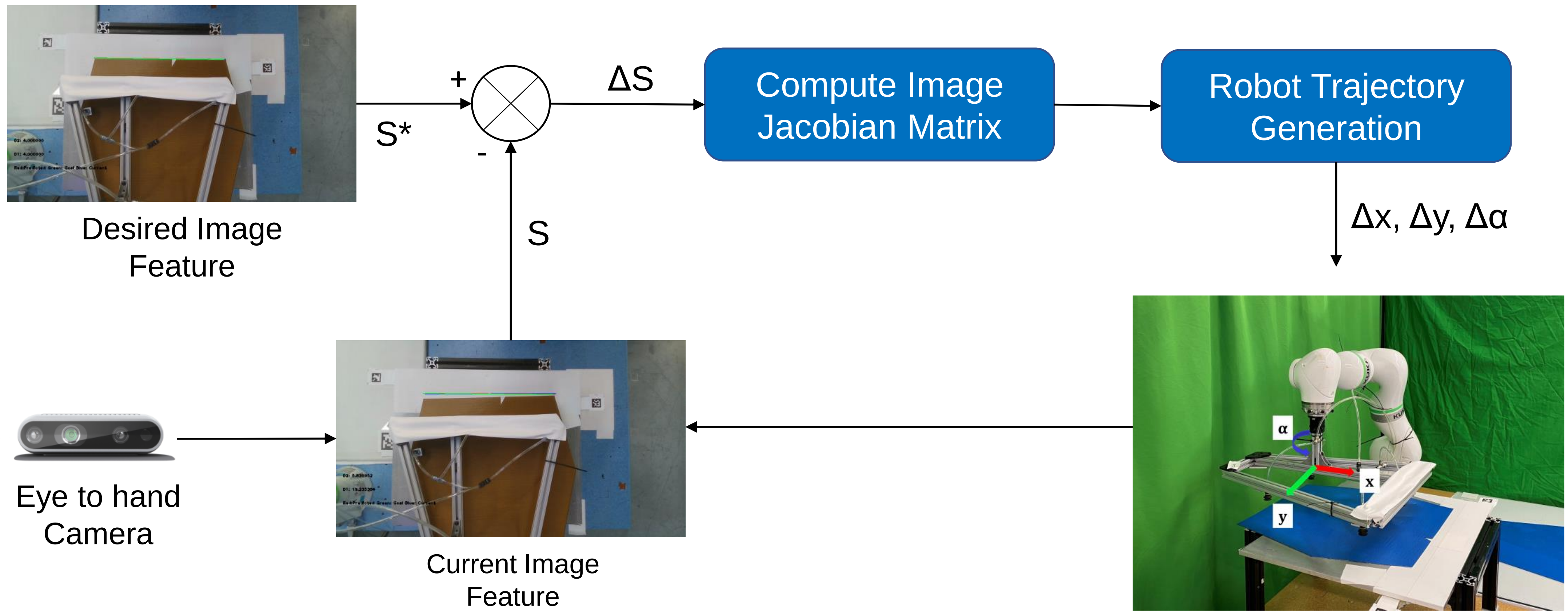
Initial Misalignment of the Feature

Compute Trajectory →

Final Aligned Feature

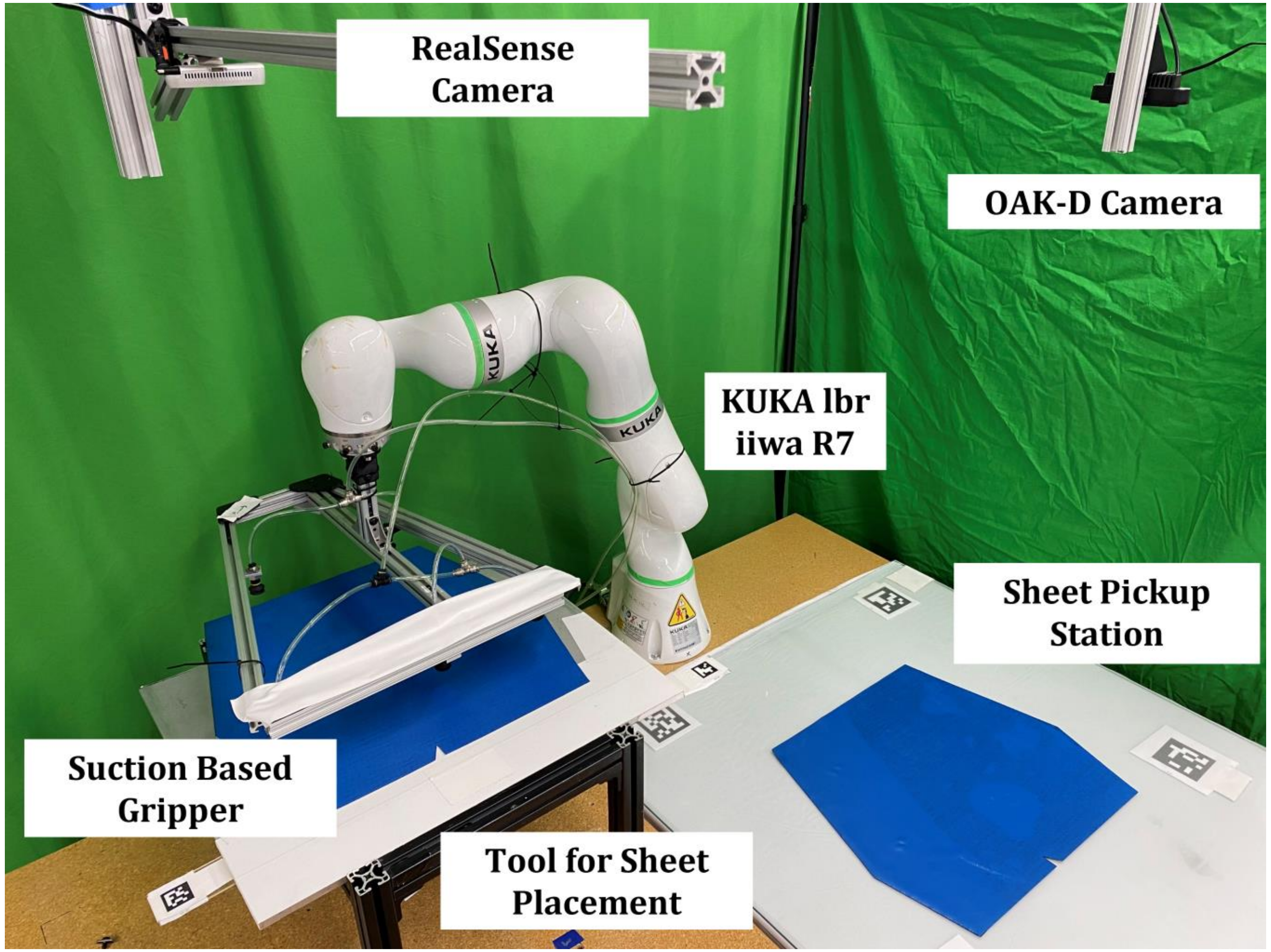
- Visual Servo is a classical method where the robot motion is controlled based on some alignment features in the image space
- Classical visual servo can be slow due to following reasons:
  - Slow convergence of the system
  - Feature recognition system
  - Estimation of Image Jacobian Matrix

Visual Servo Architecture

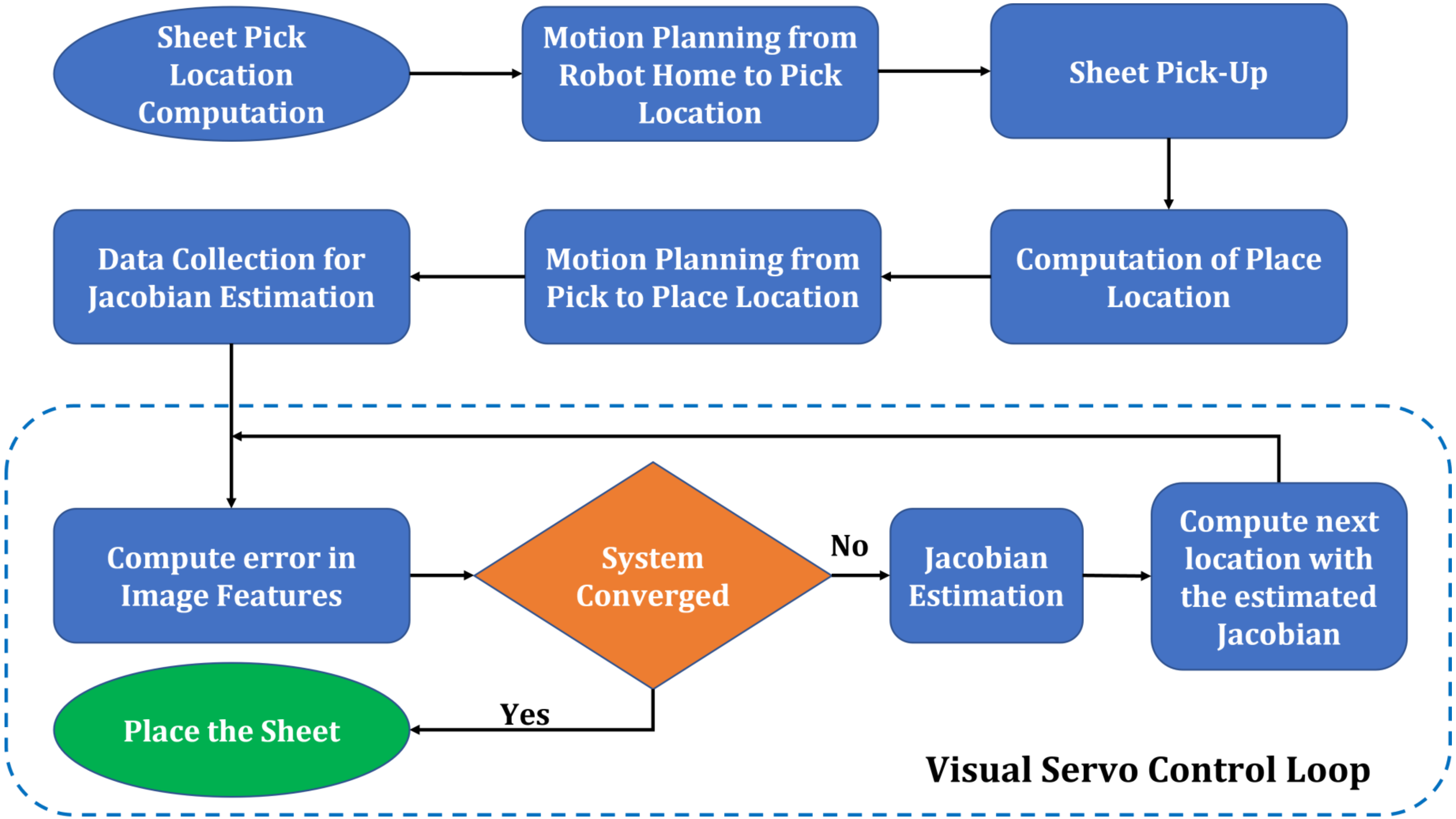


Cell Setup

- KUKA LBR Manipulator as Sheet Transport Camera
- RealSense and OAK-D cameras for vision capabilities
- Suction based tool for sheet pickup



Visual Servo Process Flow



System Overview

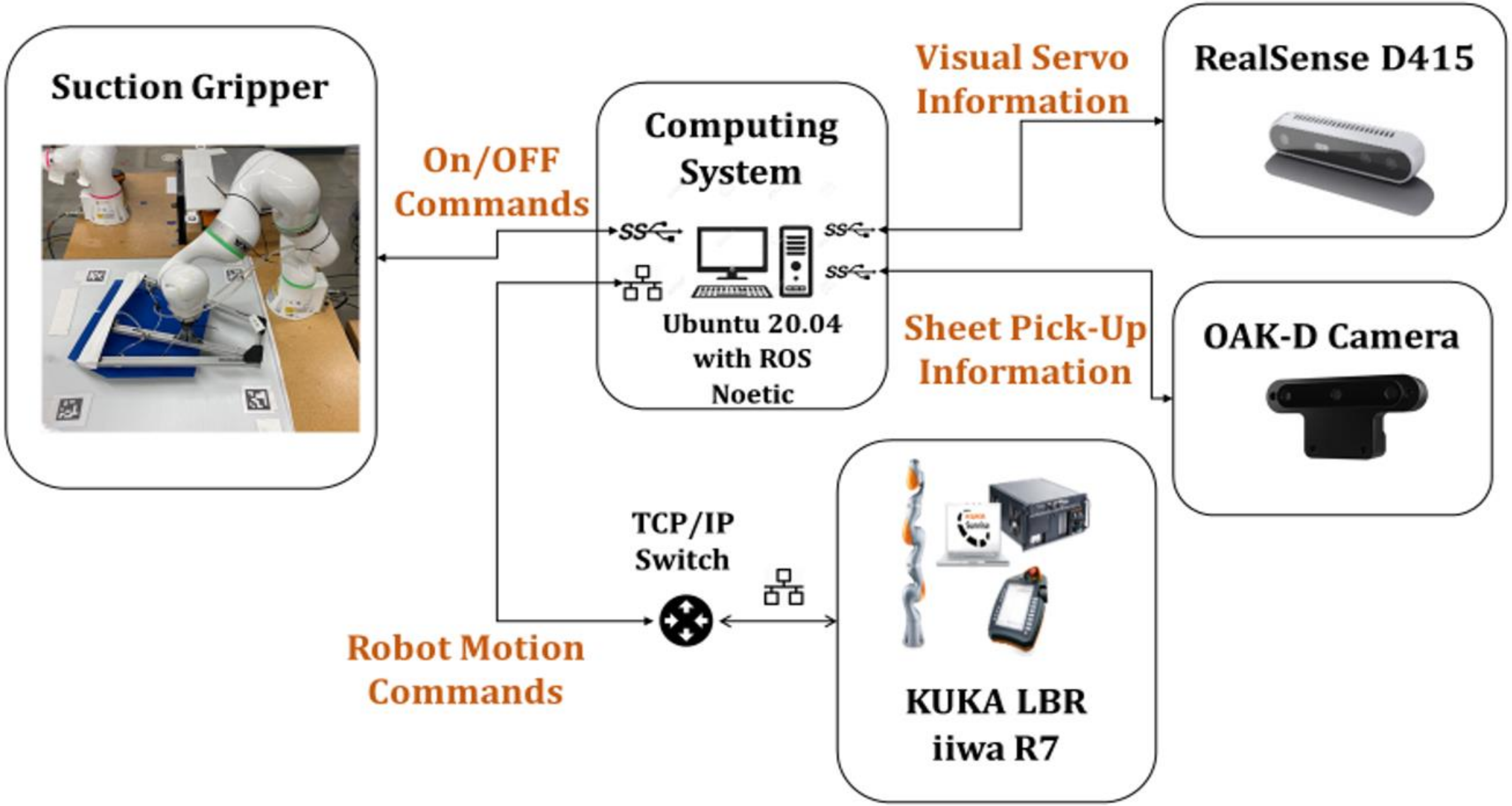
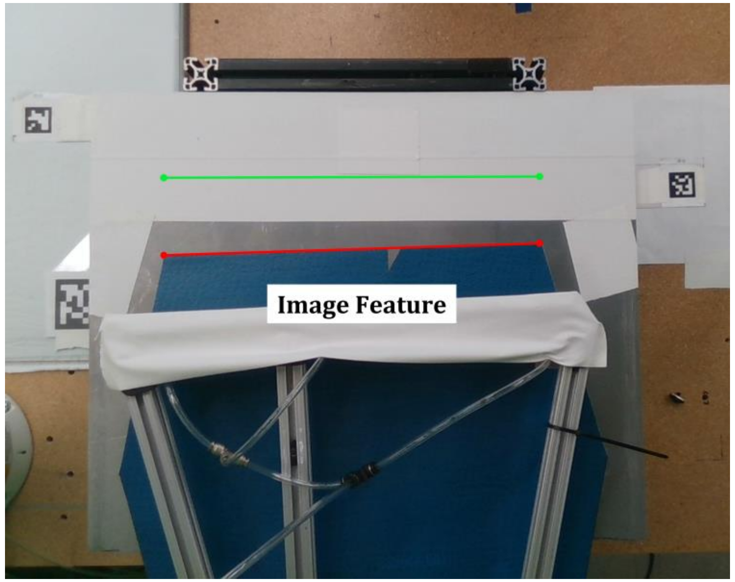


Image Feature Recognition

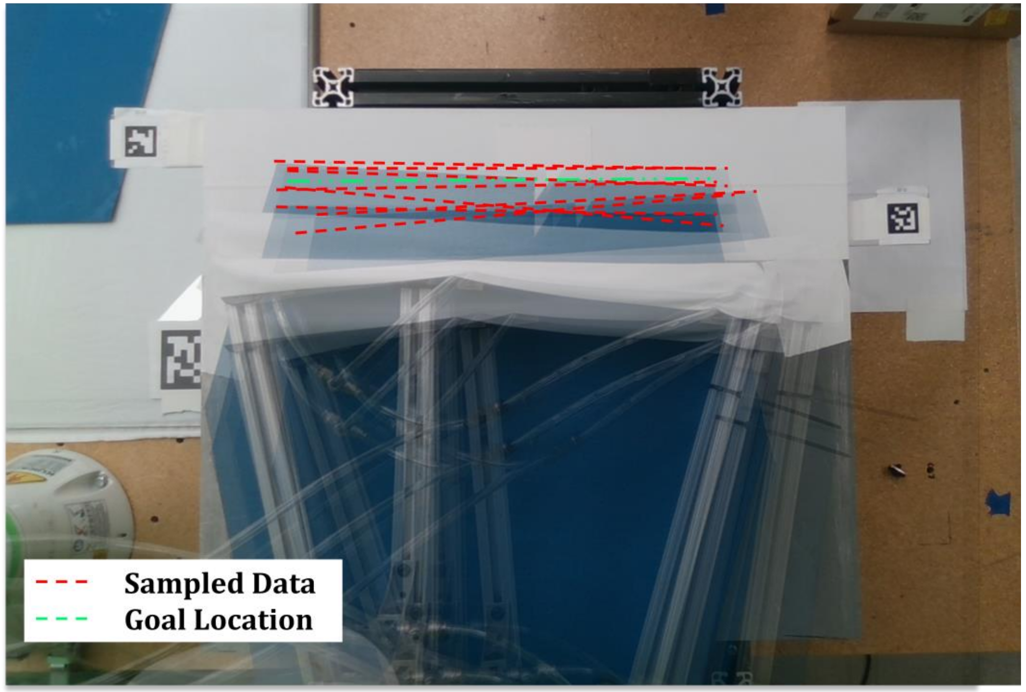
- Image feature is a crucial element of the visual servo control loop
- The objective is to choose a feature that is least affected by occlusions for easier detection
- The feature should also be unaffected by the deformability of the sheet
- The feature we chose was an edge of the sheet and the corners are the ones we track for feature alignment



Desired Image Feature in Green

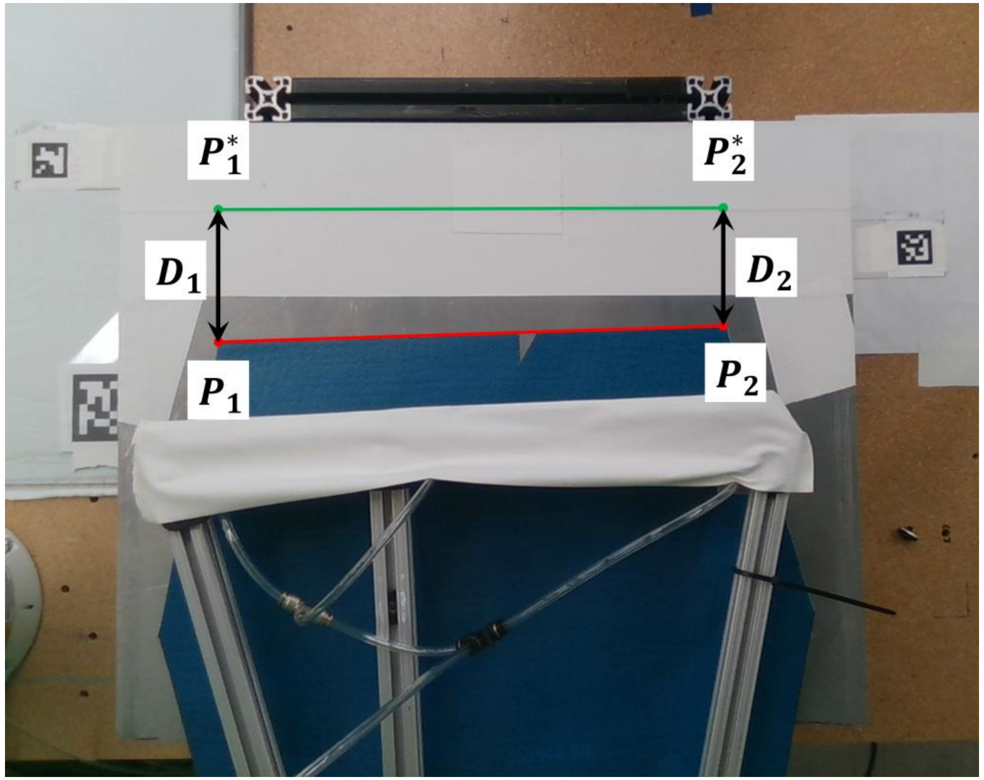
Image Jacobian Matrix Estimation

- In order to overcome the issues with the uncertainty in image feature due to sheet's deformable nature we adopt a sampling-based learning scheme
- We initially sample the space for varying values of cartesian poses and record corresponding pixel value
- We then use k-nearest neighbor search Algorithm to estimate the Image Jacobian Matrix



Trajectory Planning

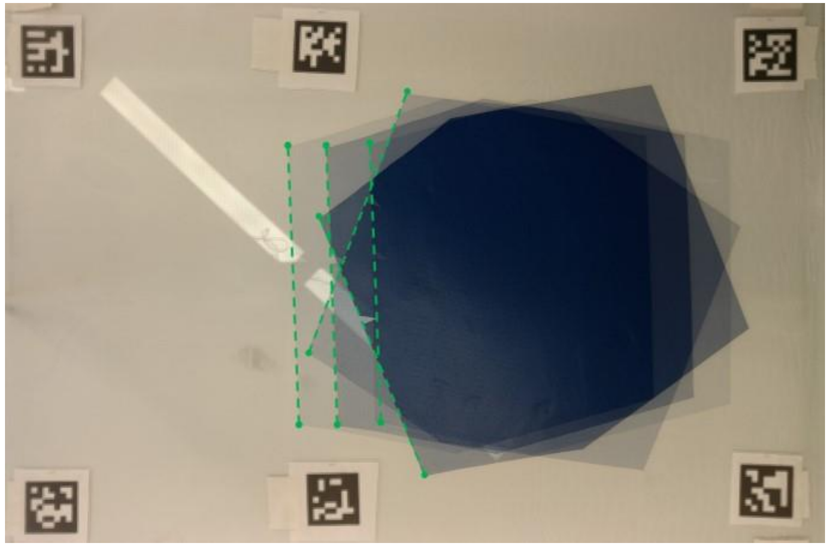
- The Image Jacobian is used to compute the robot trajectory such that the image feature error ΔS is reduced
- We run a BFGS based optimization technique to compute the path of reducing error
- The Robot was operated in Position Control mode for faster speeds and lesser vibrations of the tool



The error for the optimizer is proportional to the sum of D1 and D2

Experimental Results

- We conducted 50 trials for sheet pick and place
- Parameters Varied:
  - Sheet Loading Position ($\pm 10\ cm$) and Orientation($\pm 10°$)
- The desired results are within the tolerance in observed in the industry for composite sheet placement applications

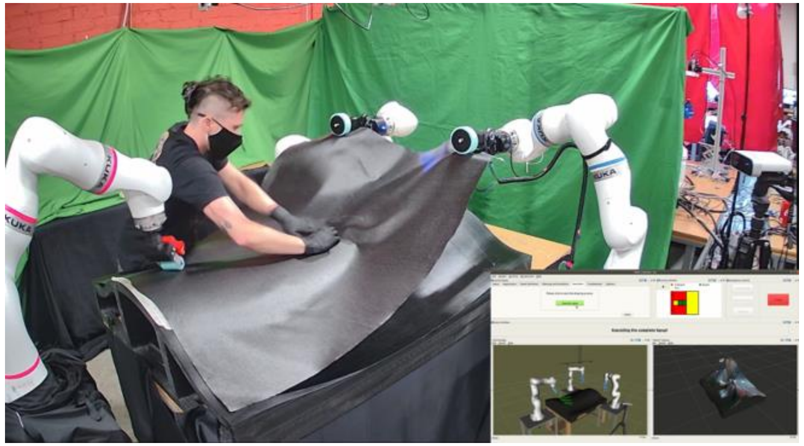


Variations in Sheet Loading Position

No of Trials	Position Error		Orientation Error		Image Jacobian Estimation Iterations	
	Avg	Max	Avg	Max	Avg	Max
50	0.8 mm	1.6 mm	0.2°	0.5°	2	4

Summary

- Composite prepreg layup is an important process in manufacturing high performance parts and will revolutionize the industry
- We have demonstrated how AI and machine learning tools can be deployed to achieve a smart robotic cell for automation of composite prepreg layup



Conclusions

- The advent of human-safe robots is enabling robots to work on ergonomically challenging tasks and amplify human productivity
- *Physics-Informed AI* is a key to realizing smart robotic assistants

Load Part

Task Robot

Let Robot to Do Work

USC Viterbi School of Engineering

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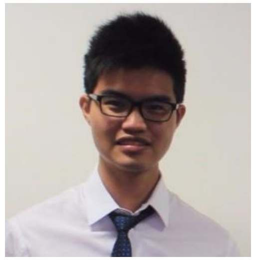
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