Advanced Robotics Manufacturing (ARM) Institute

Collaborative Robotic Sanding of Aircraft Panels

RIC Americas Annual Meeting

Project Team:
Spirit AeroSystems, Wichita State University, Southwest Research Institute

Joe Marshall and Bharath Rao

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NIAR® Wichita State University
National Institute for Aviation Research

SwRI®
Southwest Research Institute

ARM
ADVANCED ROBOTICS
FOR MANUFACTURING

Collaborative Robotic Sanding of Aircraft Panels

Joe Marshall of Spirit AeroSystems; Wichita State University and Southwest Research Institute

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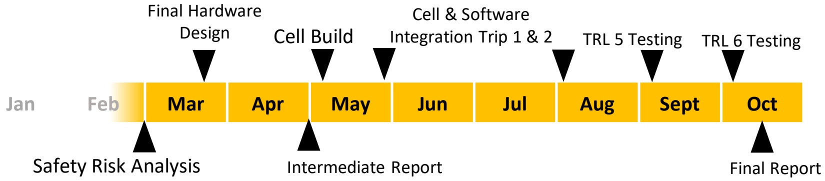
Milestones/Schedule:


Final Hardware Design
Cell Build
Cell & Software Integration Trip 1 & 2
TRL 5 Testing
TRL 6 Testing

Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct

Safety Risk Analysis
Intermediate Report
Final Report

Key Events:

- TRL 5 Achieved with Full System 9/11:
  - Camera Registration of part
  - Path Planning via ROS
  - Force Controlled Execution of paths
  - Scan of rework markings and re-sand touchup areas
- Final Testing Complete 10/9:
  - TRL 6 Tests on production part
  - Final Presentation and Report Compilation

Description: Develop a collaborative robotic system to aid skilled workers in sanding composite aircraft panels. Automation will reduce workers' hazardous exposure, increase product quality, & reduce labor hours per unit. Project will greatly reduce automation cost for large & small manufacturers.

Enables: Empower US workers to compete more effectively against low wage countries by multiplying the productivity and yield of the American worker. Achieved by lowering technical, operational, and cost barriers so that any size US manufacturer can implement surface finishing automation.

Team Partners:

- **Spirit AeroSystems:** Joe Marshall,(PI), Greg Balandran, Curtis Richardson
- **WSU**: Dr. John Tomblin (PI), Brian Brown, Michael Wescott
- **SwRI:** Matt Robinson (PI), Jorge Nicho, Tyler Marr

Technology Transition & Deliverables

- Deliverables: Interim & Final Reports of findings, Roadblocks, MRL & TRL status, CAD data, Program Files, Updated software modules & libraries
- Significantly reduce cost while empowering American workers to be competitive on a global scale.
- Easily adoptable and scalable by other USA manufacturing markets (automotive, industrial equipment, boating, consumer goods, ect…)
- All CDIP will be delivered to ARM & its members.
- Tech transfer to ARM members forecasts implementation into production environments in 2021

Collaborative Robotic Sanding Benefits

- Greatly reduced cost compared to a traditional robotic sanding solution
- Rapid deployment into production environment
- Rapid adaptability to new work statement
- Increased productivity
  ~50% reduction in labor
- 80% reduction in ergonomic issues
- No traditional NC programming
- Maintain operator in the loop- touchup, inspection, rework identification

Old Tech
TRL: 9

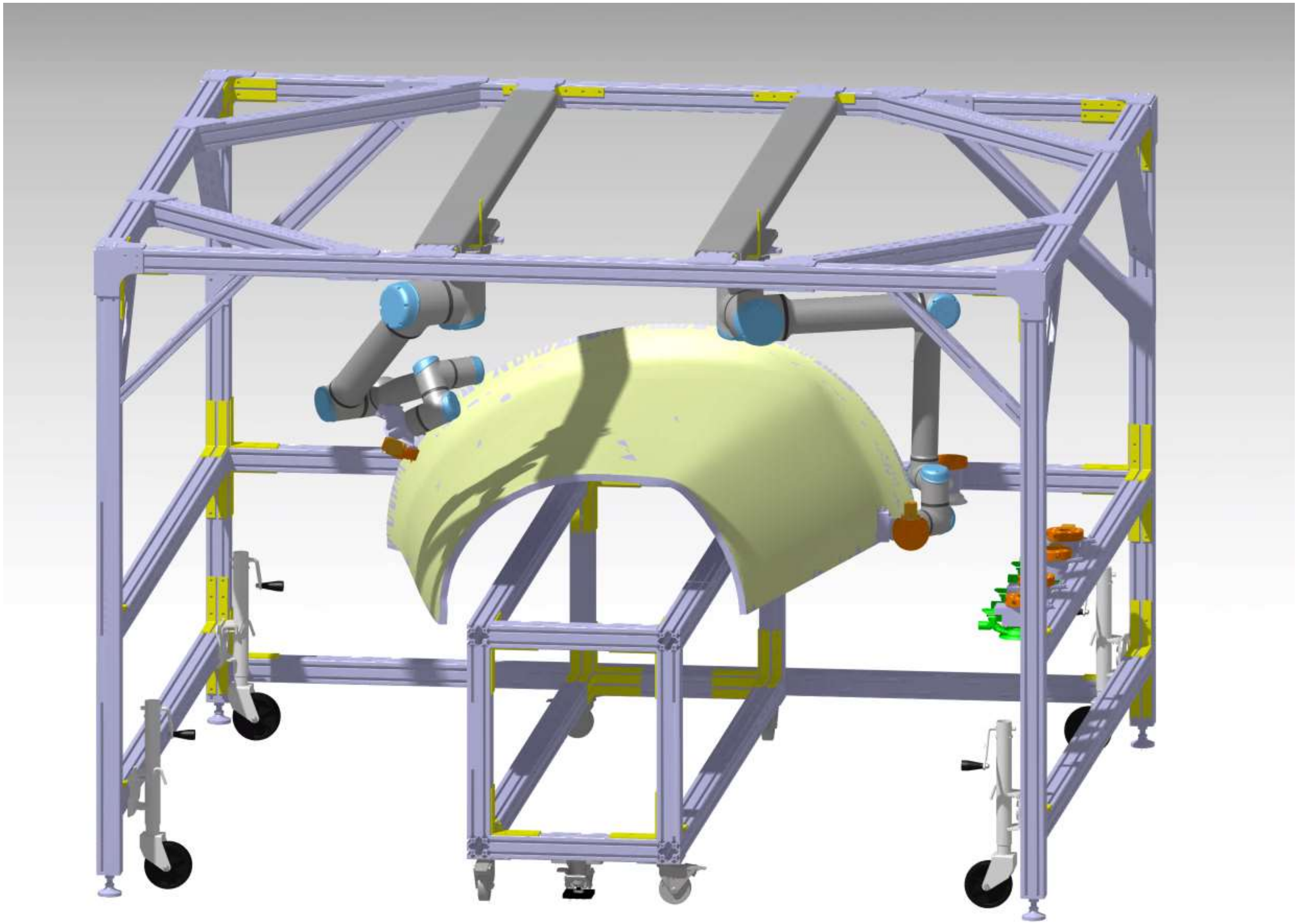
Currently available large robot sanding
$1.5M+

Lower Cost & Collaborative

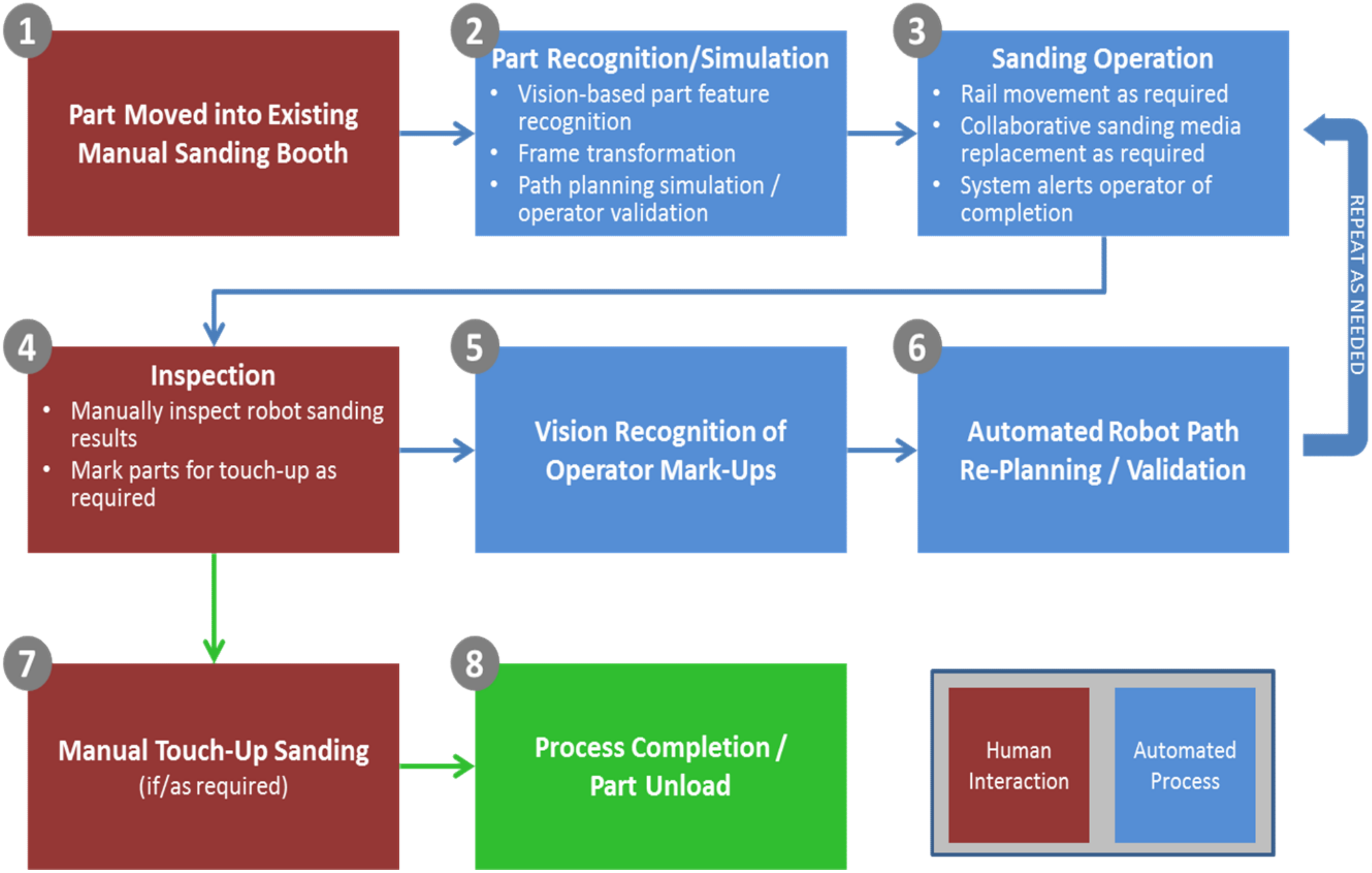
New Tech
TRL: 4

Collaborative robotic sanding
~$250K

Collaborative Robotic Sanding Cell



Concept of Operation



1 **Part Moved into Existing Manual Sanding Booth**

2 **Part Recognition/Simulation**
- Vision-based part feature recognition
- Frame transformation
- Path planning simulation / operator validation

3 **Sanding Operation**
- Rail movement as required
- Collaborative sanding media replacement as required
- System alerts operator of completion

4 **Inspection**
- Manually inspect robot sanding results
- Mark parts for touch-up as required

5 **Vision Recognition of Operator Mark-Ups**

6 **Automated Robot Path Re-Planning / Validation**

REPEAT AS NEEDED

7 **Manual Touch-Up Sanding**
(if/as required)

8 **Process Completion / Part Unload**

🟥 Human Interaction

🟦 Automated Process

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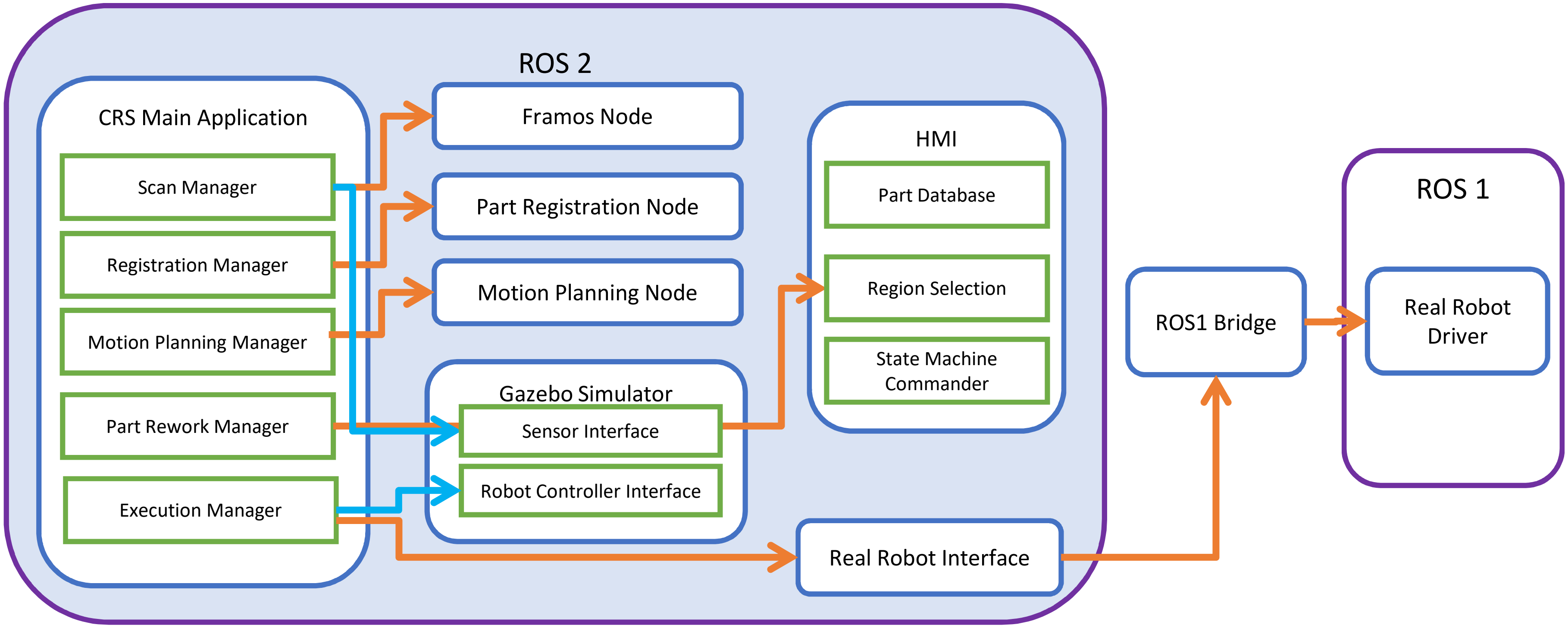
Application Modules

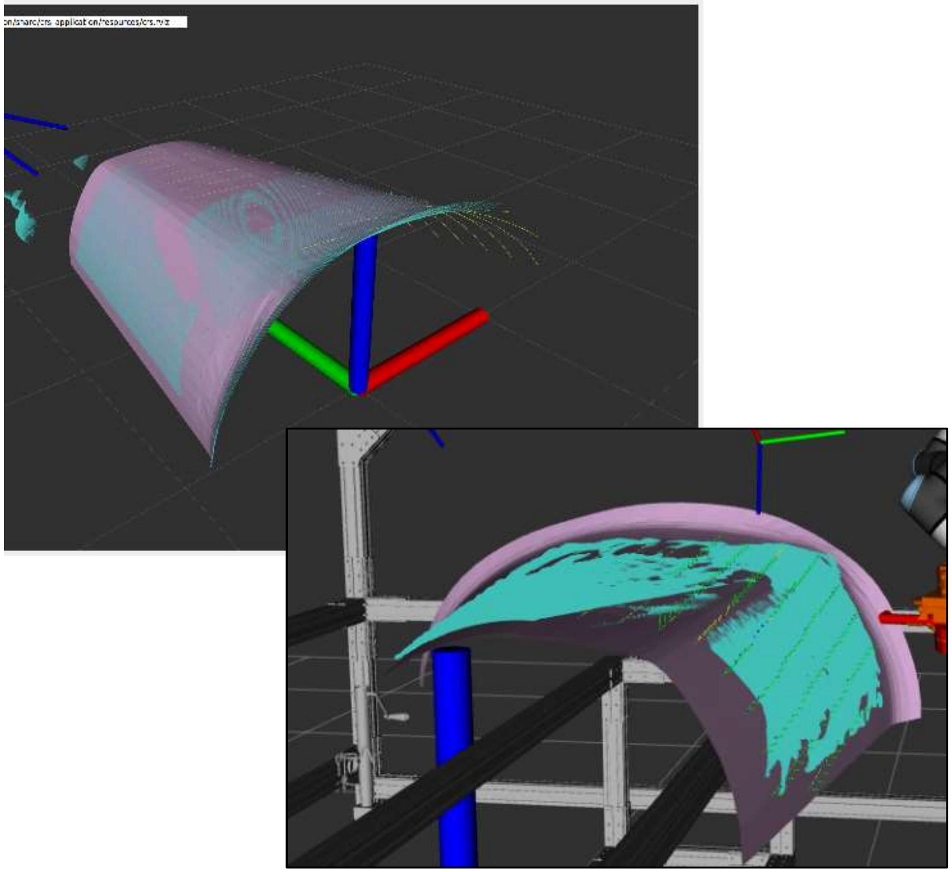
- Online Application Tasks:
  - Scanning (with D435 Framos Camera)
    - Collect multiple 3D point clouds of the scene in order to observe the part in the workcell
  - Registration
    - Locates the part in the workcell and updates the toolpath locations
  - Motion Planning
    - Computes the robot motions needed to follow the sanding toolpaths and free space moves needed to collect scans for registration
  - Process Executions
    - Stages and dispatches the motions plans produced by motion planning.
  - Force Feedback Execution
    - Allows for the robot to apply and maintain commanded force on surfaces while following the desired rasters paths.
    - Makes it possible to achieve desired sanding finish.
  - Rework Region Selection
    - Detects human-made closed-region markings using advanced perception method.
    - These regions are then used to select a sub section of the original raster path set for rework.
    - Those rework regions are sanded as needed.

Implementation Diagram



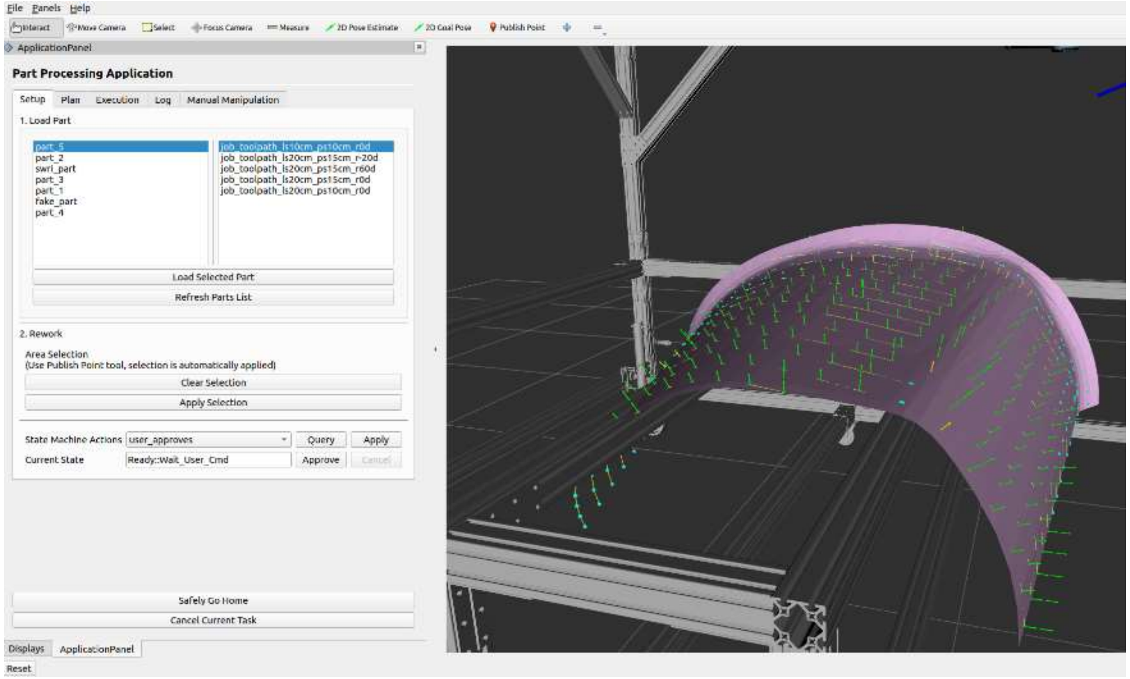
Perception

- Registration
  - The point clouds obtained from scanning are stitched together in order to create a single cloud that contains the full part model
  - Cropping is done in order to remove noise or parts of the workcell seen by the camera.
  - The part's location is then estimated using a feature matching algorithm.
  - The location transform is also applied to the toolpaths associated with the part.



Motion Planning

- Input:
  - Sanding Toolpath
  - Start and end positions
  - Part Model (collision)
  - Desired Tool speed
  - Approach and retreat distances
- Output:
  - Surface Robot trajectories
  - Configuration Change free-space motions
  - Simulation preview of paths for operator



Part Processing Application

1. Load Part

part_5
part_2
swri_part
part_3
part_1
fake_part
part_4

job_toolpath_ls10cm_ps10cm_r0d
job_toolpath_ls20cm_ps15cm_r-20d
job_toolpath_ls20cm_ps15cm_r60d
job_toolpath_ls20cm_ps15cm_r0d
job_toolpath_ls20cm_ps10cm_r0d

2. Rework

Area Selection
(Use Publish Point tool, selection is automatically applied)

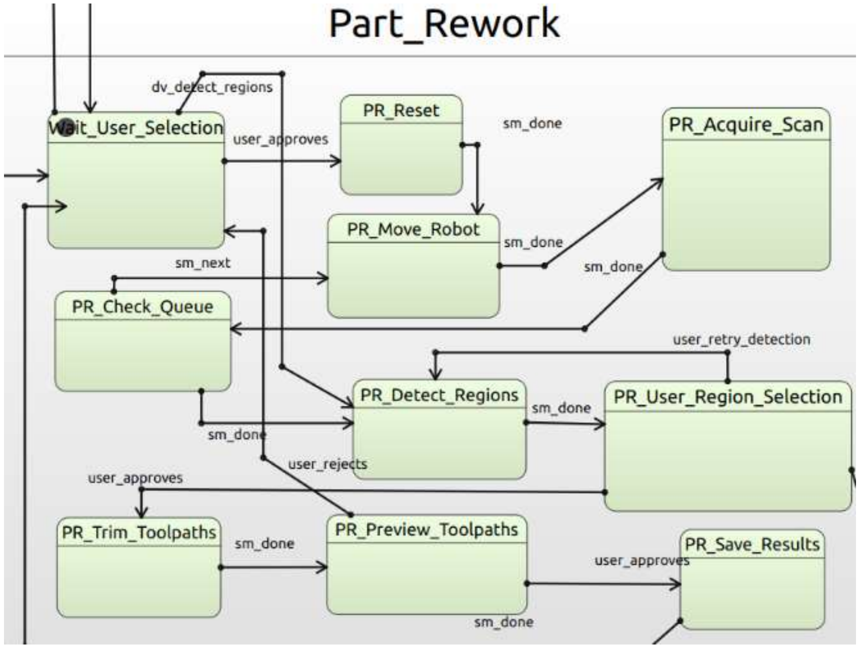
State Machine Actions: user_approves
Current State: Ready::Wait_User_Cmd

Motion Planning

- Process:
  1. Determine reachable points and split toolpath (rasters) accordingly
  2. Add approach and retreat trajectories to ends of each reachable raster
  3. Add additional splits based on desired tool speed and joint velocity limits
  4. Add additional splits for sandpaper tool changes
  5. Run final preplan process to determine optimal joint states at each point
  6. Run preplan through trajectory optimization for motion smoothing and detailed collision checking
  7. Generate free-space plans between the start and end of adjacent rasters
  8. Optimize free-space plans to generate smooth trajectories

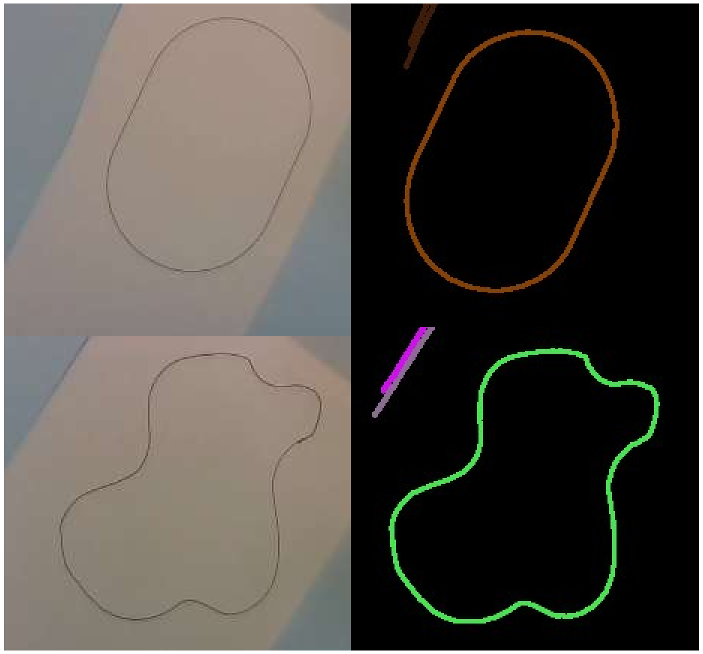
Rework Region Detection

- IR&D work funded by SwRI
- Applies OpenCV filters and PCL (Point Cloud Library) methods to identified human-marked regions
- Integrated into CRS application
  - Human Operator draws closed-regions on the part with a sharpie.
  - Application scans the part to collect images and point clouds
  - The region detection node identifies the human-made regions from the scan data.
  - Detected Regions are used to “crop” original toolpaths for sanding rework purposes
  - Cropped toolpaths are then processed for motion planning and execution.



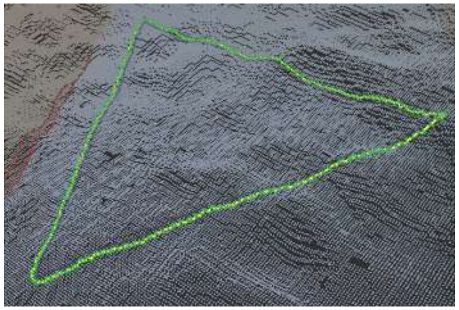
Rework Region Detection

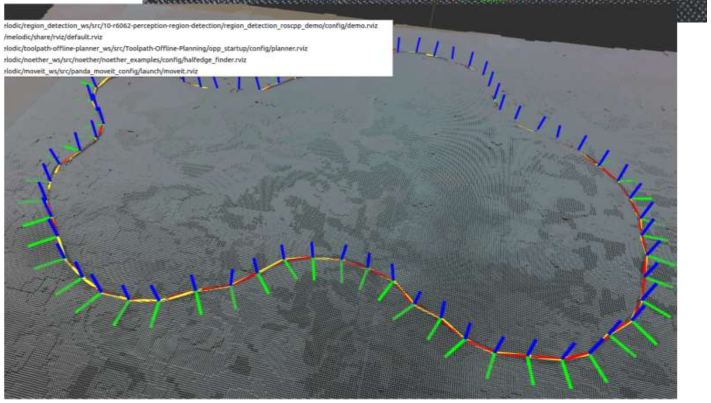
- OpenCV filtering steps
  - Converts to grayscale
  - Applies threshold
  - Dilates image
  - Canny Edge detection method
  - Extraction of contours in pixel coordinates



Rework Region Detection

- PCL Processing Steps
  - Converts pixel space coordinates from OpenCV to XYZ points
  - Applies various filters
    - Outlier removal
    - Statistical removal
    - Downsampling
  - Joins separate adjacent segments
  - Organizes them into closed and open regions
  - Computes normal vectors

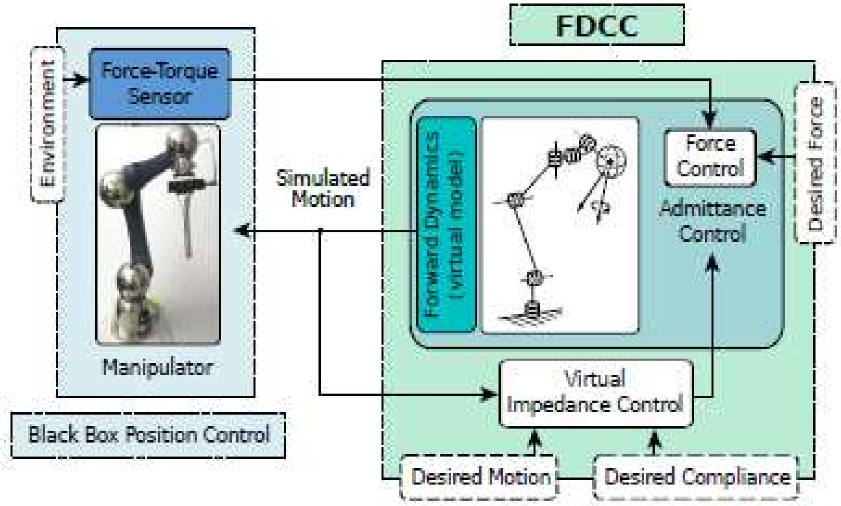




Force Controlled Trajectory Execution

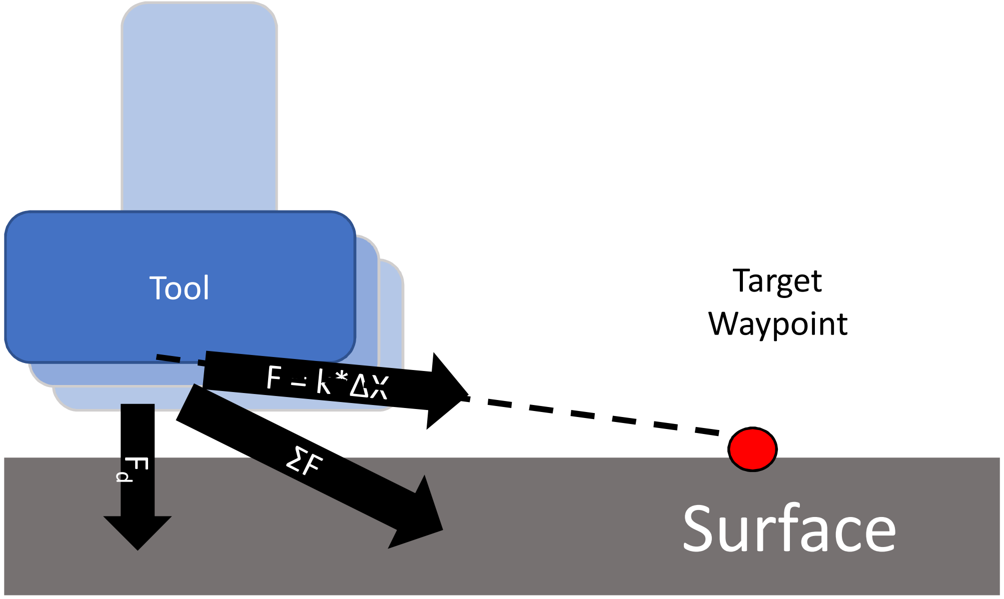
Robot Control Methodology

- Forward Dynamics Compliance Control (FDCC)
  - Impedance, admittance, and force control combined
  - Use dynamics simulations to directly control manipulator with virtual and measured forces
- Use measured, desired, and predicted forces to predict how robot should move and then implement appropriate motion

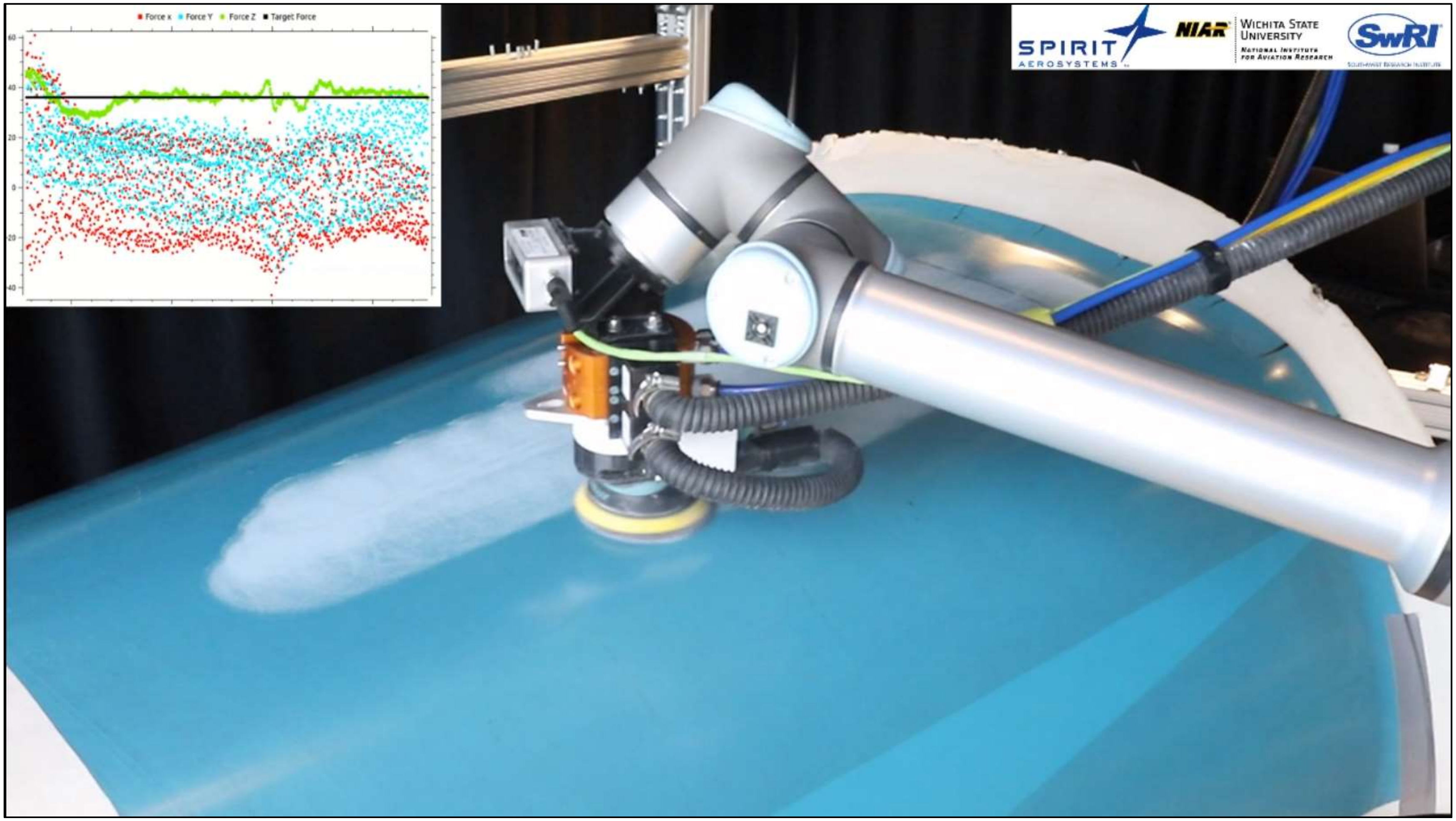


Force Controlled Trajectory Execution

- Strategy
  - Chases Virtual target waypoint



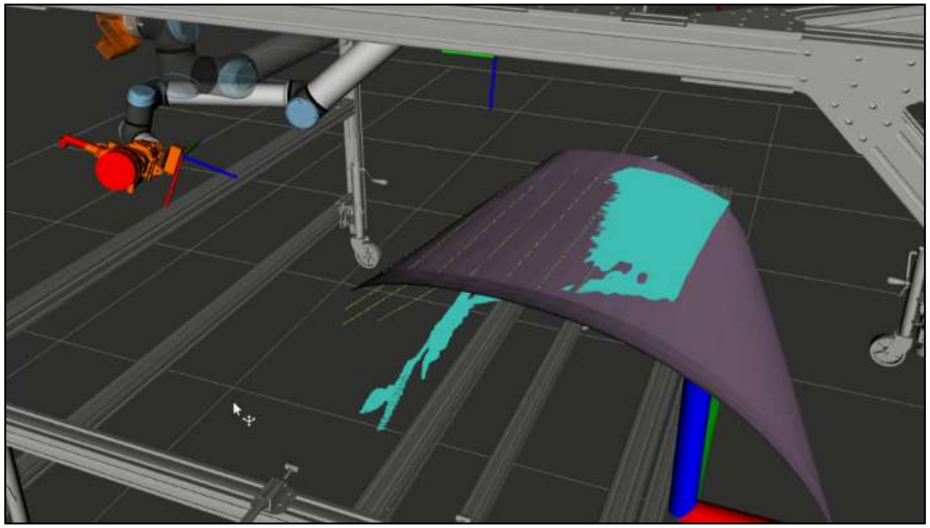
Demo Video- Generic Contour Part

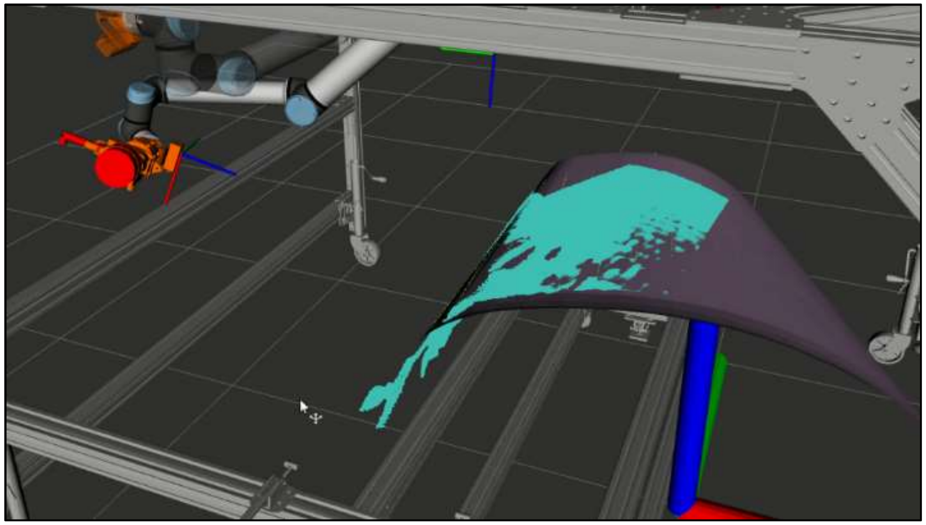


https://youtu.be/Pj_NsO22Bws

Part Registration: Testing

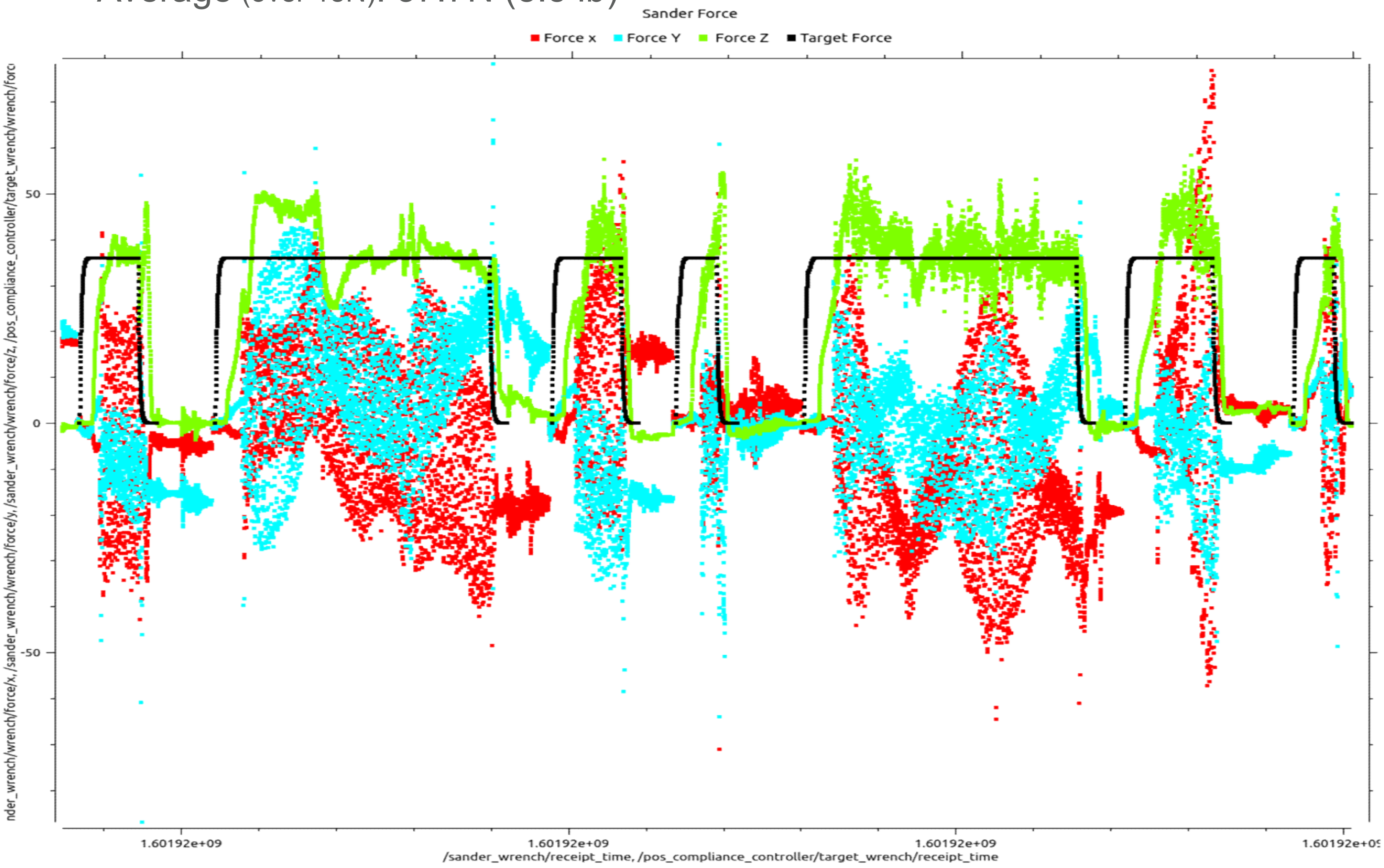
- Successfully registered multiple parts, even out of position and angles





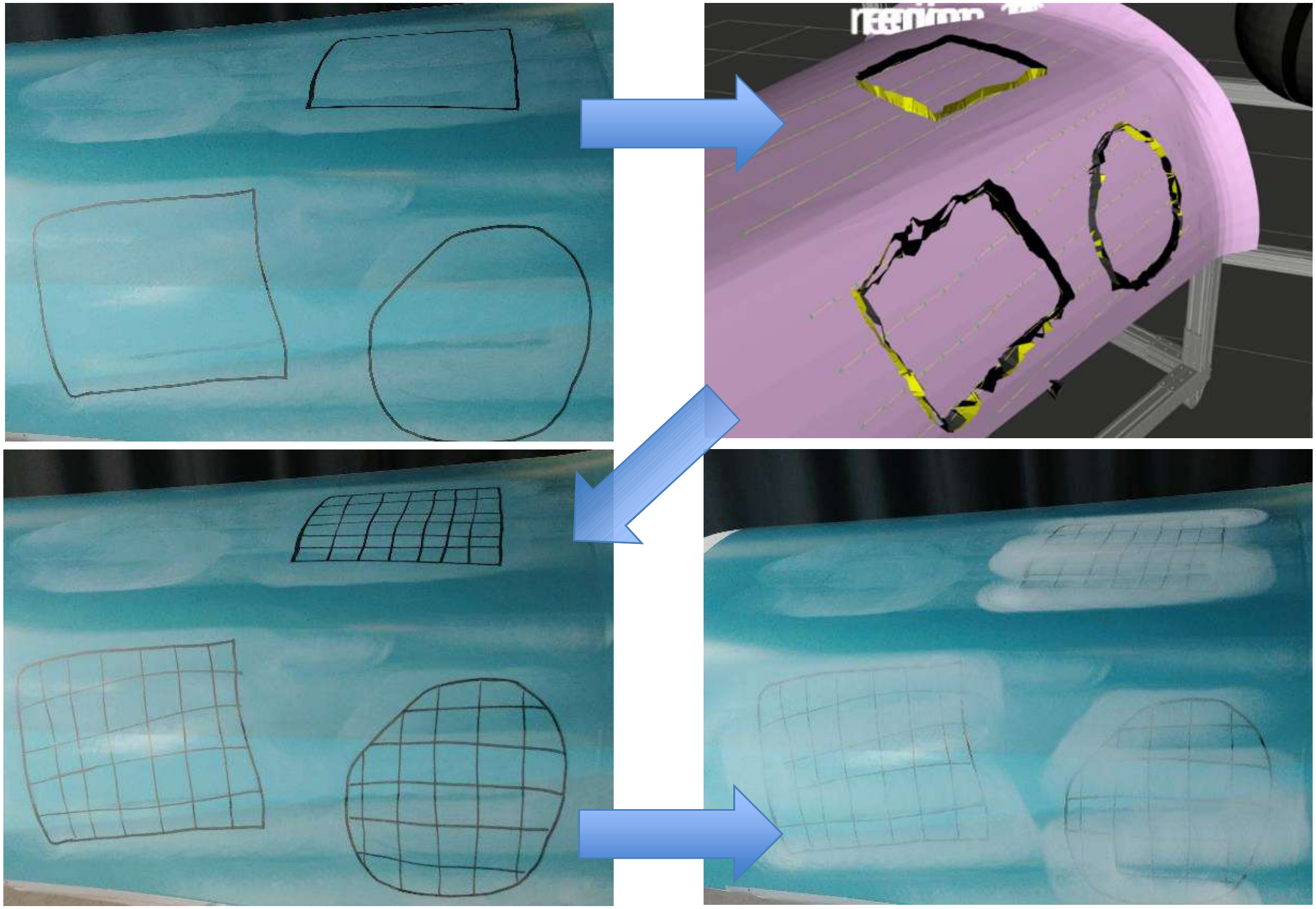
Force Graph of 8lb Test @ 100mm/sec

- Target 36N (8lb)
- Average (over 18N): 37.7N (8.5 lb)

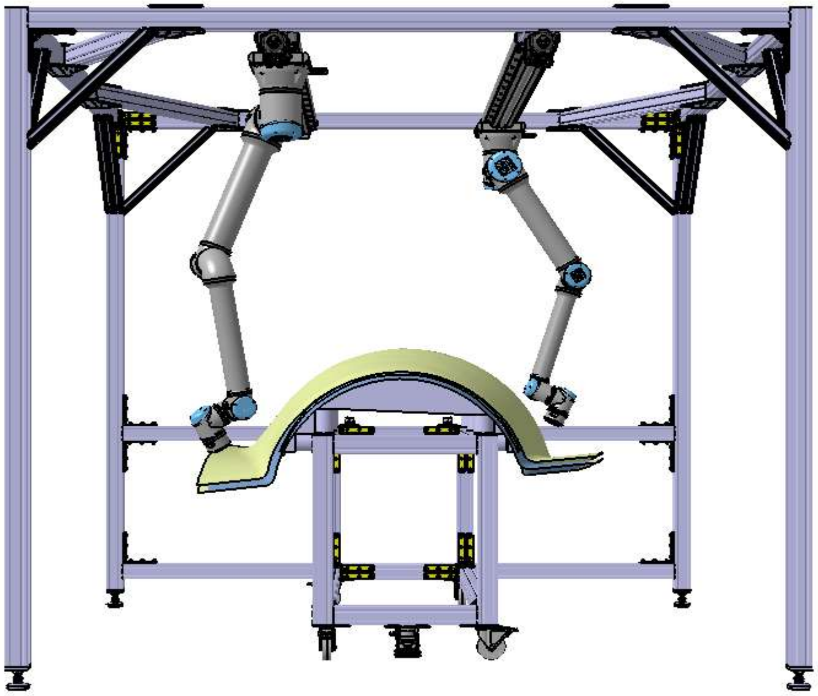


Markup Recognition and Re-sanding

- Successfully recognizes closed shapes on part drawn with marker
- Re-sanding successful – over 90% sanded area



Improvement Areas / Next Steps



- Is UR10e the best robot for your application?
  - Longer reach? (eliminate rail?)
  - Higher payload?
  - Collaboration Modes?
- Cable Management- Use off-the-shelf solution?
- Singularity Avoidance:
  - Robot Mounting on rail at angle away from part
  - Larger cell size
  - Better ROS handling of Singularity Zone
- ROS Software Improvements
  - ROS2 Robot Driver
  - GUI improvements: usability and navigation
  - Fault recovery improvements
- Human Factors Improvements
- Efficiency Improvements:
  - Cell Mounted Cameras vs. Robot camera
  - Sandpaper Changer vs. Head Swap
  - Automatic Rail Movements
    - Collaborative rail or pneumatic movements
  - Faster Processing Capability- ROS processor optimization
  - Pre-packaged routines/paths- reduce path planning load
  - Speed of Sanding Increase

Questions?

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