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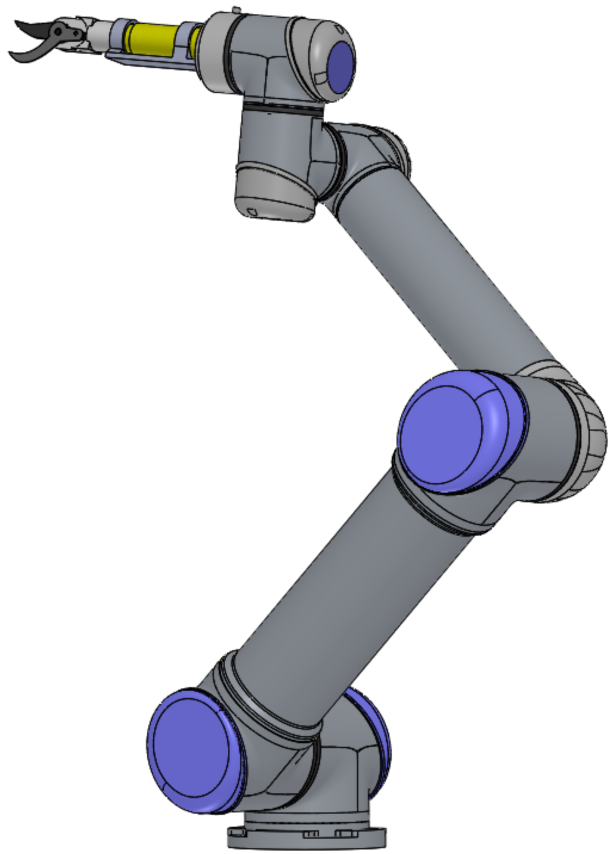
Collision free path planning of a robotic manipulator for pruning apple trees



Azlan Zahid, Long He, Daeun Dana Choi, James Schupp, Paul Heinemann

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Introduction/ Background
3


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Objectives of the study
7


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Methodology
9


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Results
18

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Introduction/ Background

Introduction: Specialty Crop Industry (U.S.)

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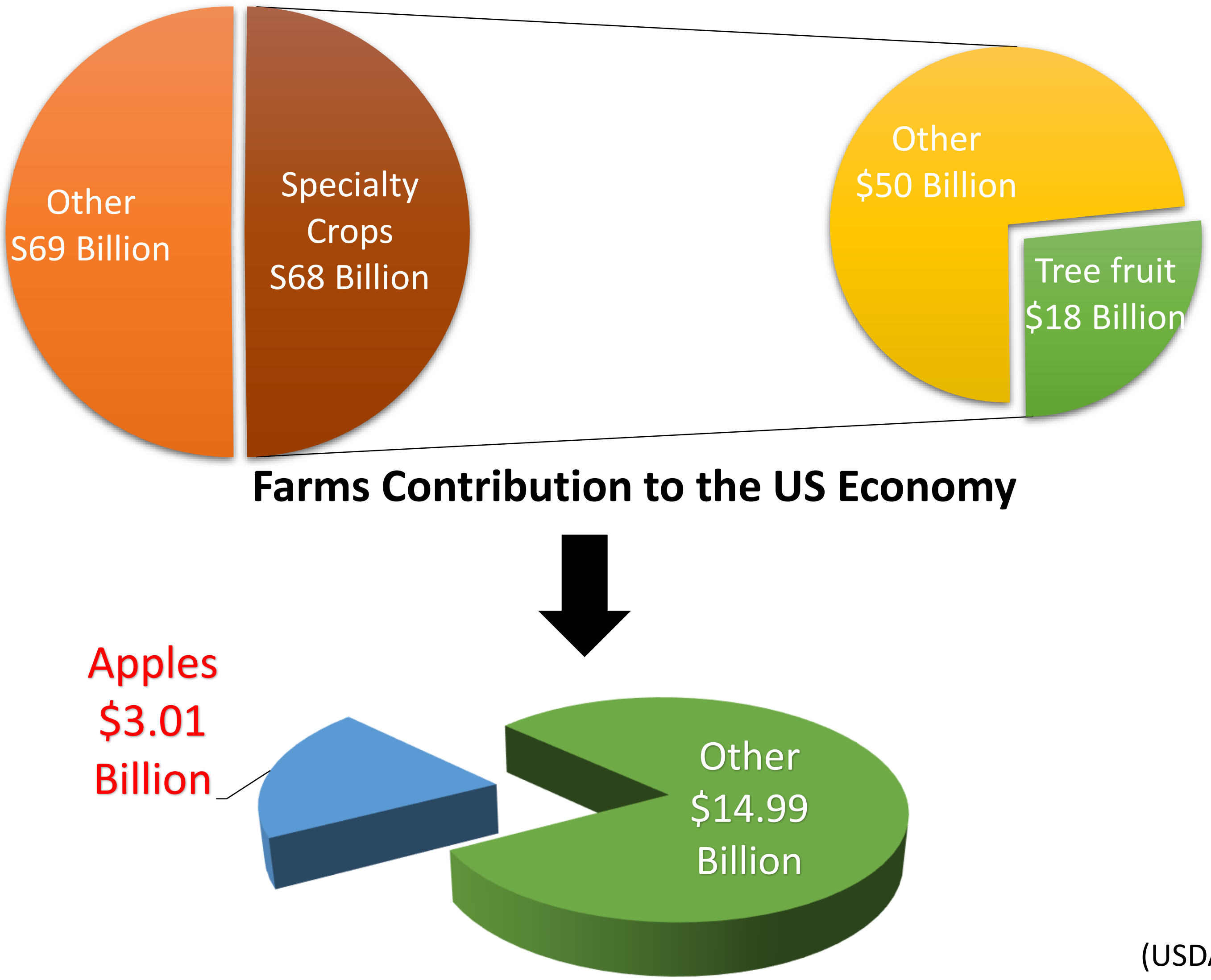

(USDA-NASS, 2019)

Tree Fruit Industry in the US Economy

Introduction: Cost Breakdown and Labor Availability

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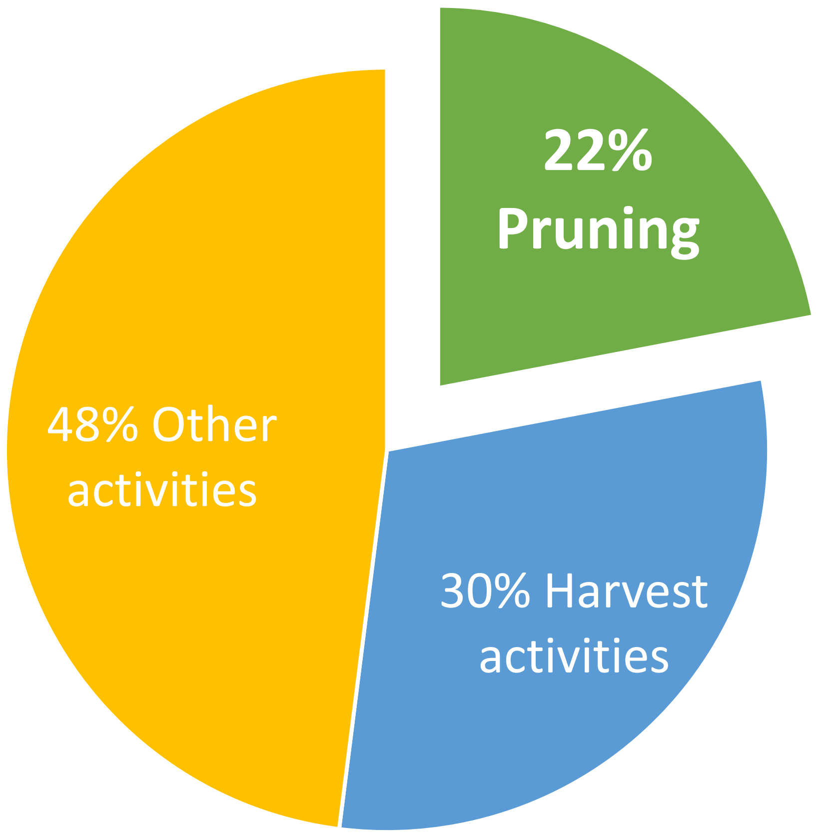

Production cost breakdown in percentage for each category Gallardo et al., (2010)

- Pruning ~ 20% of total labor cost
- ~ 80-120 working hours per hectare

Available labor decreasing!

(Mika *et al*. 2016)

Introduction: Potential Solution and Challenges

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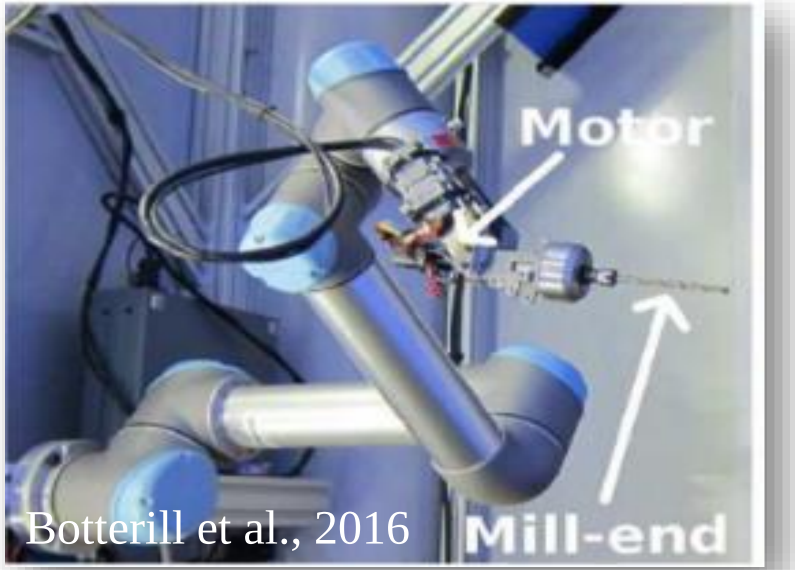
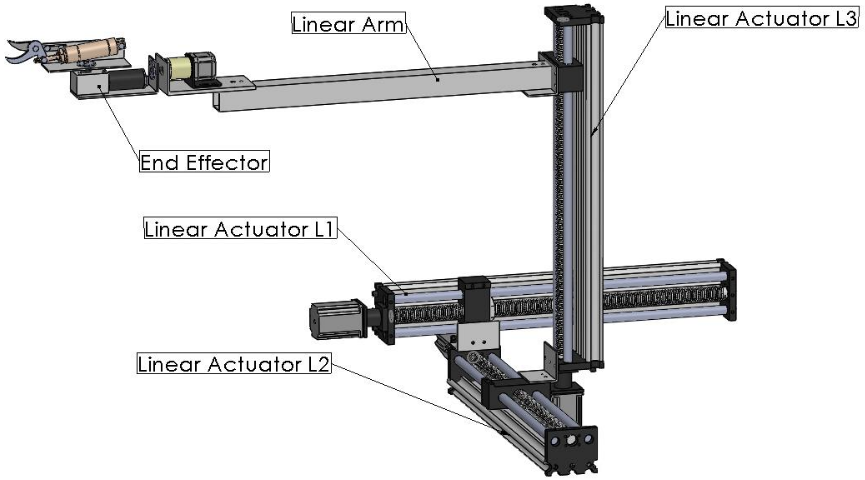
- Robotic pruning → selective pruning
- Challenges in robotic pruning
  - Detection and identification of pruning branches
  - Spatial requirements and path planning of manipulation system
- Researchers developed vision algorithms using different camera sensors
- No study has been reported on path planning for tree pruning



Botterill et al., 2016



(Zahid et al., 2020)

Objectives of the study

Objectives of the study

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1. Developing a simplified virtual environment including a robotic manipulator and a tree section for simulation in MATLAB
2. Establishing a collision-free trajectory for reaching the targeted pruning points

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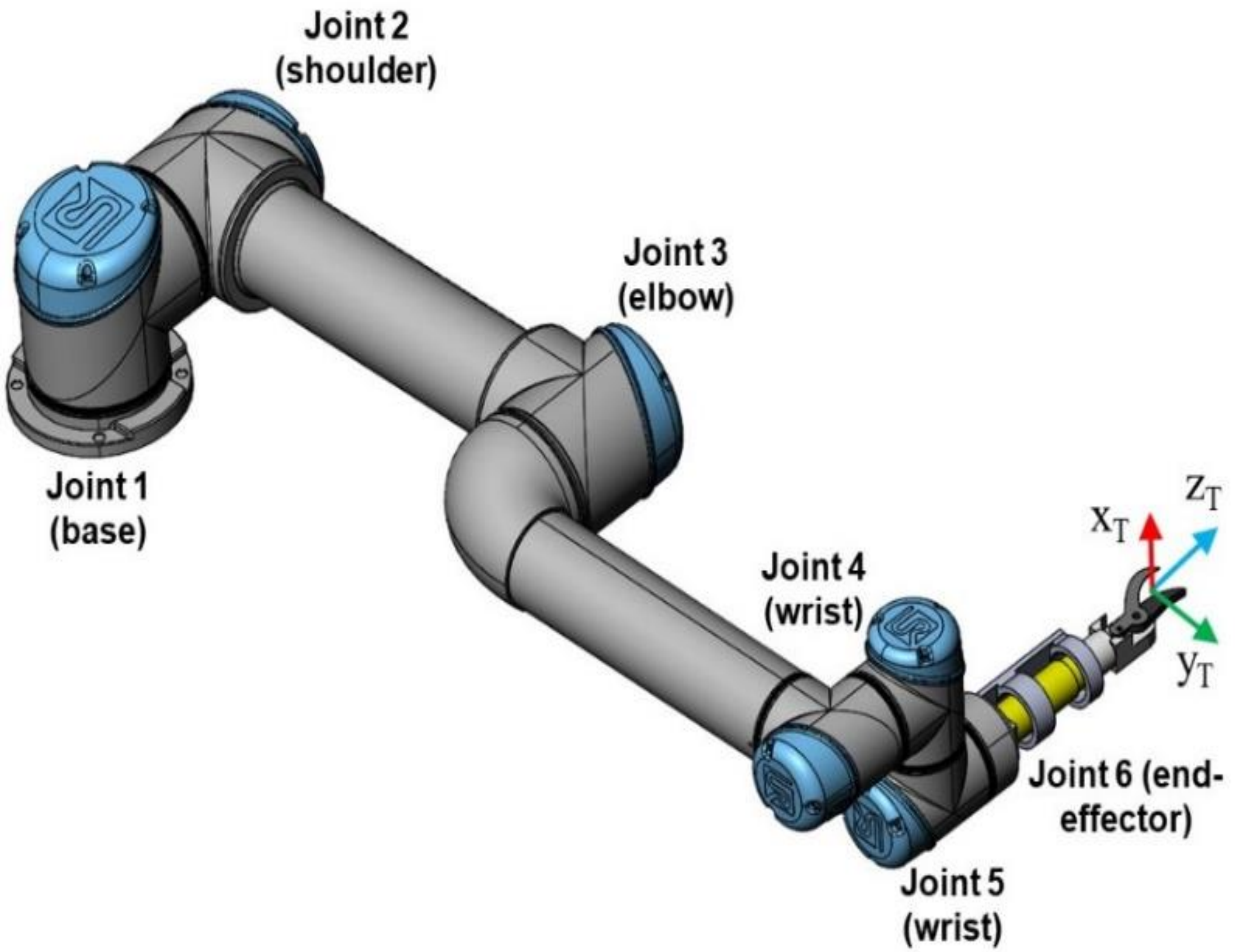
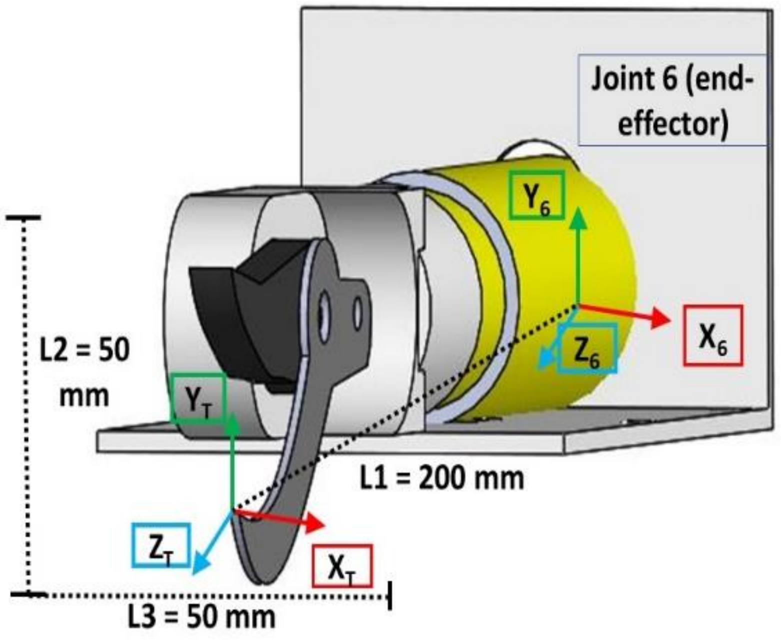
Methodology

Simulation Model Establishment: 3D CAD Model

Robotic Manipulator



End-effector



Simulation Model Establishment: Kinematic Model

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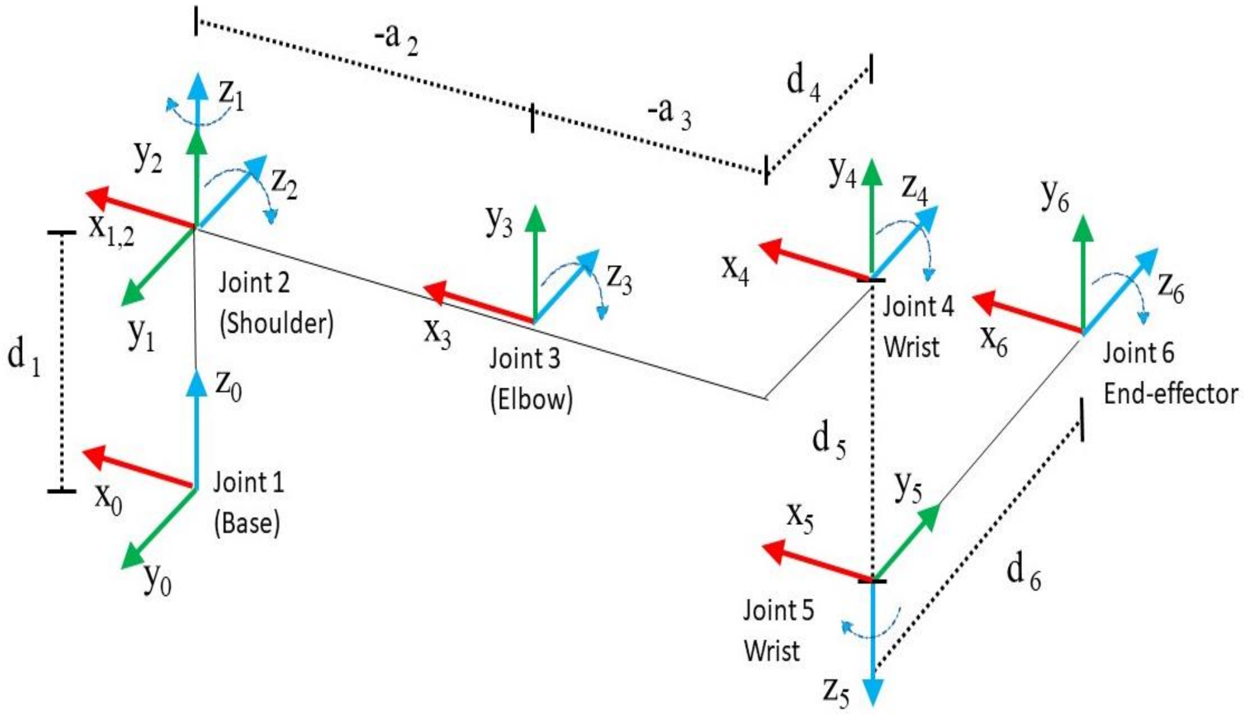
Coordinate Frames of the Manipulator



Denavit-Hartenberg Parameters

Joints	Joint angle θ_i (rad)	Link length a_{i-1} (m)	Link offset d_i (m)	Link twist α_{i-1} (rad)
Joint 1 (Base)	θ_1	0	0.1625	$\pi/2$
Joint 2 (Shoulder)	θ_2	-0.425	0	0
Joint 3 (Elbow)	θ_3	-0.3922	0	0
Joint 4 (Wrist)	θ_4	0	0.1333	$\pi/2$
Joint 5 (Wrist)	θ_5	0	0.0997	$-\pi/2$
Joint 6 (End-effector)	θ_6	0	0.0996	0

(UR-Robotics, 2020)

- Find the inverse kinematics of the manipulator
- Trajectory generation in Matlab

Simulation Model Establishment: Virtual Tree Model

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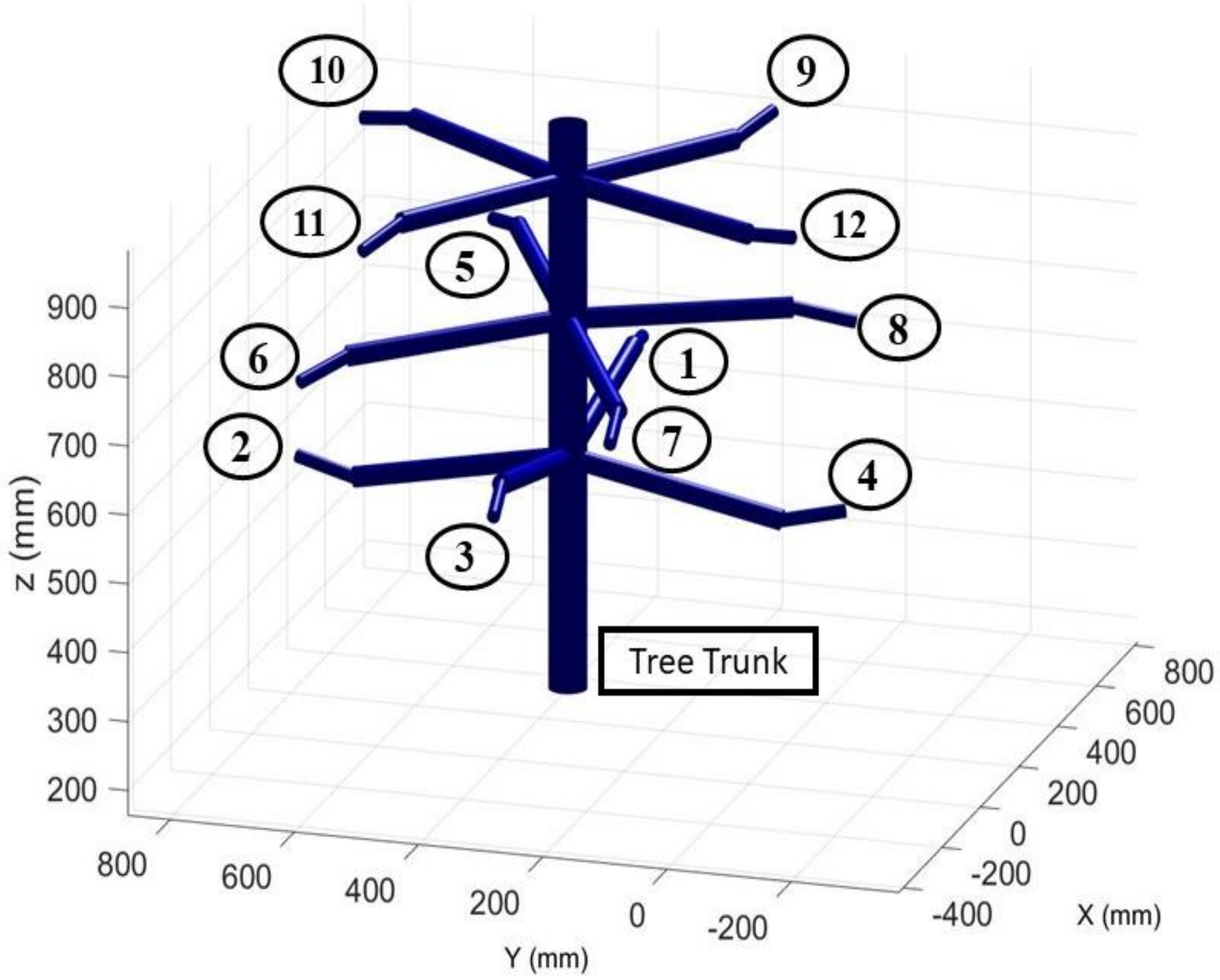

- 13 obstacles (→ 1 trunk and 12 primary branches)
- Canopy height = 600 mm
- Canopy depth = 700 mm

Simulation Model Establishment: Integrated Environment

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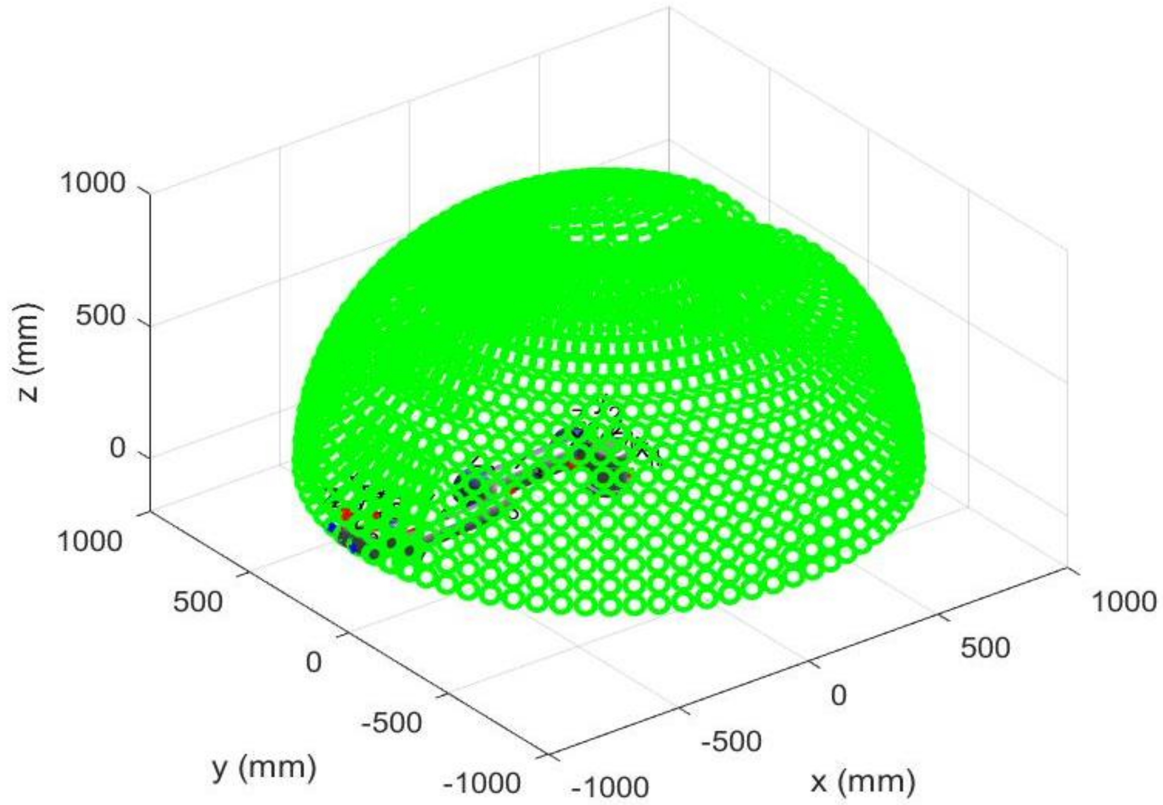
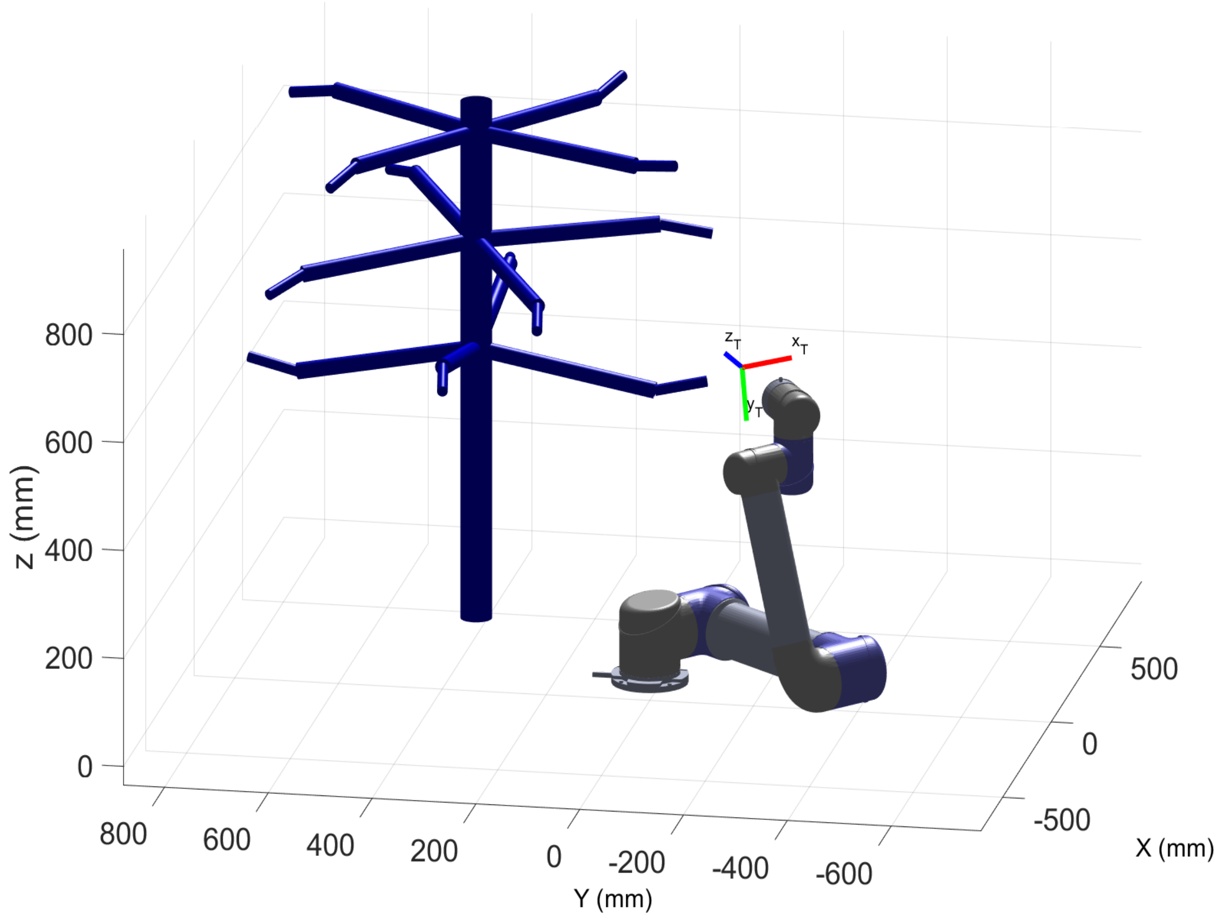
Workspace Envelope



Simulation Environment



- Reachable workspace width = 800 mm

- Manipulator position → (x, y) = (0,0) mm
- Virtual tree position → (x, y) = (400,400) mm

Path Planning Algorithm: Path Planning Method

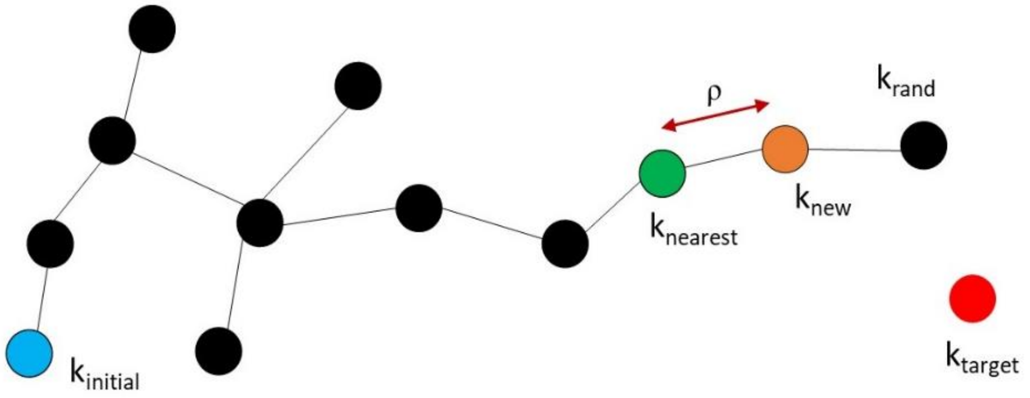
Collison Checks

- Collision free path for the end effector tool
- Manipulator body side collision with branches

RRT Path Planning

- Starting from the node $k_{initial}$
- From k_{rand} tree expanded to $k_{nearest}$
- If exist in collision free space, k_{new} is added
- Path is found by connecting all k_{new}

RRT Path Exploration



Path Planning Algorithm: Path Planning Method

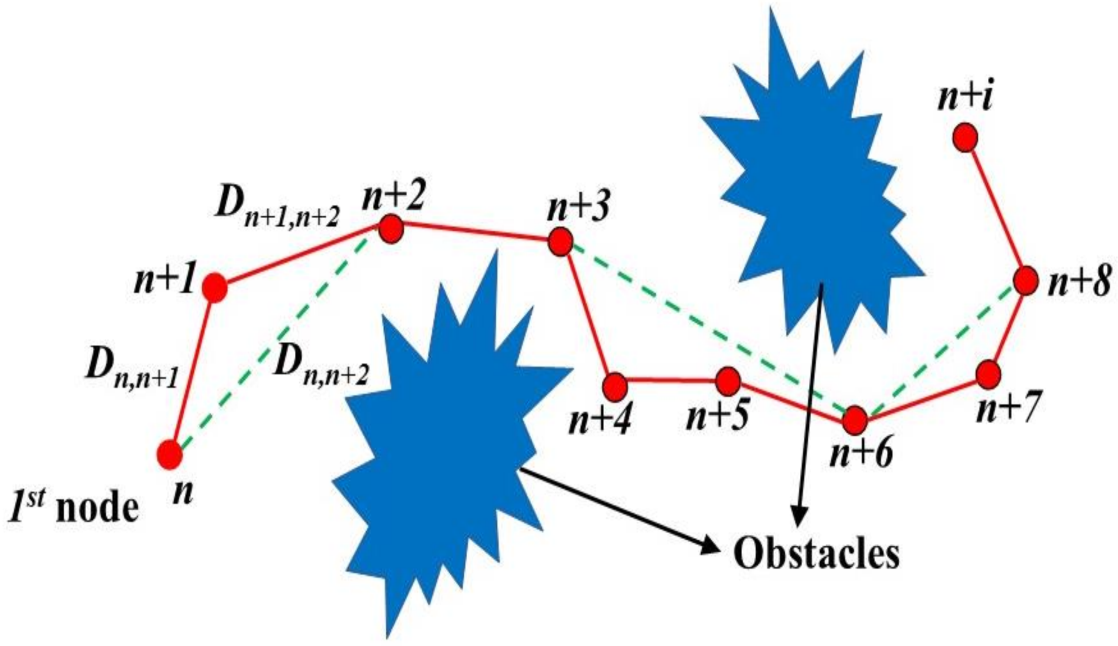
RRT Smoothing

- Distance between three consecutive nodes
- If the new distance is less to the sum, collision check performed

Path Optimization

- Non-linear optimization algorithm
- Objective function, and constraint functions
- Other parameters: Lower and upper boundaries, and min. distance from obstacles

Illustration for Path Smoothing



Simulation for Branch Accessibility: Ideal Pose

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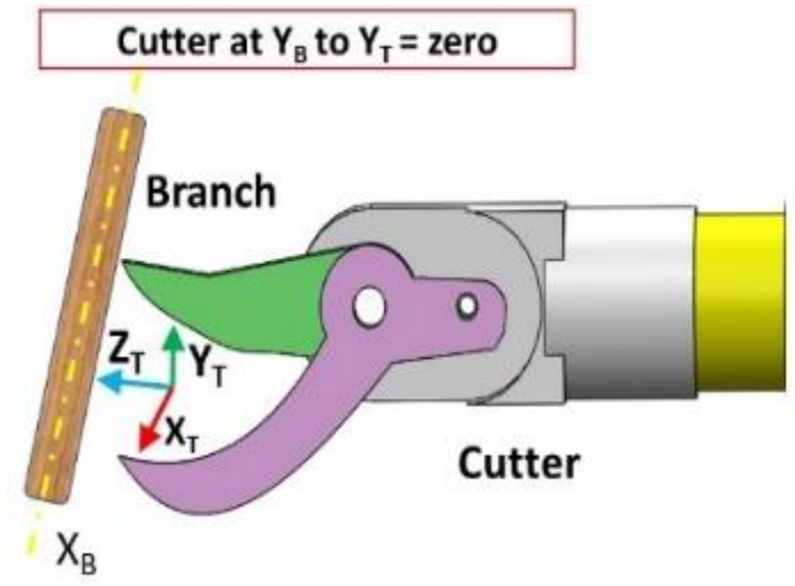
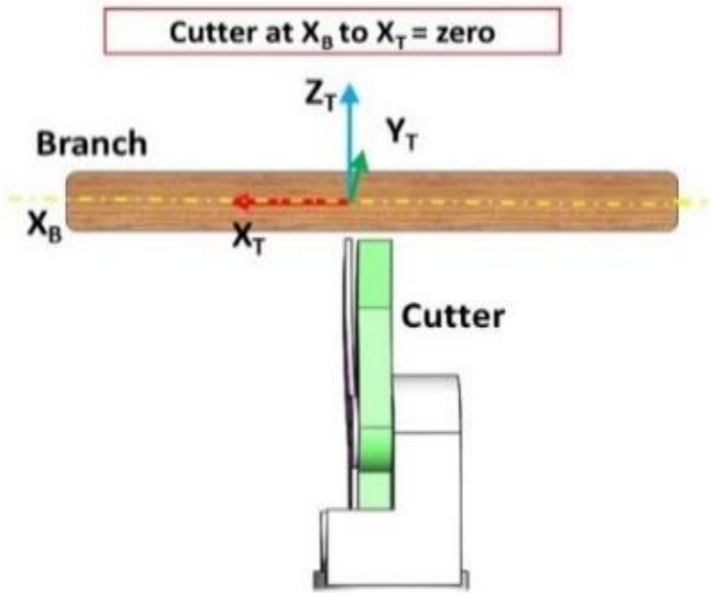
Side View



Top View



- Three target branches selected
  (branch 2, 6 and 8)
- Target point: 50 mm from the trunk
- Pose approach: Ideal cutting pose
  (Cutter plane perpendicular to branch axis)
- No. of simulation trials = 10

Simulation for Branch Accessibility: Alternate Poses

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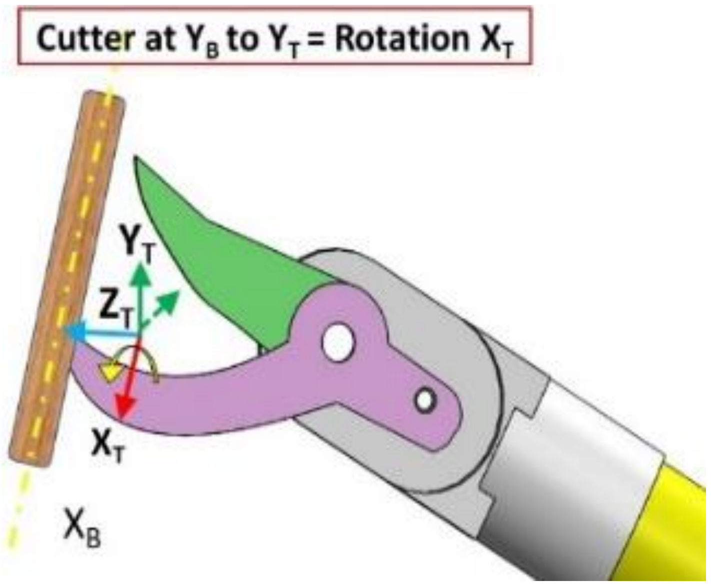
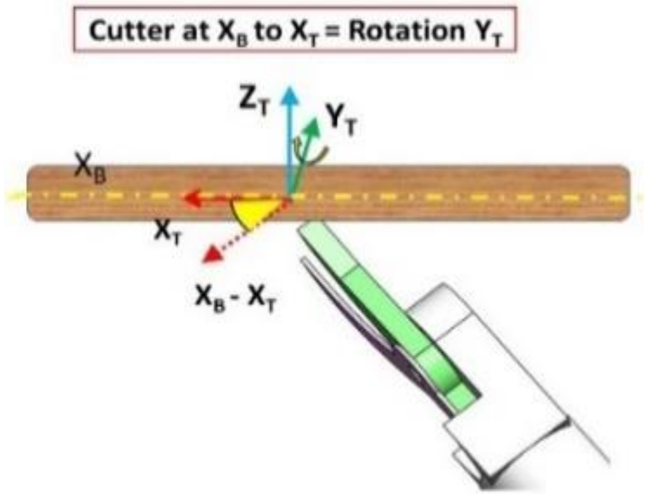
1st Pose



- Rot (X_T) = +45º
- X_T and X_B parallel

2nd Pose



- Rot (Y_T) = +30º
- X_T to X_B deviates equally

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Results

Results Comparison for RRT, RRT Smoothing, and Optimization

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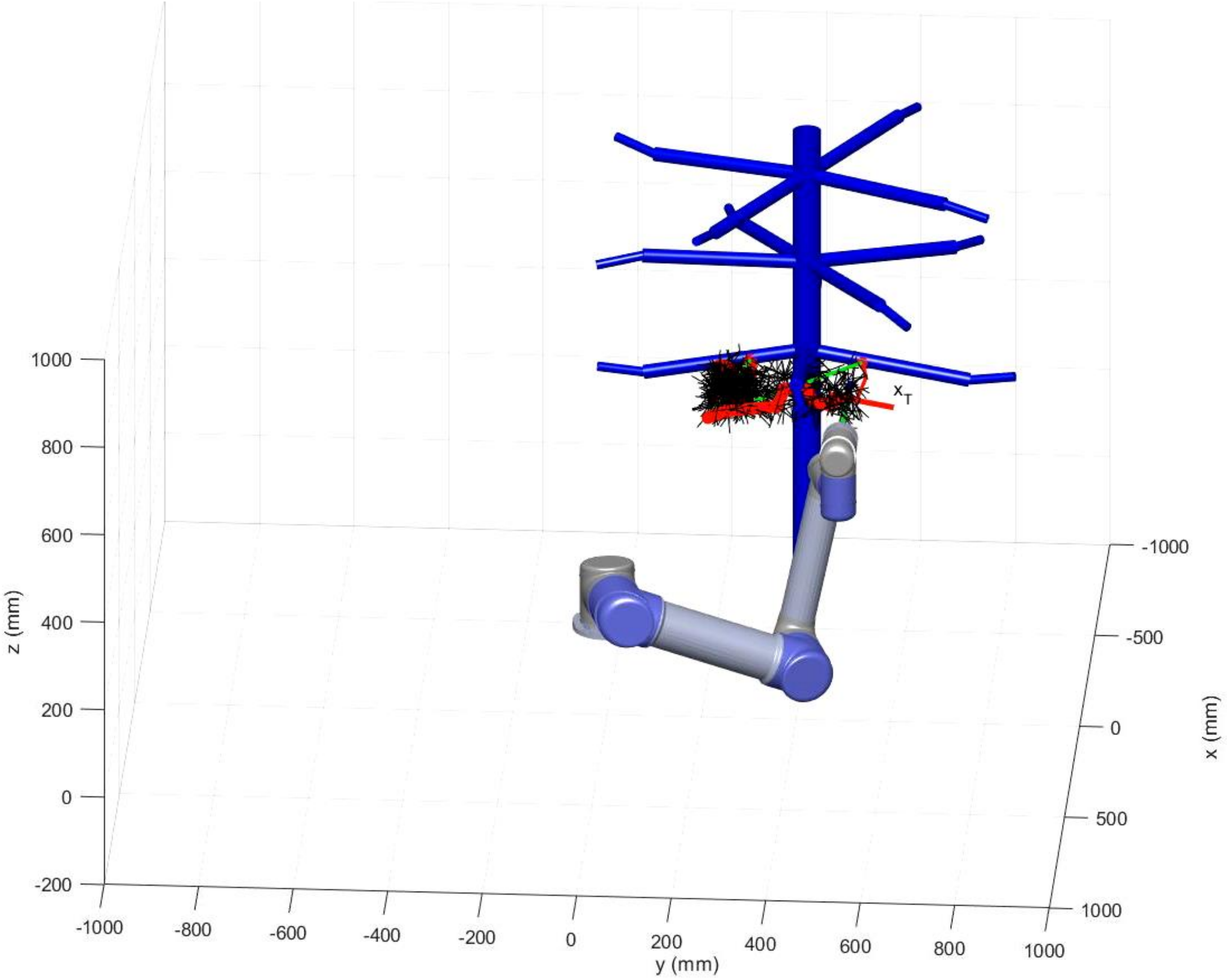

Results Comparison for RRT, RRT Smoothing, and Optimization

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Simulation results for path planning and smoothing for different target branches

Branch No.	No. of Obstacles	RRT path (mm)		RRT smoothing path		Optimized path (mm)	
		Length (mm)	Time (Sec)	Length (mm)	Time (Sec)	Length (mm)	Time (Sec)
2	1	390	19	257	21	278	36
8	1	*		*		*	
6	2	496	25	382	29	397	24

Method	Branch 2	Branch 6
	Variation coefficient (CV)	
RRT path	0.066	0.058
RRT smoothing path	0.042	0.039
Optimized path	0.037	0.031

*Fail to find the path

Maximum path length

Minimum path length

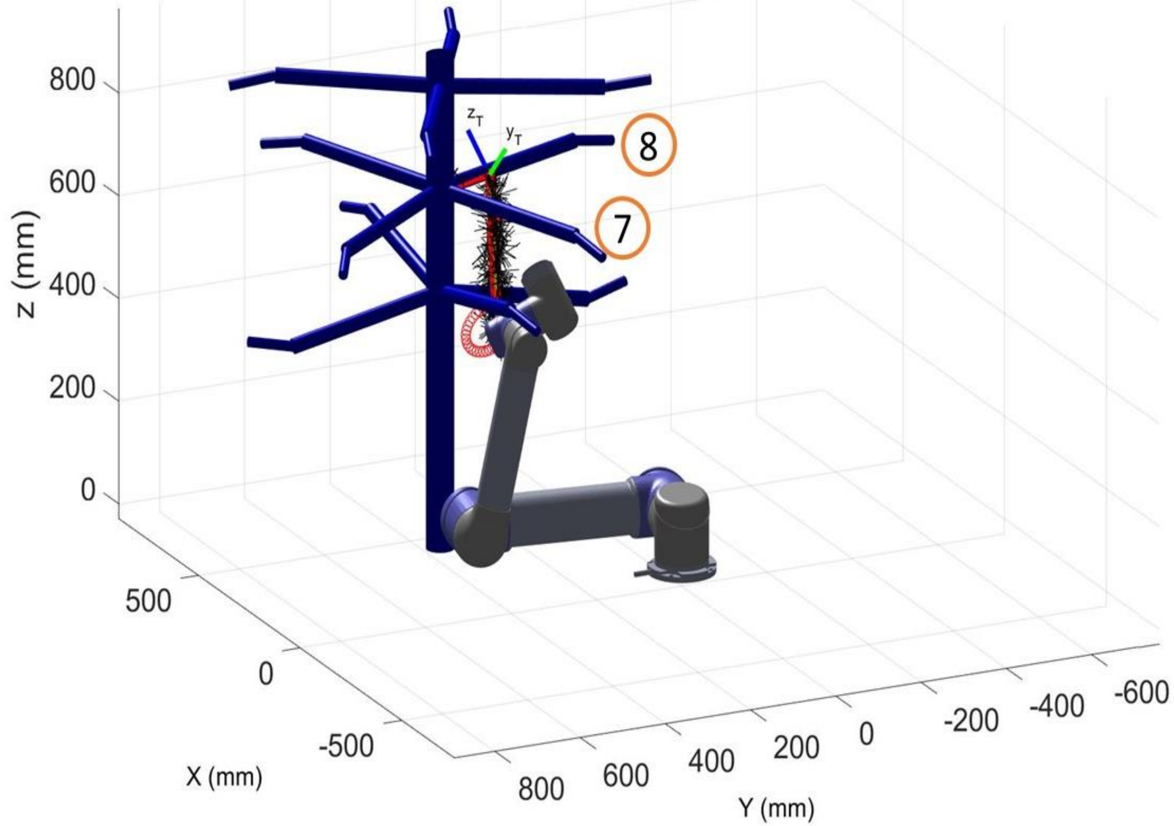
Lowest cv and St. dev

Results and Observations

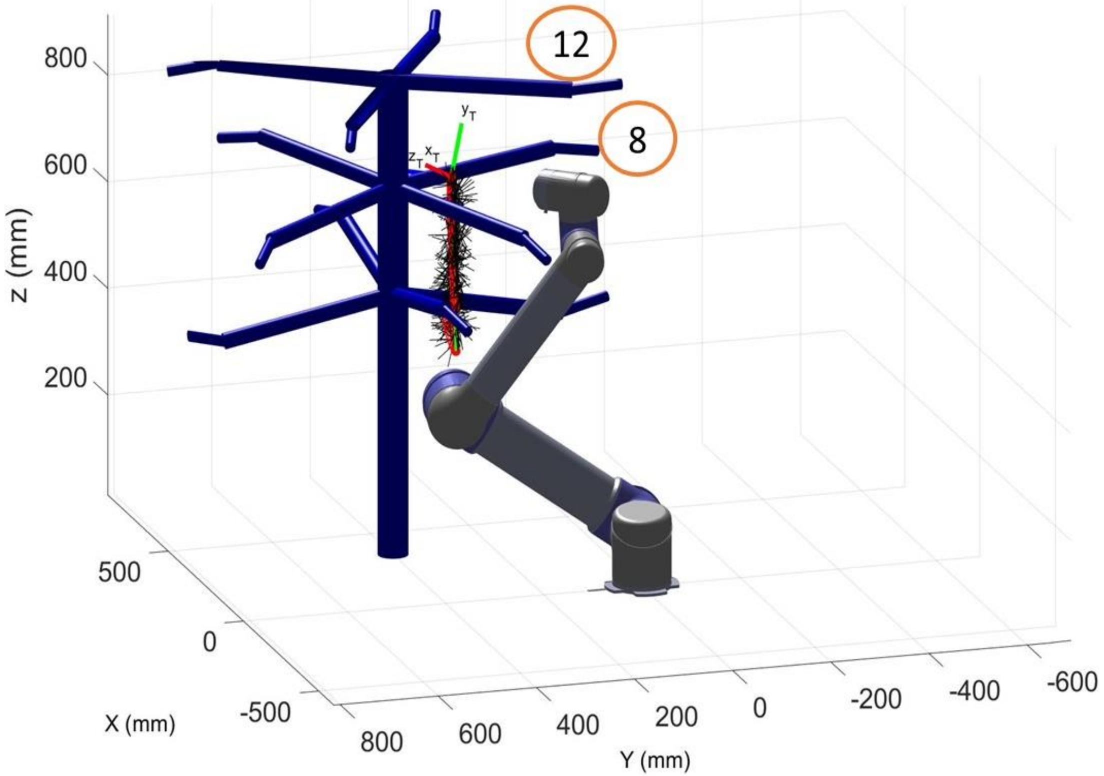
- Smoothing reduced length→ 34% and 22% for branch 2 and 6 respectively
- Optimization reduced length → 29% and 20% for branch 2 and 6 respectively
- Computational time depends on the step size, number of obstacles, distance between start and endpoint of the path

Results Effect of Approach Angle

Rot (X_T) = +45°



Rot (Y_T) = +30°



Results Effect of Approach Angle

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Simulation results for RRT path planning and smoothing for different target branches

Branch No.	No. of Obstacles	Approach pose with x-axis rotation (X_T = +45°)		Approach pose with y-axis rotation (Y_T = +30°)	
		Length (mm)	Time (Sec)	Length (mm)	Time (Sec)
2	1	427	28	382	27
8	1	485	27	478	23
6	2	531	31	566	29

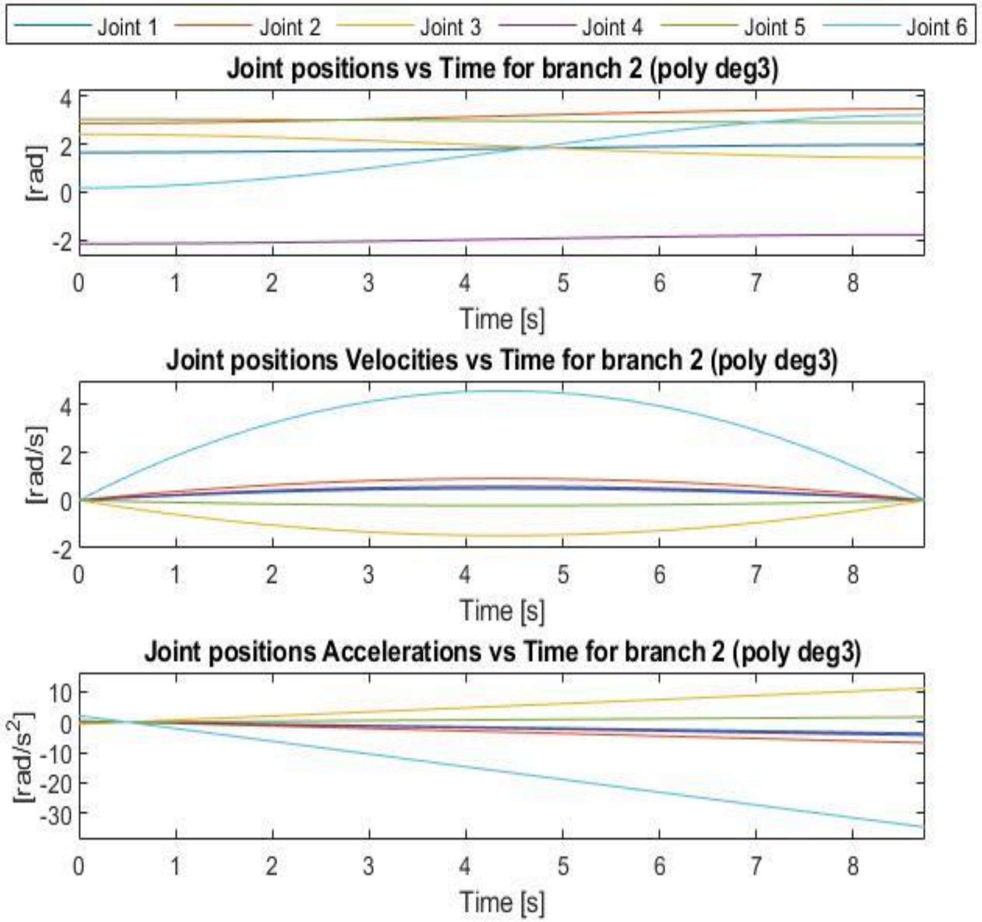
Successful to find path

Results and Observations

- Improves the path finding success
- Smoothing reduced the path length considerably
- Computational time was approximately similar for all approaches
- Computational time depends on how much manipulator move sideways for each pose

Validation: Path planning using UR5

Hardware Interface



Validation: Path planning using UR5

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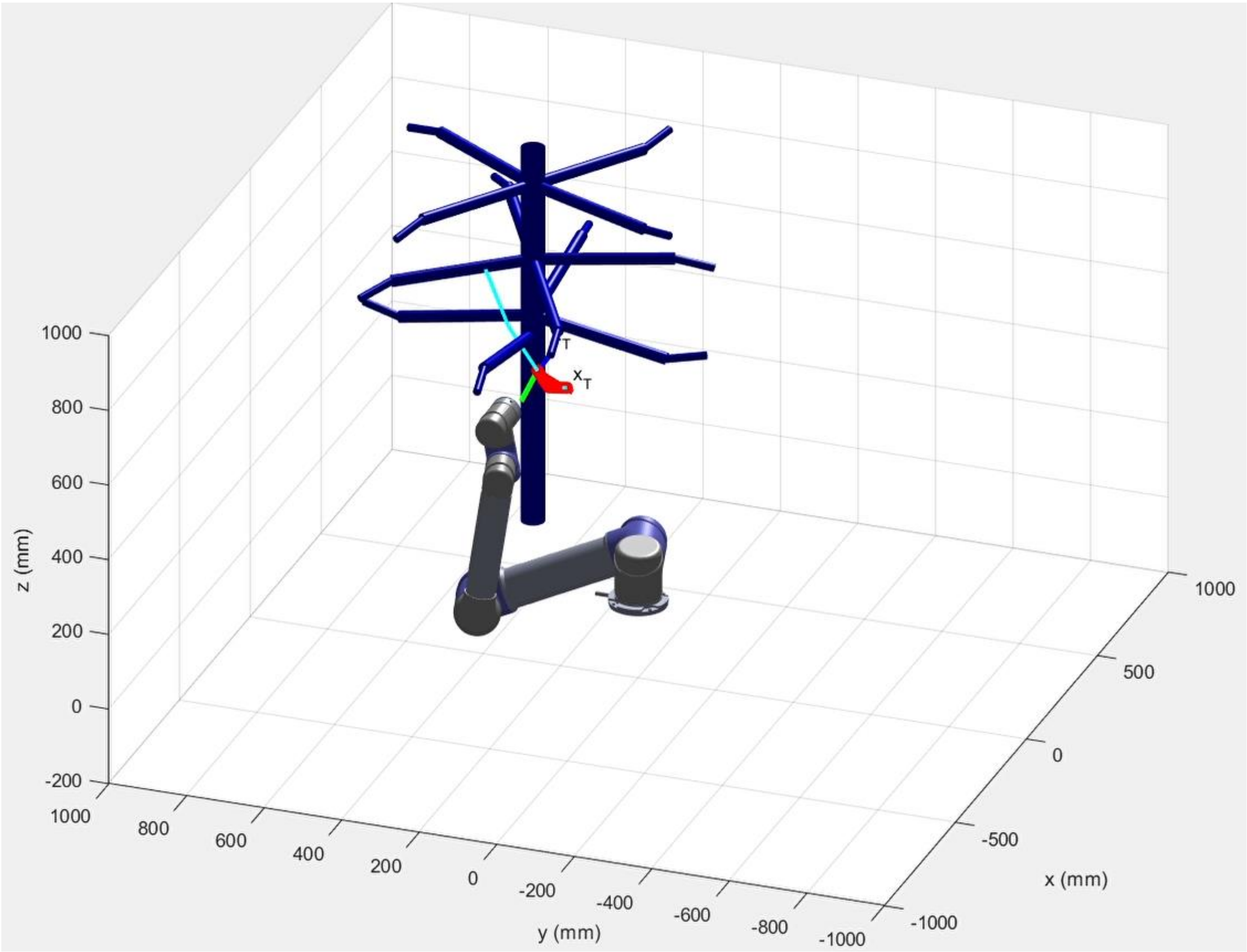

Conclusions

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- The RRT algorithm was successful in finding a collision-free path
- The smoothing method successfully reduced the RRT path lengths
- The alternate poses improves the path finding success
- A modified RRT is suggested with optimization algorithms (Genetic Algorithm) to stabilize and improve the obstacle avoidance

Future Work: Tests will be conducted to validate the simulation results using a UR5 manipulator

Acknowledgements

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SHAP

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Thank you!