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College of Agricultural Sciences

Development of a 3R DoF End-effector for Pruning Apple Trees

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Introduction: Labor Requirements for Manual Pruning

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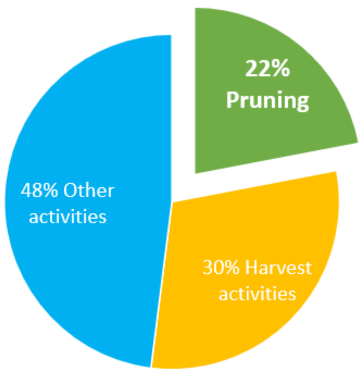
- ❖ Pruning ~ 22% of total labor cost
- ❖ ~ 30 - 40 working hours per acre

Available labor decreasing!

Cost Breakdown for Apple Production



(Mika *et al.* 2016)

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Objectives of the study

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1. Design an integrated 3R DoF pruning end-effector for apple trees

2. Simulate the reachable workspace, and cutter tool orientations

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Methodology: 3D CAD Model

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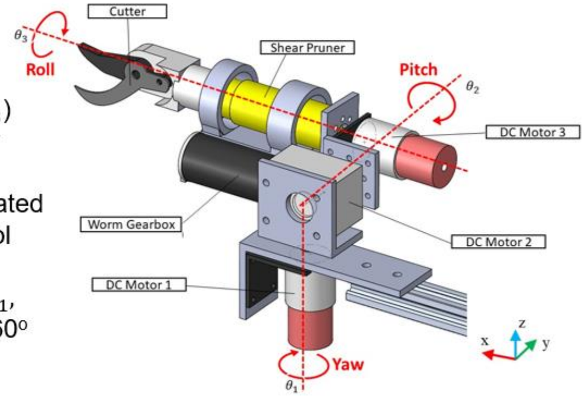
- ❖ Yaw, pitch, and roll (θ_1, θ_2, and θ_3) along z, y, and x axis respectively
- ❖ Modified shear pruner was integrated to the last joint (θ_3) as a cutter tool
- ❖ The maximum rotation limits for θ_1, θ_2, and θ_3 was 240°, 360°, and 360° respectively

Integrated 3R DoF End-effector



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Results: Simulation of the End-effector

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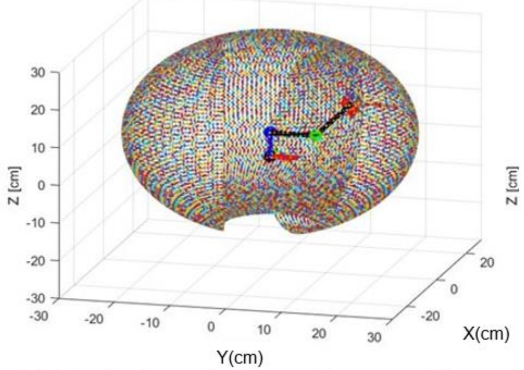
Reachable Workspace

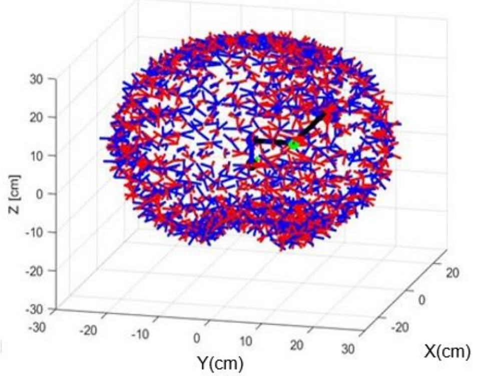
Reachable Workspace with Discretization Function



- ❖ Spherical reachable workspace with diameter = 24 cm
- ❖ Void in the workspace due to limit of Yaw

Cutter Orientation

Cutter Plane with Discretization Function



- ❖ Cutter plane at each reachable point (cutter along z-x axes as blue-red)
- ❖ Multiple orientations at each point

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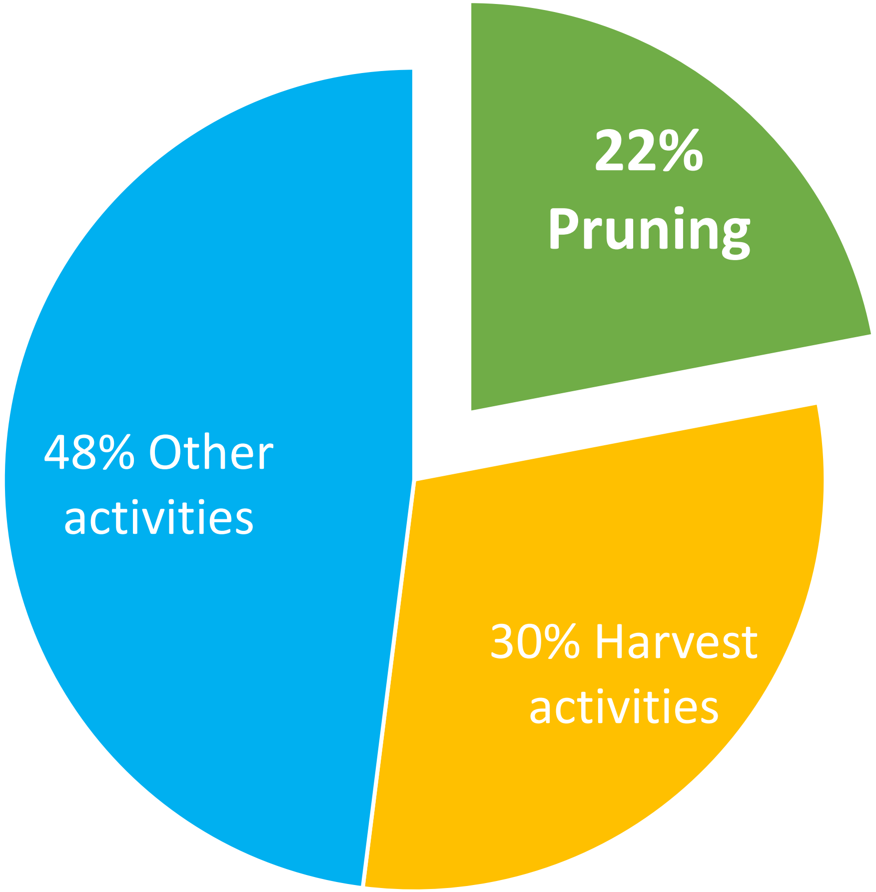

(Mika *et al*. 2016)

Introduction: Potential Solution and Challenges

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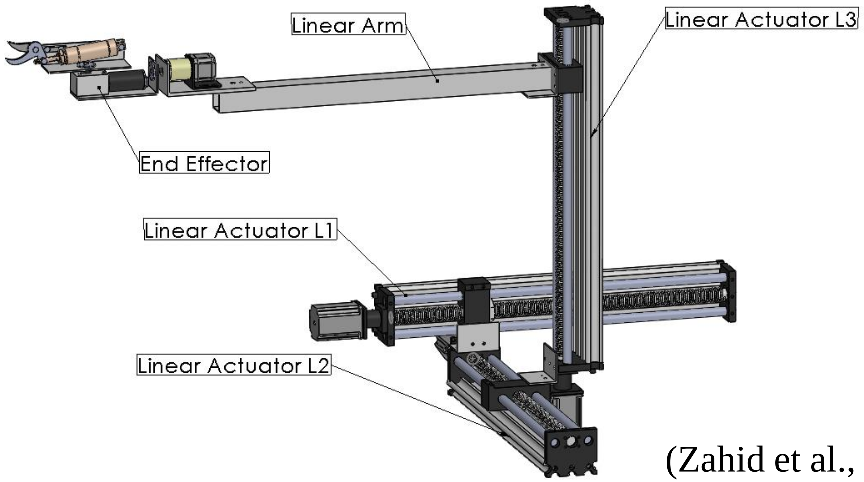
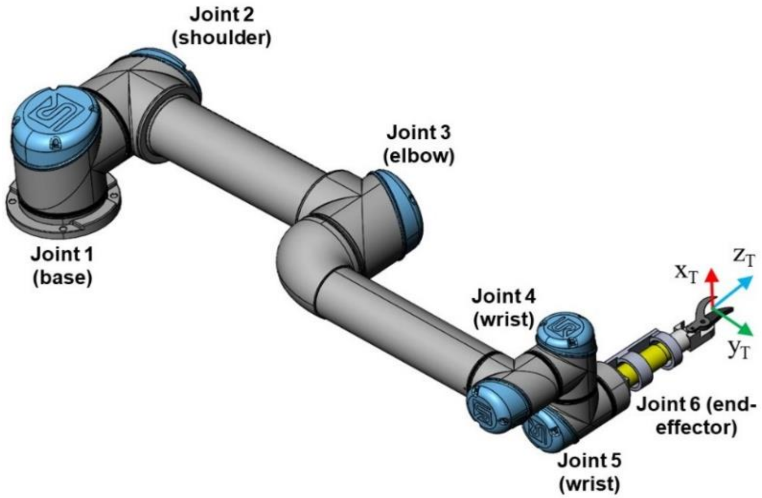
- ❖Robotic pruning → selective pruning
- ❖Challenges in robotic pruning
  - Detection and identification of pruning branches
  - Spatial requirements of manipulation system
- ❖Researchers developed sensing systems using different camera sensors
- ❖Only few studies have been reported on development of tree pruning system



(Zahid et al., 2019)



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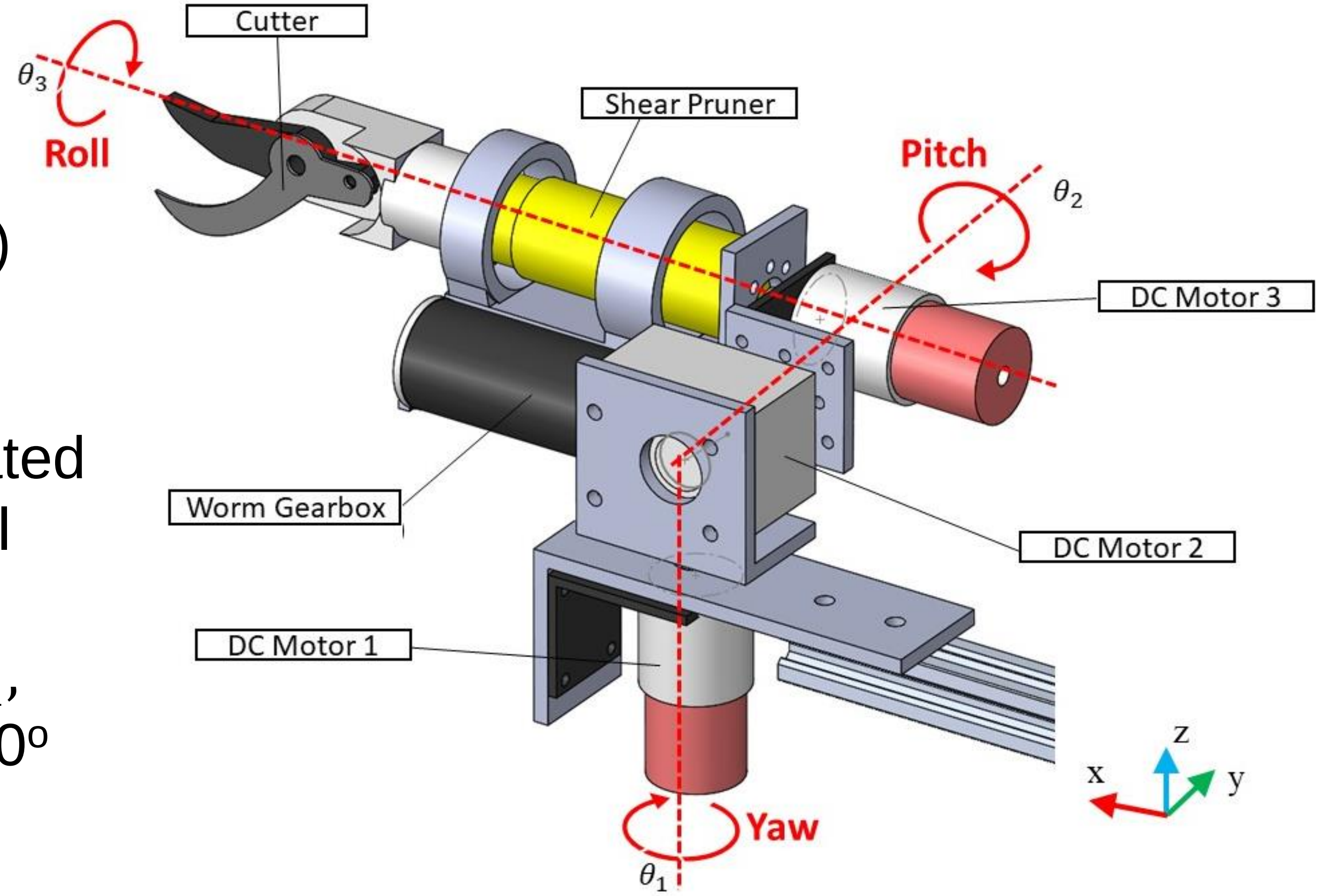
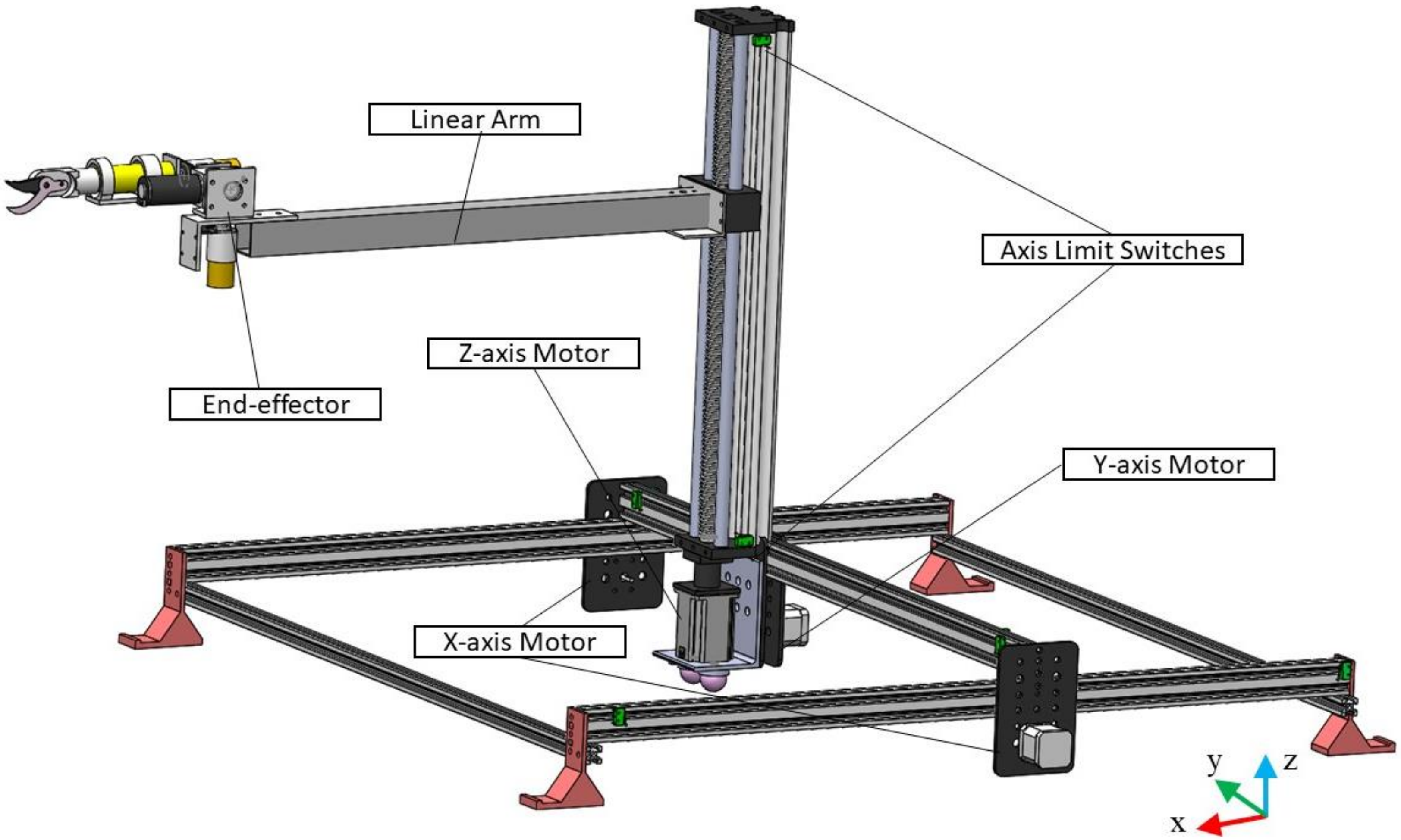


Methodology: 3D CAD Model

Integrated Cartesian Manipulator and Pruning End-effector

- Cartesian manipulator with a rigid square platform
- The pruning end-effector was attached to a linear arm
- Integrated Arduino-Matlab control system and GUI



Methodology: Kinematic Model for Simulation

❖ Calculate the forward kinematics and inverse kinematics

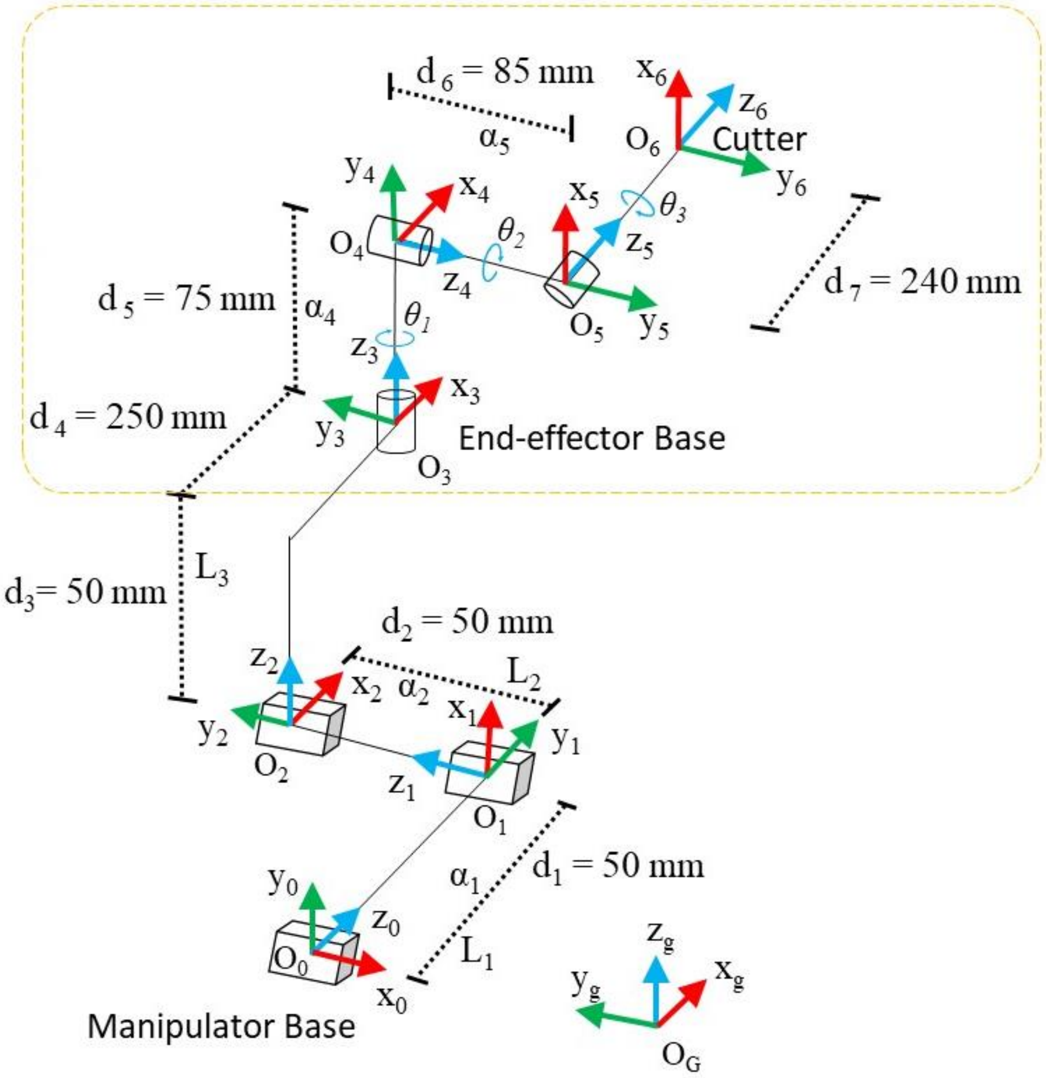
$$^{i-1}_{i}T = \begin{bmatrix} \cos(\theta_i) & -\cos(\alpha_i).\sin(\theta_i) & \sin(\alpha_i).\sin(\theta_i) & a_i.\cos(\theta_i) \\ \sin(\theta_i) & \cos(\alpha_i).\cos(\theta_i) & -\sin(\alpha_i).\cos(\theta_i) & a_i.\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

❖ Position vector for the cutter frame

- Reachable workspace simulation
- Cutter tool orientations simulation

$$P_{G,x} = d_7.\cos(\theta_2 + 90).\sin(\theta_1) + \sin(\theta_2 + 90).\cos(\theta_1)$$
$$P_{G,y} = -d_7.\cos(\theta_2 + 90).\cos(\theta_1) - \sin(\theta_2 + 90).\sin(\theta_1)$$
$$P_{G,z} = d_5 + d_7(-\cos(\theta_2 + 90))$$

Coordinate Frames of the Manipulator



Methodology: Experimental Setup

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Integrated Manipulator System

End-effector

- ❖ Trellis fruiting wall tree architecture at Fruit Research and Extension Center
- ❖ Five trees selected randomly
- ❖ 8 to 10 branches selected from each tree

Results: Simulation of the End-effector

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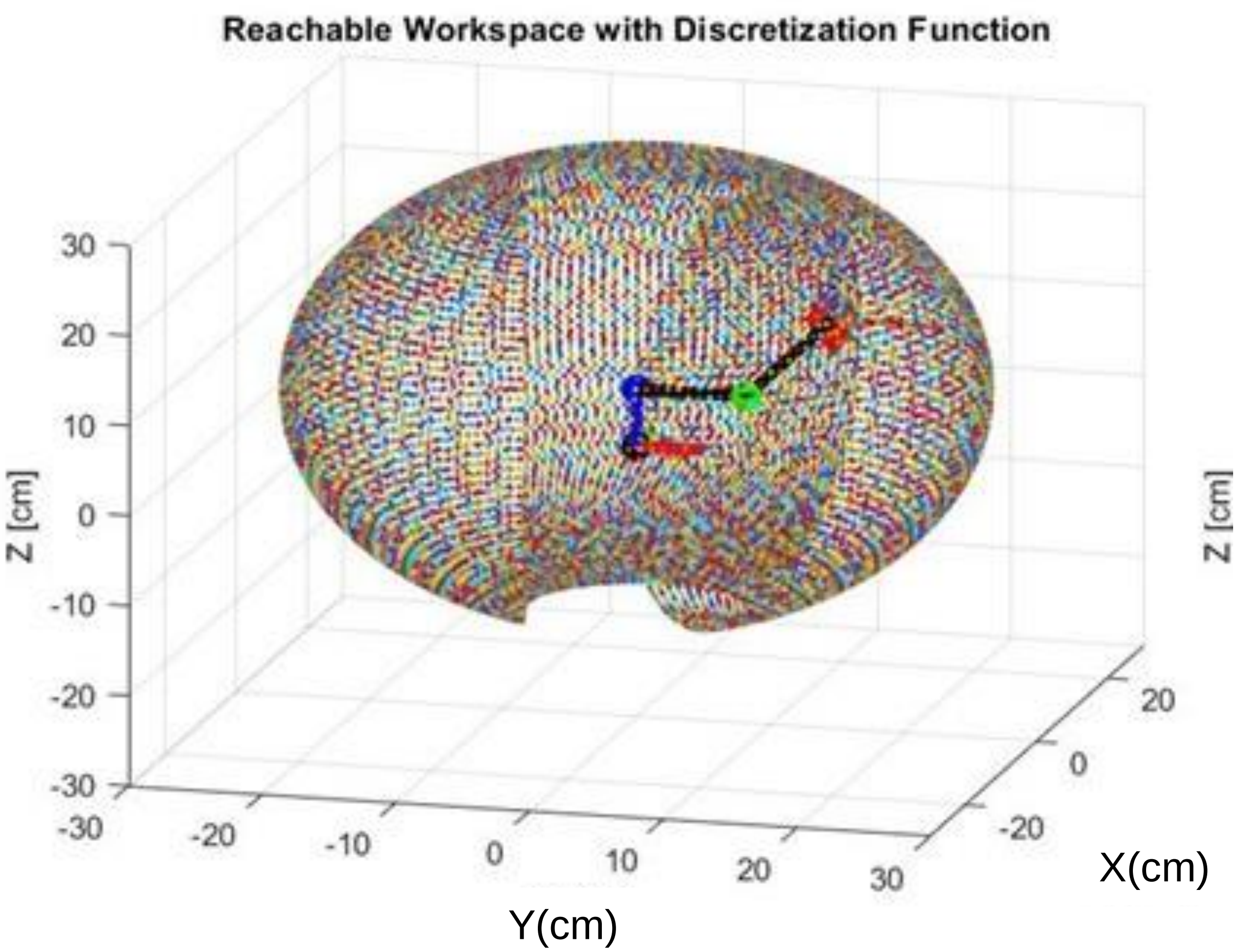
Reachable Workspace



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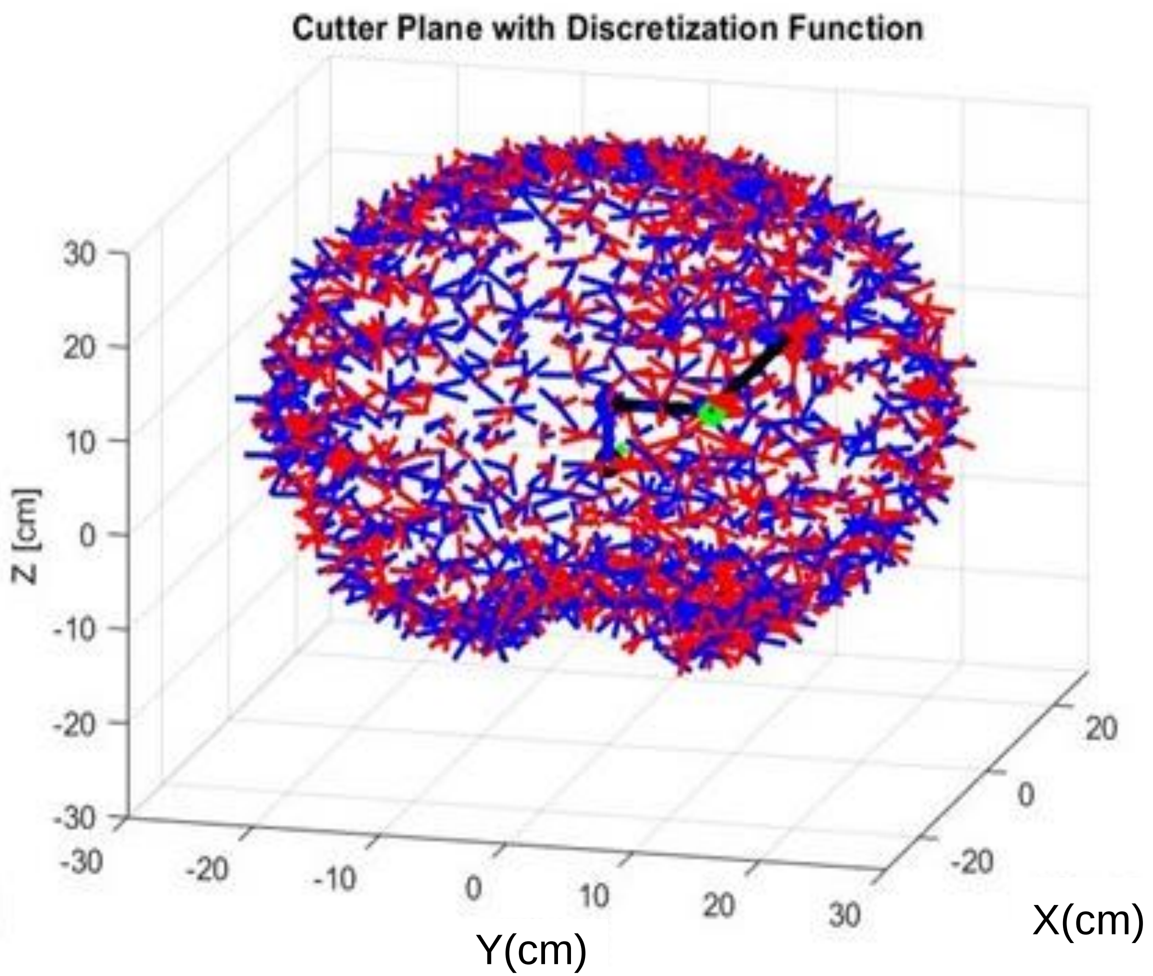
Cutter Orientation



- ❖ Cutter plane at each reachable point (cutter along z-x axes as blue-red)
- ❖ Multiple orientations at each point

Results: Field Tests

Data subset from the field experiment of the end-effector performance assessment

Test	Branch Diameter (mm)	Angle θ_1 (deg)	Angle θ_2 (deg)	Angle θ_3 (deg)
1	12	30	40	25
2	25[a]	40	-25	15
3	22	15	00[b]	75
4	19	00[b]	55	00
5	23	-25	15	75
6	17	15	40	-45
7	16	-35	70	00[b]
8	13	-20[c]	-25	15
9	12	65	75	15
10	18	30	40	90

Maximum diameter

'0' is home position

Negative indicate clockwise

Results and Observations

❖ The joint limits for θ_1, θ_2, and θ_3 were validated for collision or interferences

❖ Target point close to the trunk → perpendicular cutting posture may not be suitable, alternate posture suggested

Conclusions

- ❖ The end-effector has a spherical reachable workspace with a void due to the presence of a physical constraint
- ❖ The end-effector cutter tool can be aligned at multiple orientations at each point on the reachable workspace
- ❖ The pruning end-effector was able to cut the branches up to 25 mm diameter

Future Work: Collision-free path planning for reaching target pruning points using algorithms such as RRT, and GA

Acknowledgements

PennState
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- Northeast Sustainable Agriculture Research and Education (SARE)

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United States Department of Agriculture
National Institute of Food and Agriculture

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SHAP

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Thank you!

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