A Digital Twin-Enabled Approach for Precision Weed Management in Specialty Crops using a 4-DoF Robotic System

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Date: July 30, 2024

Introduction: Specialty Crops

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Onions are one of the most widely produced specialty crop with 105 billion pounds produced globally [3]

Manual weeding is expensive and time-consuming [2]

Specialty crops comprise one-third of the United States crop receipts [1]

Between 2017 and 2023, the production value of carrots in the U.S. increased by over 160% [4]

Onion Field in Vidalia, GA

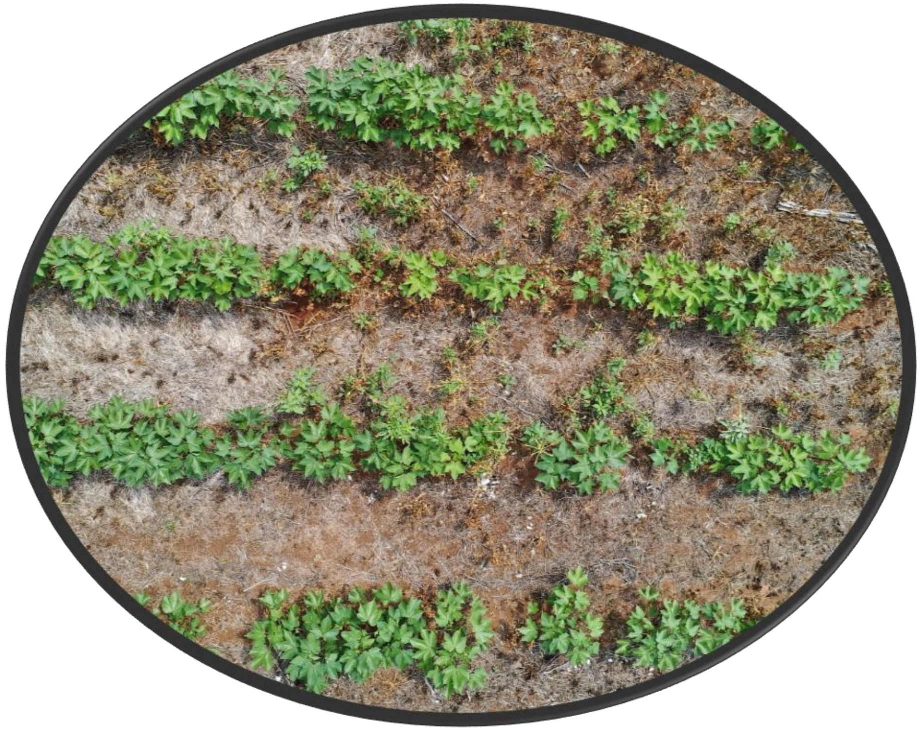
Introduction: Hazards of Weed Plants

Weeds cause $138 Billion annual loss in the USA [5]

Weed management accounts for more than 30% of production costs in specialty crops [6]

Weeds degrade the quality of specialty crops by competing for essential nutrients

Critical to control weeds within the first 4-6 weeks of crop plantation [7]



Weeds in cotton field at J. Phil Campbell Sr. UGA Research Center, Watkinsville, GA

Introduction: Challenges In Conventional Weed Management

Manual Weeding

Manual weed removal [8]

- Time consuming
- Labor intensive
- Damaging to healthy vegetation
- Inefficient

Herbicide Application

Chemical weed control [9]

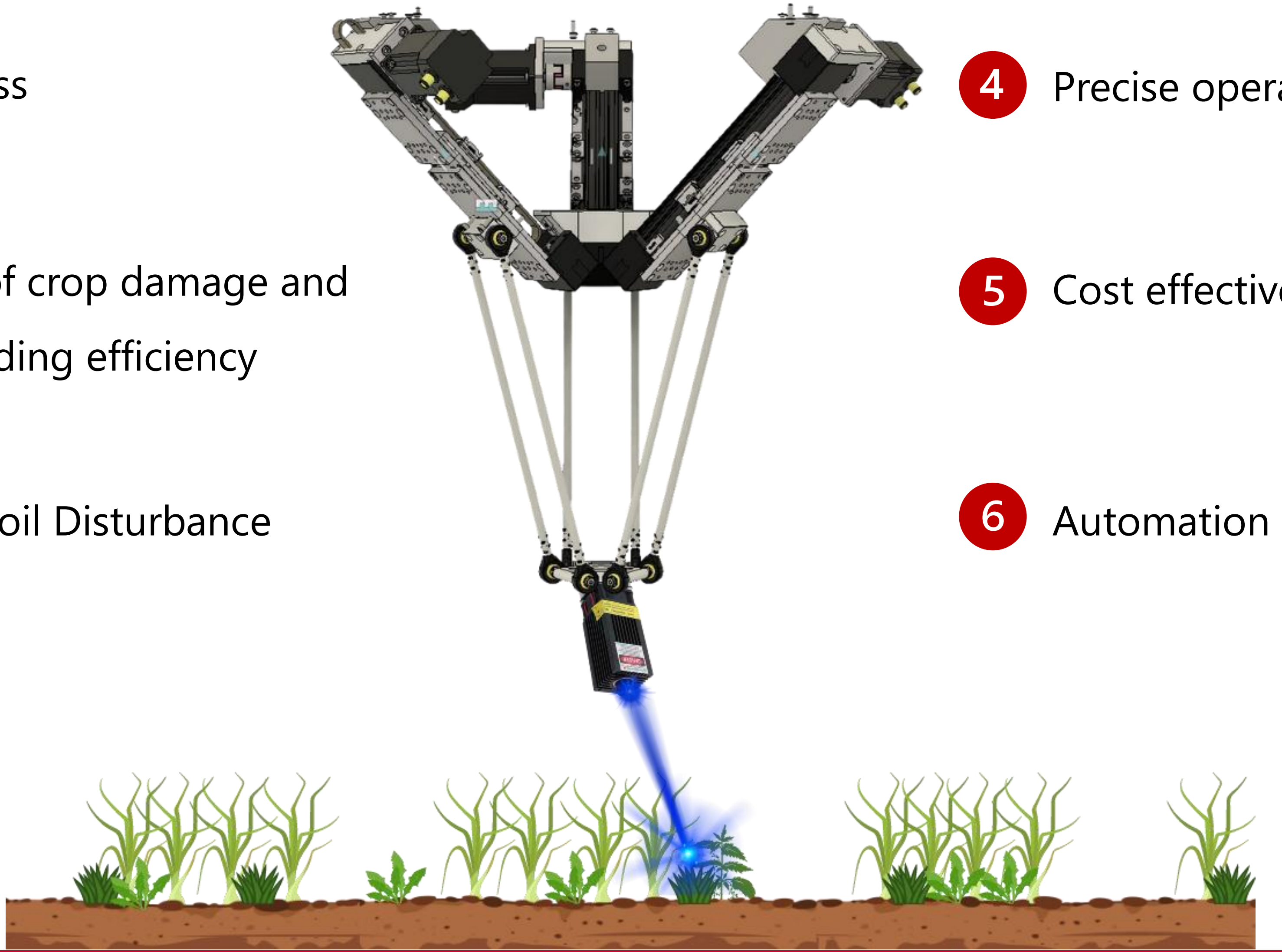
- Weed resistant plants
- In-organic
- Crop injury
- Negative impact on environment

Robotic Laser Weeding

1 Organic process

2 Reduced risk of crop damage and increased weeding efficiency

3 Reduction in Soil Disturbance



4 Precise operation

5 Cost effective

6 Automation and labor savings

Goal and Objectives

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A 4 DoF robotic manipulator, designed in 3D CAD, delivering highest accuracy in laser positioning within a digital twin environment

1

Robotic Manipulator 3D Design

3D CAD model of the manipulator and end-effector ensuring structural soundness and functionality

2

4 DoF Kinematic Configuration

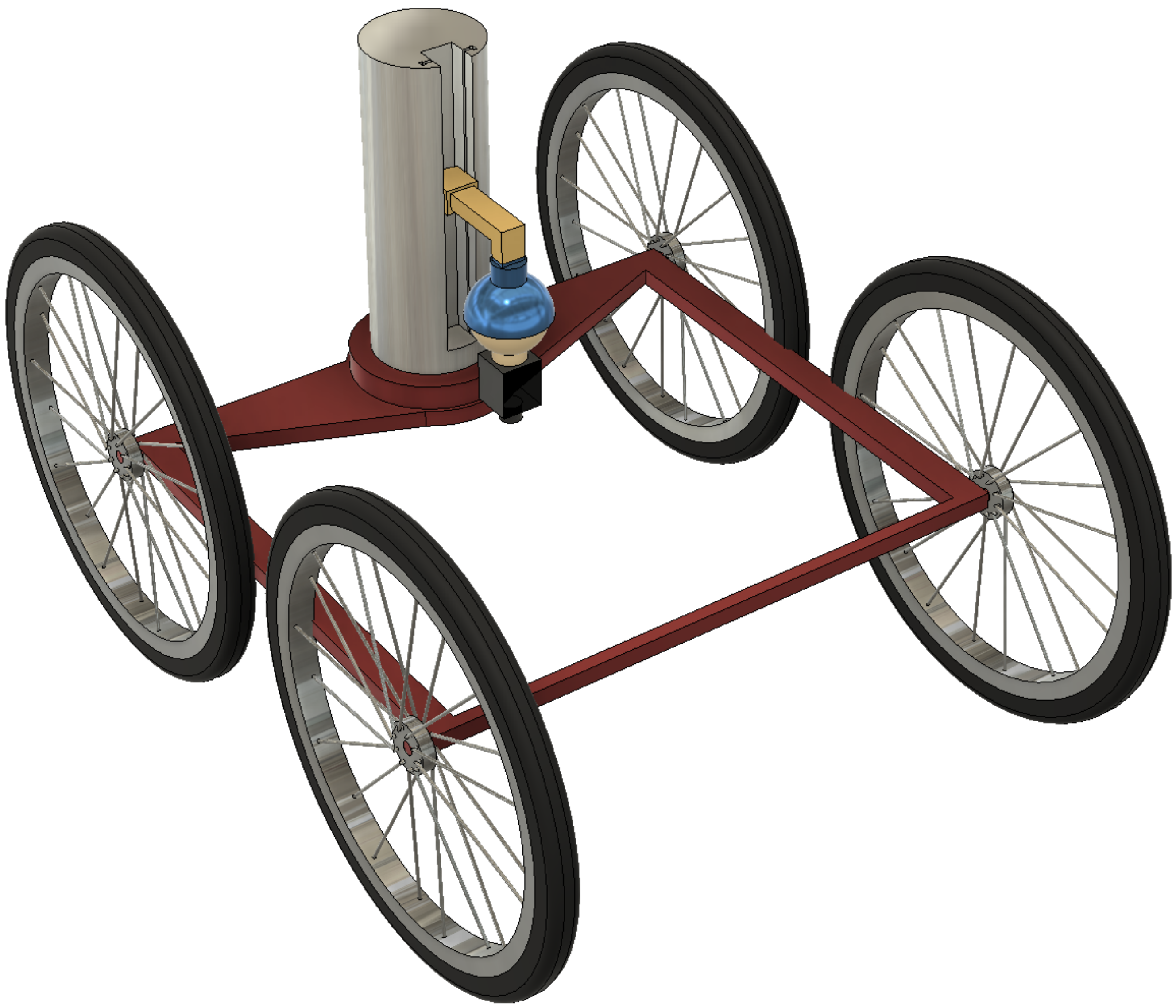
Kinematic configuration of the robotic system to achieve the target work envelope with four degrees of freedom (DoF)

3

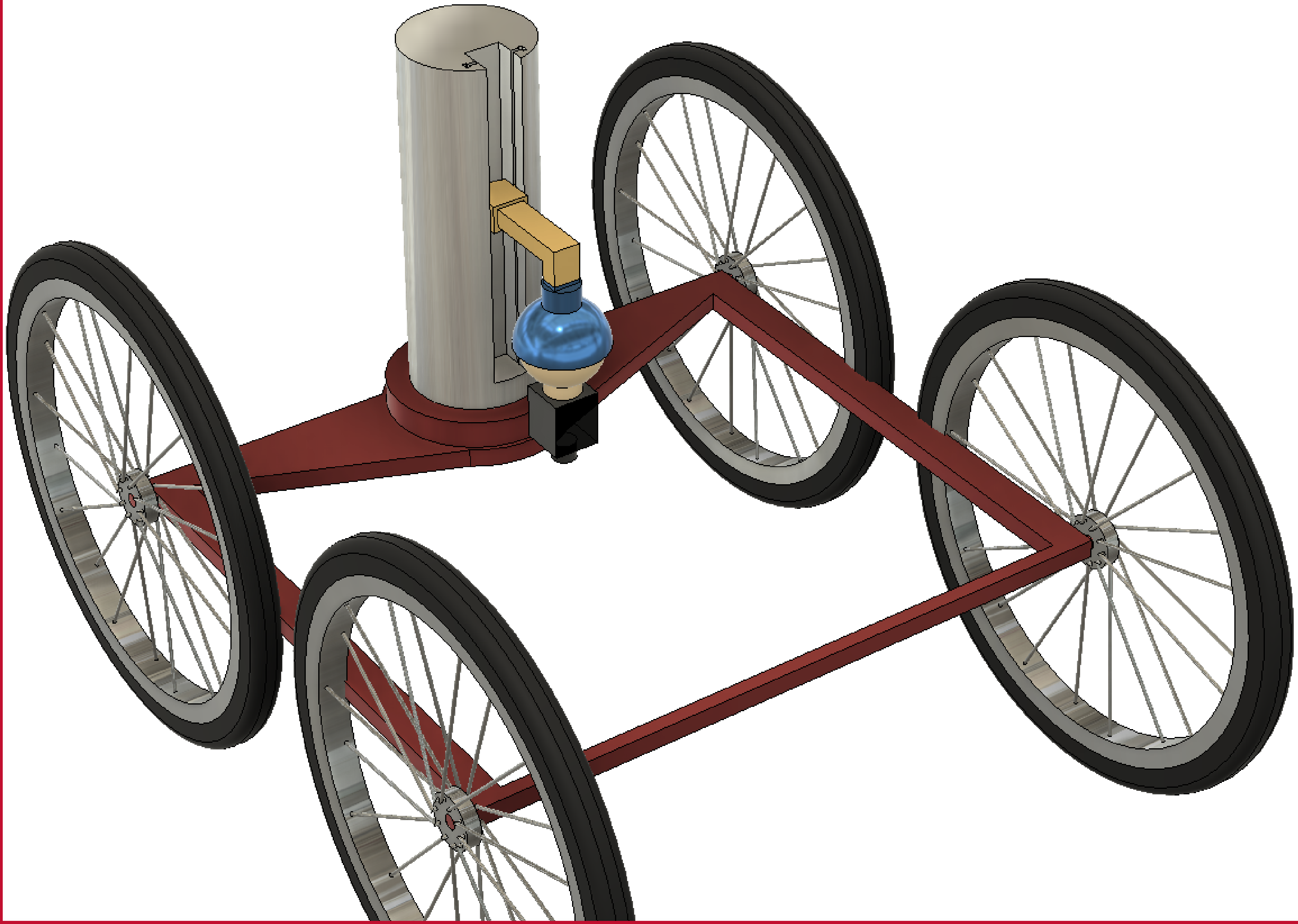
Simulate Field and Deploy Robot

Digital Twin of the field with robot deployed to test and validate the autonomous performance

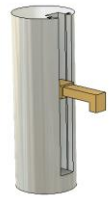
Methodology: 3D Design



Methodology: 3D Design Main Components



1 Mobile base

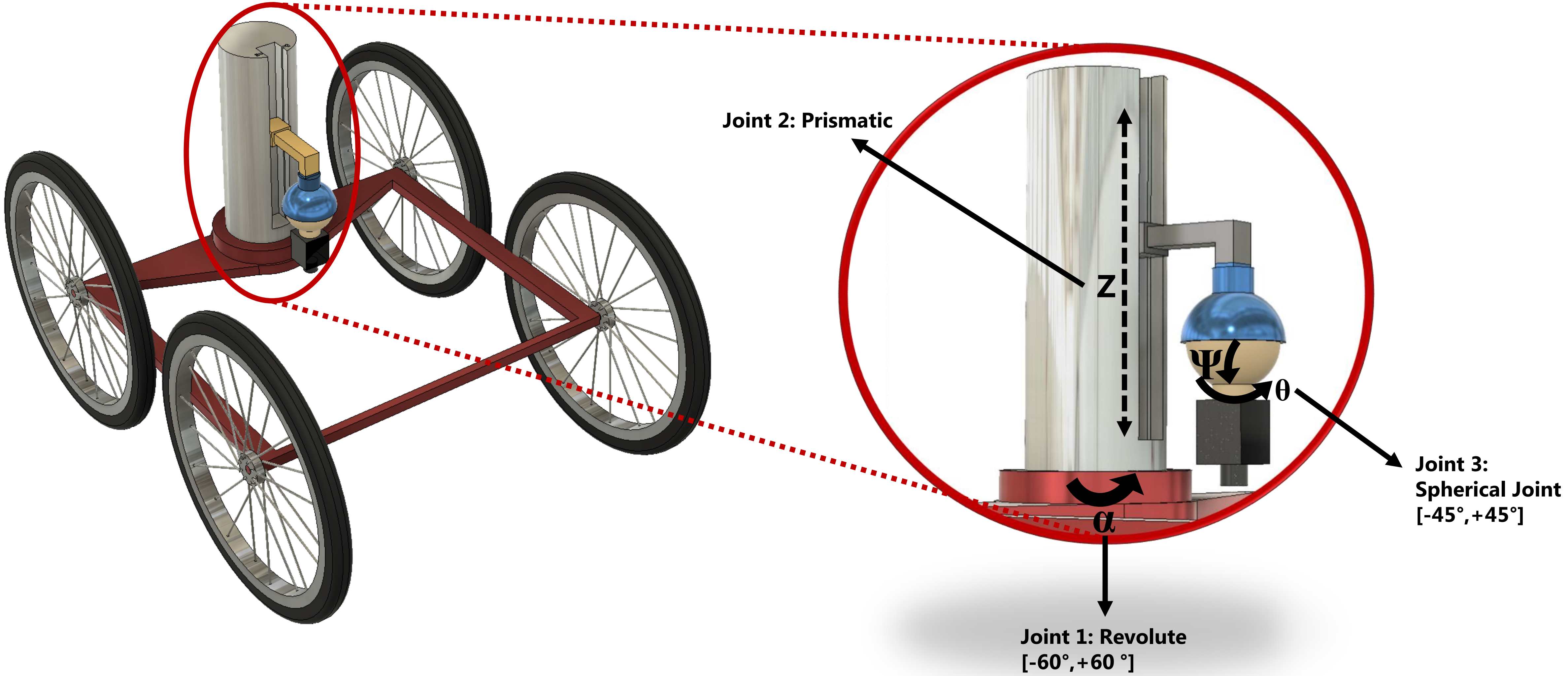


2 Manipulator

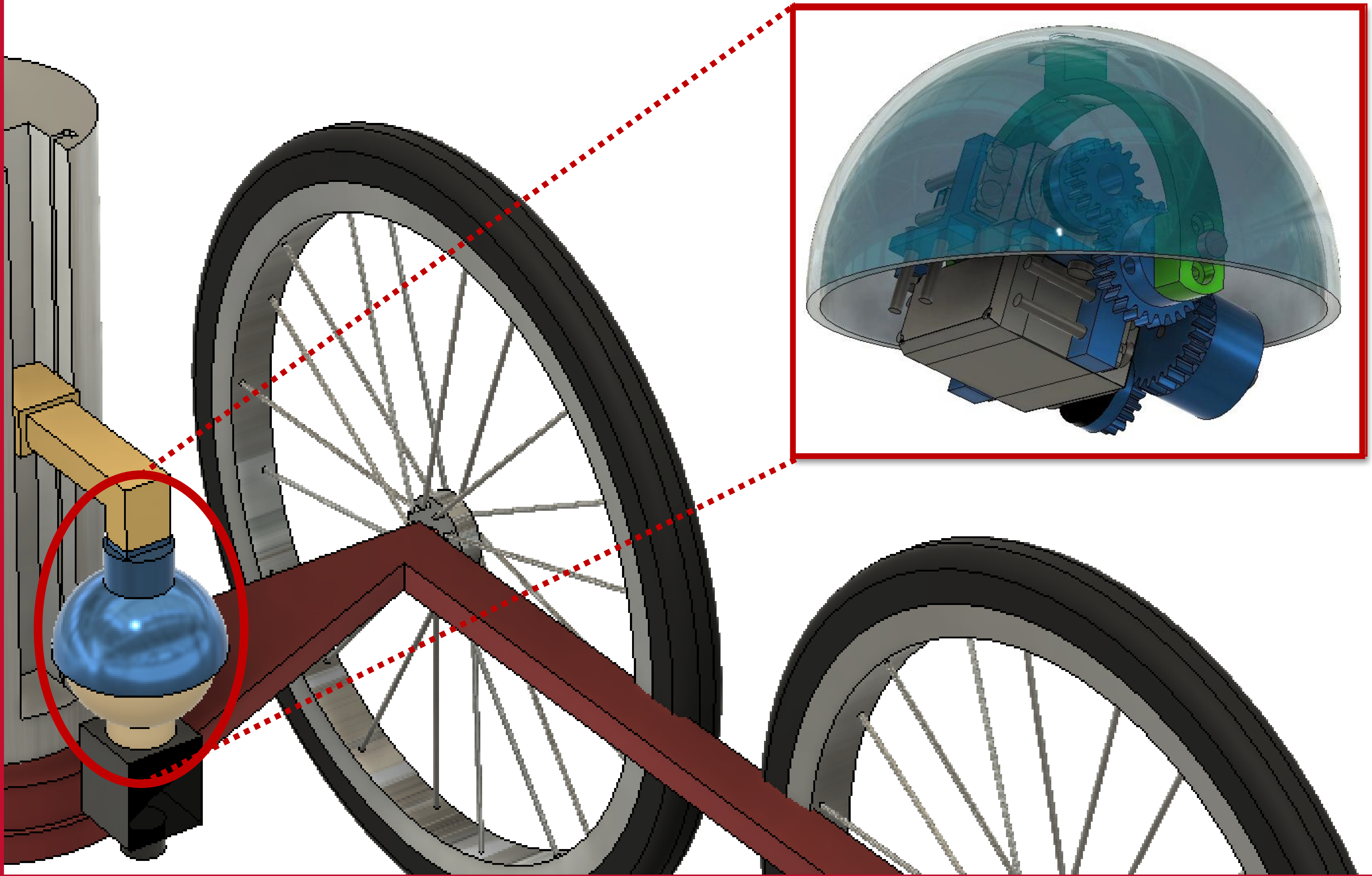
3 End-effector

4 Laser

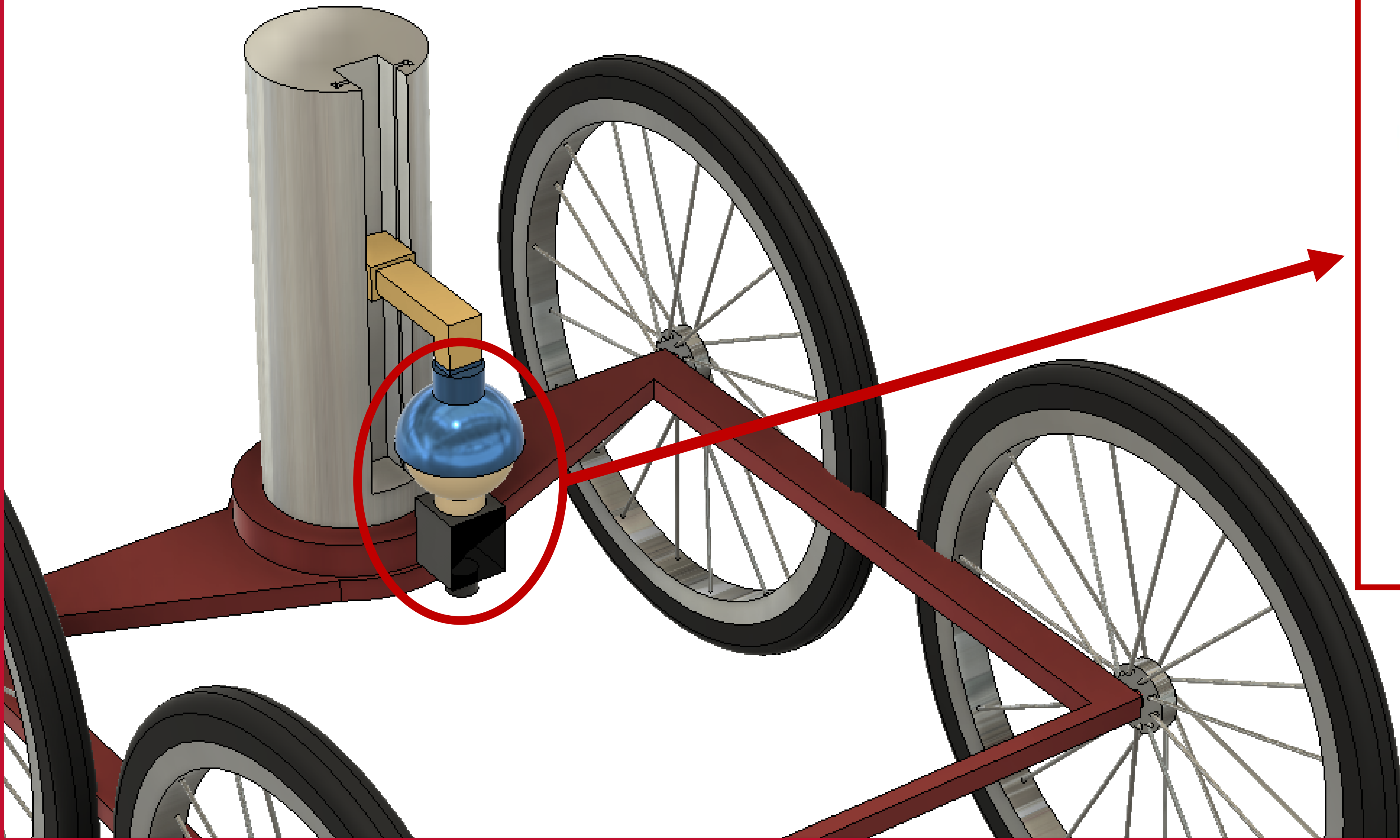
Methodology: Joints and Movements

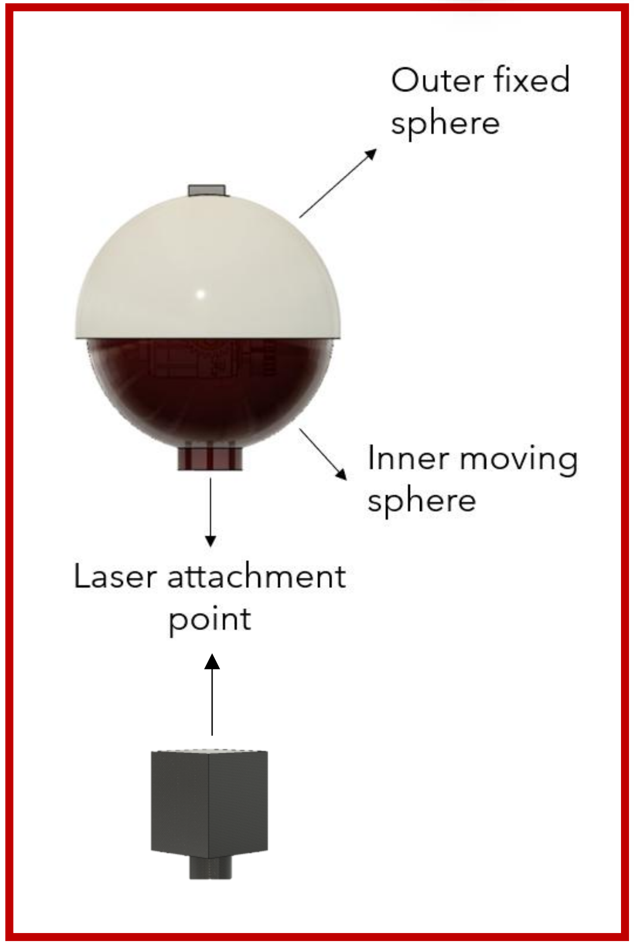


Methodology: End Effector Inner Mechanism

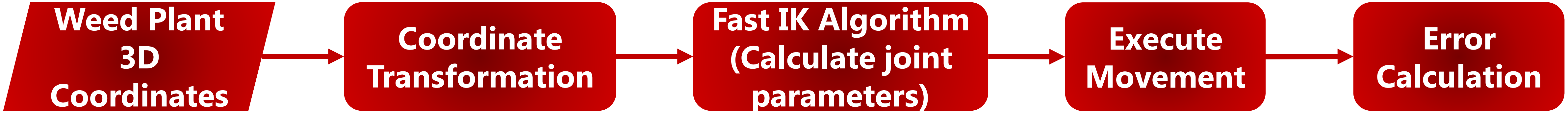


Methodology: Laser Attachment

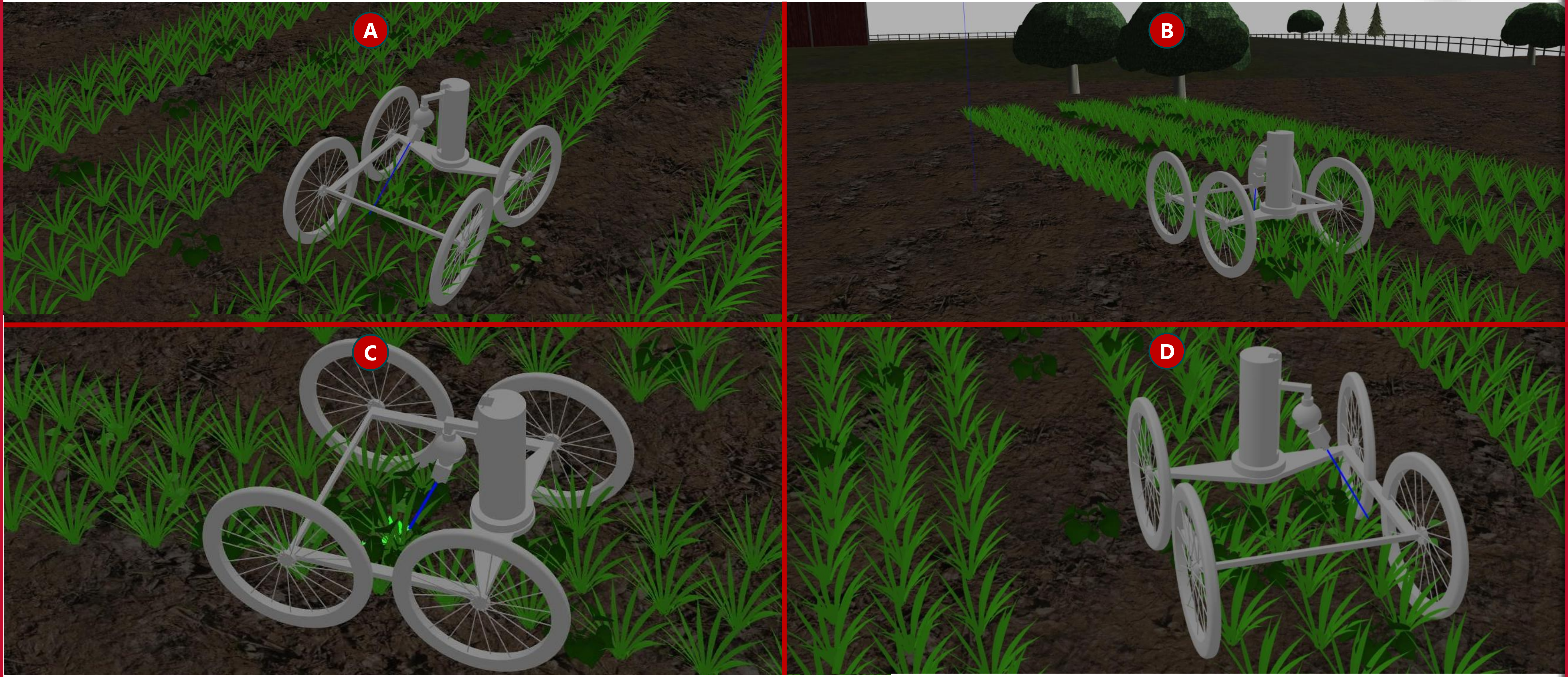




Methodology: Kinematics



Results



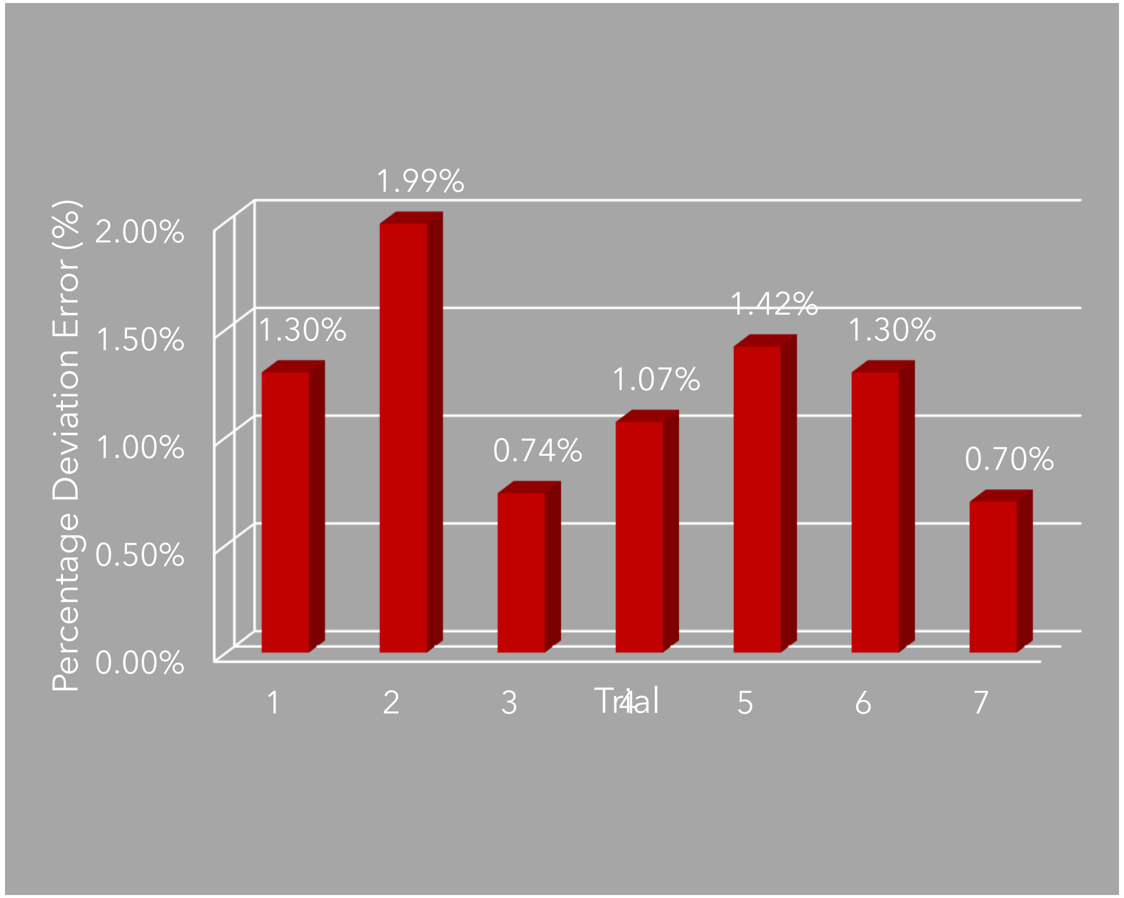
- A, B, C and D illustrate simulation results in Gazebo at different instances
- Conducted 8 calculated trials for performance evaluation

Results

Position Accuracy and Error Analysis

Trial	Target Position (x, y, z)	Achieved Position (x, y, z)	Percentage Error (%)
1	(1.00, 2.00, 0.231)	(1.00, 2.00, 0.228)	1.30%
2	(0.50, 1.00, 1.50)	(1.51, 1.02, 1.48)	1.99%
3	(1.50, 2.50, 0.272)	(1.50, 2.50, 0.270)	0.74%
4	(3.00, 4.00, 0.187)	(3.00, 4.00, 0.189)	1.07%
5	(0.50, 1.00, 0.211)	(0.50, 1.00, 0.208)	1.42%
6	(2.00, 3.00, 0.154)	(2.00, 3.00, 0.152)	1.30%
7	(1.00, 3.00, 0.285)	(1.00, 3.00, 0.283)	0.70%
8	(2.50, 2.50, 0.192)	(2.50, 2.50, 0.190)	1.04%

Percentage Deviation Error Across Trials



$$Percentage\ Error = \frac{1}{3}\left(\frac{\Delta x}{x_{target}} + \frac{\Delta y}{y_{target}} + \frac{\Delta z}{z_{target}}\right) \times 100$$

$$\Delta x = x_{\text{achieved}} - x_{\text{target}}$$

$$\Delta y = y_{\text{achieved}} - y_{\text{target}}$$

$$\Delta z = z_{\text{achieved}} - z_{\text{target}}$$

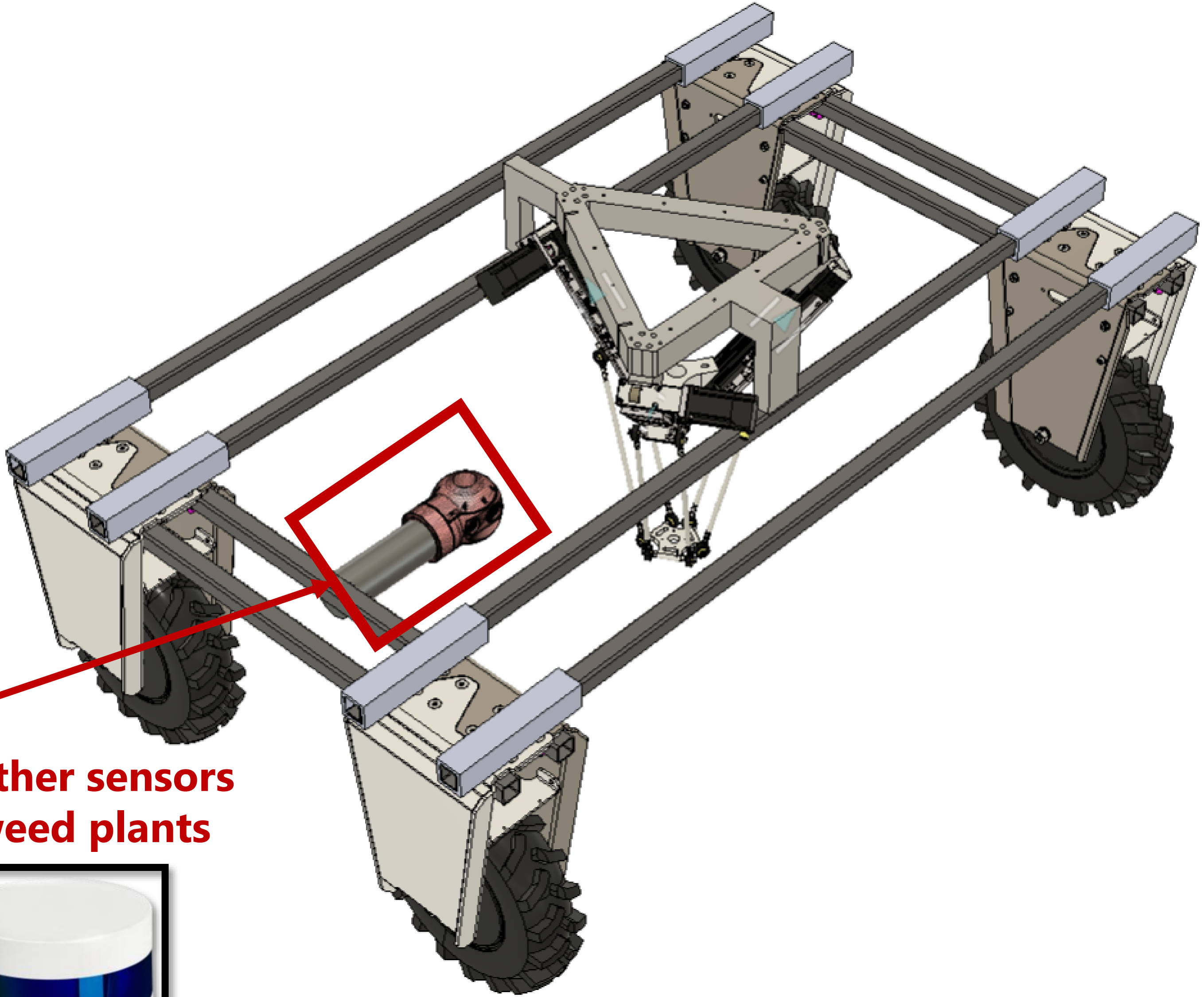
Discussion: Challenges and Unconsidered Factors

- **Simulation Accuracy:** This research presents preliminary results. As precise simulation of manipulator dynamics and environment interactions requires ongoing parameter tuning
- **Actuator Dynamics:** The impact of actuator characteristics (torque, speed, etc.) on manipulator performance was not explicitly modeled
- **Trajectory Planning:** Optimal path generation for the end-effector has not been addressed
- **Real-time Performance:** The computational efficiency of the proposed algorithms for real-time control has not been evaluated.

Conclusion

- Precise laser weed removal is feasible through optimized design, simulation, and control parameterization.
- A robust simulation model has been developed as a foundation for future hardware development.
- Real-world implementation, including field testing and optimization, is the next step.
- Integration of advanced sensor technologies and AI can enhance system autonomy and adaptability.

Future Direction



1

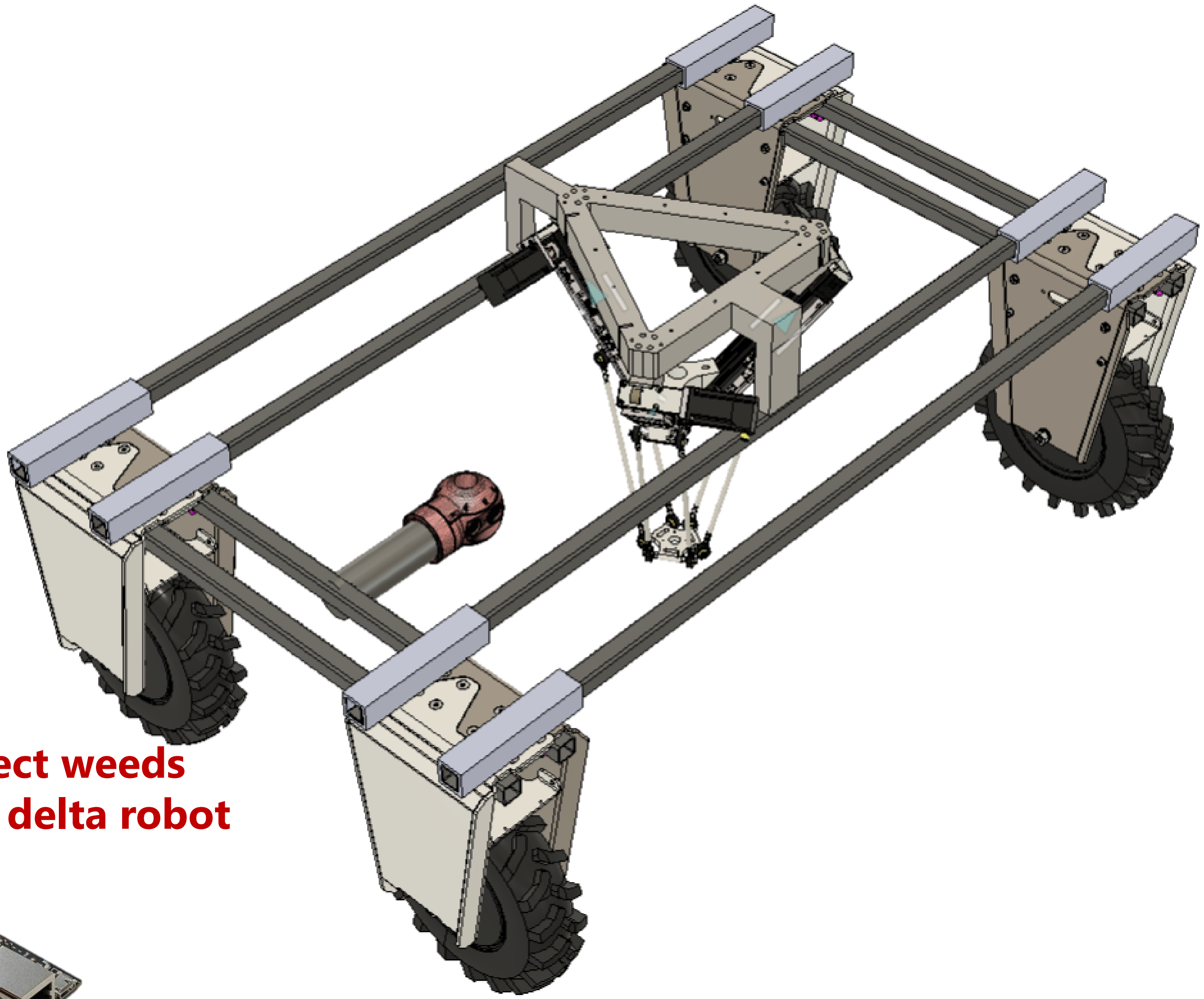
- RGB Camera and other sensors
- Detect and locate weed plants

RGB Camera

+

LiDAR

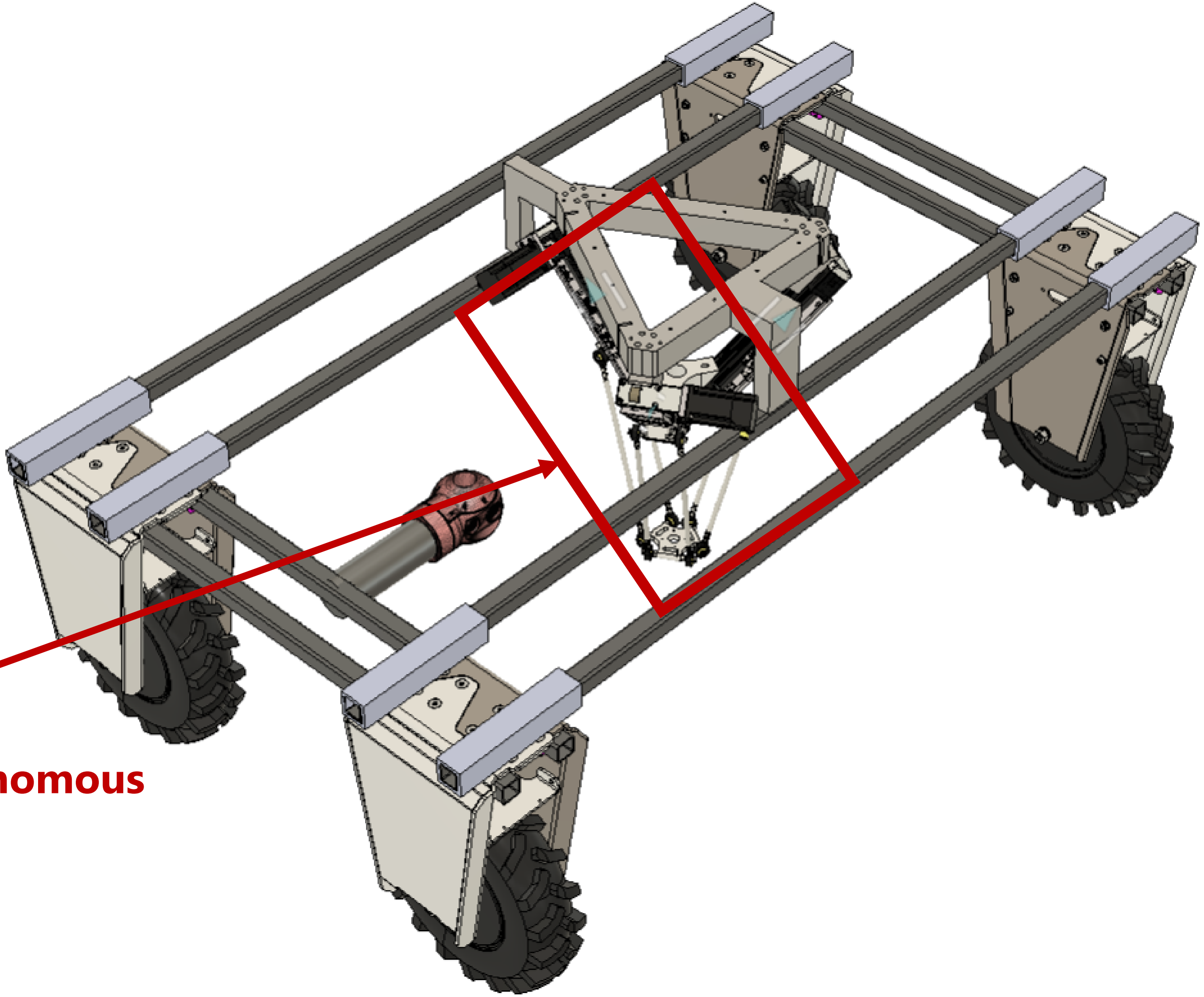
Future Direction



2

- **Process inputs and detect weeds**
- **Send control signals to delta robot**

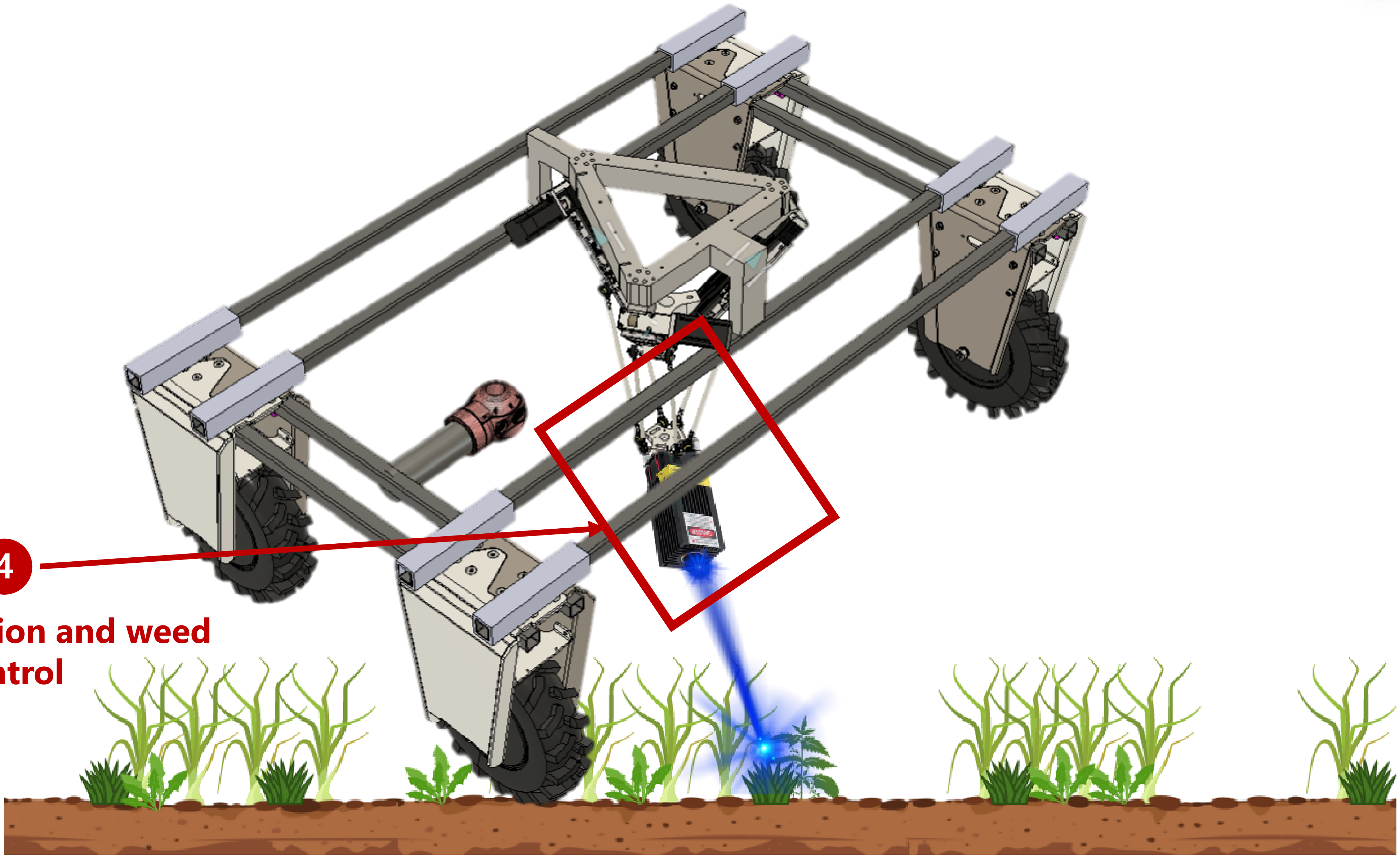
Future Direction



3

Execute robot's autonomous movements

Future Direction



Acknowledgements

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USDA

AG2PI

Agricultural Genome to Phenome Initiative

Institute for Integrative Precision Agriculture
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This research was supported by the intramural research program of the U.S. Department of Agriculture, National Institute of Food and Agriculture, [Agricultural Genome to Phenome Initiative, grant no. 2022-70412-38454, 2021-70412-35233, and 2020-70412-32615]

Thank you!
Any Question?

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