Design and Development of a Novel Autonomous Scaled Multi-wheeled Vehicle

Master of Applied Science in Mechanical Engineering

Thesis Defence

Aaron Hao Tan

Supervisors: Dr. Moustafa El-Gindy and Dr. Haoxiang Lang

Outline

1. Introduction
2. Literature Review
3. Design and Development of the Scaled Multi-wheeled Vehicle
4. Implementation of Autonomous Navigation
5. Vision-based Control System for Precise Positioning
6. Experimentation and Results
7. Conclusion and Future Work

Introduction

- Software algorithms are improving at an exponential rate alongside hardware affordability
- As a result, there is a demand to replace humans with autonomous robotic systems to save lives

Light Armored Combat Vehicle (LACV)

Objective and Contributions

Objective

- To design and develop a 1:6 Scaled Electric Multi-wheeled Vehicle by integrating autonomous navigation with vision based control and a multi-steerable system

Contributions

- Novel mechanical and electrical design of Scaled Electric Multi-wheeled Vehicle
- Implementation of mapping, localization and path planning algorithms with the physical prototype
- Propose a precise vision based control scheme for pose correction to improve upon the limitations constrained by current navigation methodologies
- Integrate all hardware and software with experimental validation

Literature Review

Topics	Summary
Light Armored Combat Vehicle	• All improvements since the 80's has been focused primarily on engine output and passenger protection • Lack of research and development in exploring multi-steered systems and autonomous features
Scaled Multi-wheeled and Multi-steered (MWMS) Robotic Platforms	• Focused on four-wheel variations with a lack of eight-wheeled designs that mimic the LACV • Lack of car like features (suspension, steering) • Either MW or MS and rarely the combination of both • MWMS papers are focused on simulation results rather than physical implementation
Precise Positioning Techniques	• Lack of applications that utilizes alternative steering modes and vision-based approaches for better maneuverability

Overall System Design Requirements

The Scaled Electric Multi-wheeled Vehicle (SEMV)

Mechanical System

- Mimic the design of a typical LACV at 1:6 scale
- Large travel suspension

Electrical System

- Independent wheel actuation
- Necessary electronics for navigation

Software System

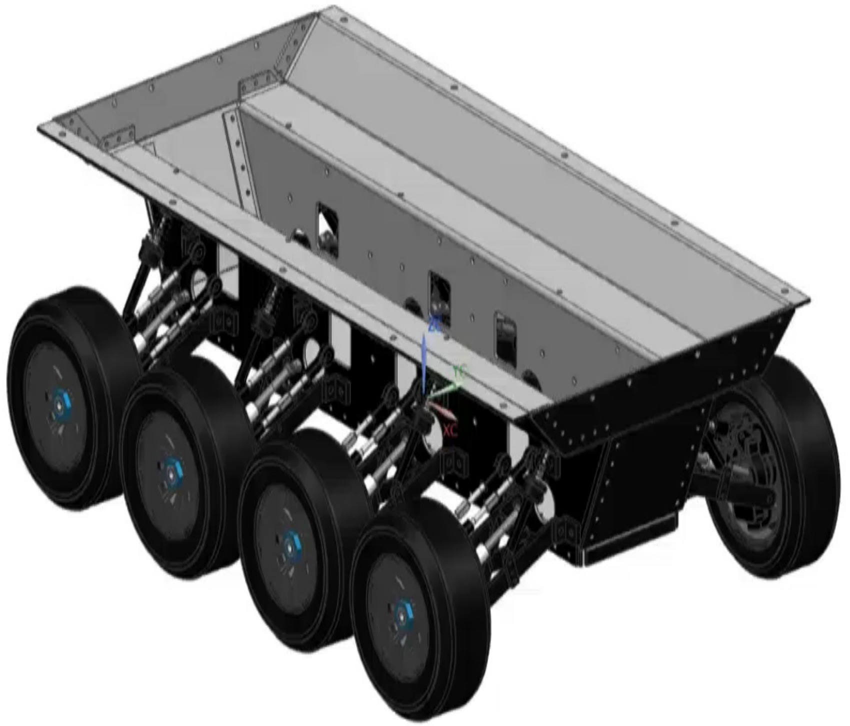
- Autonomous navigation

SEMV Prototype

Mechanical System Design

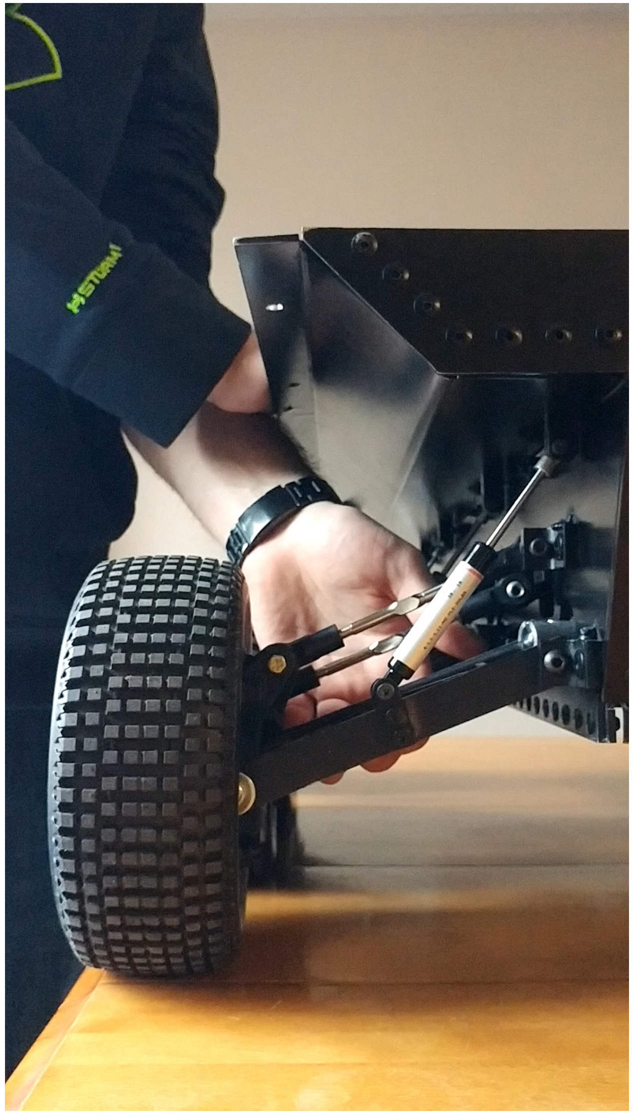
Key Features

- Dimension and weight are 1:6 scale of the life size counterpart
- Custom chassis made of aluminum
  - Three internal layers to house all components
- Independent wheel actuation
  - Driving: DC motors
  - Steering: linear actuators
- Independent suspension
  - Double wishbone design for large travel and minimal camber change
- Aesthetic exterior with an aluminum sensor bridge



SEMV CAD Model

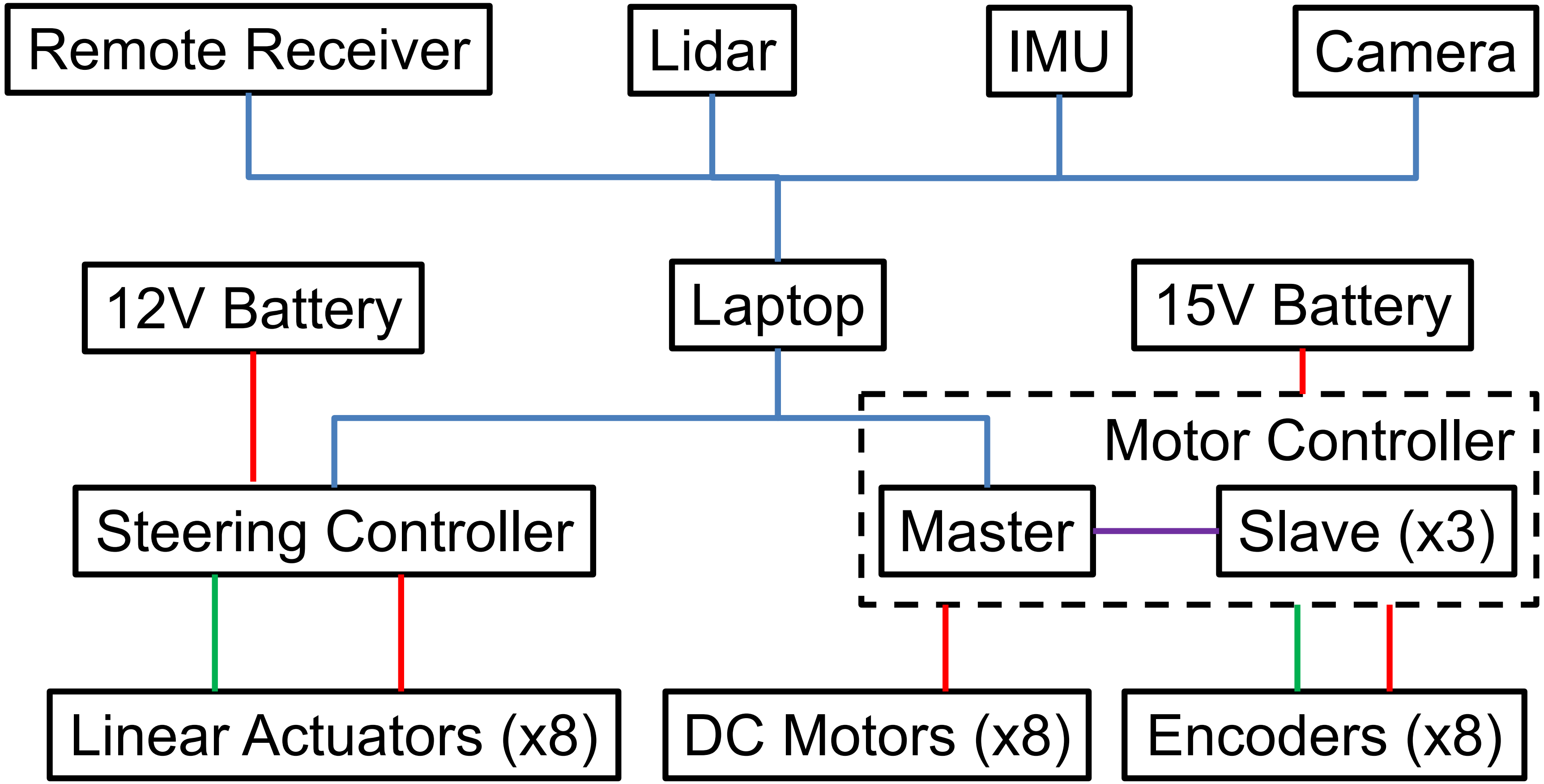
Mechanical Design



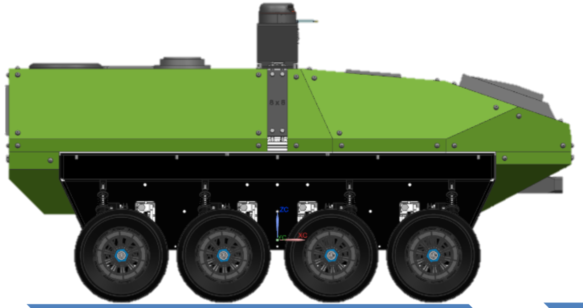
Electronic System Architecture

Legend

USB
Power
Data
CAN



Autonomous Navigation Procedure



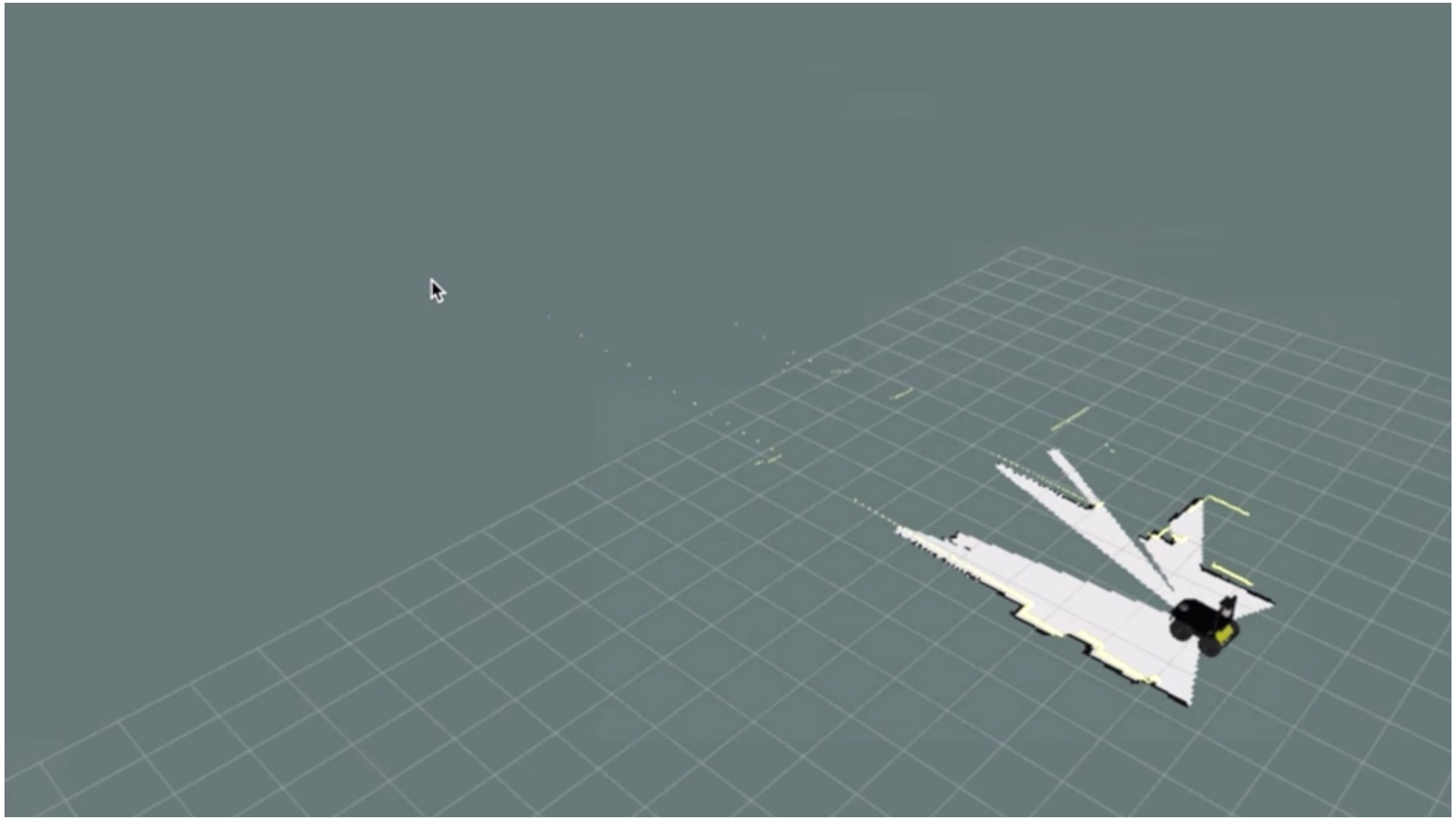
Mapping → Localization → Path Planning → Low-Level Control

- Stage 1: Create a map of the workspace (only need to do once)
- Stage 2: Localize within the acquired map
- Stage 3: Plan a path from initial to desired position and orientation
- Stage 4: Low-level control of driving and steering actuators

Mapping

Simultaneous Localization and Mapping (SLAM)

- FastSLAM 2.0 (GMapping in ROS)
- Using particle filter to estimate a robot's pose and its surrounding based on partial and noisy observations
- Builds a two dimensional map of visited space

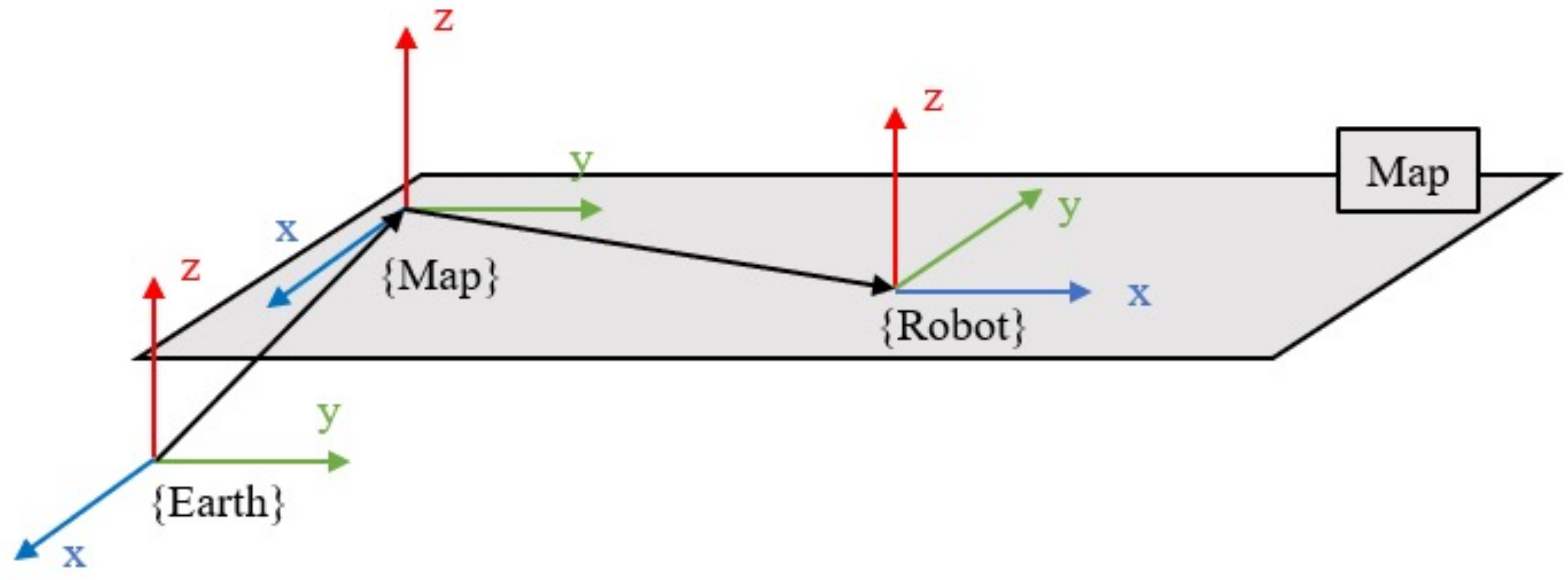


SLAM Demonstration

Localization

Incremental Localization

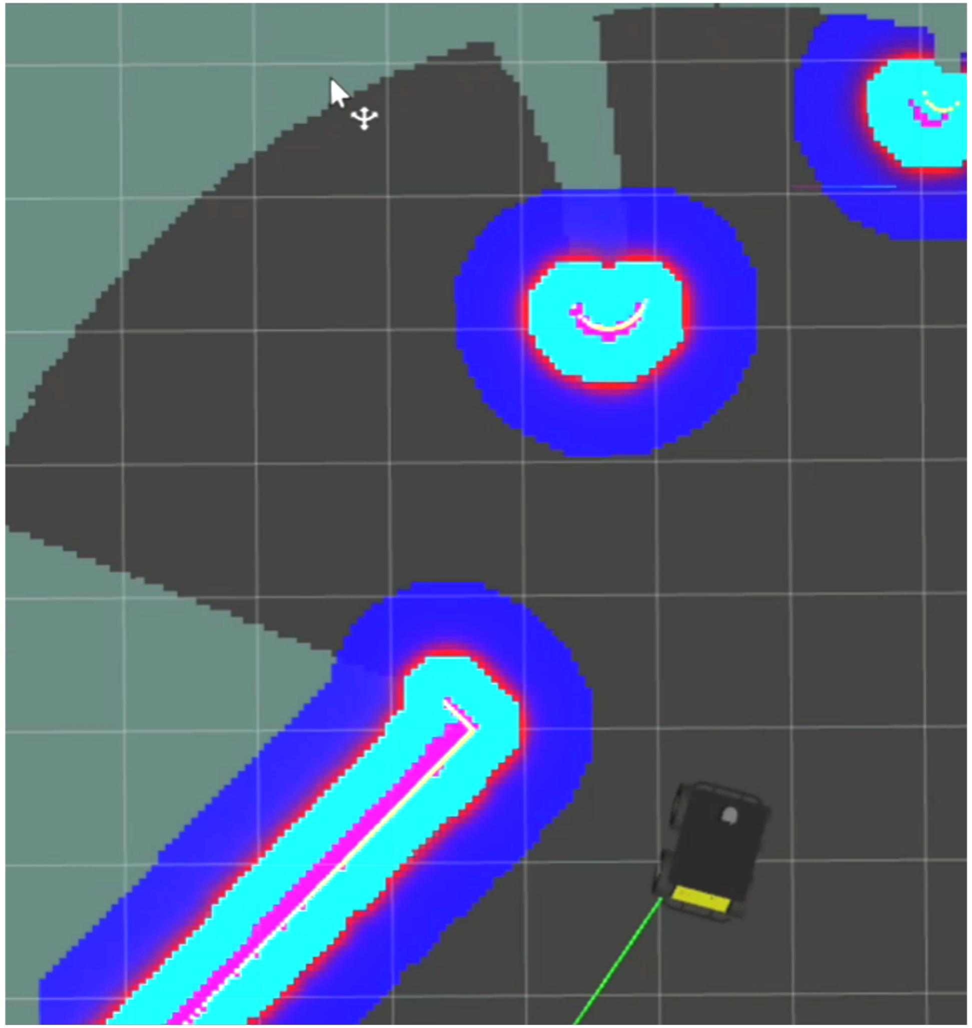
- Need to localize the mobile robot within the map frame
- Encoder + IMU = Position and Orientation Update



Frames of Interest

Path Planning

1. **Cost map**
   – All obstacles detected are inflated by an user specified radius to create a “cushion zone” for the path planner
2. **Global Path Planner**
   – To generate a global path on the map to go from start to finish
   – The output is a series of waypoints
   – Dijkstra’s Algorithm
3. **Local Path Planner**
   – To follow the global path and avoid previously unknown obstacles
   – Convert waypoints in to achievable velocities
   – Timed Elastic Band (TEB)



Path Planning in RVIZ

SEMV Kinematics Model

- Kinematics model

$$\dot{x} = v\, cos(\boxed{\theta} + \boxed{\varphi})$$

$$\dot{y} = v\, sin(\boxed{\theta} + \boxed{\varphi})$$

$$\dot{\theta} = \frac{v}{l}\sin(\varphi)$$

Steering angle

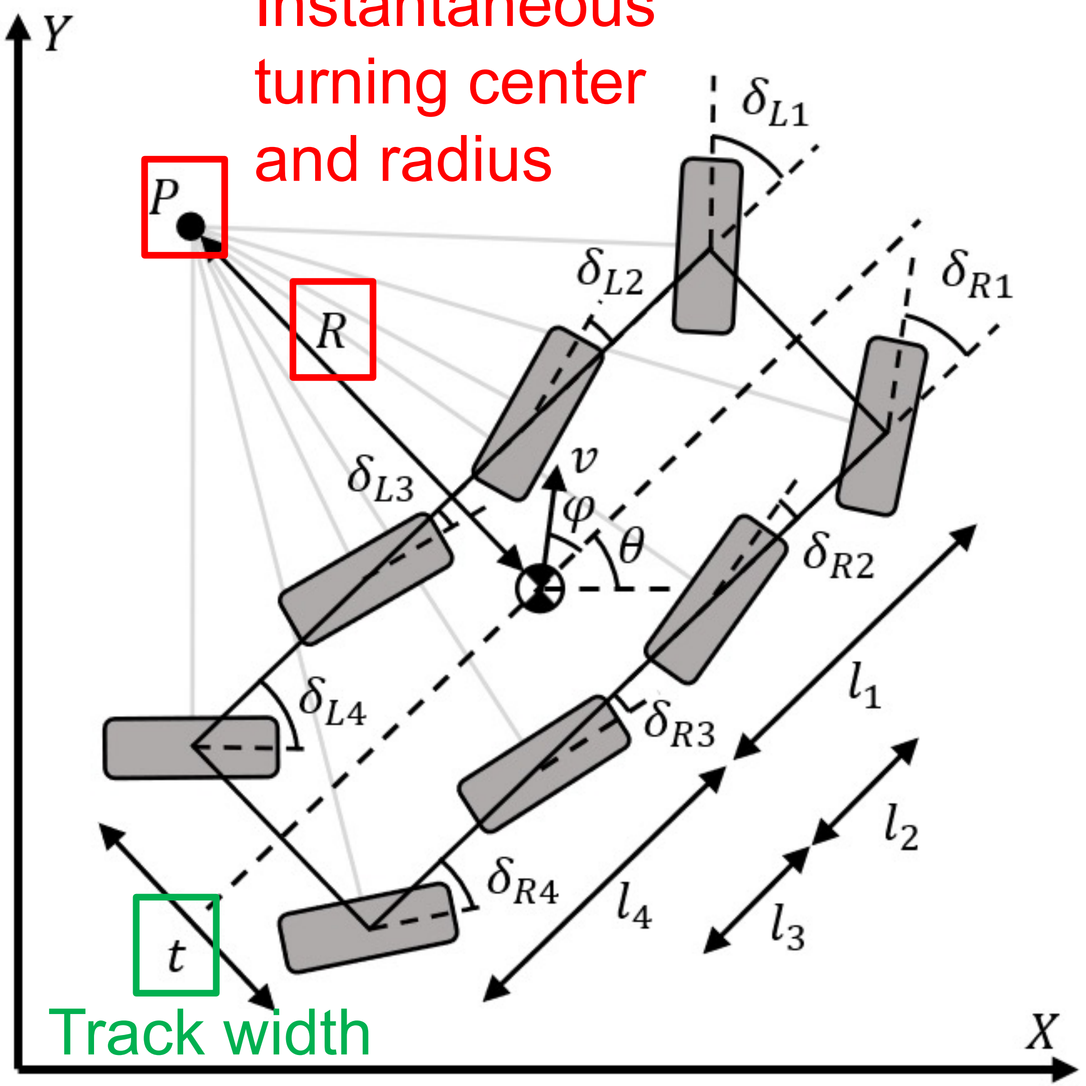
Heading angle

- Ackerman steering geometry for first two wheels

$$\delta_{L1} = \tan^{-1}\left(\frac{l_1}{R - t/2}\right)$$

$$\delta_{R1} = \tan^{-1}\left(\frac{l_1}{R + t/2}\right)$$

Instantaneous turning center and radius

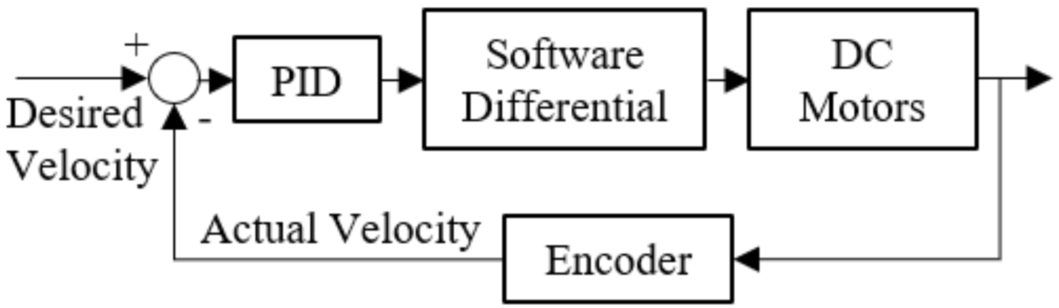


Track width

Low Level Control

Driving (Speed) Controller

- Software differential to increase maneuverability

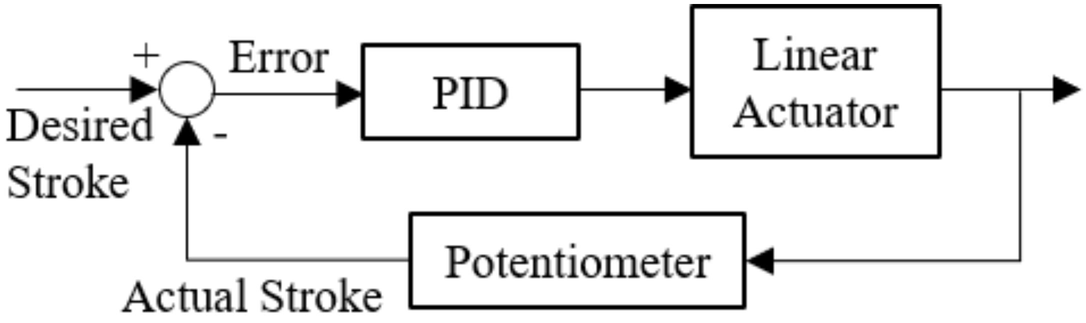


$$Right_{velocity} = v - (\dot{\theta} * t/2)$$

$$Left_{velocity} = v + (\dot{\theta} * t/2)$$

Steering Controller

- Stroke to steering model acquired from physical experiment



Left steering angle

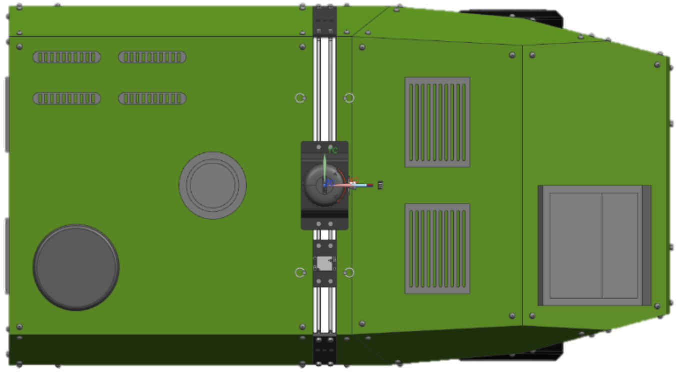
$$Stroke_{left} = (5 * 10^{-5})\boxed{\delta_L^3} + 0.0014\boxed{\delta_L^2} - 0.76\boxed{\delta_L} + 24.97$$

$$Stroke_{right} = -(5 * 10^{-5})\boxed{\delta_R^3} + 0.0014\boxed{\delta_R^2} + 0.76\boxed{\delta_R} + 24.97$$

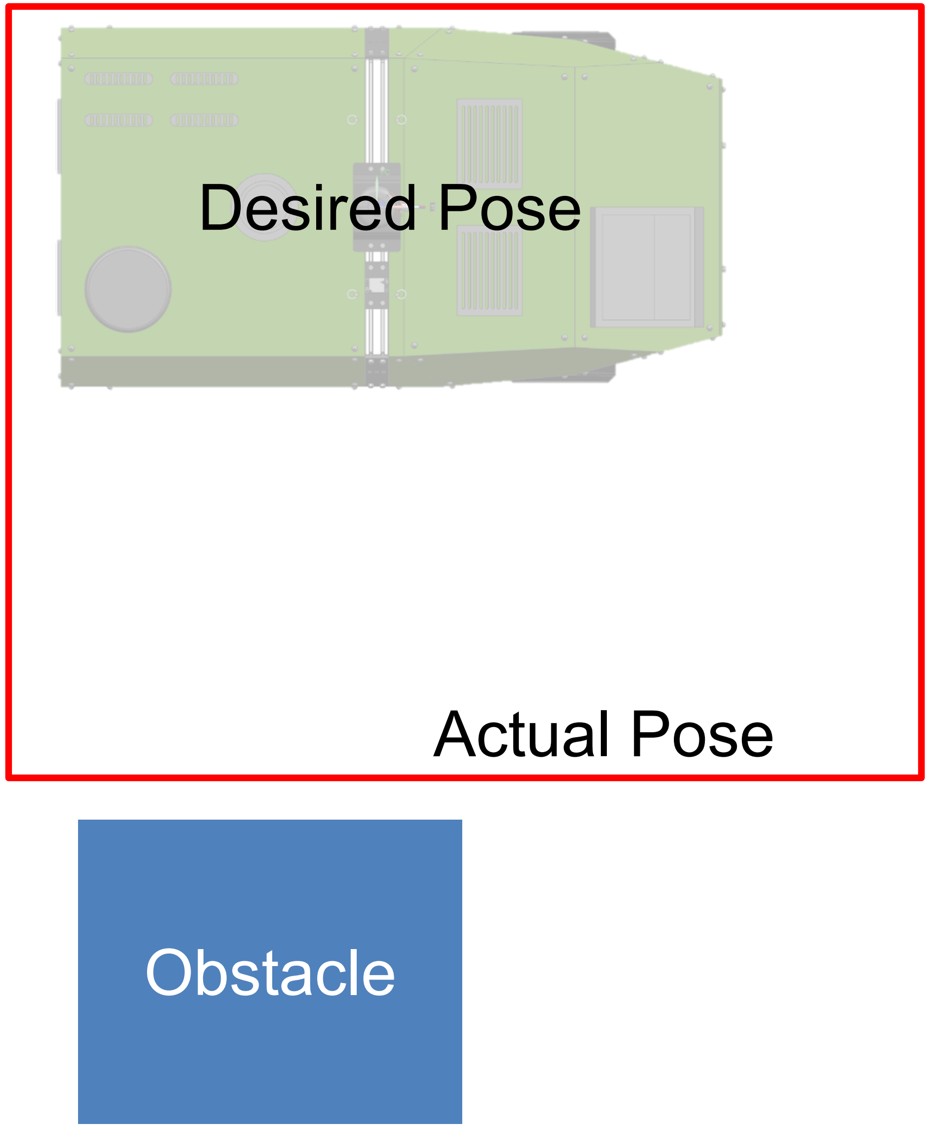
Right steering angle

Autonomous Navigation Limitations

- There is a high tolerance of error with the previously mentioned navigation methodologies
- Reasons:
  - Sensor inaccuracy and error accumulation
  - Mechanical system imperfections

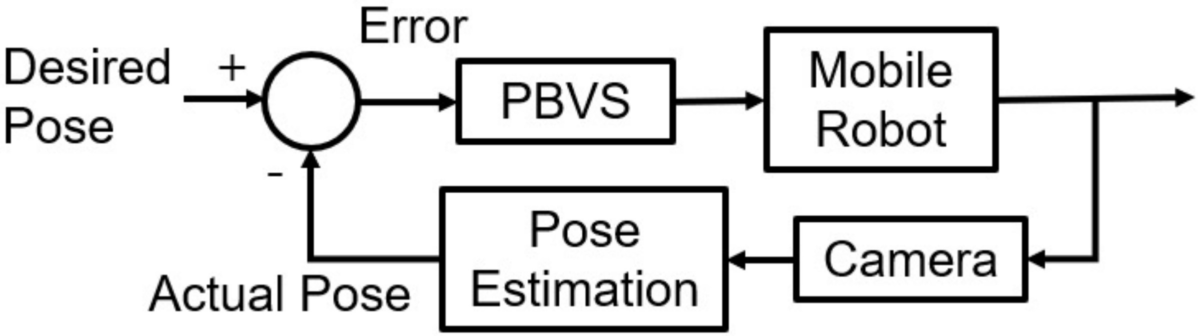


Close Quarters Pose Correction
Pose Correction

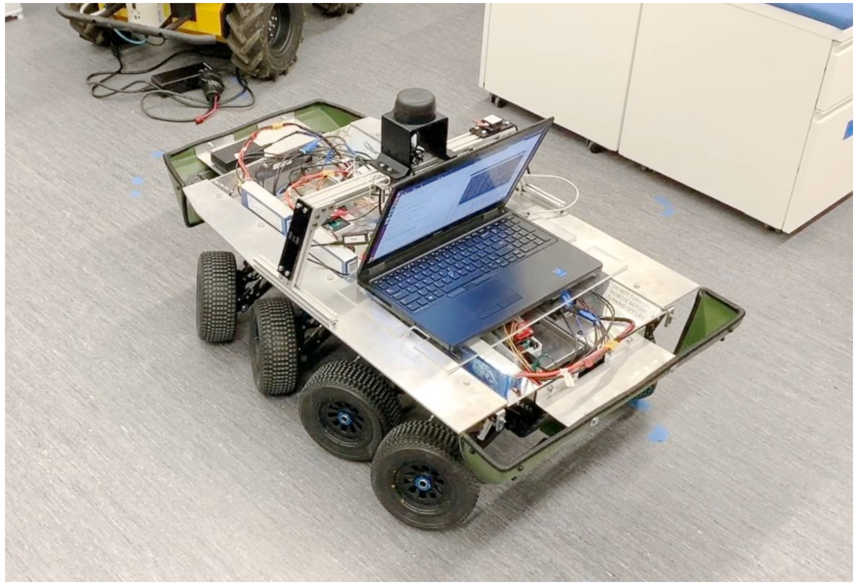


Position Based Visual Servoing

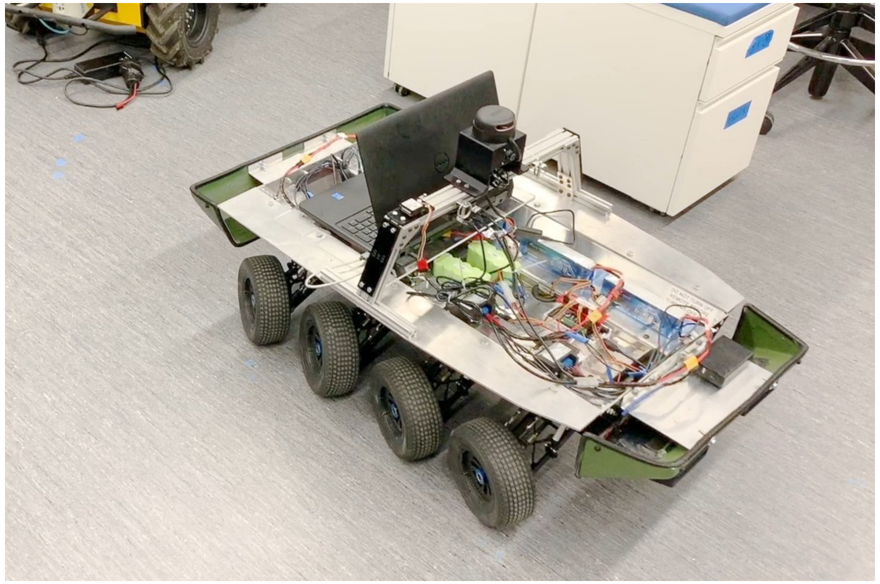
- Utilizes vision as feedback to achieve closed loop motion control



- Modified Position Based Visual Servoing (M-PBVS)



Diamond Steer

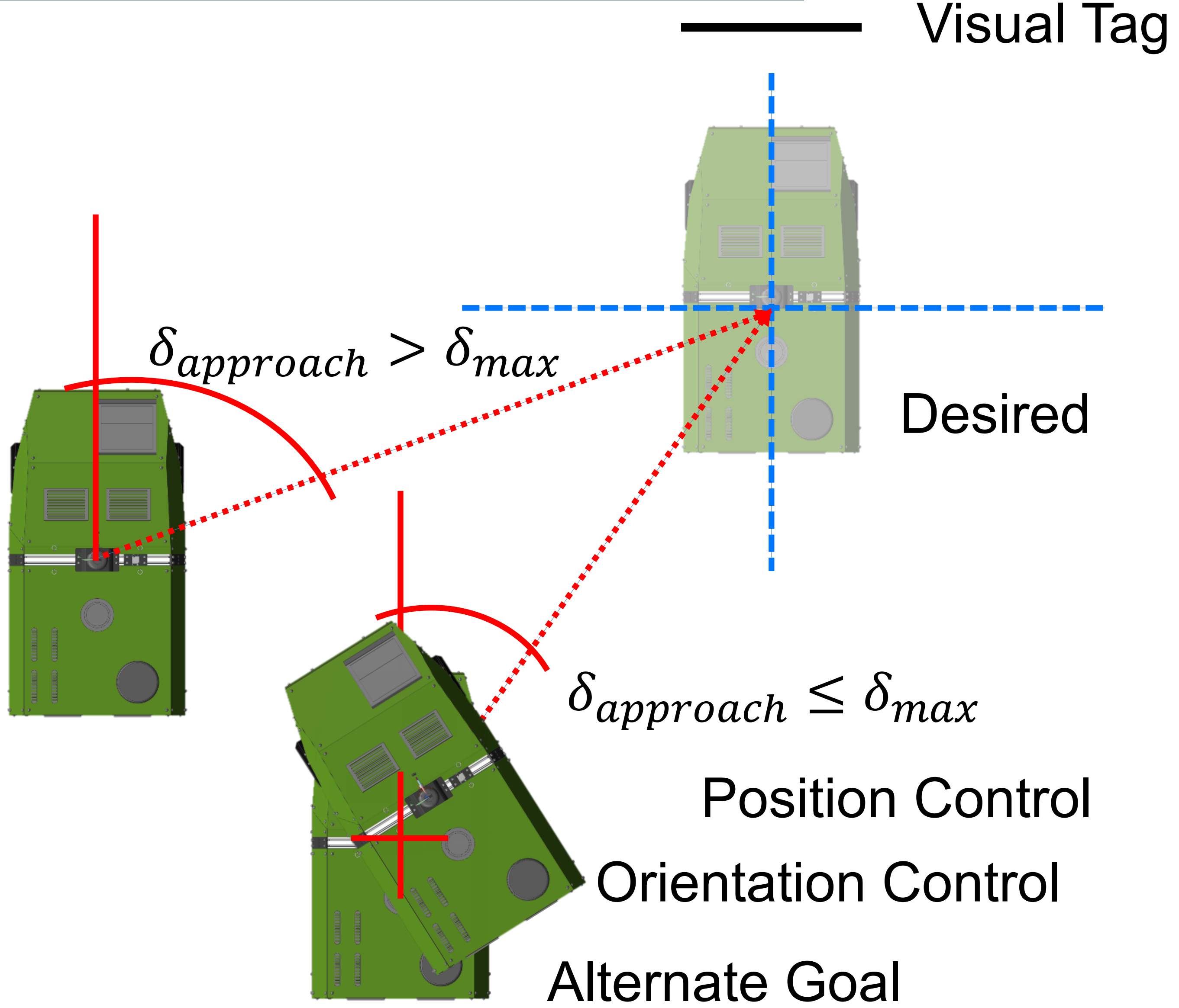


Synchronous Steer

Modified Position Based Visual Servoing

M-PBVS Two Stage Approach

- Stage 1: Orientation Control
  - Diamond Steer
- Stage 2: Position Control
  - Synchronous Steer
  - Two Scenarios:
    - Direct Goal Scenario
      - $\delta_{approach} \leq \delta_{max}$
    - Alternate Goal Scenario
      - $\delta_{approach} > \delta_{max}$



M-PBVS Kinematics Model

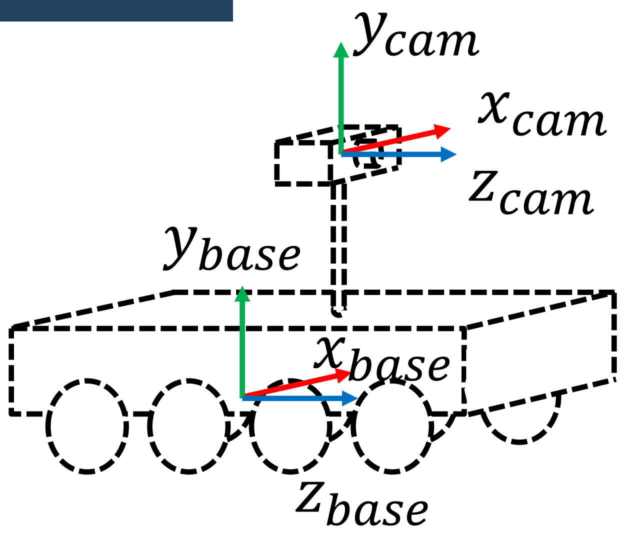
- Model the SEMV as a two joint manipulator: Revolute + Prismatic

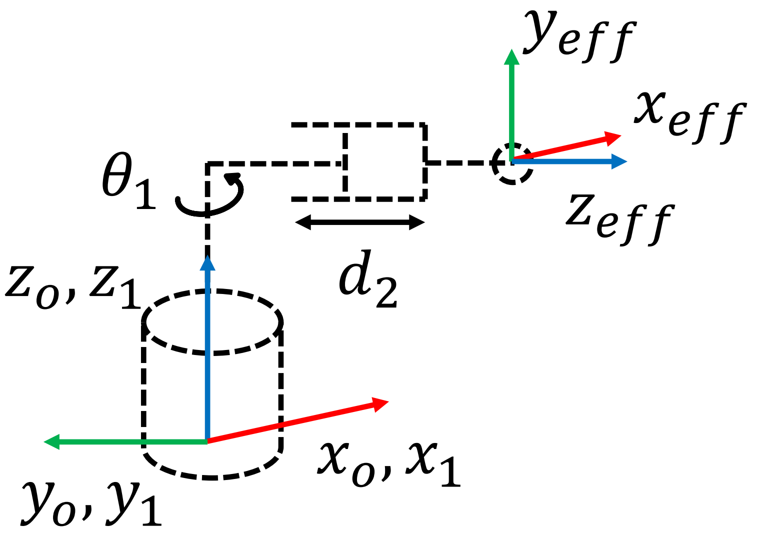
- The forward kinematics solution is calculated as shown below

Angular velocity

$$ {}^{0}_{eff}V = \begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} d_2C_1 & S_1 \\ d_2S_1 & -C_1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{d}_2 \end{bmatrix} = J \begin{bmatrix} \dot{\theta}_1 \\ \dot{d}_2 \end{bmatrix} $$

Linear velocity





M-PBVS Control Law Derivation

Stage 1: Orientation Control

- Based on manipulator analogy, Stage 1 will only control the revolute joint
- Lyapunov's proportional control scheme

$$\dot{e(t)}_w = -k\, e(t)_W$$

- Orientation control law

Pseudoinverse Jacobian Orientation error

Angular velocity $$\boxed{\dot{\theta}} = \boxed{-k}\,\boxed{J_w^{+}}\,\boxed{{}^{0}_{base}R\ {}^{base}_{cam}R\ \left({}^{cam_d}_{cam}R\right)^T\ T(\phi)}\,\boxed{e(t)_w}$$

Gain Transformation matrix

- Convert angular velocity in to left and right wheel speed

$$\dot{\theta} = \begin{bmatrix} -\frac{r}{l} & \frac{r}{l} \end{bmatrix} \begin{bmatrix} \omega_{left} \\ \omega_{right} \end{bmatrix}$$

M-PBVS Control Law Derivation

Stage 2: Position Control

- Once the orientation is corrected and the goal (Direct or Alternate) is calculated, the vehicle enters Stage 2
- Both revolute and prismatic joints are considered in this stage
- The revolute joint angle represent the steering angle (with angle constraint)
- Position control law:

Gain Pseudoinverse Jacobian

Linear and steering velocity $\boxed{\begin{bmatrix} v \\ \dot{\varphi} \end{bmatrix}} = \boxed{-k}\boxed{J^{+}}\boxed{E\ L}\boxed{e(t)}$ Error

Transformation matrix

$$E = \begin{bmatrix} {}^{0}_{base}R & 0_{3x3} \\ 0_{3x3} & {}^{0}_{base}R \end{bmatrix} \begin{bmatrix} {}^{base}_{cam}R & s(d)\,{}^{base}_{cam}R \\ 0_{3x3} & {}^{base}_{cam}R \end{bmatrix} \quad L = \begin{bmatrix} \left({}^{cam_d}_{cam}R\right)^{T} & 0 \\ 0 & \left({}^{cam_d}_{cam}R\right)^{T} * T(\phi) \end{bmatrix}$$

Vehicle Performance Test

- Max Speed

Run	Distance (m)	Time (s)	Speed (km/h)
1	5	2.67	6.75
2	10	5.20	6.92
3	15	8.02	6.73
4	20	10.57	6.81
5	25	13.06	6.89
		Average	6.82

- Steering Response Time

Run	Time (s)
1	0.9834
2	0.9652
3	0.9733
4	0.9863
5	0.9901
Average	0.9797

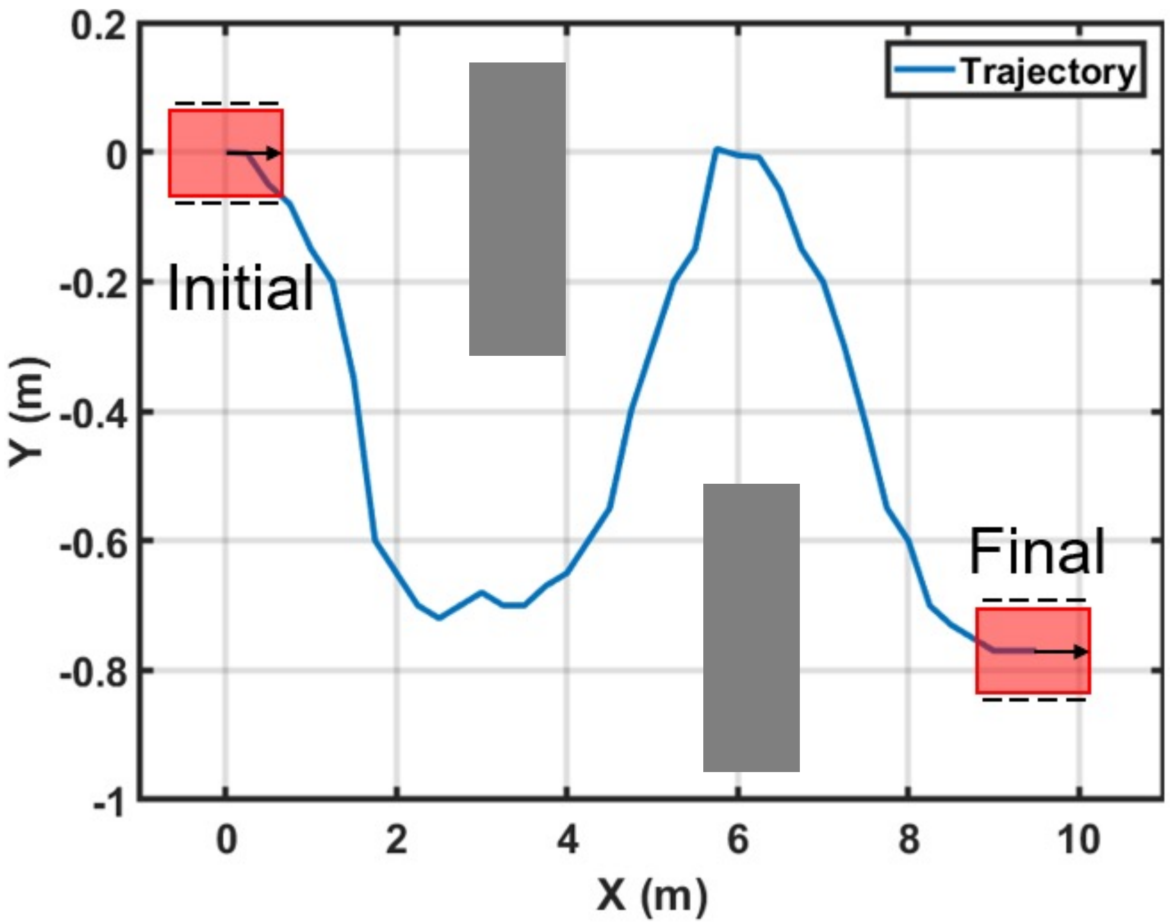
Vehicle Performance Test

- Minimum Turning Radius

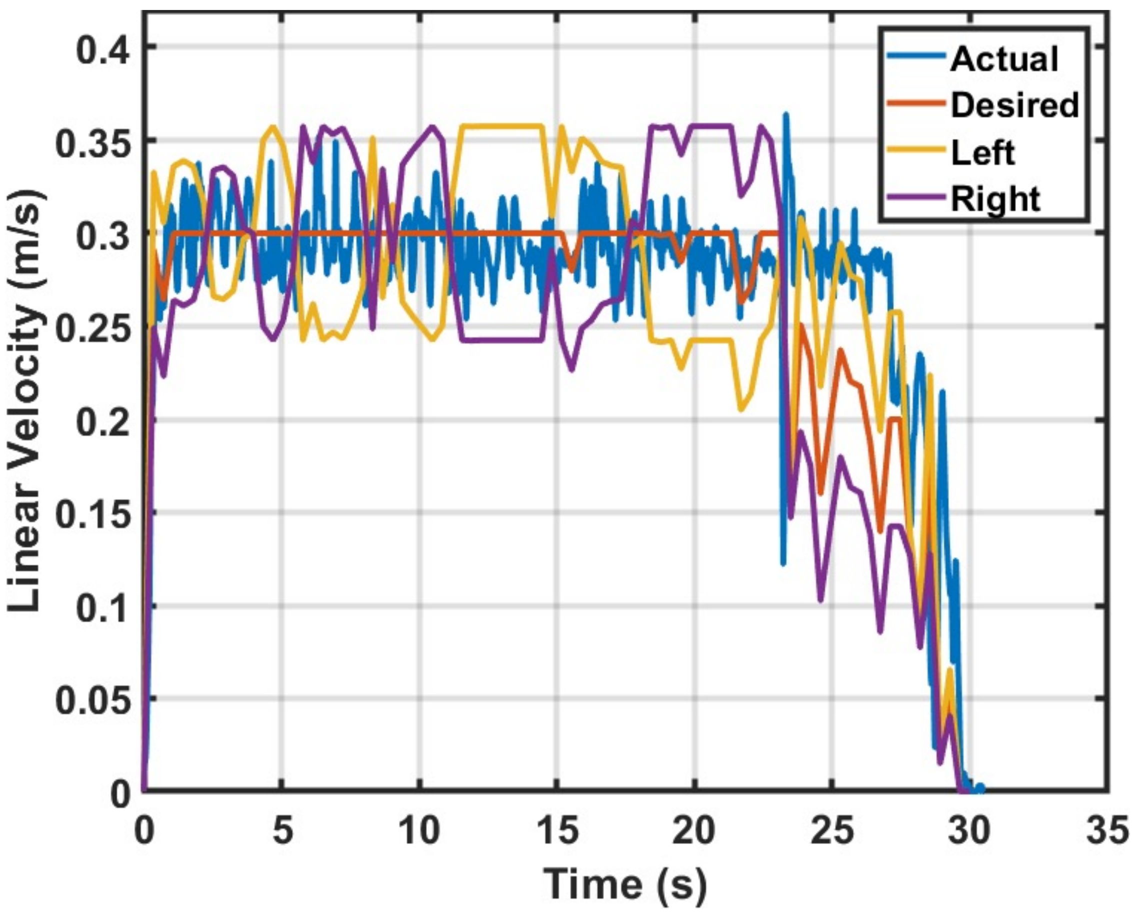
Steering Mode	Minimum Radius	Theoretical Radius	Error %
FWS	1.67 meters	1.62	3.09
4AS	1.41 meters	1.37	2.92
AWS	1.14 meters	1.08	5.56

Experimentation: Navigation Video

Experimentation: Slalom Results

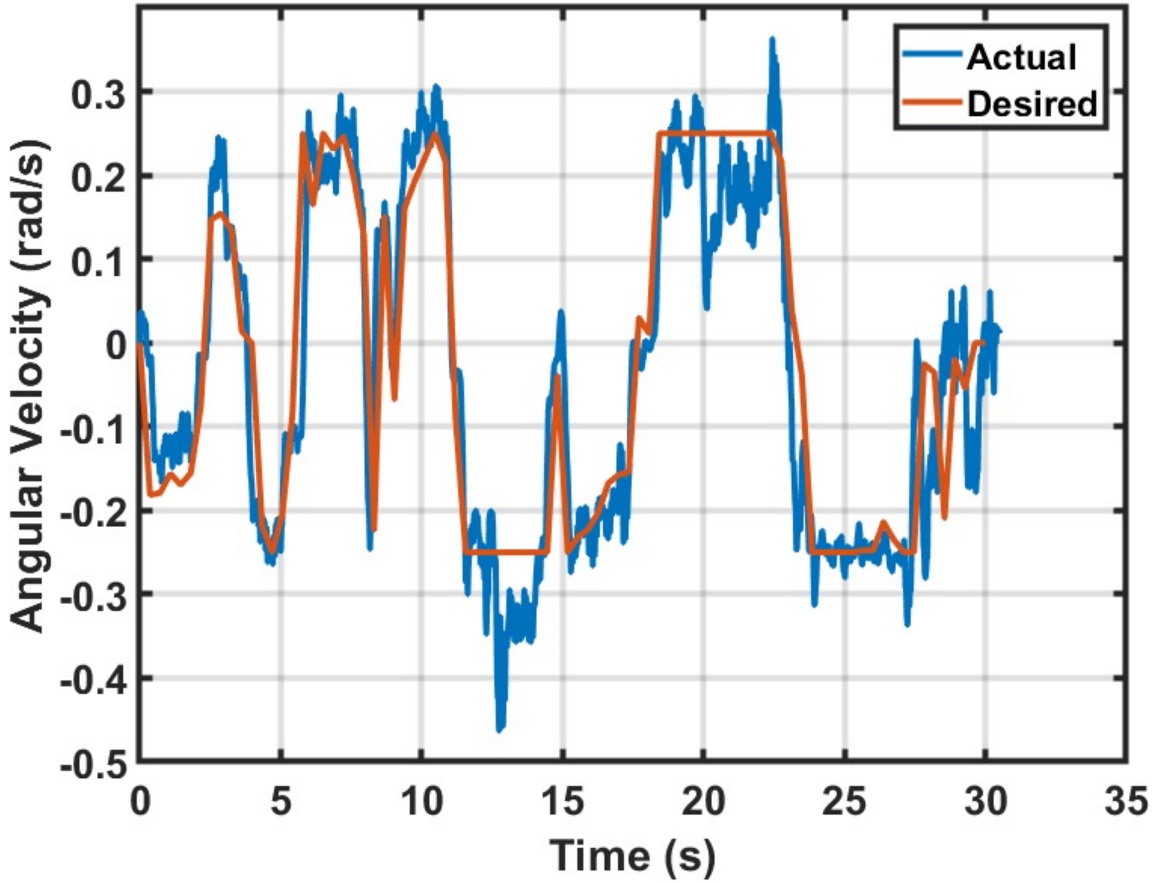


Trajectory

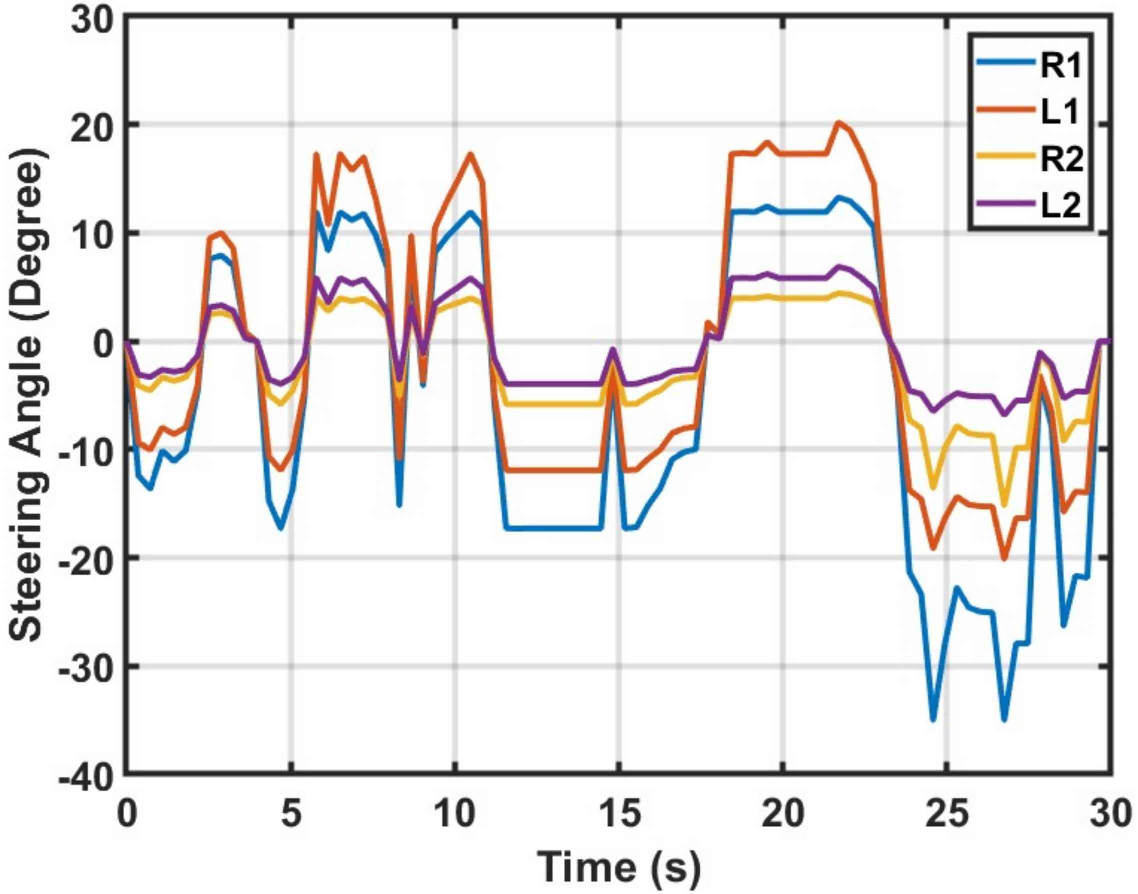


Linear Velocity

Experimentation: Slalom Results



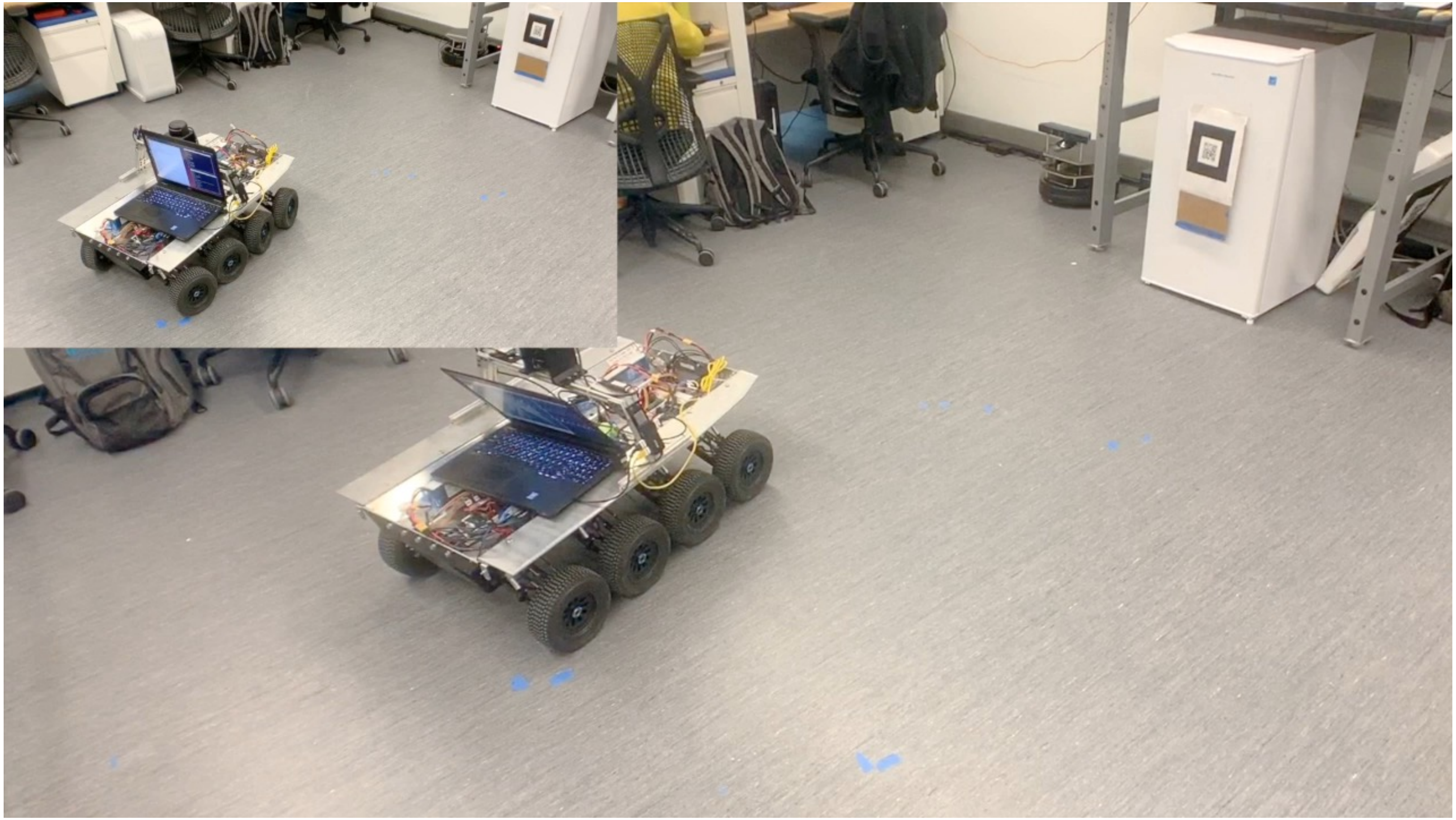
Angular Velocity



Steering Angles

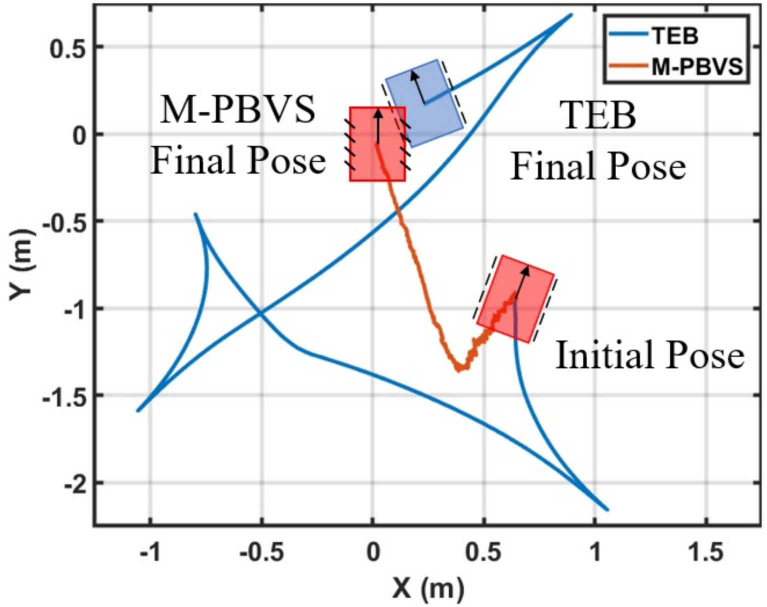
Experimentation: M-PBVS Video

Experimentation: Comparison Video

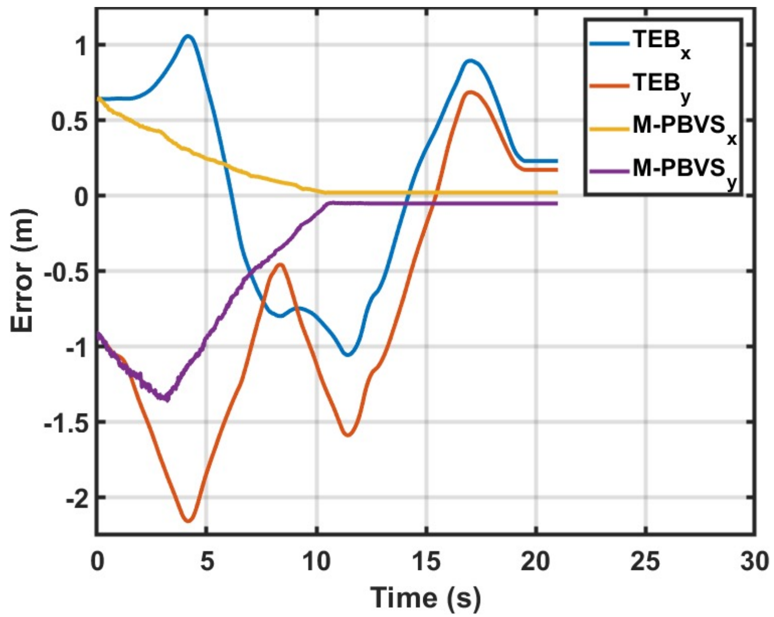


Experimentation: Comparison Results

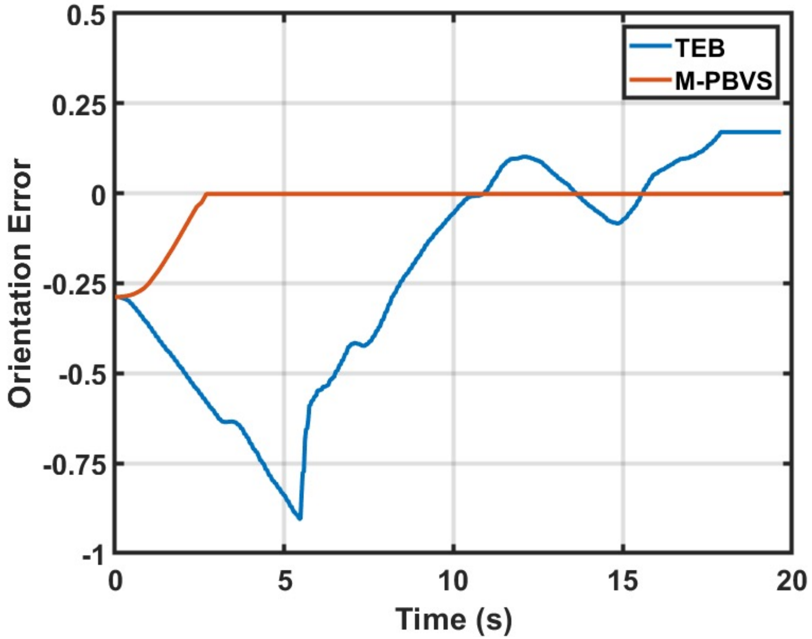
Alternate Goal Test



Trajectory



Position Error



Orientation Error

	Final Pose	Pos. Error %	Ori. Error %	Total Distance
TEB	(0.23, 0.17, 0.17)	27.31%	60.71%	8.91 m
M-PBVS	(0.02, -0.05, -0.002)	4.67%	0.68%	1.85 m

Conclusion

- Designed and developed a fully functional and instrumented Scaled Electric Multi-wheeled Vehicle
- Completed both high and low-level controllers for vehicle actuation while successfully implementing mapping, localization and path planning algorithms
- Proposed a Modified Position Based Visual Servoing approach that outperforms currently available navigation methodologies in close quarters pose correction
- Integrated and troubleshooted all software and hardware developed with physical experimentation and validation
- Concluded on vehicle navigation ability and the improvements made by the proposed pose correction algorithm

Future Work

SEMV Improvements

- Battery monitoring system and a unified charging port

Autonomous Navigation Improvements

- Develop a more sophisticated localization algorithm that employs sensor fusion for precise long-distance navigation
- Use machine learning algorithms for obstacle detection and classification

M-PBVS Algorithm Improvements

- Panoramic camera to increase field of view
- Advanced controllers for visual servoing

Publications

Journal Publications

- A. H. Tan, A. Al-Shanoon, H. Lang and Y. Wang, ”Mobile Robot Docking with Obstacle Avoidance and Visual Servoing," *International Journal of Robotics and Automation*, 2022 (In Press).
- A. H. Tan, H. Lang and M. El-Gindy, "The Design and Development of a Novel Autonomous Multi-Wheeled Vehicle," *Robotica*, 2021.

Conference Publications

- A. H. Tan, H. Lang and M. El-Gindy, "A Novel Autonomous Scaled Electric Combat Vehicle," in ASME IDETC/CIE, Anaheim, 2019. (Accepted).
- A. H. Tan, A. Al-Shanoon, H. Lang and M. El-Gindy, "Mobile Robot Regulation with Image Based Visual Servoing," in *ASME IDETC/CIE*, Quebec City, 2018.
- A. Al-Shanoon, A. H. Tan, H. Lang and Y. Wang, "Mobile Robot Regulation with Position Based Visual Servoing," in *IEEE CCECE*, Ottawa, 2018.

The End
Thank You