TEXAS A&M UNIVERSITY

DESIGN AND DEVELOPMENT OF A CROP MONITORING AND INSPECTION ROBOT

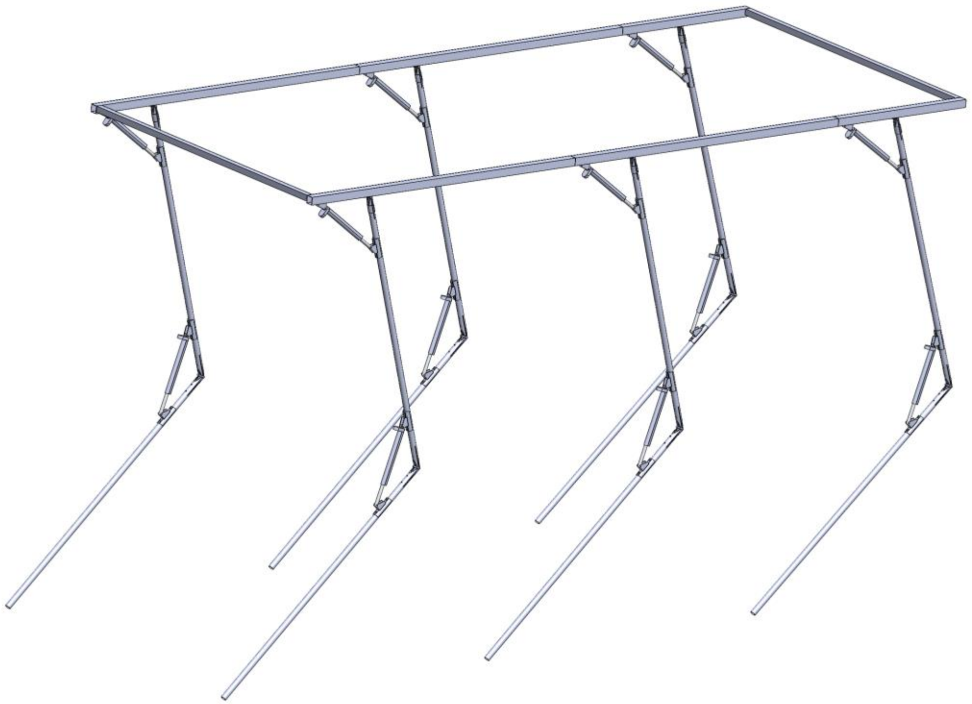
Master's Thesis Defense

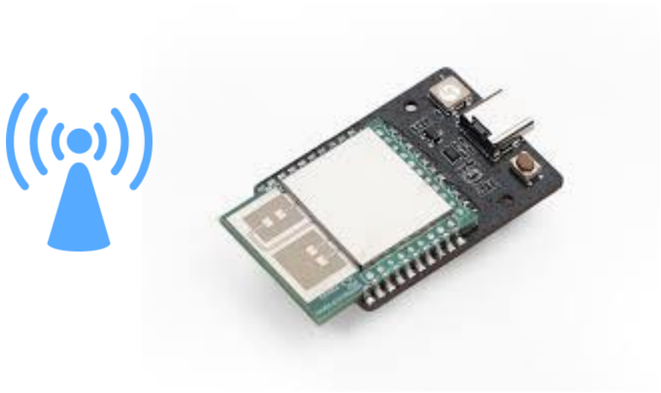
Om Adikrao More

J. Mike Walker '66 Department of Mechanical Engineering

INTRODUCTION

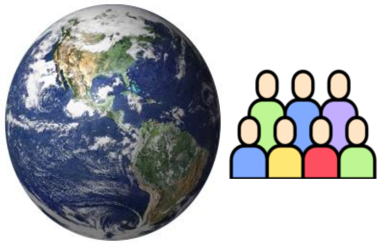
"Inspection robot is a six-legged autonomous platform designed to traverse uneven and vegetative terrain.





Specifically designed for carrying sensitive instruments like mmWave radar devices."

MOTIVATION



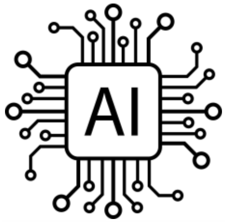
Population is predicted to meet **10 billion** by **2050**

2/3rd of will be urbanized by **2050**

Low

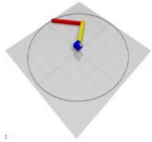
High

Staple Food



PROBLEM STATEMENT

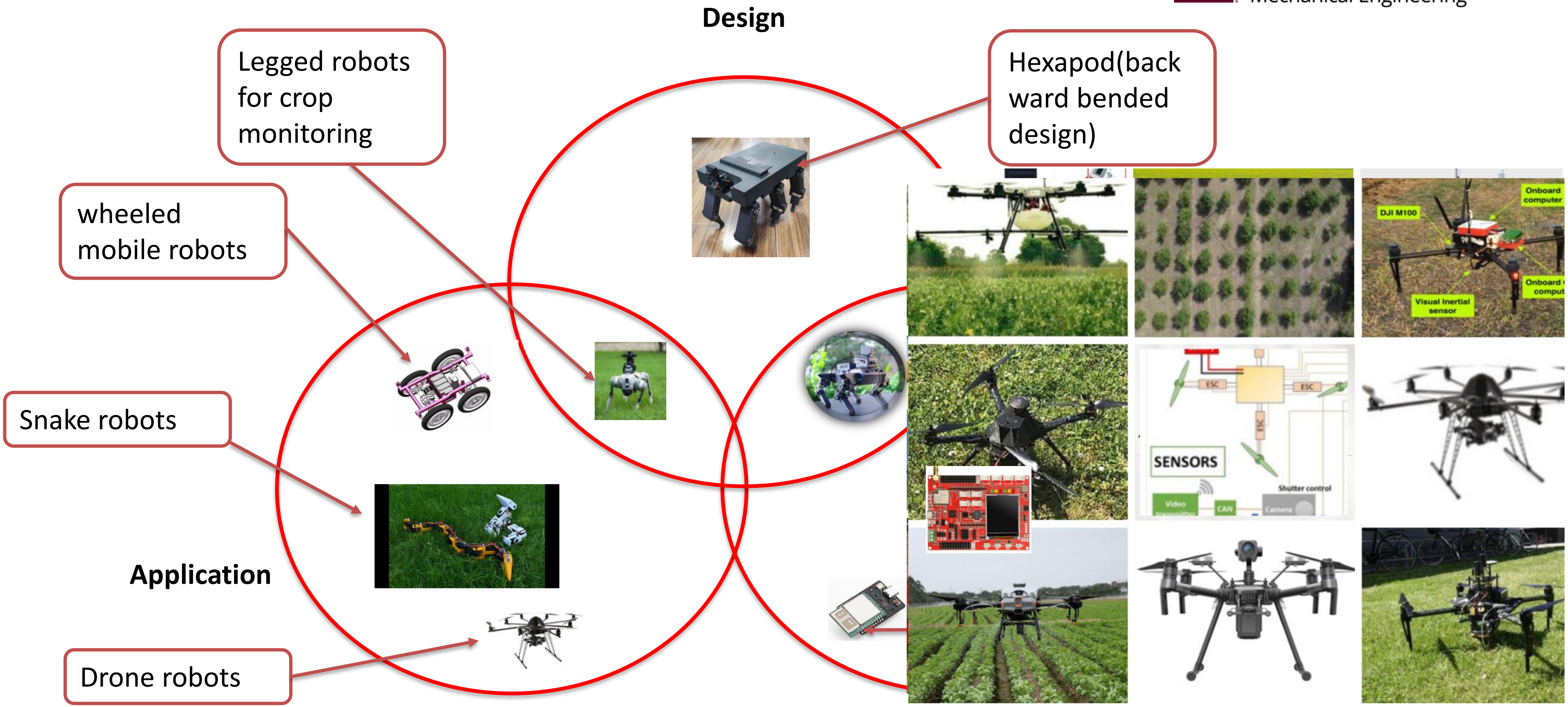
Highly Dense Field



Need of :

- Low powered device
- Highly stable platform
- Legged mechanism which can avoid obstacle
- Larger workspace

PRIOR WORK


Design
Legged robots for crop monitoring
Hexapod(back ward bended design)
wheeled mobile robots
Snake robots
Application
Drone robots
Onboard computer
DJI M100
Visual Inertial sensor
SENSORS
ESC
Shutter control
CAN

PRIOR WORK(gaps)

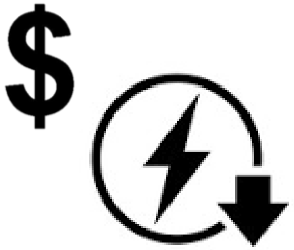
TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

- Lack of Effective Navigation in Dense Crop Fields
- Inadequate Early Detection of Subsurface or Internal Crop Diseases
- Limited Sensor Integration with Legged Platforms
- Insufficient Research on Autonomous Gait and Terrain Adaptability for Agricultural Robots
- Barrier to Adoption: Cost and Complexity of Smart Farming Solutions




CONTRIBUTION

Ground Based Stable Transportation



Cost and Power Effective and robotic system

Reliable Platform for mm-wave Radar Technology

Modular Network Architecture

METHODOLOGY
(Design)

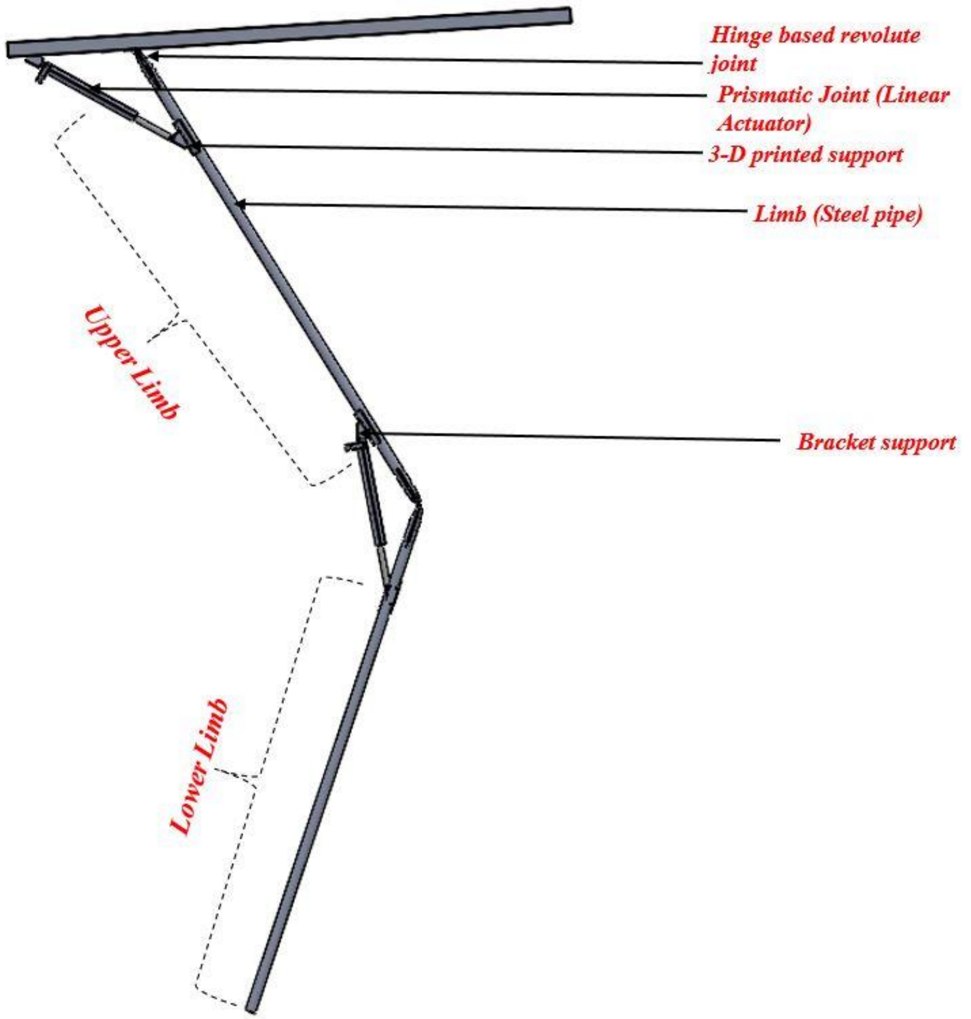
- **Structural Considerations**
  - Height
  - Width
  - Length

$$\tau_2 = m_2 g \frac{l_2}{2} \cos(\theta_1 + \theta_2)$$

- **Torque Requirements**
  - Joint Torque

$$\tau_1 = (m_1 g \frac{l_1}{2} + m_2 g l_1) \cos(\theta_1) + m_2 g \frac{l_2}{2} \cos(\theta_1 + \theta_2)$$

- **Task Space and Leg Movement mechanism**
  - Actuator Mechanism
  - Stance reach
    - Length
    - Height



TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

METHODOLOGY
(Modelling)

$$y_{n_f} = l_{n_1}\sin(\theta_{n_1}) + l_{n_1}\sin(\theta_{n_1} - \theta_{n_2}),$$

$$x_{n_f} = l_{n_2}\cos(\theta_{n_1}) + l_{n_2}\cos(\theta_{n_1} - \theta_{n_2}).$$

Joint Space to Task Space
{Joint Angle Values}

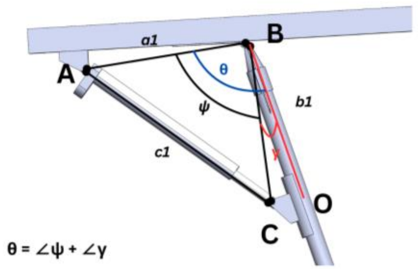
Forward Kinematic Model

Inverse Kinematic Model

Task Space to Joint Space
{Height
Stride Length}

$$\theta_2 = -\left(\arccos\left(\frac{{x_{nf}}^2 + {y_{nf}}^2 - {l_{n1}}^2 - {l_{n2}}^2}{2l_{n1}l_{n2}}\right)\right)$$

$$\theta_{n1} = \arctan\left(\frac{x_{nf}}{y_{nf}}\right) - \arctan\left(\frac{l_2\sin(\theta_{n2})}{l_{n1} + l_{n2}\cos(\theta_{n2})}\right)$$

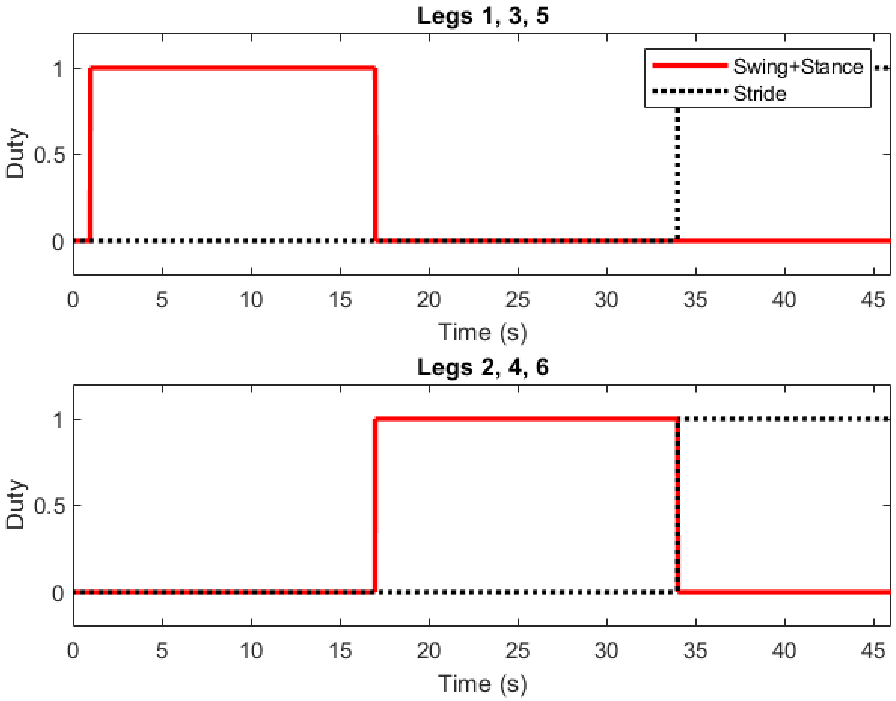


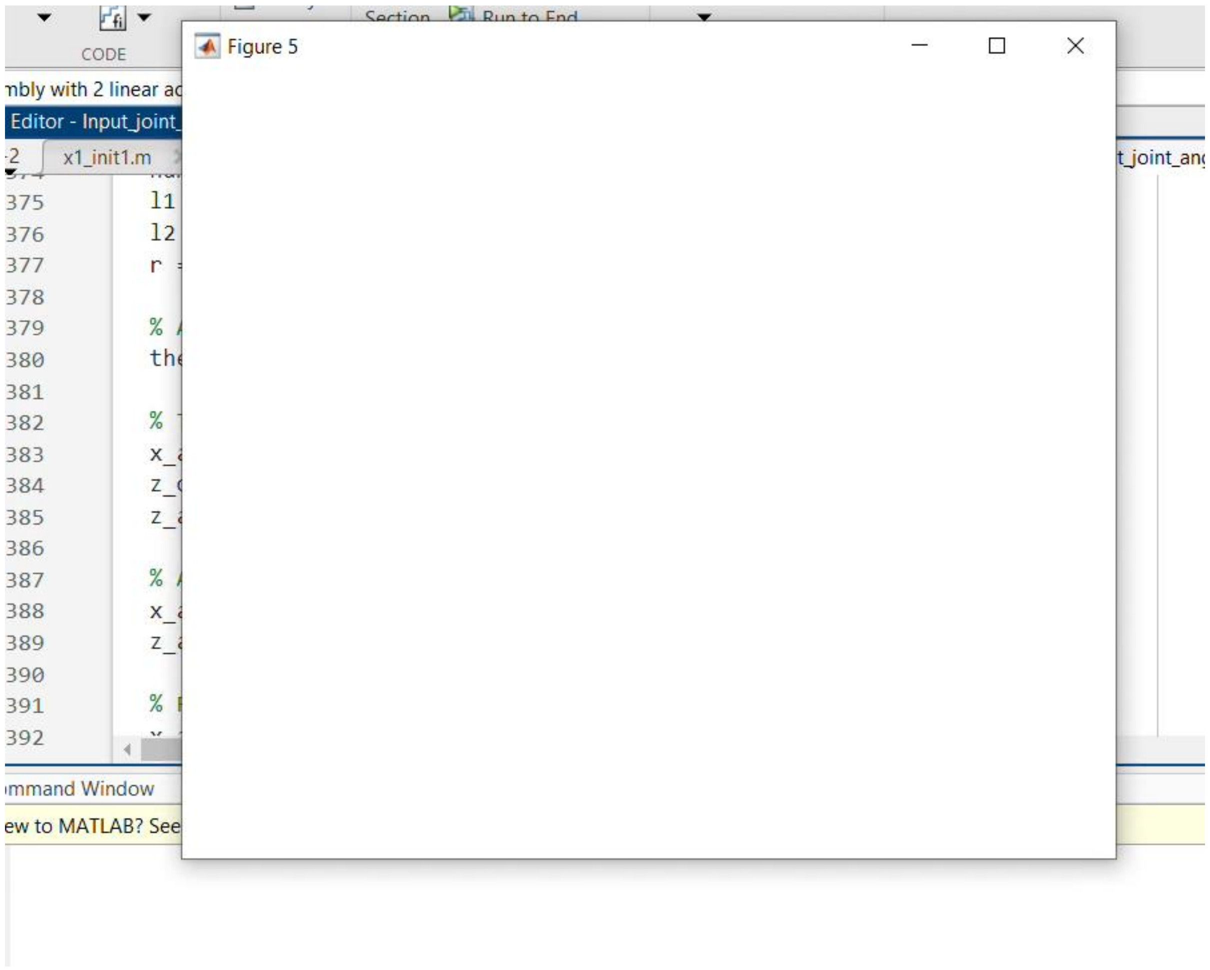
Joint Angle to Actuator length conversion model

$$c_1 = \sqrt{a_1^2 + b_1^2 - 2(a_1)(b_1)\cos(\theta - \gamma)}$$

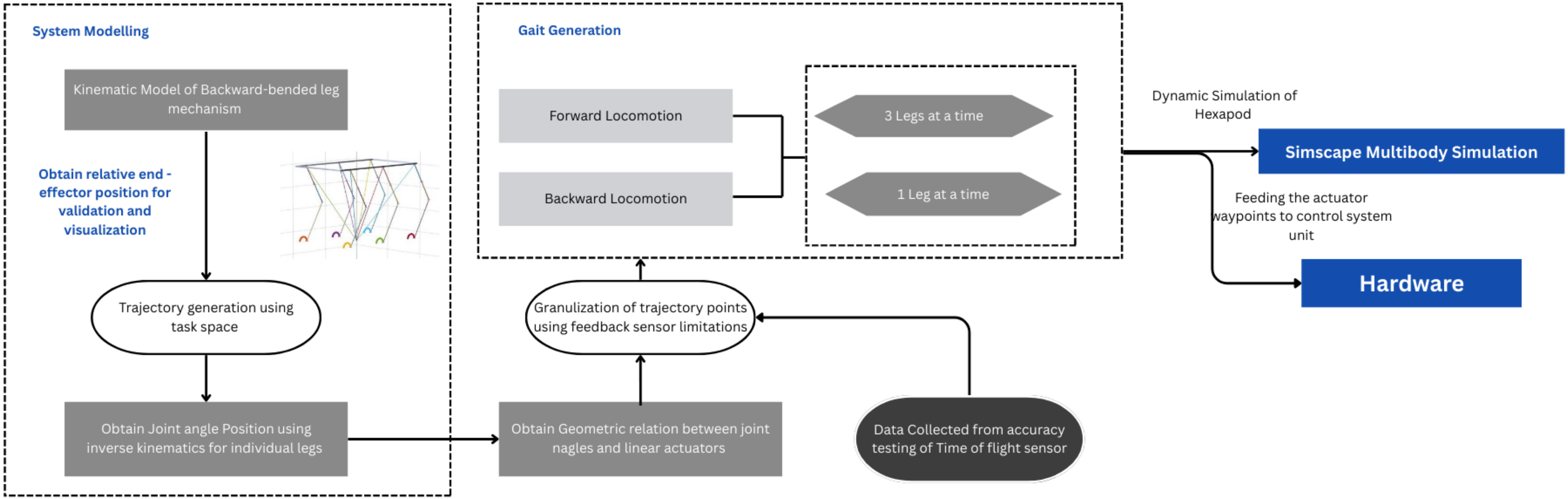
Locomotion Trajectory

- Semicircular Trajectory
- Adjustable Height-Swing-Stance
- Swing Phase(Even numbered Legs) in sync with stance phase of other legs.

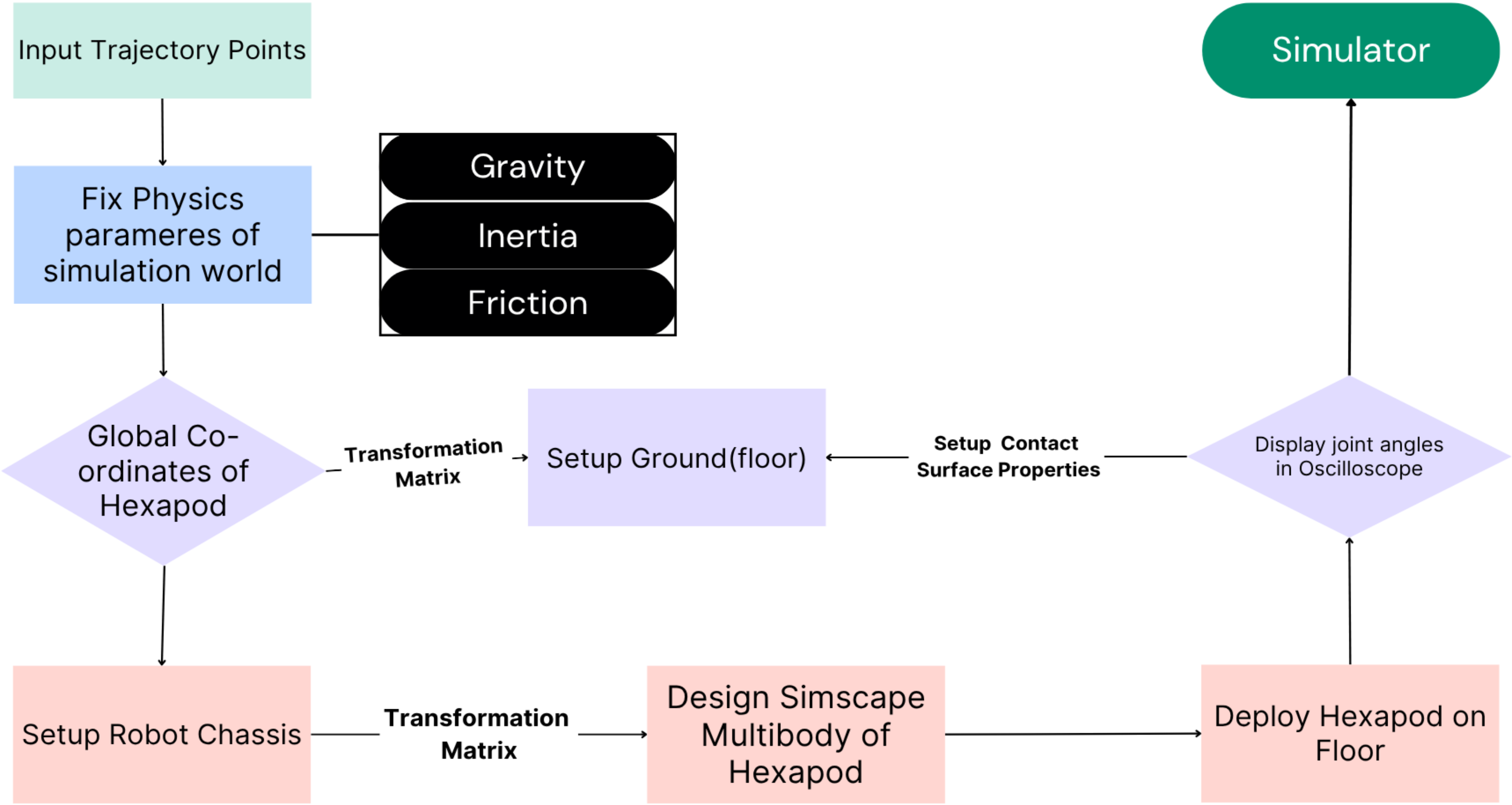




MODELLING IMPLEMENTATION



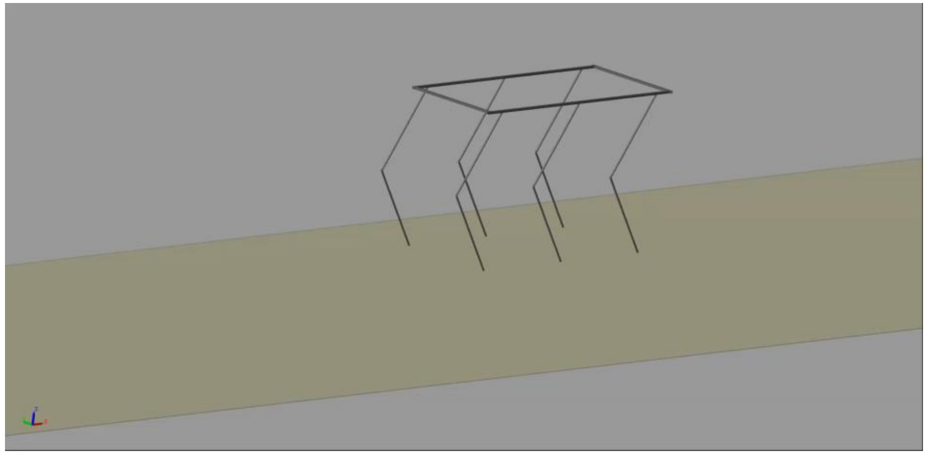
SIMSCAPE MULTIBODY SIMULATION



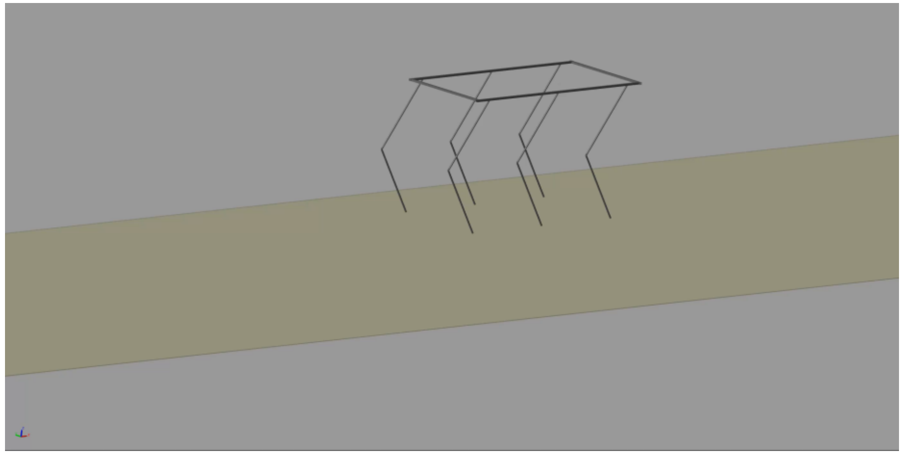
SIMULATION VIDEOS

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

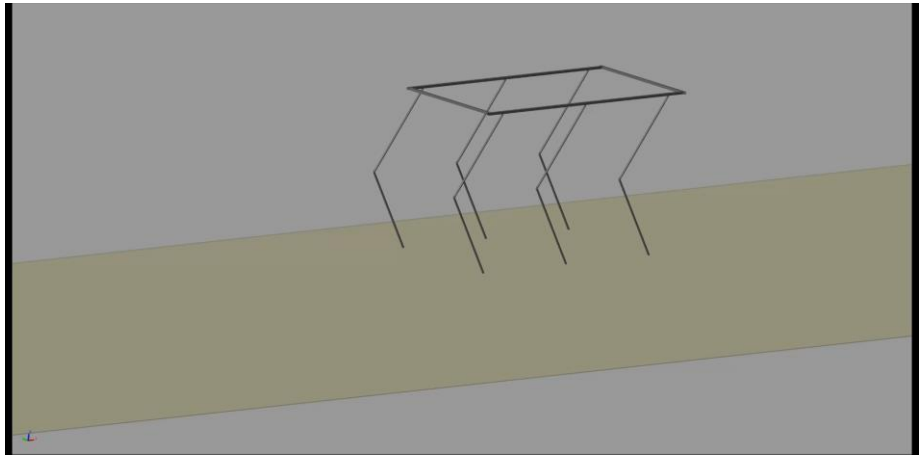
Forward Locomotion (Single leg)



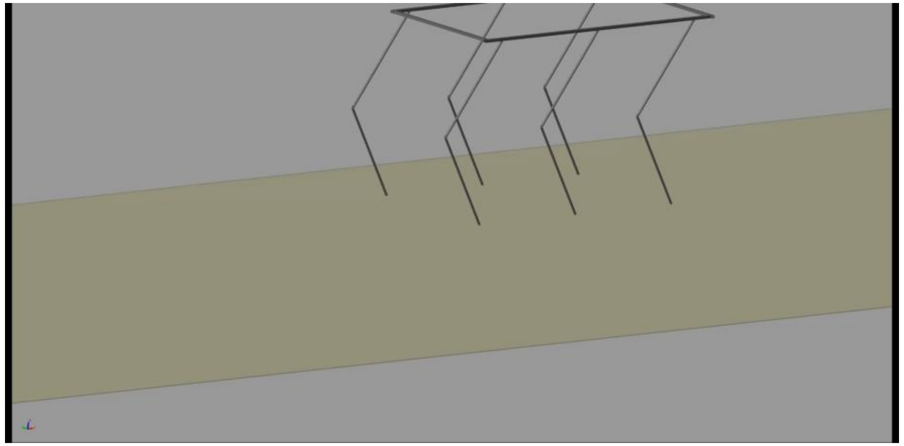
Backward Locomotion (Single leg)



Forward Locomotion (Triple leg)



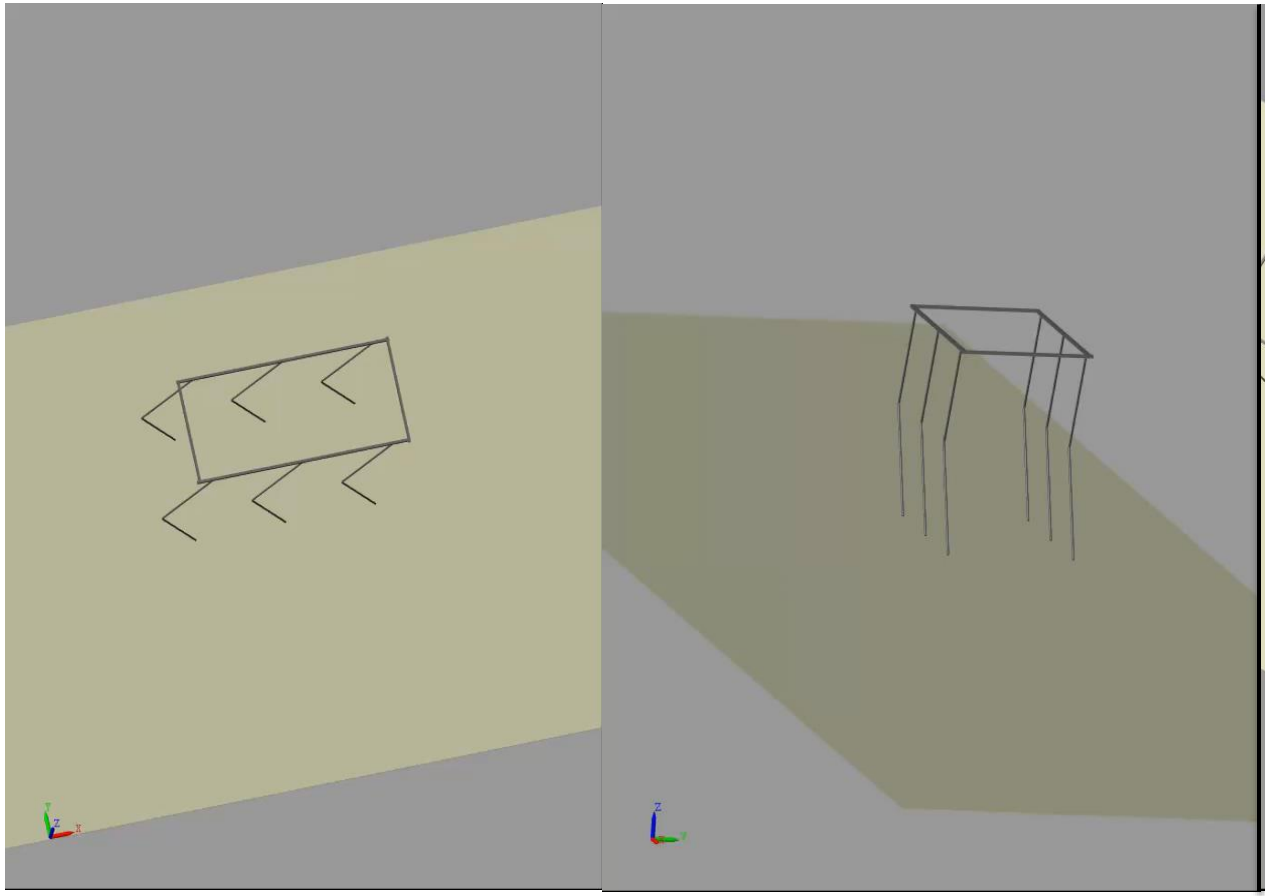
Backward Locomotion (Triple leg)



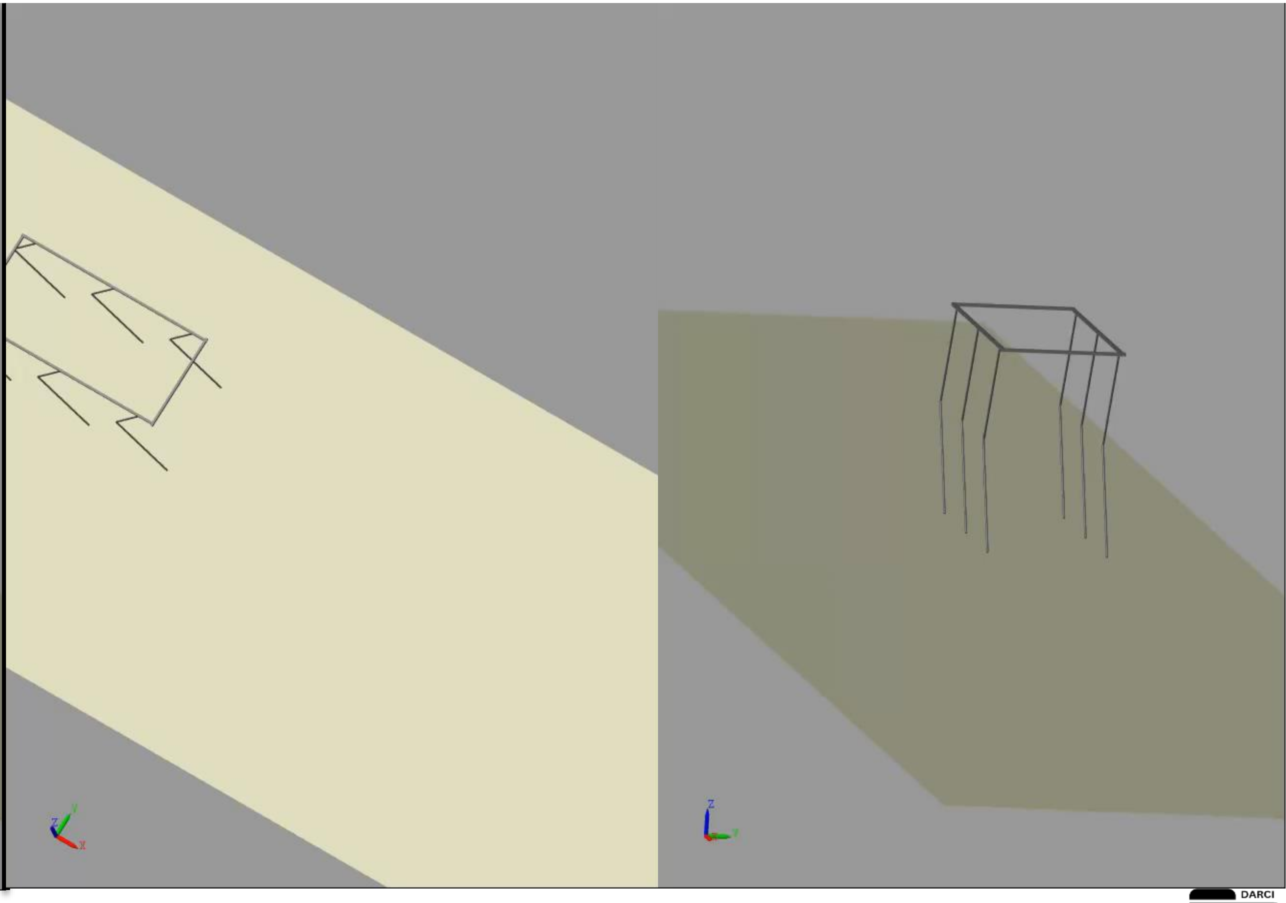
SIMULATION VIDEOS

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

Left Turning

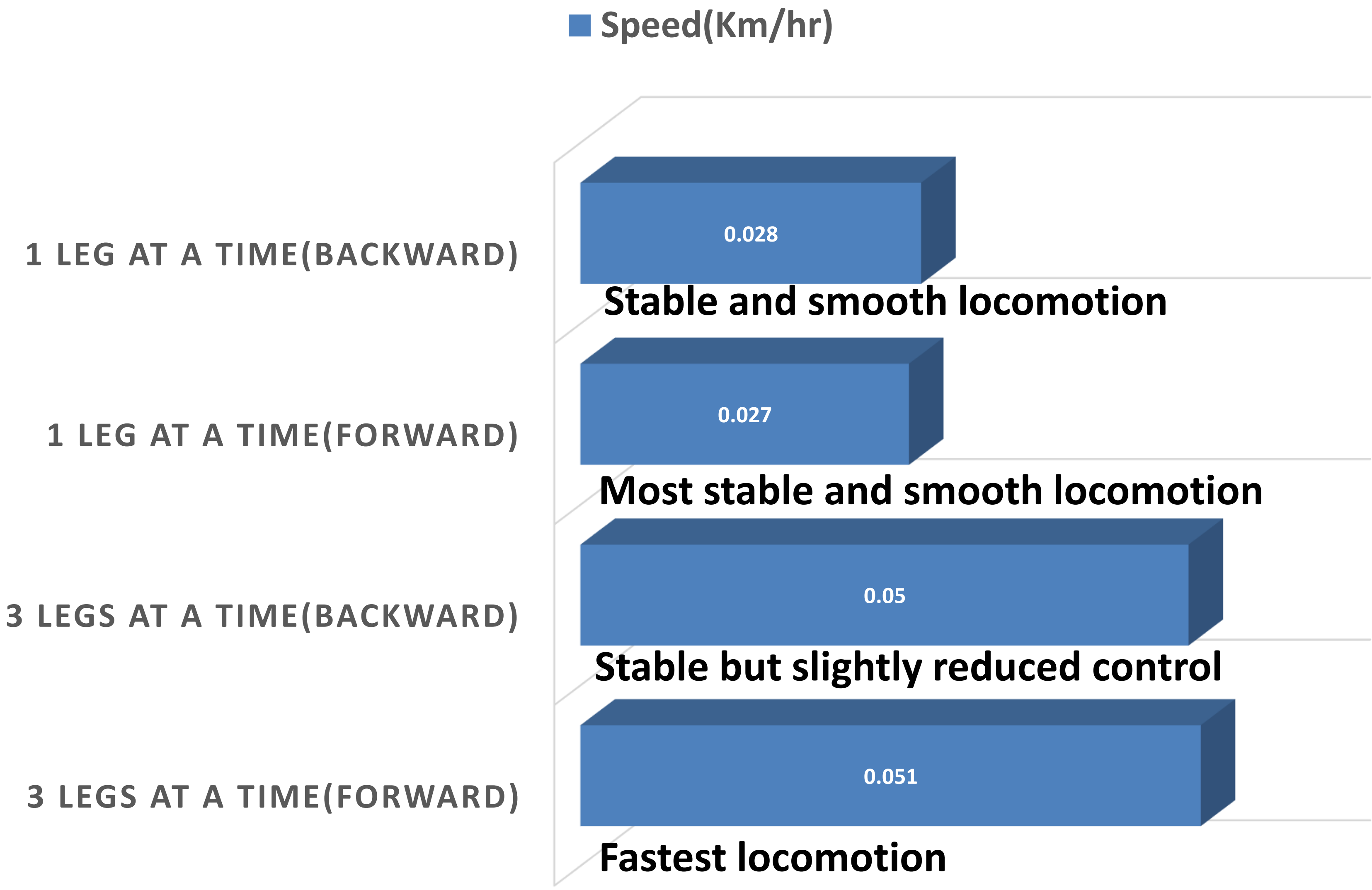


Right Turning



GAIT STRATAGIES AND OBSERVATIONS

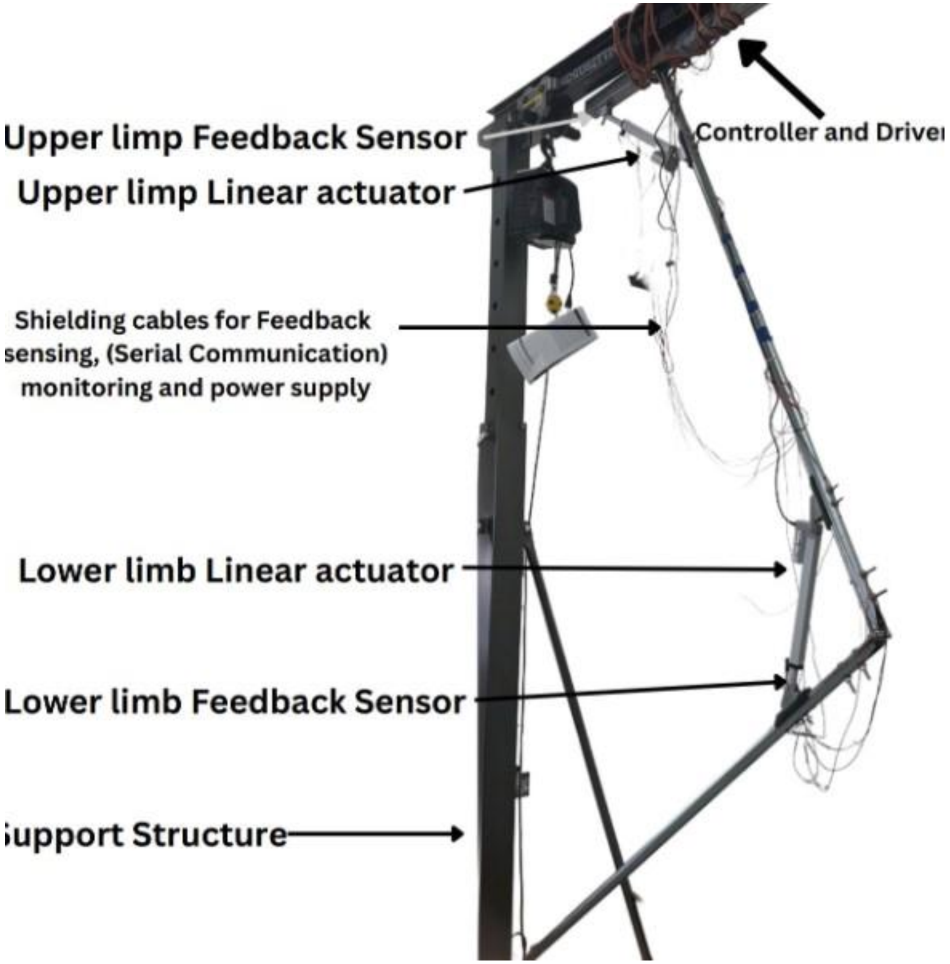
TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering



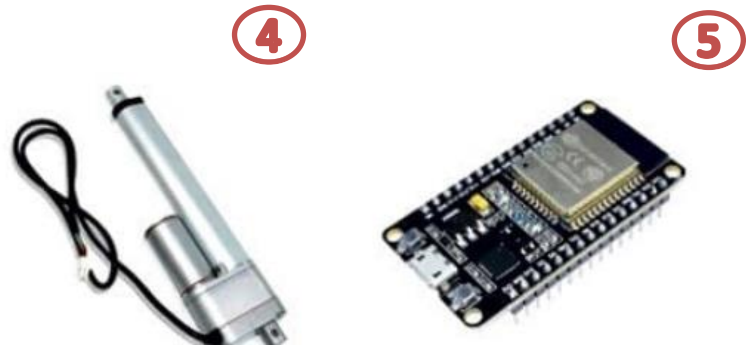
COMPONENT SELECTION

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

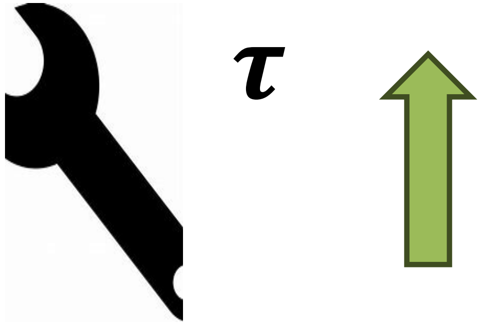
1)Actuator Supporting Bracket
2)Square Forged Tube (Chassis)
3)Cylindrical Tube (Legs)



COMPONENT SELECTION



4)Linear Actuators
5)Microcontroller (ESP 32)



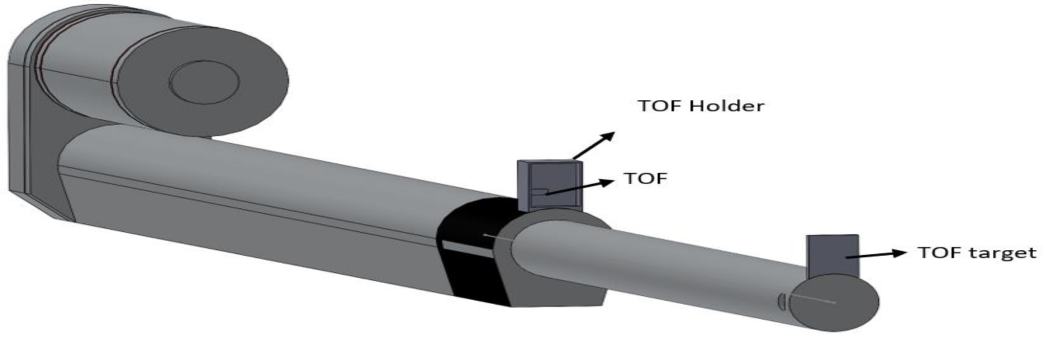
COMPONENT SELECTION

6

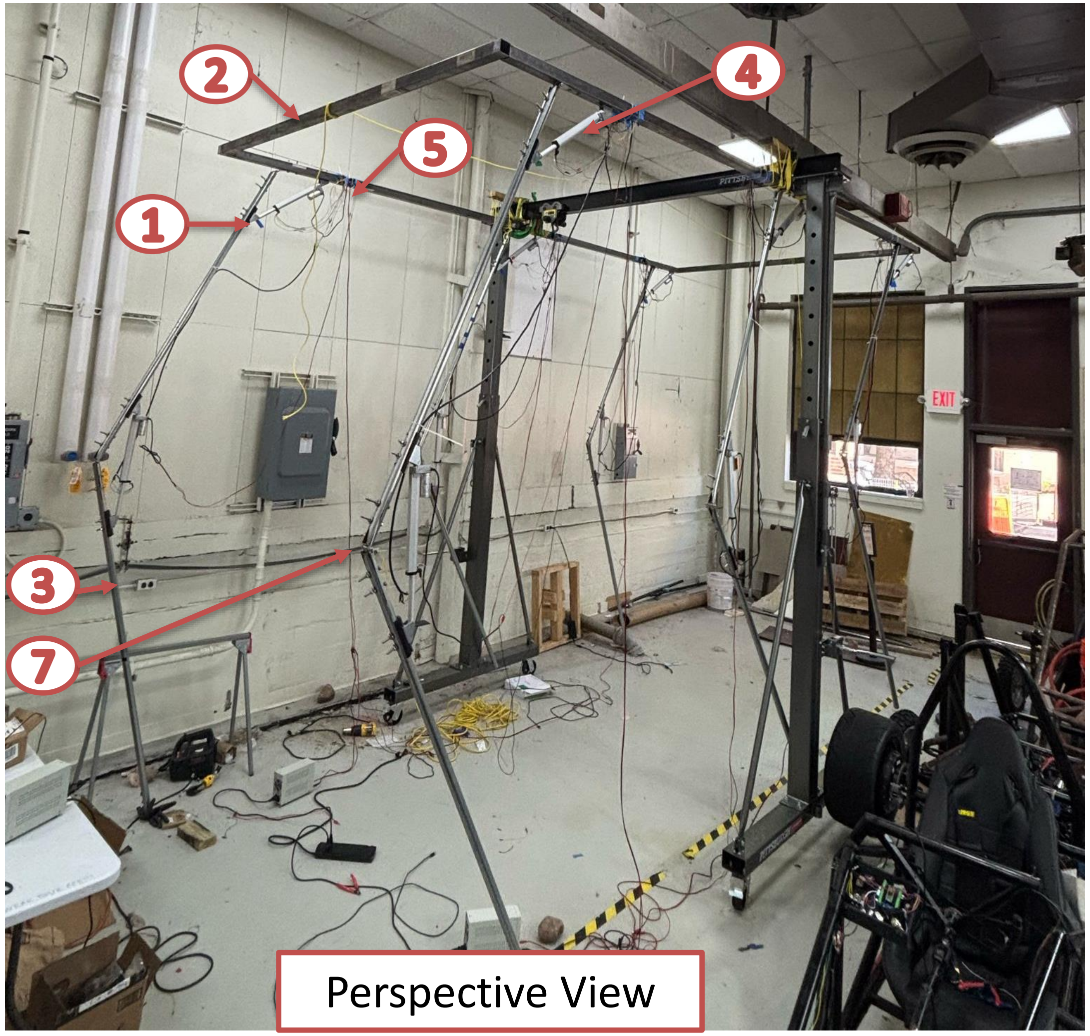
7

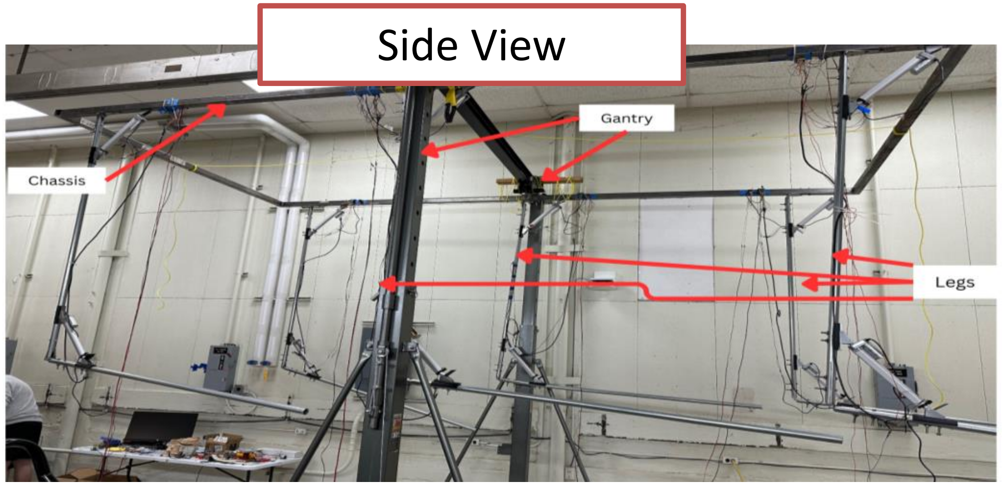
8

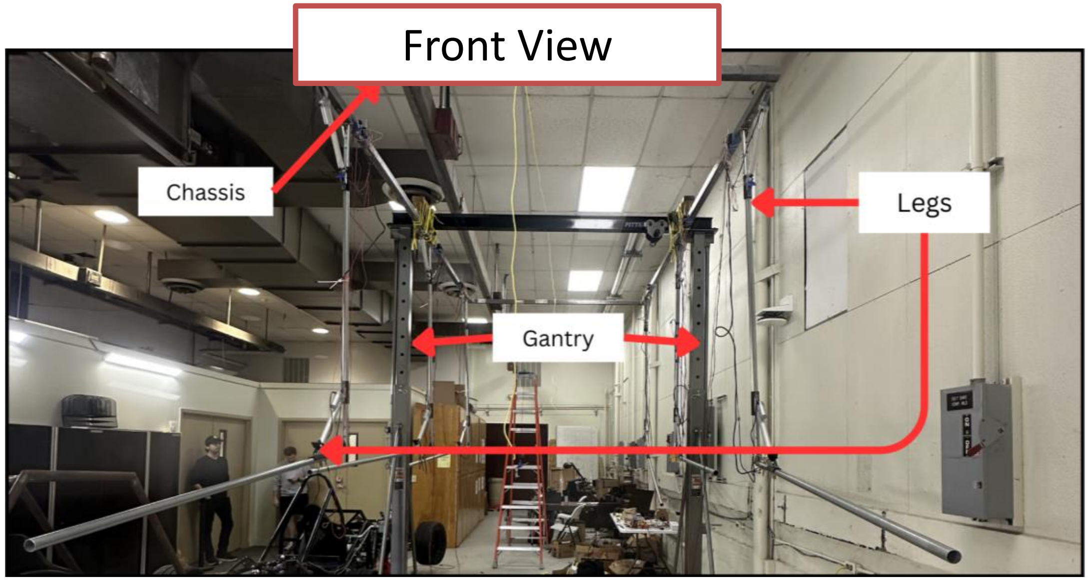
6)Feedback Sensor(VL53L0X TOF)
7)Hinge(Joint)
8)Motor Driver(L298N)



MECHANICAL ASSMEBLY



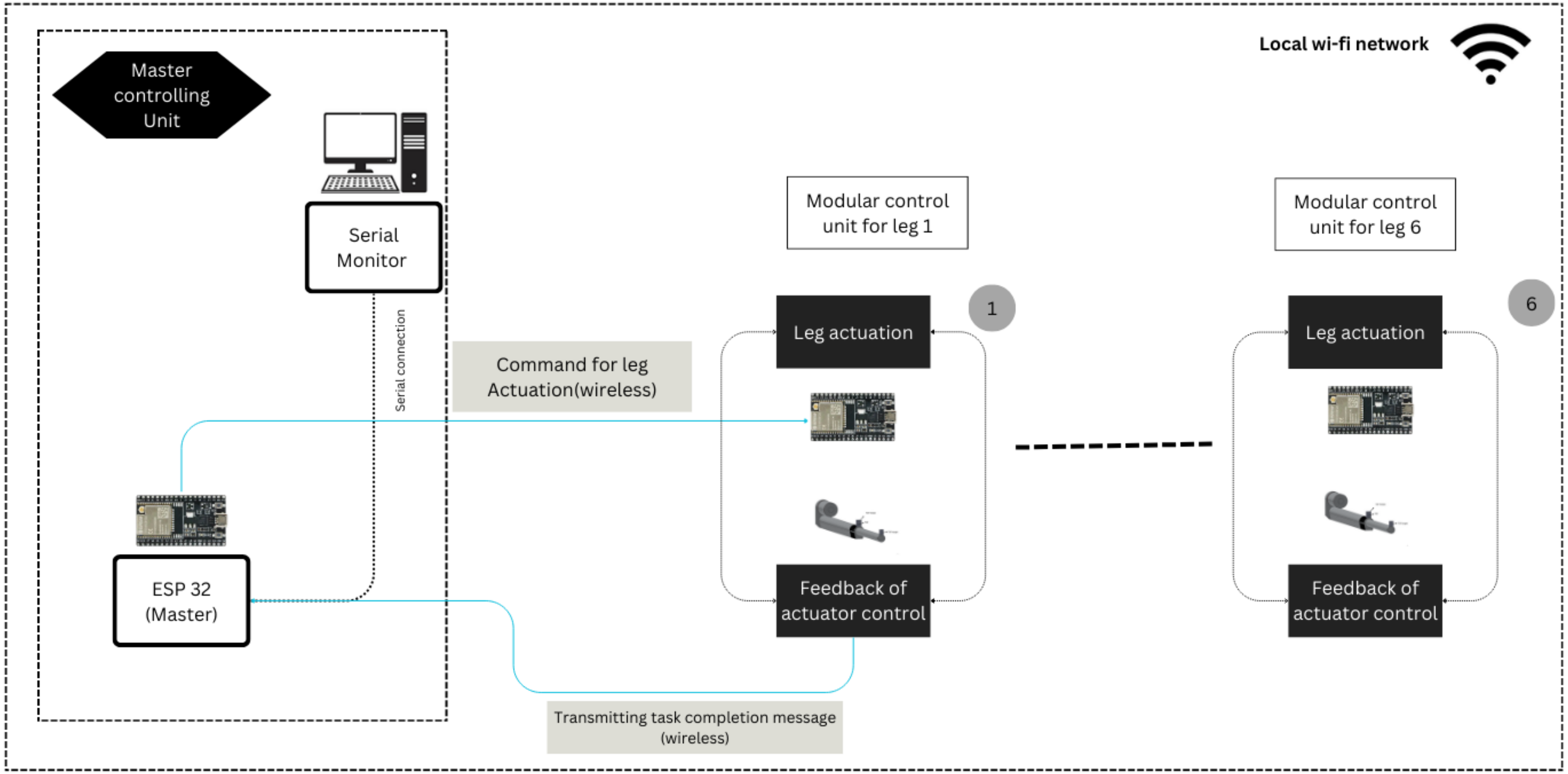




DARCI

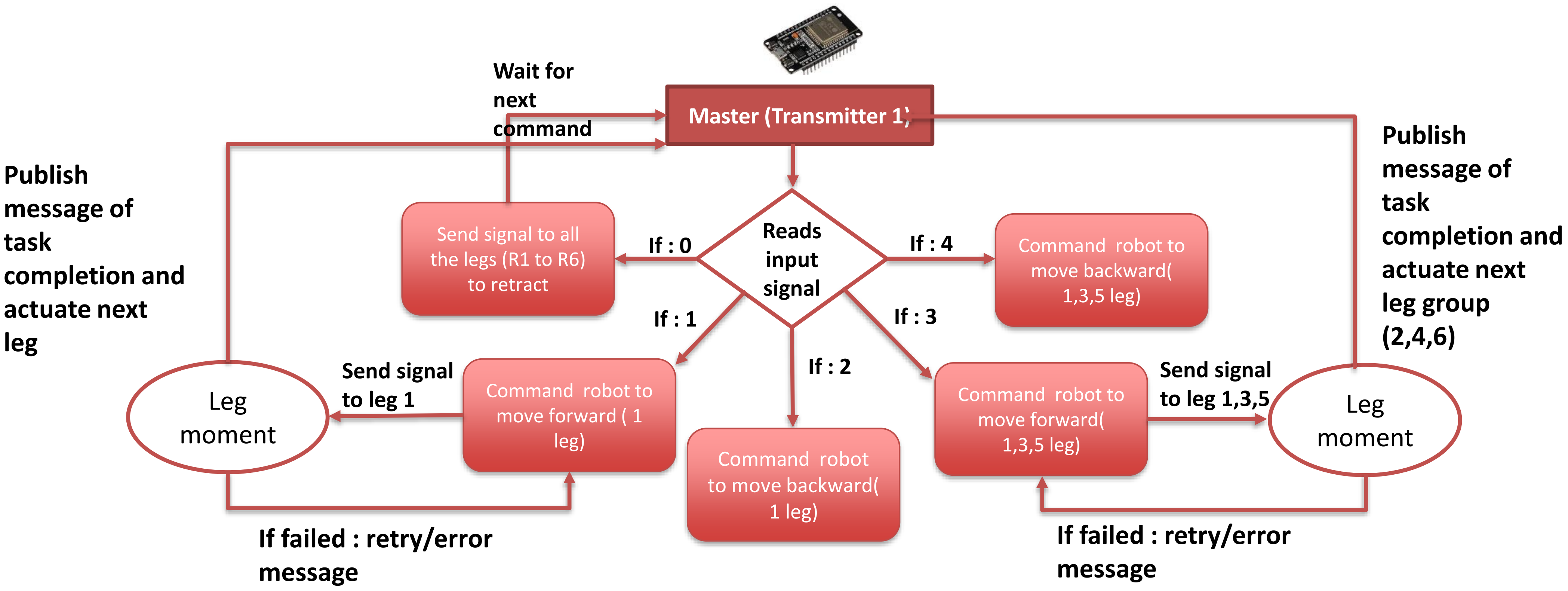
SENSING AND CONTROL ARCHITECTURE

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering



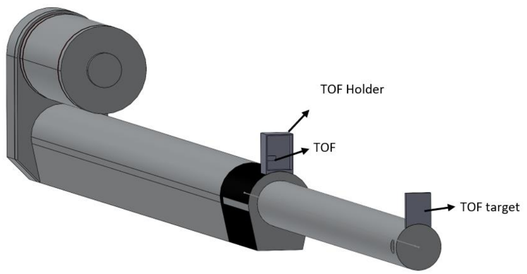
SENSING AND CONTROL ARCHITECTURE

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering



SENSING AND CONTROL ARCHITECTURE

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering



(Receiver 1)

R.T.O.S.

Receives signal to start actuation

Reads current position of the actuator

If: diff > 0

Actuate forward

If: diff < 0

Actuate backward

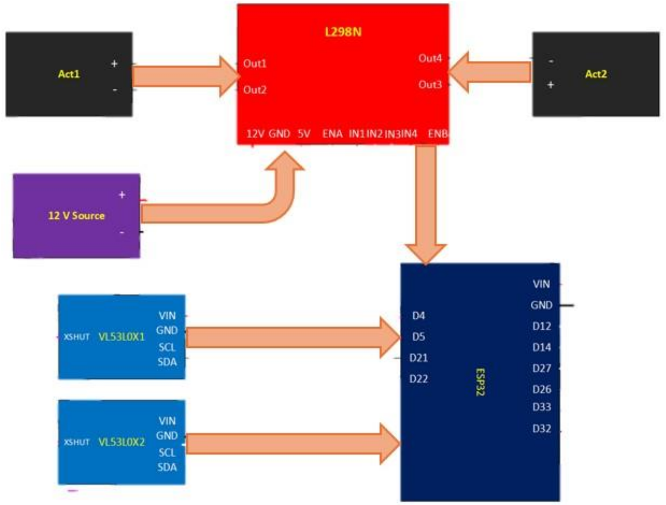
Stop upon achieving the required trajectory point

I + 1^{th} trajectory point

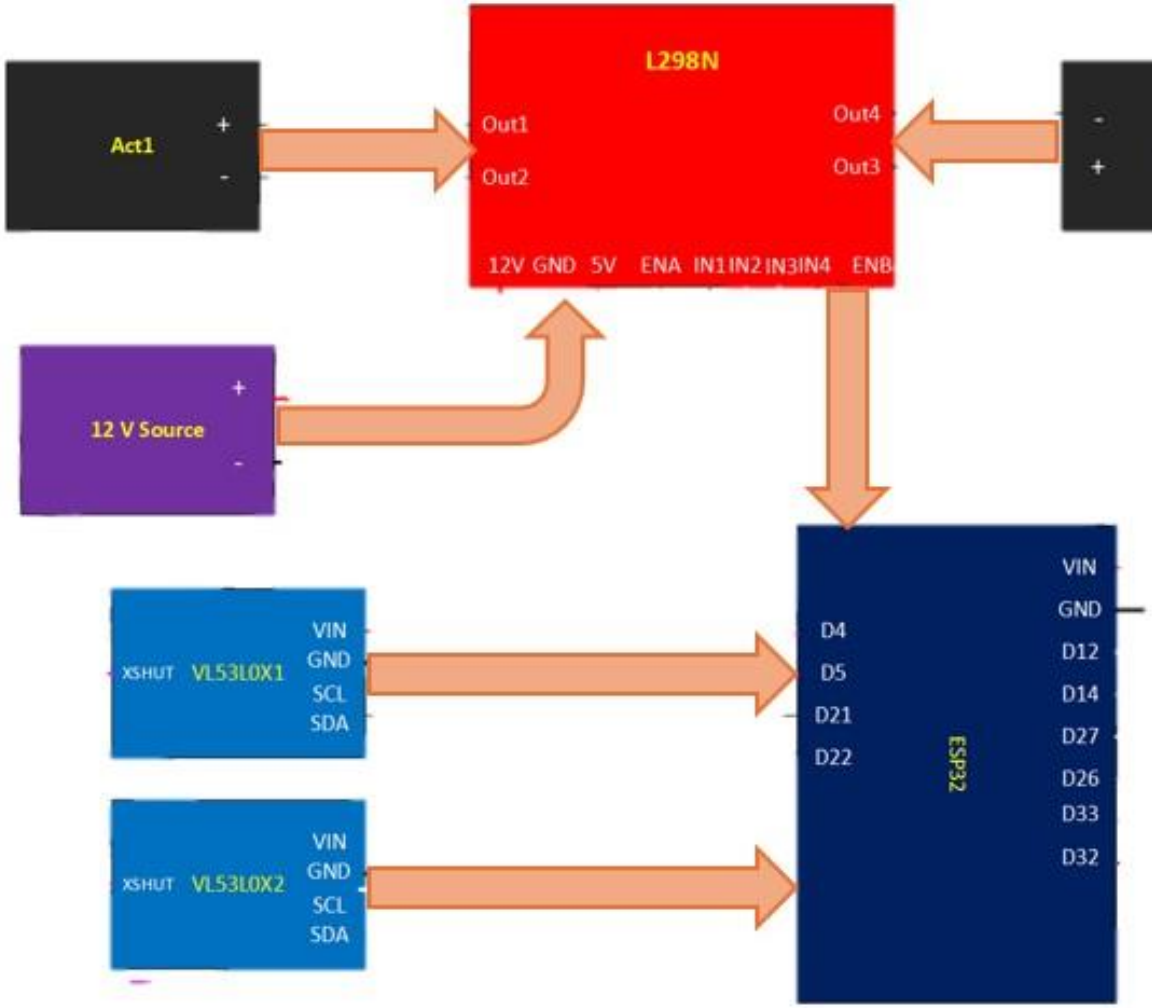
Continuously Monitor Feedback sensor

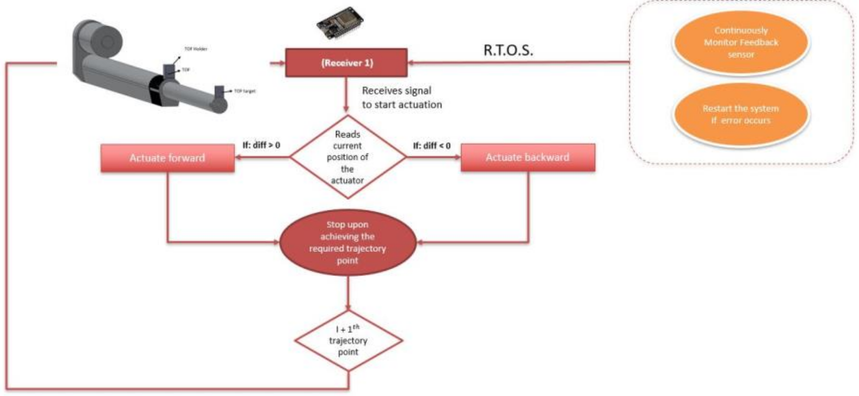
Restart the system if error occurs

Noise Filtering Using Moving Average



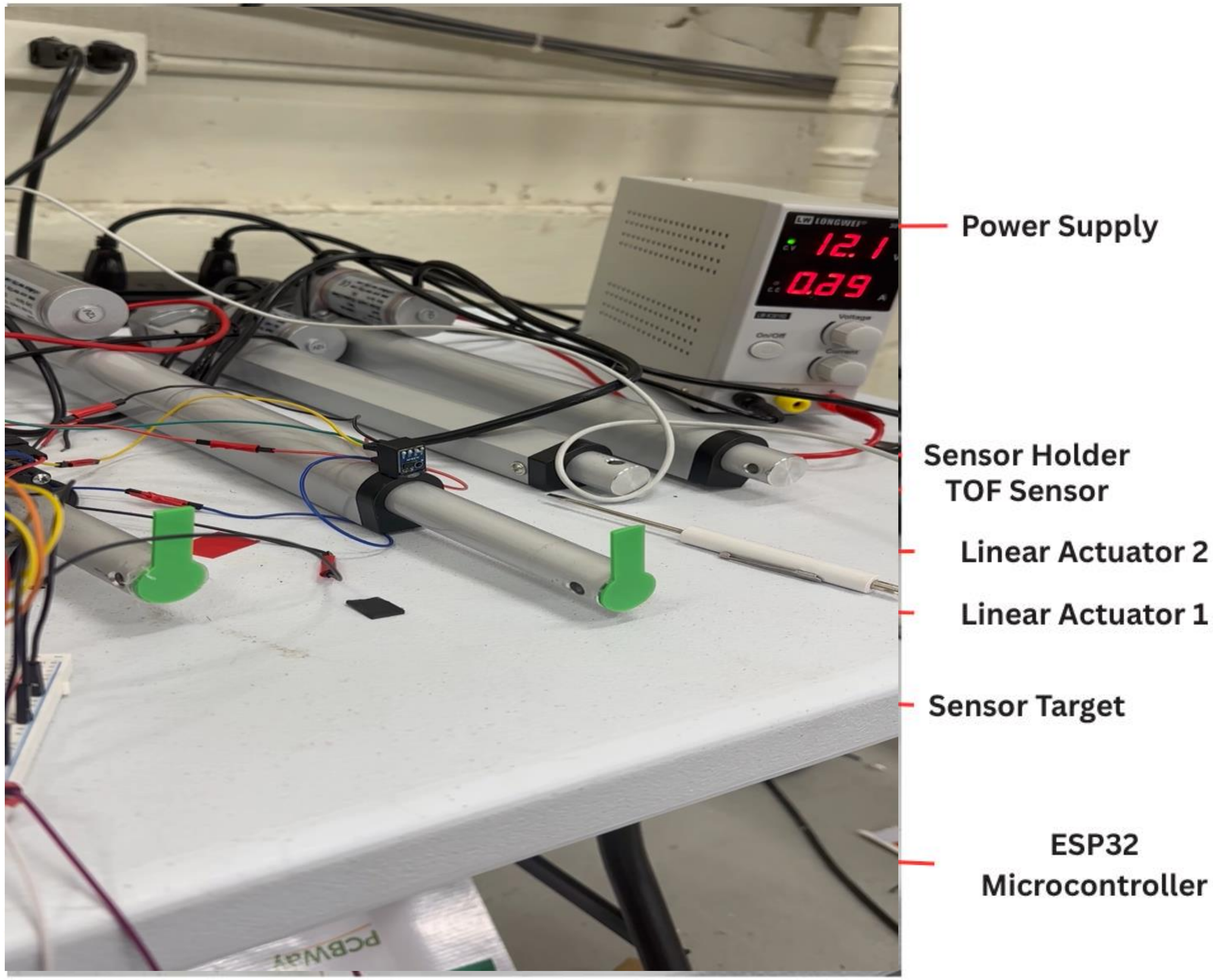
SENSING AND CONTROL ARCHITECTURE





EXPERIMENTAL EVALUATION

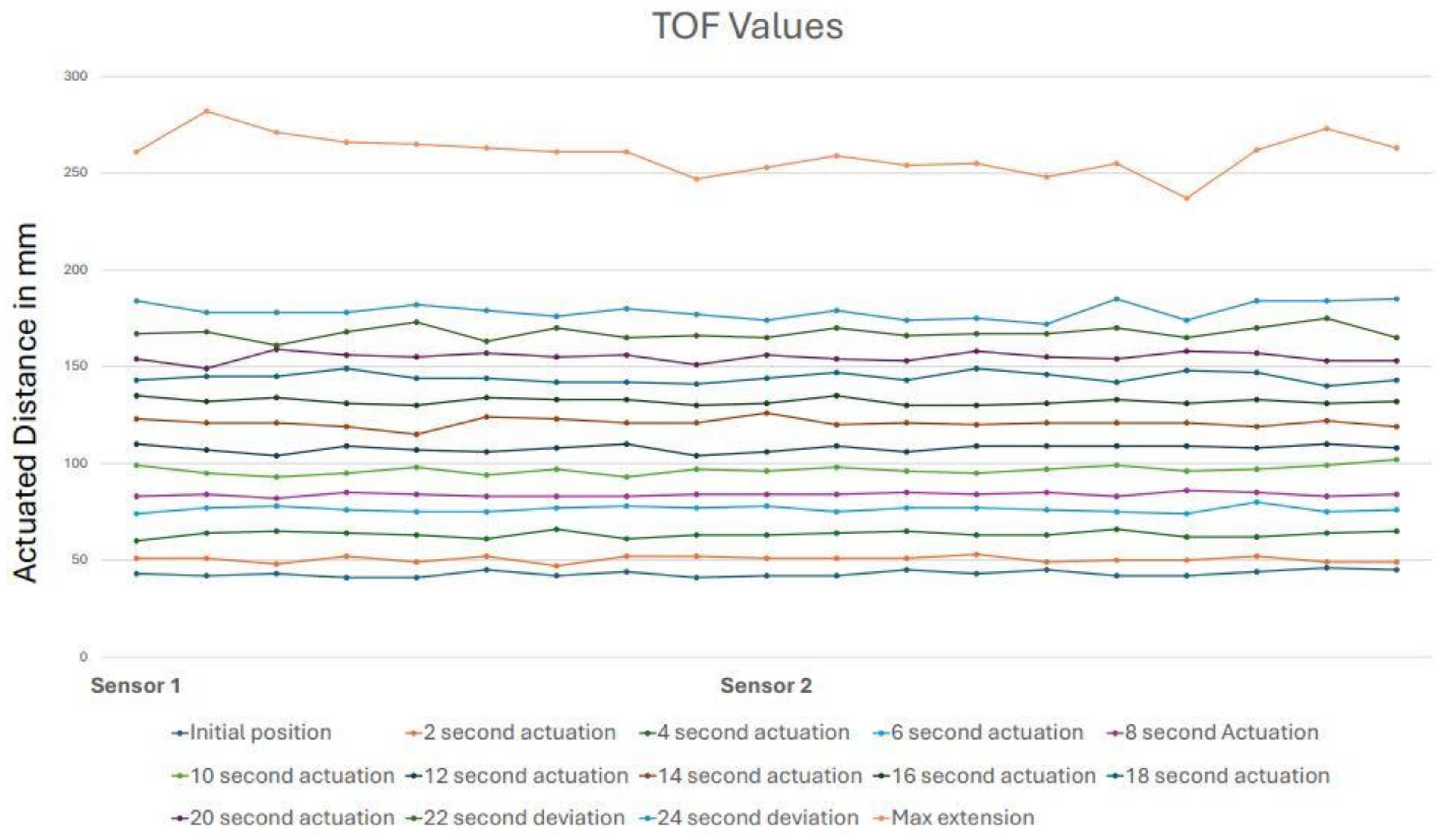
- Feedback Mechanism Precision Test Setup

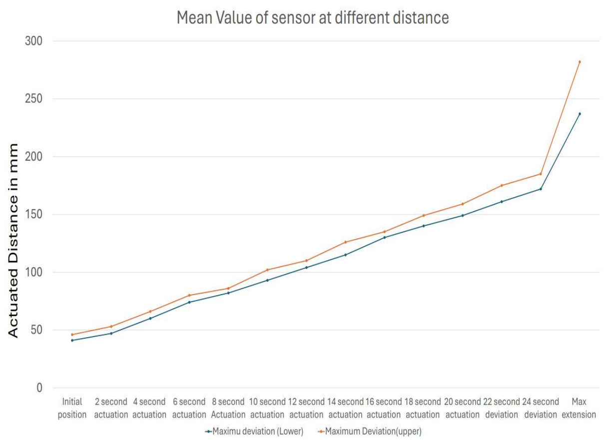


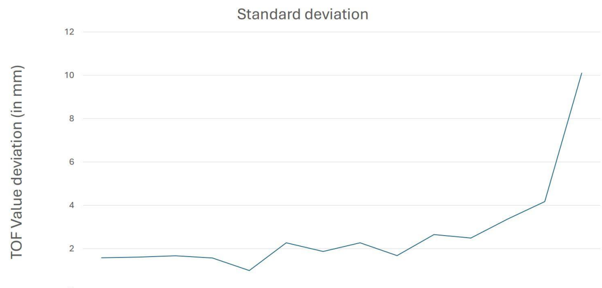
EXPERIMENTAL EVALUATION

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

- Feedback Mechanism Precision Test Setup





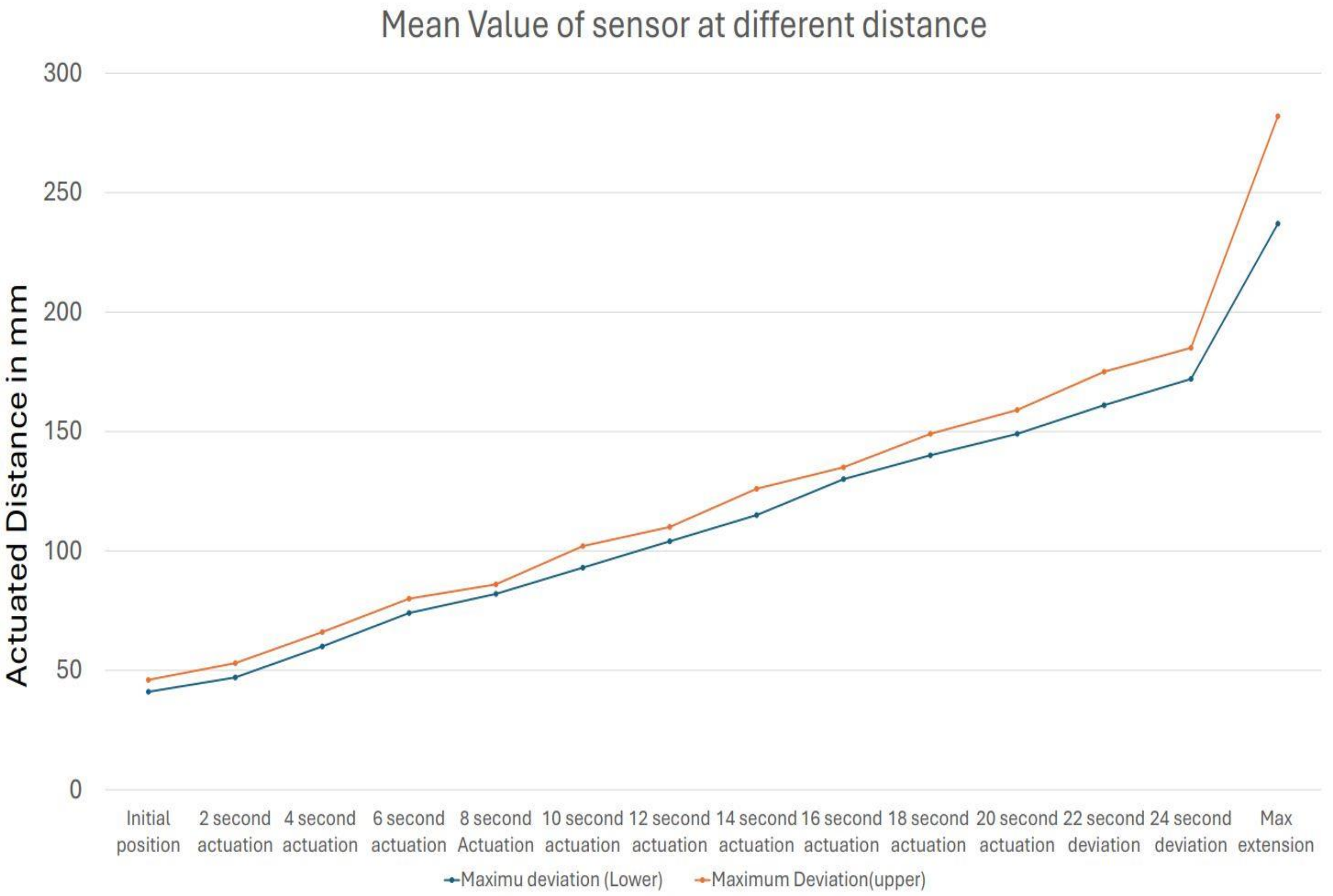


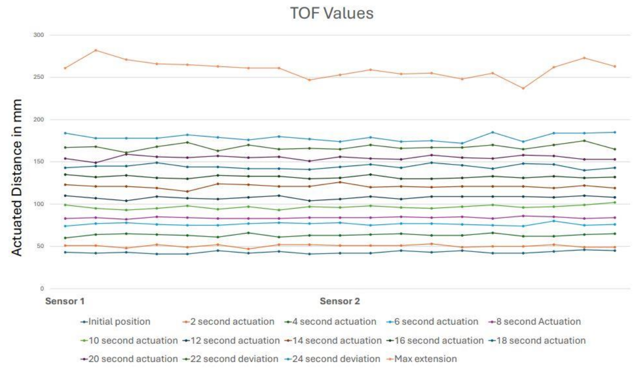
	Initial position	2 second actuation	4 second actuation	6 second actuation	8 second Actuation	10 second actuation	12 second actuation	14 second actuation	16 second actuation	18 second actuation	20 second actuation	22 second deviation	24 second deviation	Max extension
Standard deviation	1.58	1.61	1.67	1.57	0.99	2.27	1.87	2.27	1.68	2.65	2.49	3.37	4.17	10.1

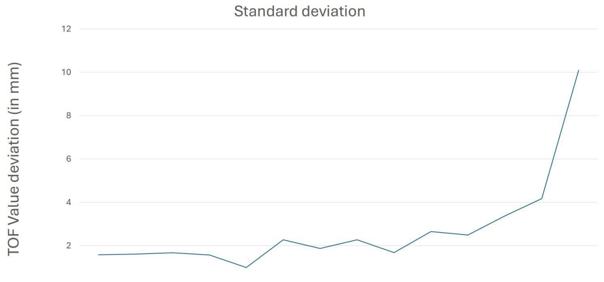
EXPERIMENTAL EVALUATION

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

- Feedback Mechanism Precision Test Setup



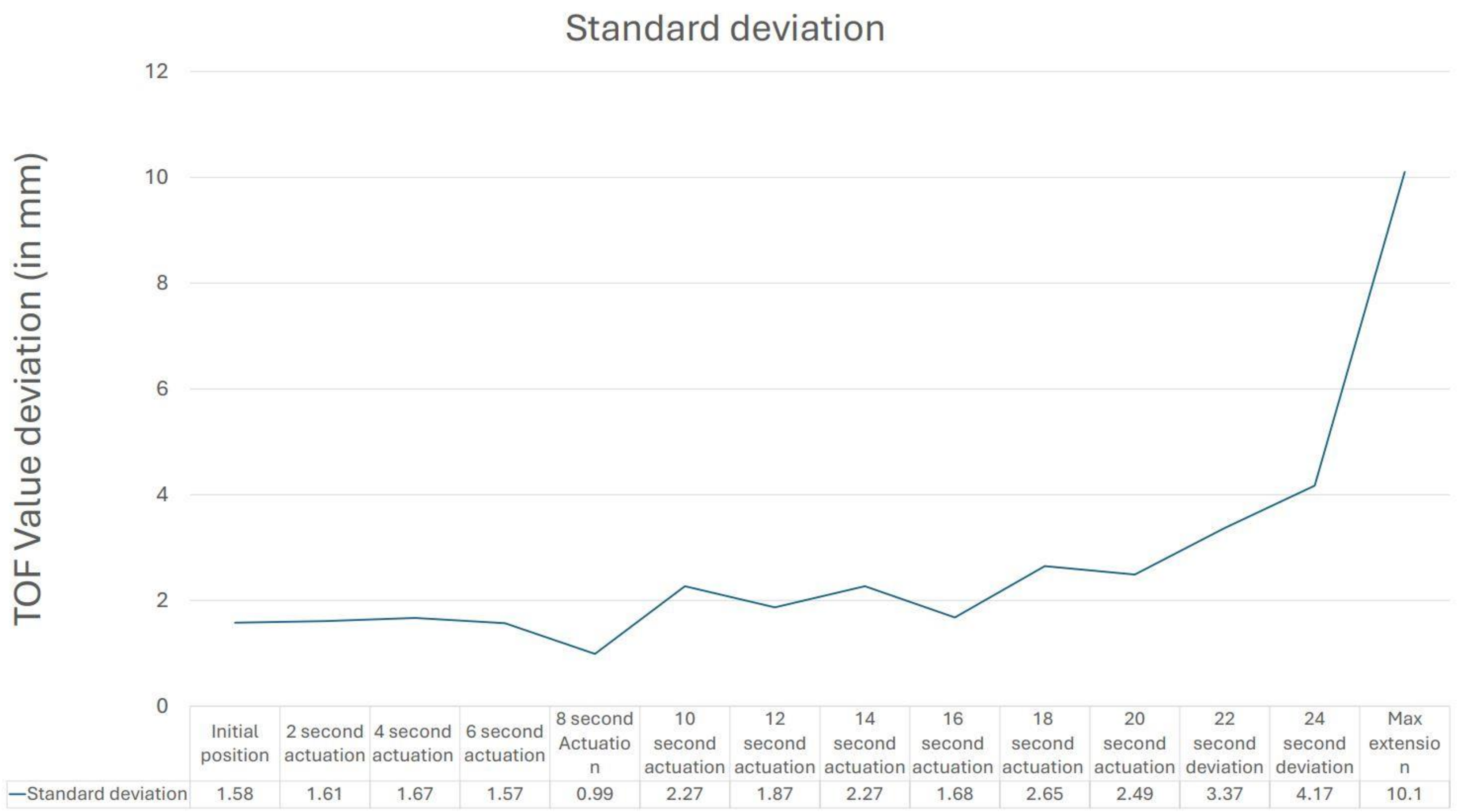


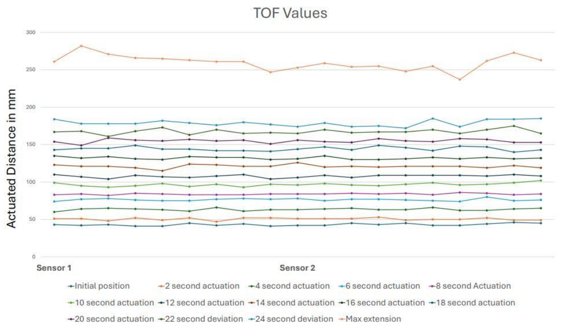


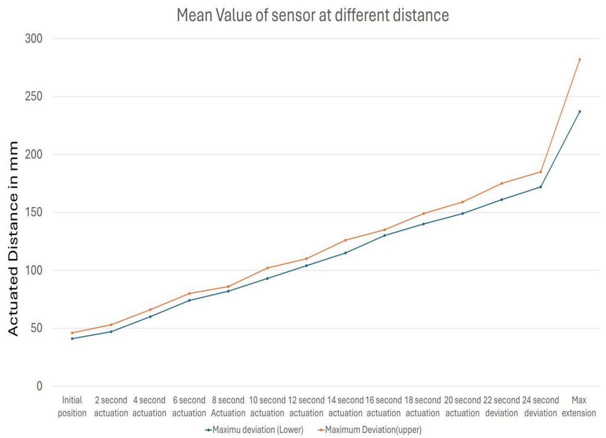
	Initial position	2 second actuation	4 second actuation	6 second actuation	8 second Actuation	10 second actuation	12 second actuation	14 second actuation	16 second actuation	18 second actuation	20 second actuation	22 second deviation	24 second deviation	Max extension
Standard deviation	1.58	1.61	1.67	1.57	0.99	2.27	1.87	2.27	1.68	2.65	2.49	3.37	4.17	10.1

EXPERIMENTAL EVALUATION

- Feedback Mechanism Precision Test Setup



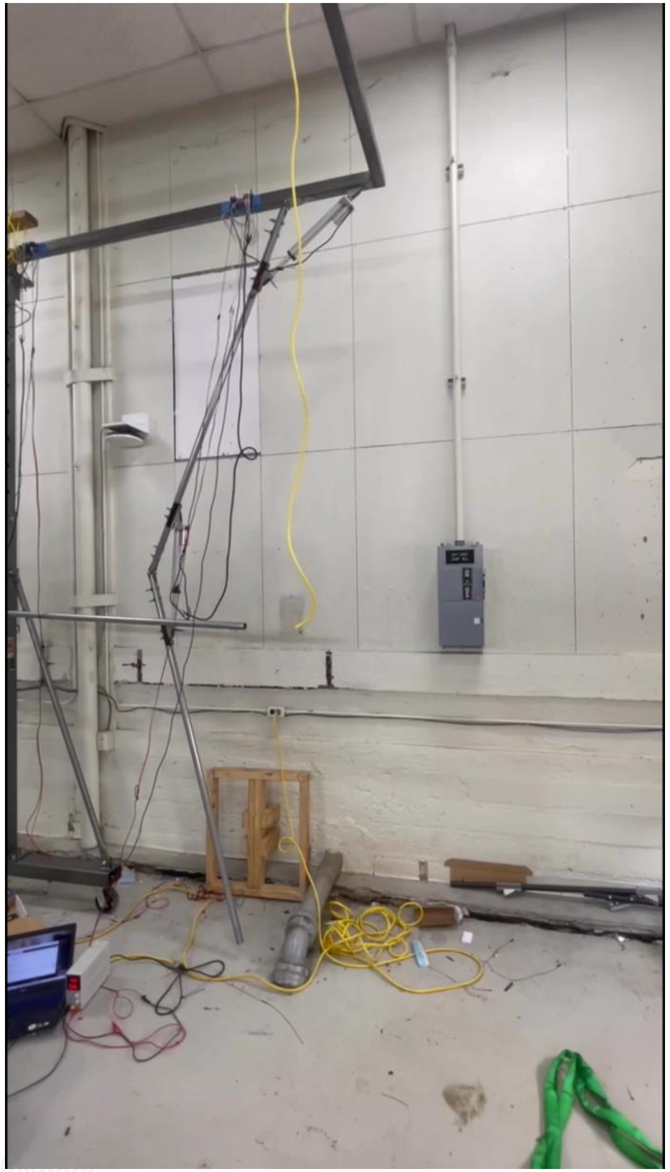




EXPERIMENTAL EVALUATION

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

- Feedback Mechanism Precision Test Setup
- Open Loop Control



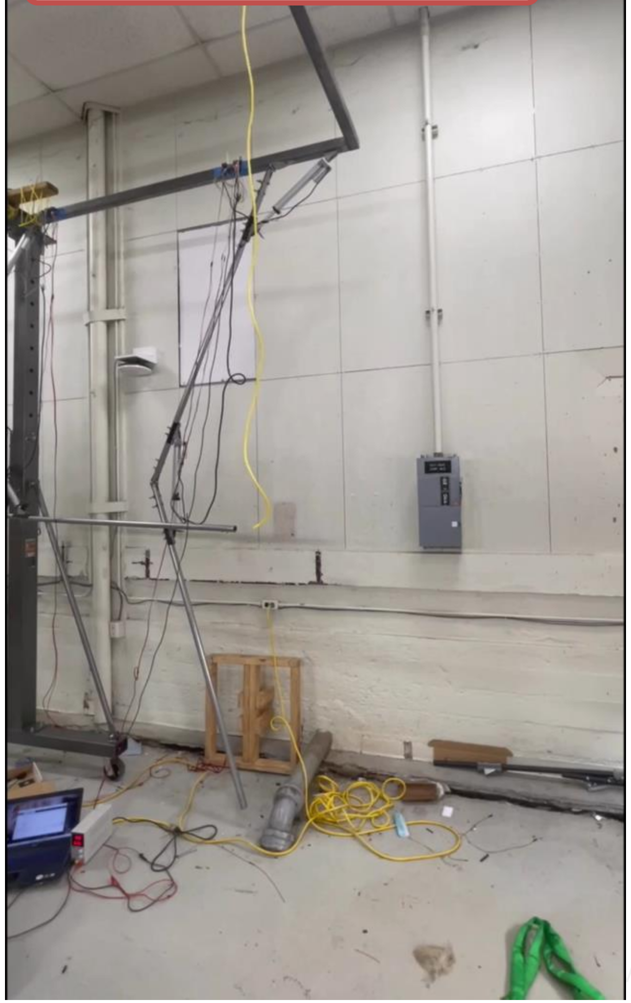
TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

EXPERIMENTAL EVALUATION

- Feedback Mechanism Precision Test Setup
- Open Loop Control
- Close Loop Control

Forward Locomotion (10 FT)

Backward Locomotion (10 FT)



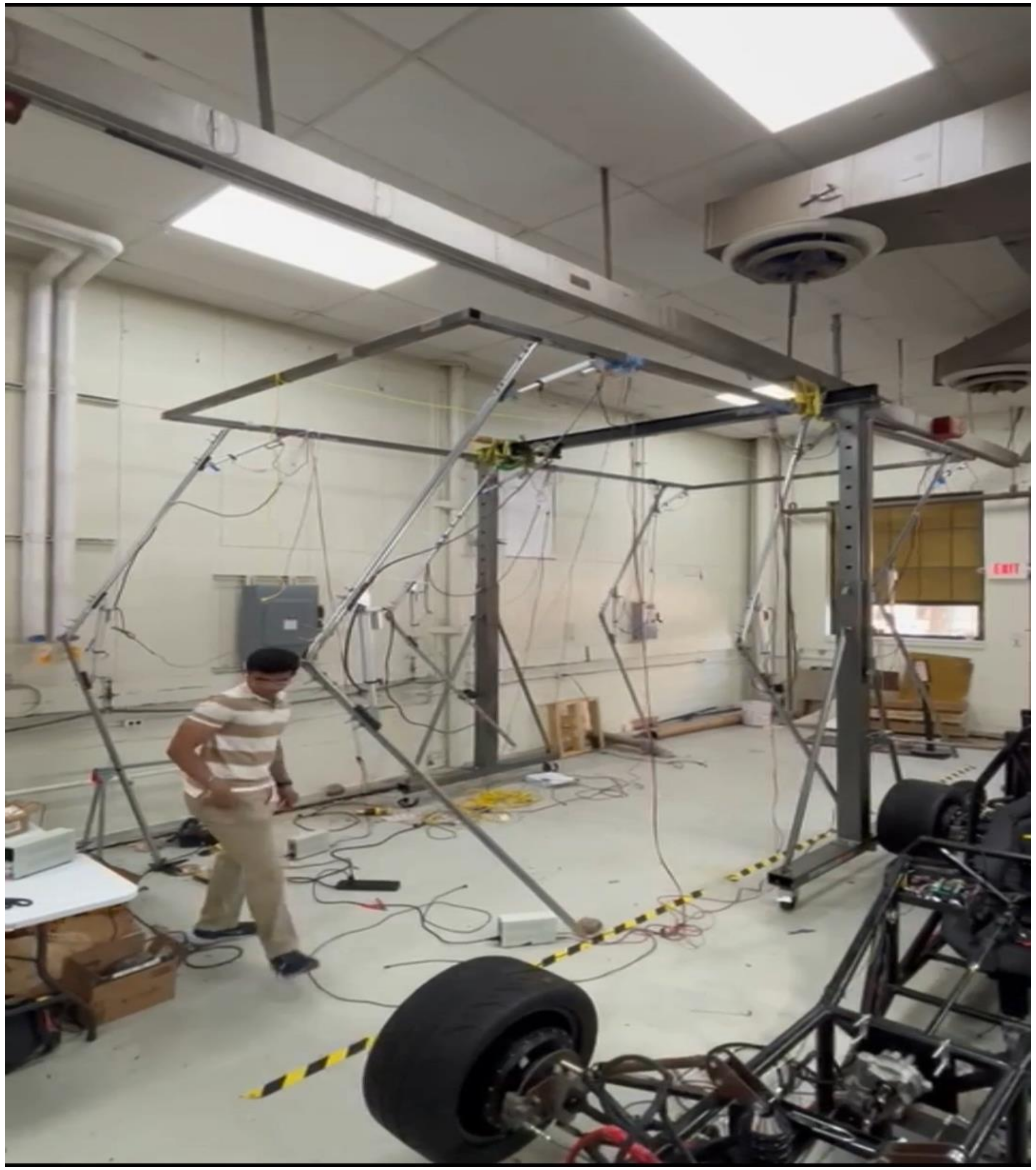
Forward Locomotion (8 FT)

Backward Locomotion (8 FT)

EXPERIMENTAL EVALUATION

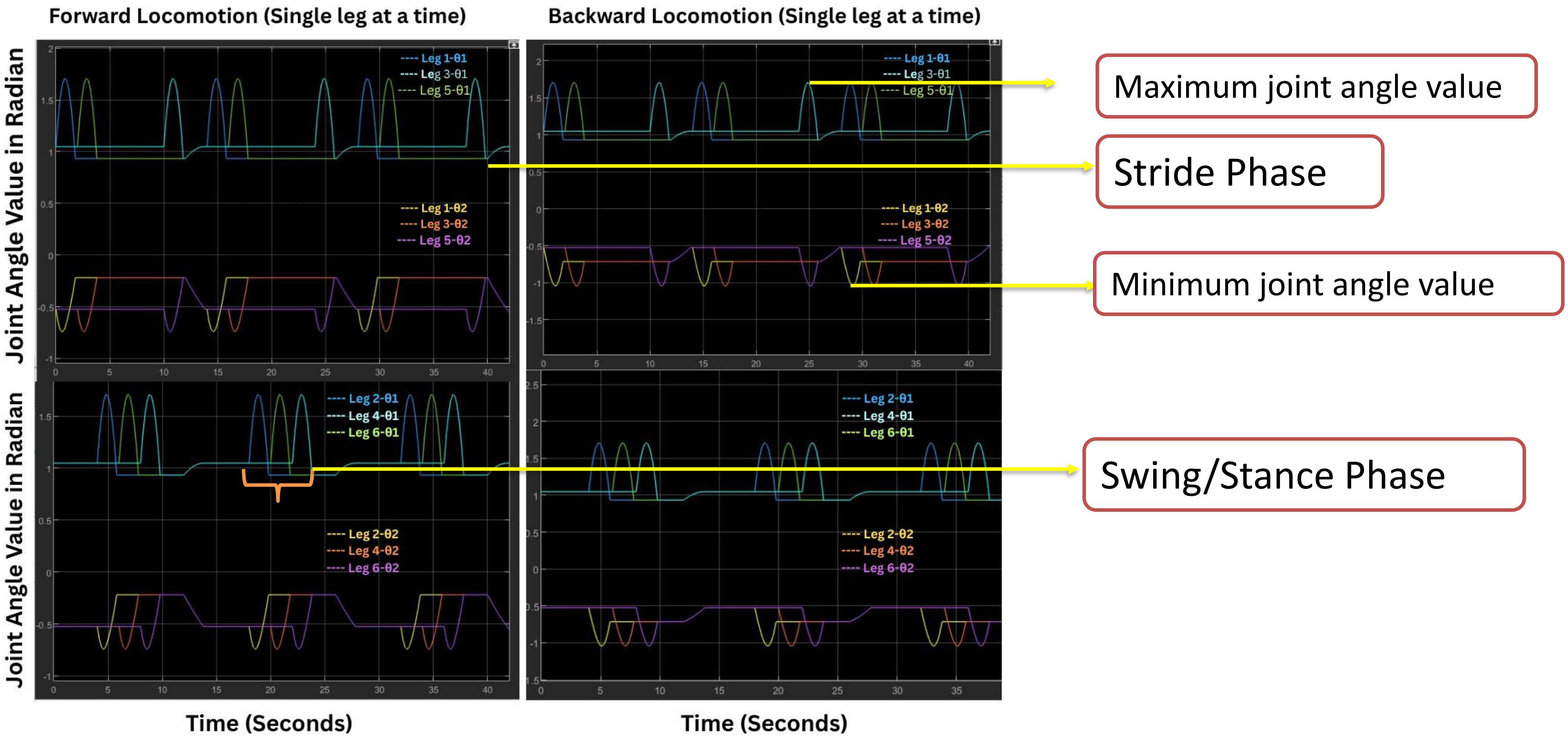
TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

- Feedback Mechanism Precision Test Setup
- Open Loop Control
- Close Loop Control
- Final Testing



EXPERIMENT RESULTS (Joint Space Analysis)

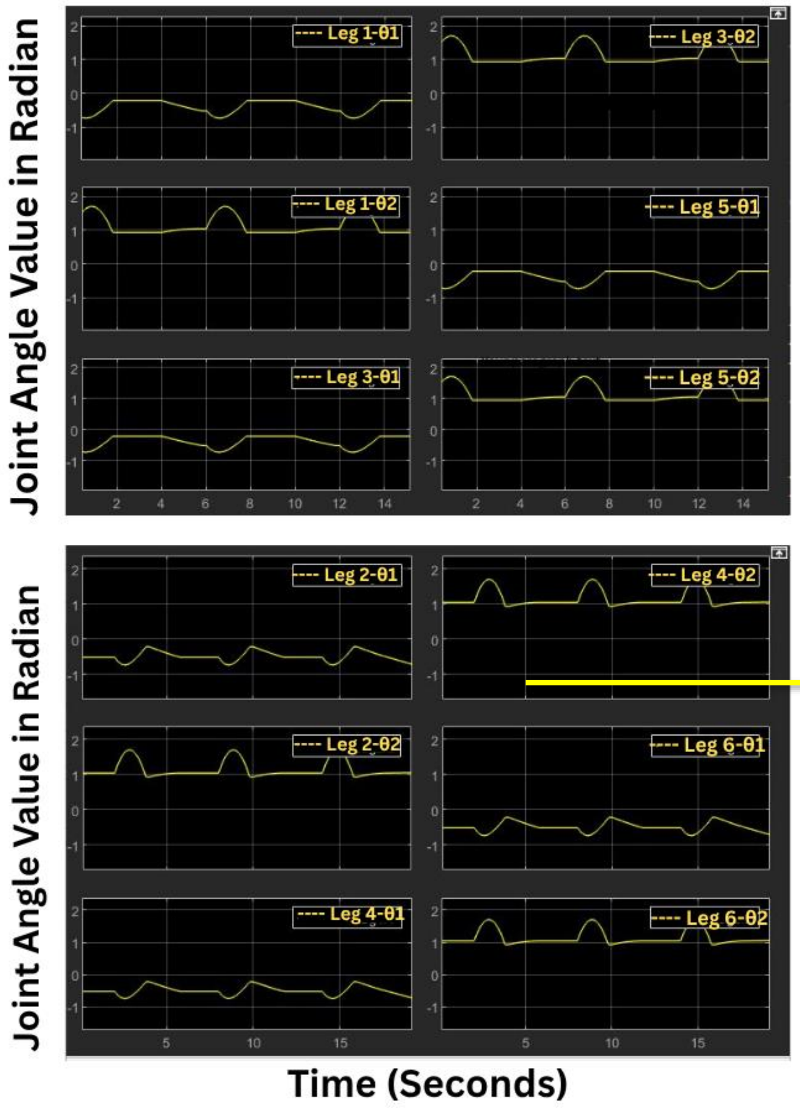
TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering



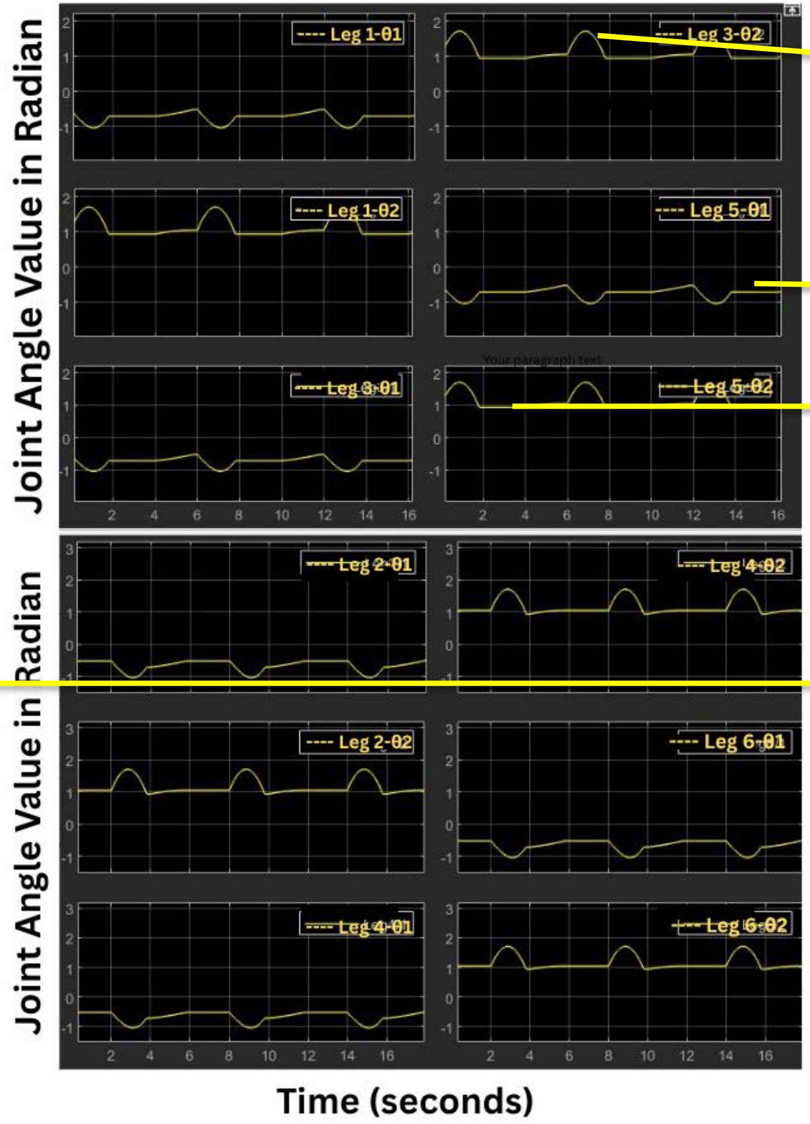
EXPERIMENT RESULTS (Joint Space Analysis)

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

Three legs at a time (Forward)



Three legs at a time (Backward)



Maximum joint angle value

Stride Phase

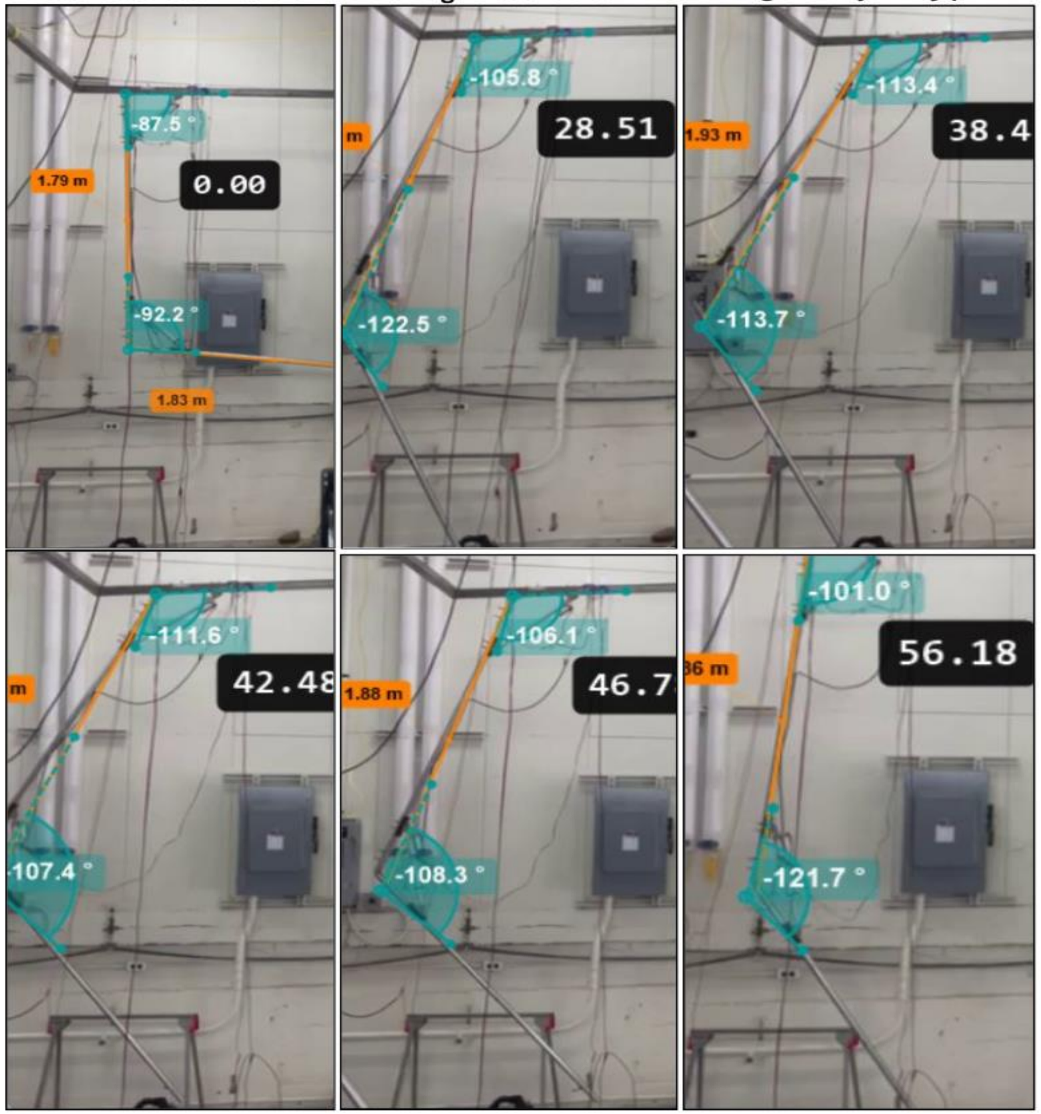
Minimum joint angle value

Swing/Stance Phase

EXPERIMENT RESULTS (Joint Space Analysis)

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

Initial Retracted Position | Swing Initial Position | Swing 3rd Trajectory point



Swing 5th Trajectory point | Swing 7th Trajectory point | Swing Final Position

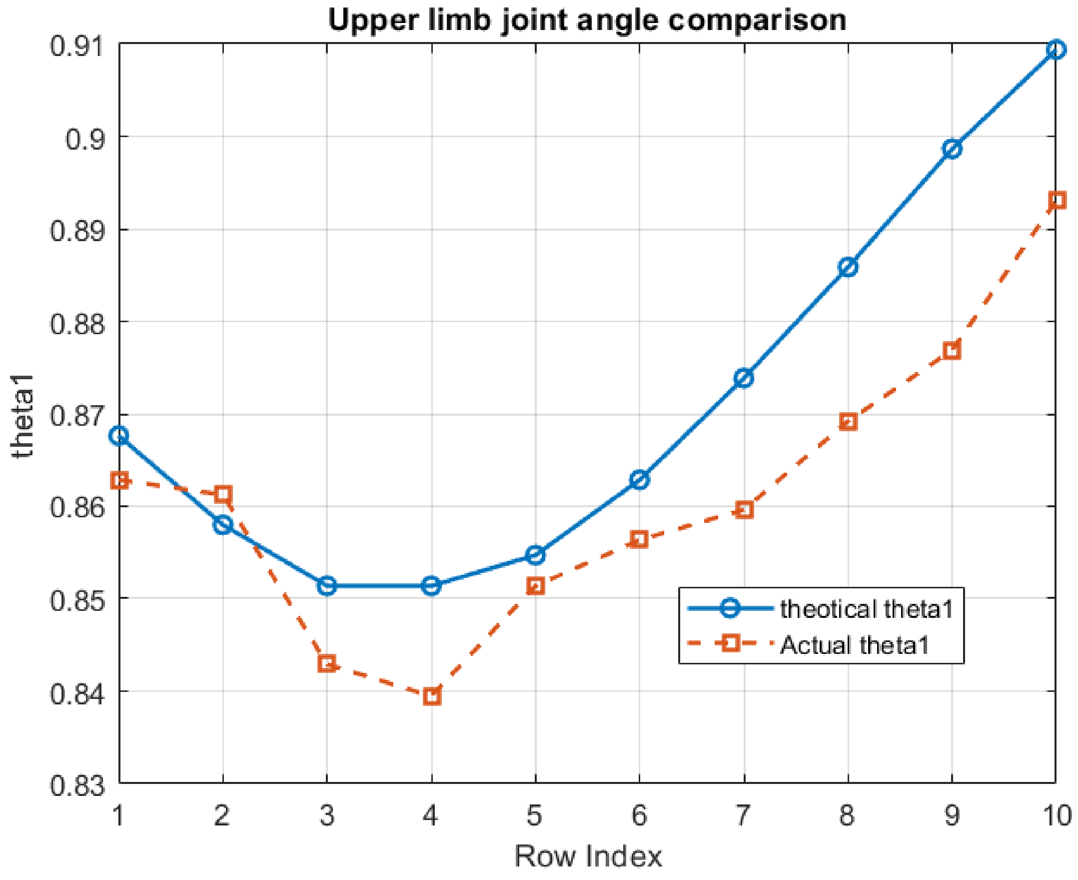
Joint angle value

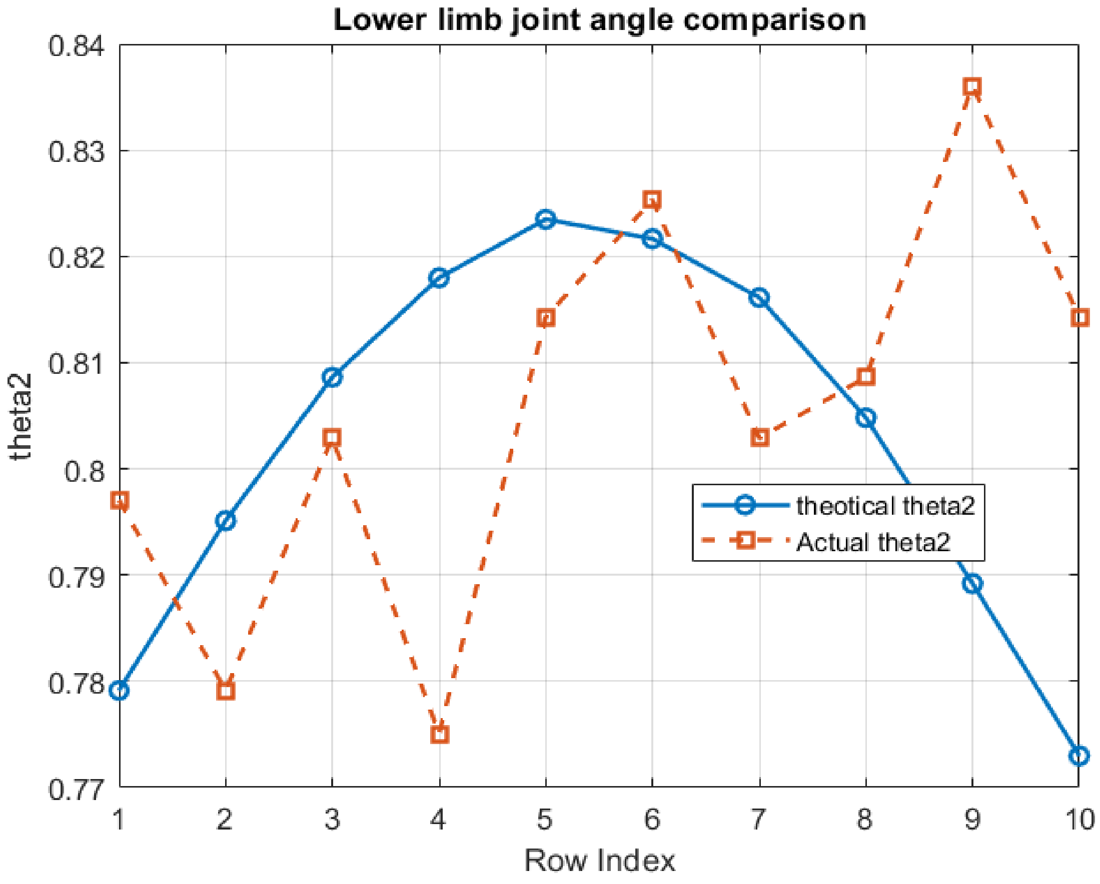
Swing/Stance Phase

Actuation Time

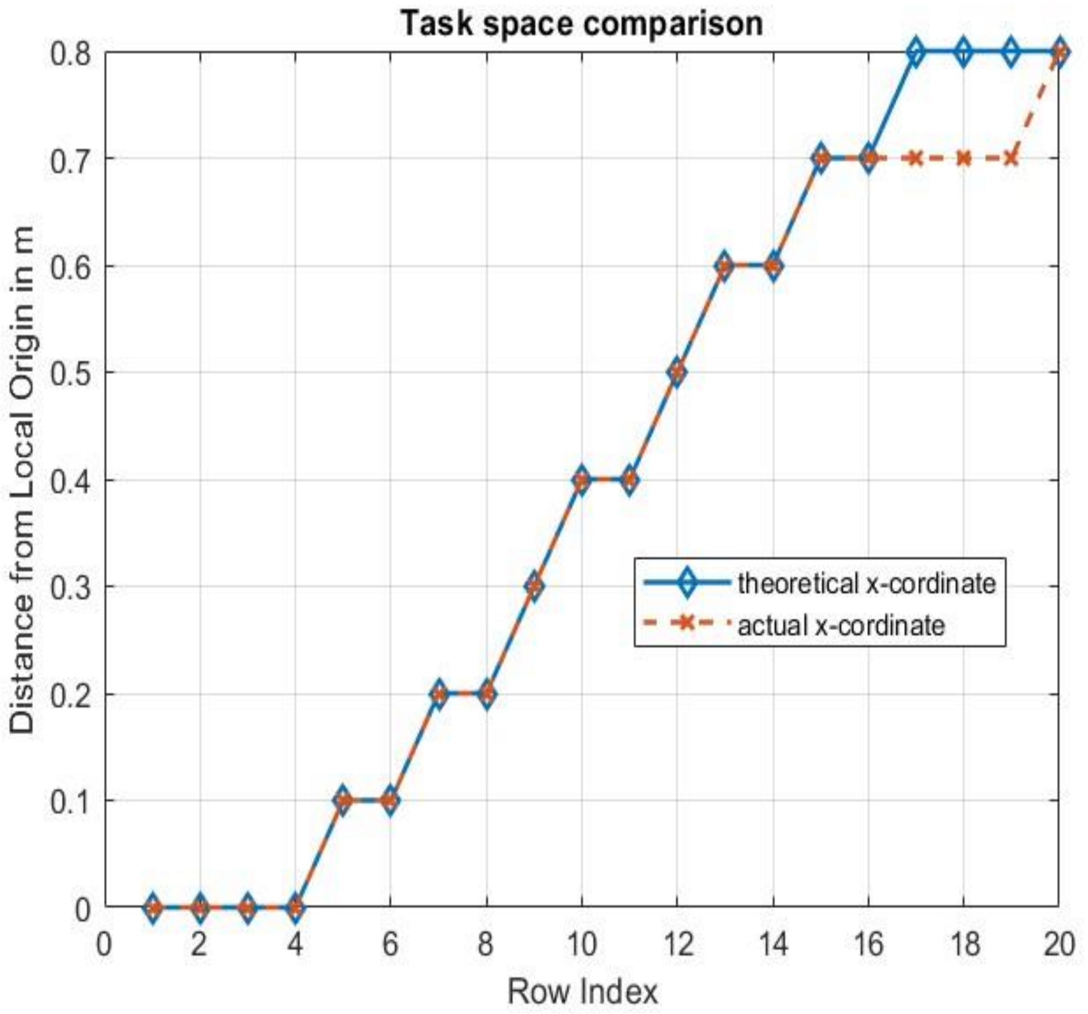
EXPERIMENT RESULTS (Joint Space Analysis)

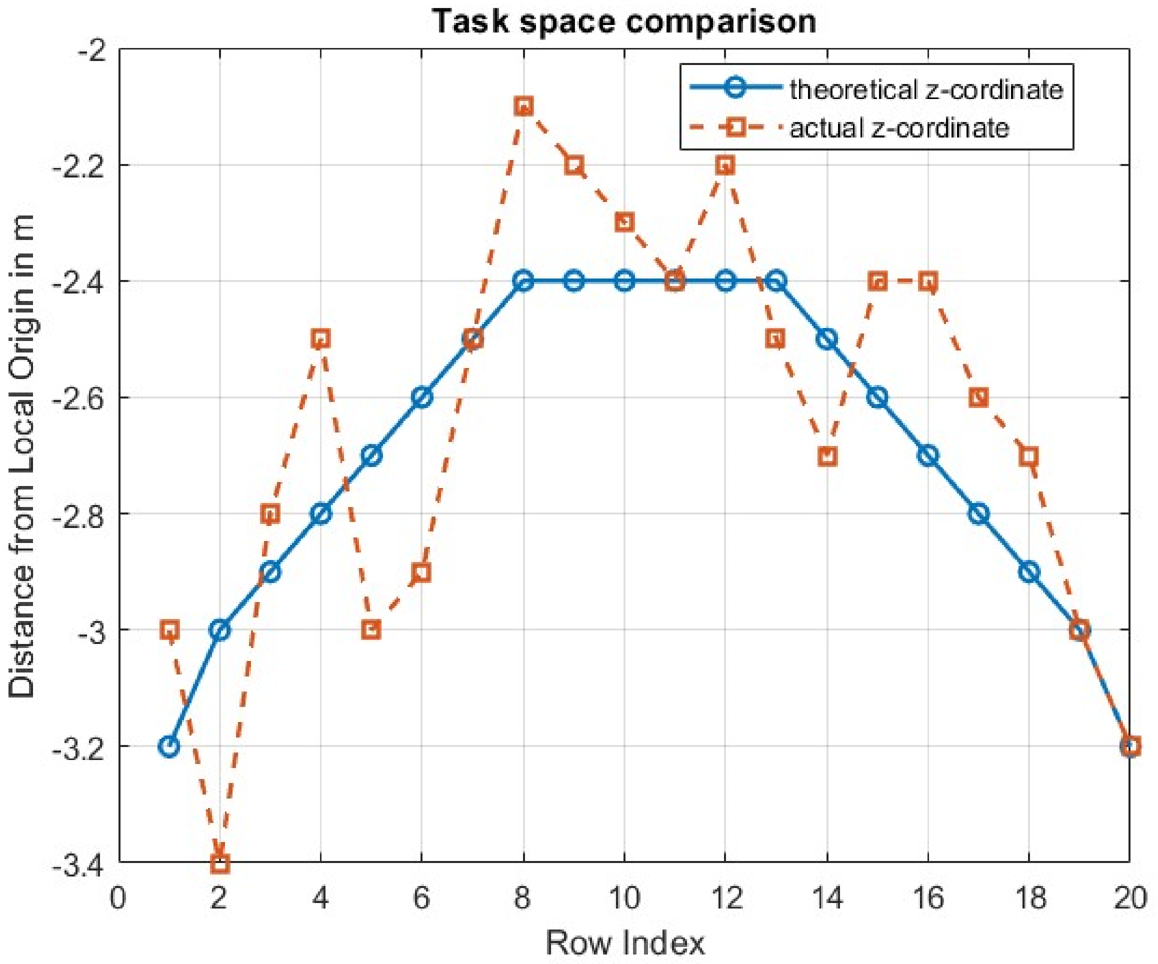
TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering





EXPERIMENT RESULTS (Task Space Analysis)





REAL WORLD EXPERIMENT RESULTS

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

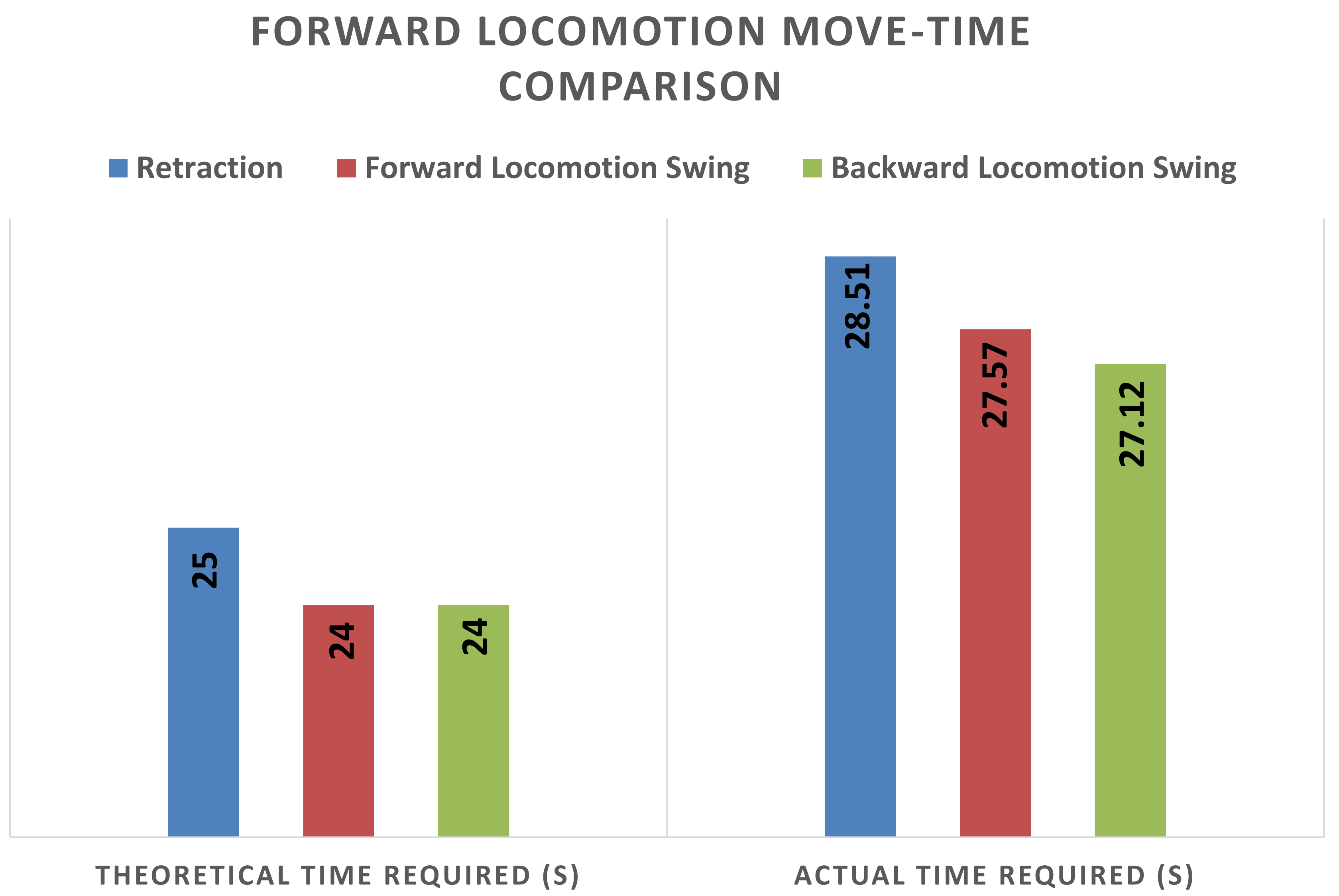
Initial θ_1 / Final θ_2	Theoretical Values	Actual Values
Retraction	[illegible]	[illegible]
Forward Locomotion Swing	[illegible]	[illegible]
Backward Locomotion Swing	[illegible]	[illegible]

Deviation of less than 10%

- **Fabrication/machining Errors**
- **Controller Overshoot**
- **Tracking margin of error**

REAL WORLD EXPERIMENT RESULTS

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering



CONCLUSION

- Developed and validated a multifunctional hexapod robot for autonomous crop monitoring and inspection.

- Integrated mmWave radar, wireless ESP-NOW communication, and modular sensor-actuator control.

- Demonstrated a scalable, cost-effective solution for precision agriculture in small- to medium-scale farms.

- Achieved stable locomotion and reliable performance in varied terrain and gait conditions.

“Thank You”

Appendix

Appendix

Robot Morphology	Power Consumption	Stability	Payload Capacity	Speed	Inspection Visibility	Obstacle Avoidance
Wheeled Robots	High	High	High	Medium	High	Low
Soft Robots (Snake Robots)	Low	Low	Low	Medium	High	Low
UAVs	High	Low	Low	High	Low	High
Legged Robots	Low	High	High	Low	High	High

Board	Bluetooth	Wi-Fi	PWM Pins	UART Support	Cost
Arduino Uno	No	No	6	1	Low
ESP32	Yes (BLE)	Yes	Up to 16	3	Low
Raspberry Pi (4/3/Zero W)	Yes	Yes	2–4 (software)	1–2	Medium
STM32 (Blue Pill)	No	No	Up to 15	2	Low
Teensy 4.0	Yes (via add-on)	No	Up to 31	7	Medium

Appendix

Gait Type	Speed(Km/hr)	Stability Comment
3 Legs at a Time(Forward)	0.051	Little unstable and fastest locomotion
3 Legs at a Time(Backward)	0.050	Stable but slightly reduced control
1 Leg at a Time(Forward)	0.027	Most stable and smooth locomotion
1 Leg at a Time(Backward)	0.028	Stable and smooth locomotion

Appendix

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

Move-type	Theoretical Time Required (s)	Actual Time Required (s)
Retraction	25	28.51
Forward Locomotion Swing	24	27.57
Backward Locomotion Swing	24	27.12

Move-type	Initial θ_1 Theoretical	Initial θ_1 Actual	Final θ_1 Theoretical	Final θ_1 Actual	Initial θ_2 Theoretical	Initial θ_2 Actual	Final θ_2 Theoretical	Final θ_2 Actual
Retraction	0^O	$-2.5\ ^O$	$30\ ^O$	30.8^O	$90\ ^O$	$92.2\ ^O$	$60\ ^O$	$62.5\ ^O$
Forward Locomotion Swing	$30\ ^O$	$30.8\ ^O$	$24\ ^O$	$26\ ^O$	$60\ ^O$	$62.5\ ^O$	$61\ ^O$	$61.7\ ^O$
Backward Locomotion Swing	$30\ ^O$	$30.8\ ^O$	$34.95\ ^O$	$34.1\ ^O$	$60\ ^O$	$62.5\ ^O$	$61\ ^O$	$61.7\ ^O$

REFERENCES

. Gao, J. Li, L. Fan, Q. Zhou, K. Yin, J. Wang, C. Song, L. Huang, and Z. Wang, “Review ofwheeled mobile robots’ navigation problems and application prospects in agriculture,” IeeeAccess, vol. 6, pp. 49248–49268, 2018.

T. Aoki, S. Inada, and D. Shimizu, “Development of a snake robot to weed in rice paddy fieldand trial of field test,” in 2024 IEEE/SICE International Symposium on System Integration(SII), pp. 1537–1542, IEEE, 2024

https://ozrobotics.com/shop/four-legged-ai-bionic-robot-pet-dog-based-on-esp32/

https://link.springer.com/article/10.1007/s00138-022-01339-1

https://eprints.uklo.edu.mk/id/eprint/6312/

https://droneblocks.io/revolutionizing-agriculture-with-quadruped-robotics-the-future-is-here/

FUTURE SCOPE

- Side support can be designed for revolute joint of upper-limp to avoid lateral movement.
- IMU can be used to enhance the stability and balance of the robot's legs by providing real-time orientation and motion data, particularly on uneven or shifting terrain.
- PID Controller can be designed to avoid mechanical vibrations during sharp change of directions in linear actuator.
- Reinforcement learning techniques can be implemented to improve terrain adaptability and energy efficiency.