Active Bionic Antennas for Object Detection and 3D Localization with Self-Sensing Ego-Motion Cancellation

Supervisors : Dr. Nalin Harischandra, Dr. Isuru Navinne

E/19/295 - K. H. J. D. Premachandra

E/19/300 - L. M. A. H. Premawansha

E/19/495 - A. G. D. C. Thilkarathne

Department of Computer Engineering

Faculty of Engineering

University of Peradeniya

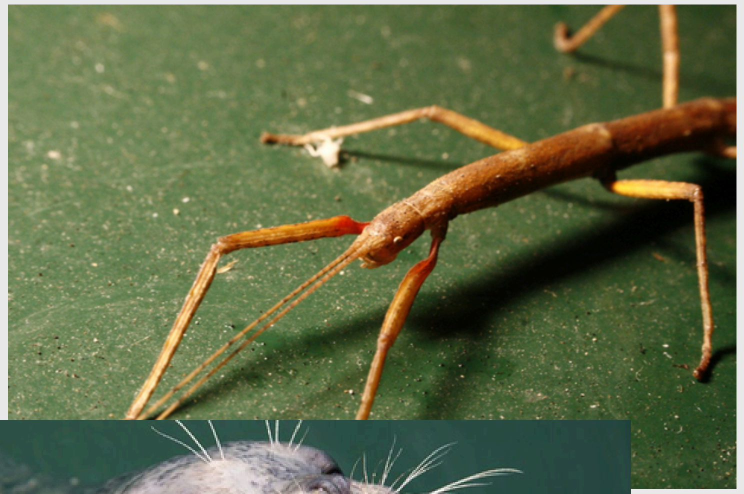
17/02/2025

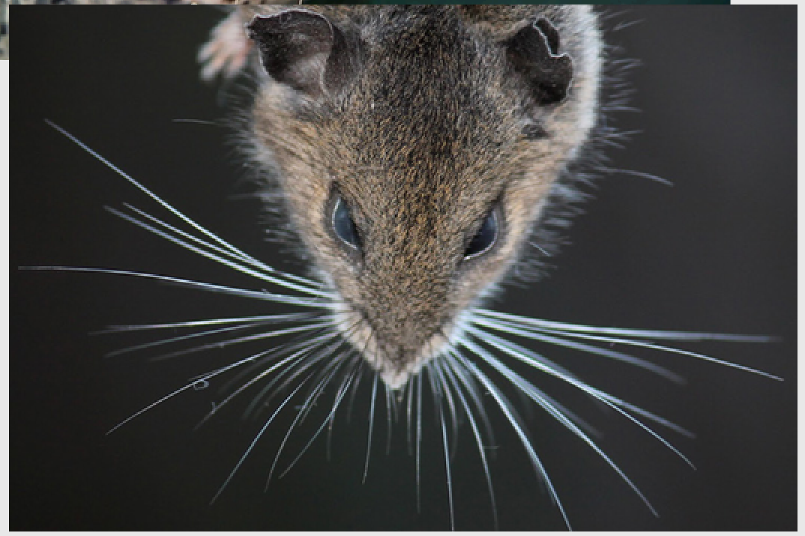
Table of Content

Introduction

Active Tactile Sensing in Nature

- Many animals use active tactile sensing for exploration and navigation.
- **Stick Insect** detects vibrations with its antennae for obstacle localization.
- **Rats** and **Harbor Seals** use whiskers to map surroundings with high spatial resolution.
- These systems operate without vision, enabling precise object detection even in darkness.



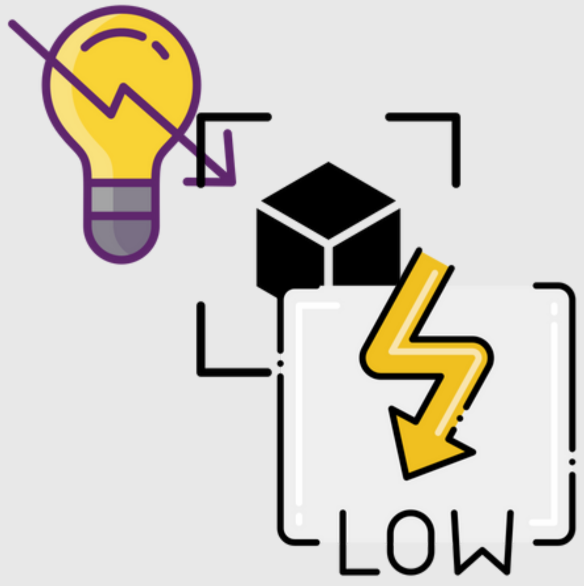


Bionic Tactile Sensors Inspired by Nature

- Engineers have developed bionic tactile sensors mimicking biological antennae and whiskers.
- They actively **Sweep** the environment, generating tactile data through mechanical interactions.
- Integrated with machine learning, they enable real-time material classification, object detection, and 3D localization.

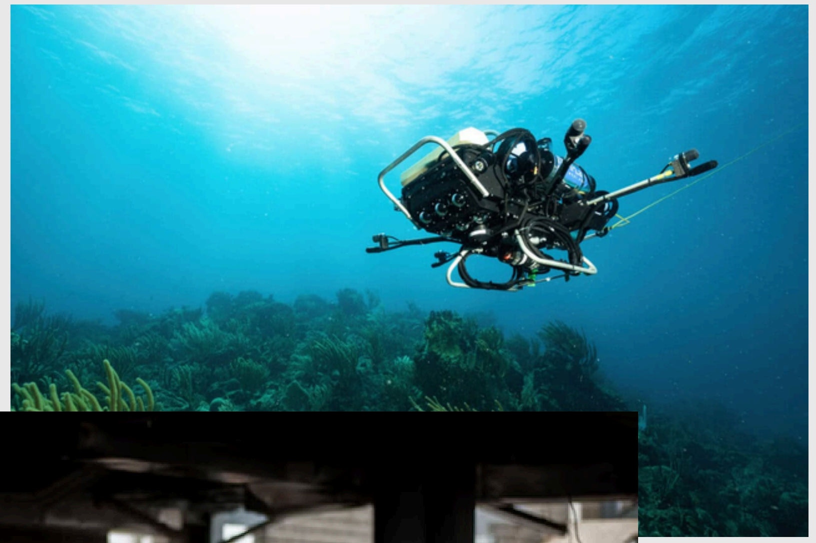
Why Tactile Sensing?

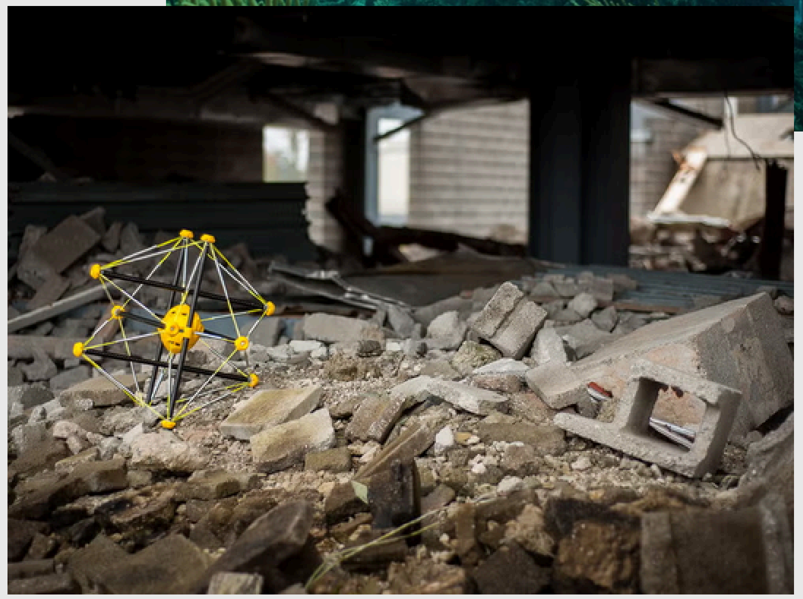
✅ Works in low-light, occluded, or cluttered environments where vision-based sensors fail.
✅ Provides direct physical interaction for reliable object detection and mapping.
✅ Offers mechanical simplicity, low power consumption, and resistance to electromagnetic interference.



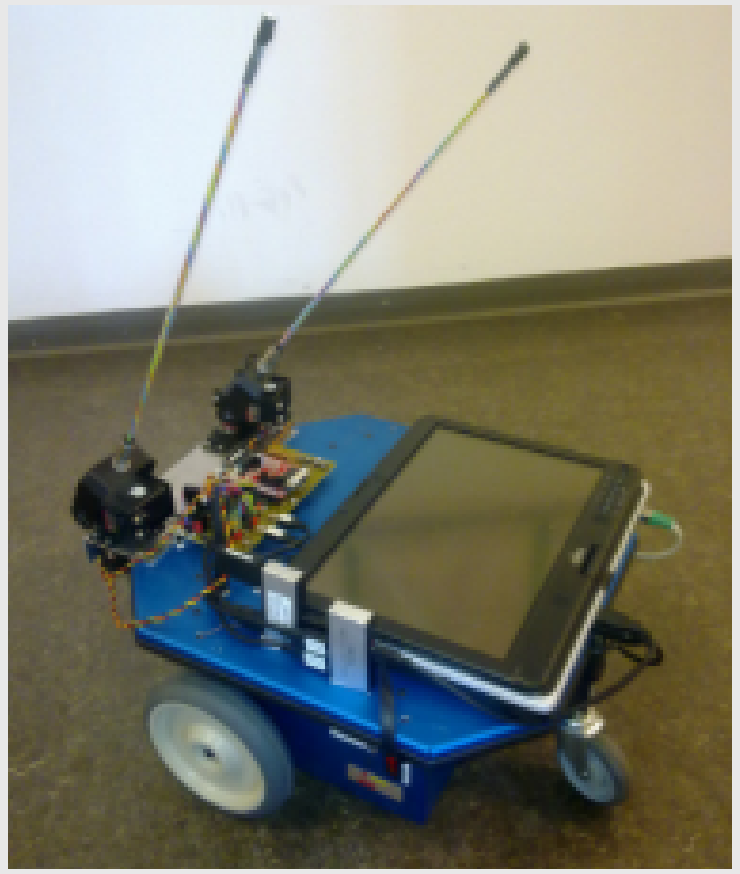
Applications of Bionic Tactile Sensors

- **Disaster Zones** – Navigate through debris and unstable terrain.
- **Underwater Habitats** – Function effectively in murky, low-visibility conditions.
- **Extraterrestrial Exploration** – Operate in dust-covered, unstructured environments.





Key Problems in Tactile Sensing



Self-Sensing Interference

- The robot's own motion introduces unwanted vibrations and noise in tactile sensor readings
- Leads to false detections and misinterpretation of contact events.

Inaccurate 3D Localization

- Tactile sensors only register data upon contact, resulting in sparse environmental mapping.
- Pose estimation errors arise due to limited tactile reference points.
- Conventional Simultaneous Localization and Mapping relies on vision or LiDAR, making adaptation for tactile-based localization challenging.

Research Questions

1. How can self-sensing interference be effectively canceled in tactile-based robotic systems?

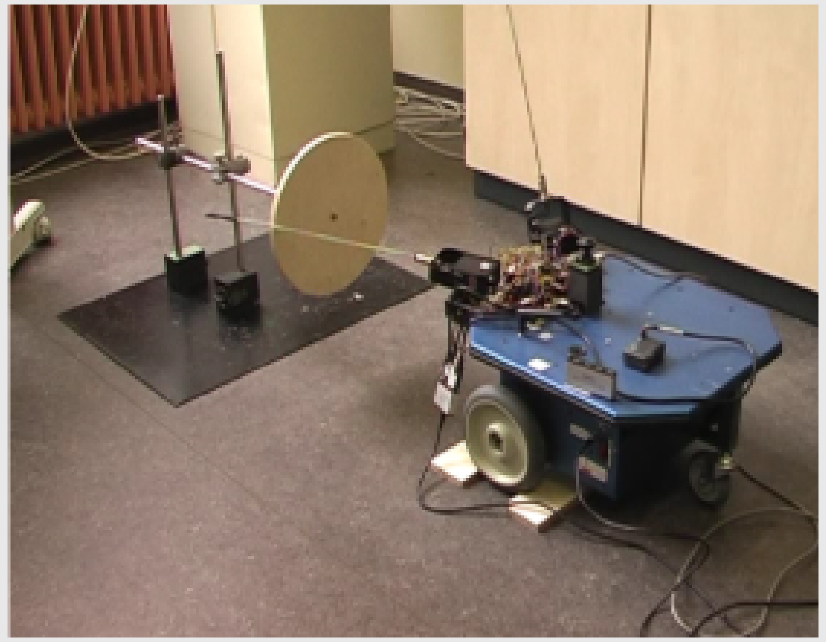
Research Focus:

- Developing a self-sensing cancellation framework using Echo State Networks (ESNs) to filter out motion artifacts.
- Utilizing proprioceptive feedback and forward models to predict and subtract self-induced signals.

2. How can 3D localization accuracy be improved using tactile sensors in unstructured environments?

Research Focus:

- Adapting Google Cartographer (SLAM) to process tactile-based input instead of traditional LiDAR or vision data.
- Implementing a multi-contact sampling strategy to enhance spatial awareness.



Research Objectives

Objectives

Develop self-sensing cancellation techniques to eliminate ego-motion interference.

Enhance 3D localization accuracy using multi-antenna strategies and adaptive learning.

Integrate and validate the system for real-world applications like robotic exploration and industrial automation.

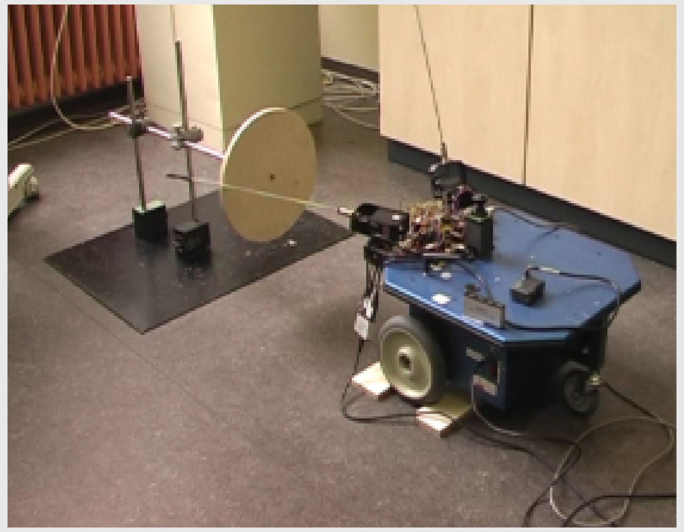
Literature Review

Summary of Previous Research

1. **Biological Inspiration**

   - *Insect Antennae -*
     - *Insects like stick insects and honeybees use their antennae to detect obstacles, recognize textures, and coordinate movements.*
     - *Researchers like Dürr et al. and Hoinville et al. found that insects actively move their antennae to explore their surroundings, inspiring vibration-based designs for robotic sensors.*
   - *Mammalian Whiskers -*
     - Animals like rats and seals use whiskers to gather spatial and texture information.
     - Studies by Prescott et al. and Solomon & Hartmann showed that robotic whiskers inspired by these animals could improve shape and contour detection.
   - *Honeybees -*
     - Honeybees learn through touch and adapt using feedback from their antennae.
     - Erber et al. discovered that this adaptability could inspire more responsive robotic sensors

2. Development of Bionic Antennae



The review traces the evolution of bionic tactile sensors.

- *Early Developments* -
  - The first bionic antennae had built-in sensors but faced issues like motion noise.
  - Kaneko et al. made the first attempts, but motion-induced noise was a big challenge.

- Adaptive Sensing -
  - Researchers like Okada and Patané introduced dynamic sensing, where sensors adjust based on movement, improving accuracy.

- Challenges -
  - A major challenge is motion-induced noise, which affects the accuracy of mobile robots.

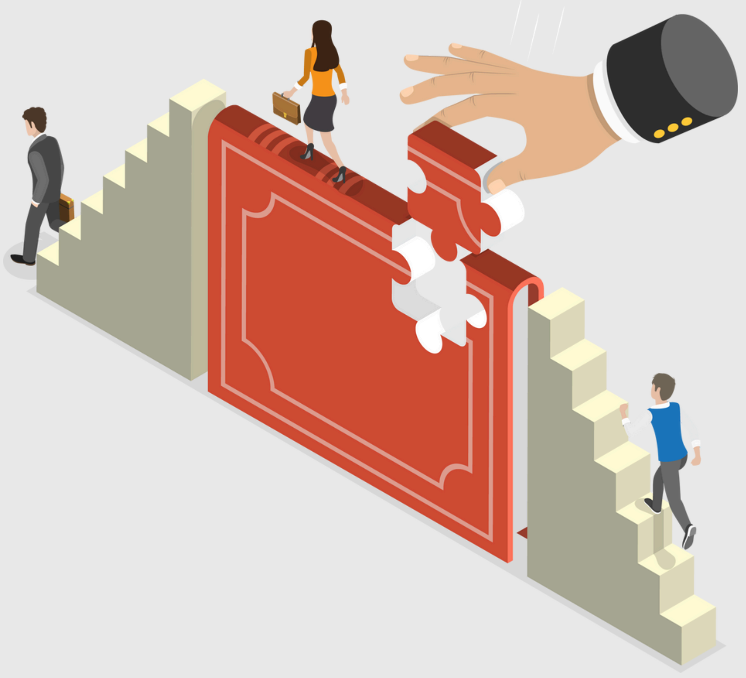
3.Self-Sensing Cancellation

- Hartmann (1st Researcher)- Introduced adaptive filtering for self-sensing cancellation.
- Robotics Adaptation- Later applied in robotic systems for improved sensing accuracy.
- Recent Advancements
  - Deep Learning (ESNs) - Enhances sensor adaptation.
  - Reinforcement Learning - Improves real-time decision-making.
  - Proprioceptive Feedback - Helps sensors adjust dynamically and reduce noise

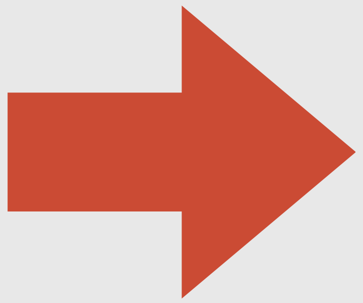
4.3D Localization and Mapping

- Multi-antenna systems help in 3D mapping but bring challenges like cross-axis interference and high computational requirements.

Gap in the Literature



- The cancellation of self-sensing interference due to ego motion, which disrupts accurate perception.
- Accurate 3D localization using bionic tactile sensors, which remains difficult due to motion-induced noise and computational constraints.



- Develop novel techniques for self-sensing cancellation, allowing bionic tactile sensors to function without interference from ego motion.
- Improve 3D localization accuracy by integrating multi antenna motion strategies and adaptive learning-based spatial mapping.

Theoretical Frameworks

- **Bio-inspiration**

Mimicking tactile sensing in insects and mammals, focusing on mechanoreception, active exploration strategies, and neural processing.

- **Signal Processing and Machine Learning**

Using

- adaptive filtering,
- neural networks
- reinforcement learning for self-sensing cancellation and improved localization accuracy.

- **Robotics and Sensor Design**

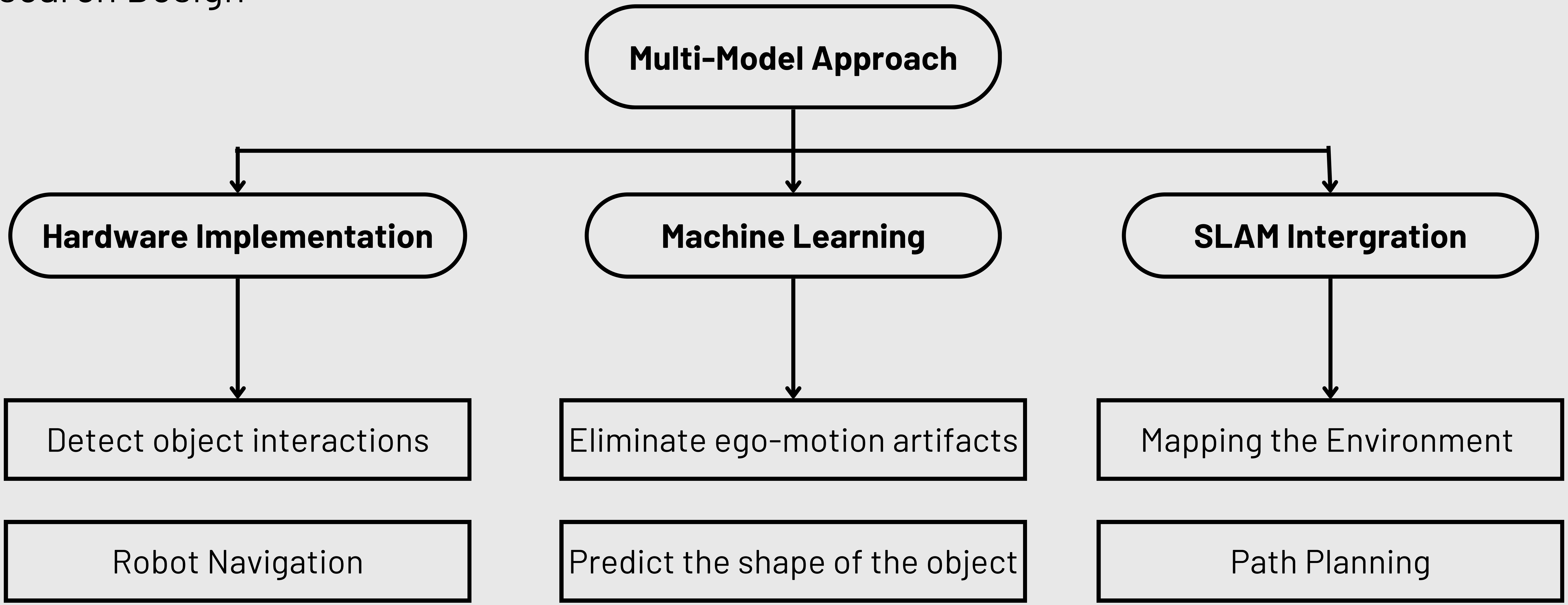
Designing bionic antennae using appropriate materials, sensor placement, and control systems.

- **Adaptive Systems**

Creating sensors that dynamically adjust to environmental interactions.

Methodology

Research Design



Data Collection Methods

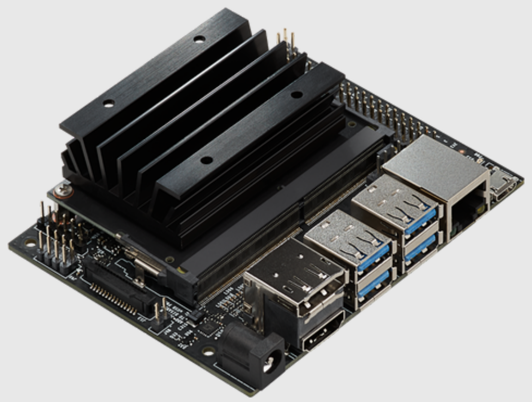
Sensor Data

Vibration Data → MPU6050 Accelerometers

Servo Motor Commands → MG90 Servo Motors

IMU Data → MPU6050 Accelerometers

Jetson Nano



Development Stages

Online Model Development	Offline Model Development
Static Environment	Dynamic, Unstructured Environments
Gather Data for Fine Tune the Algorithms	Evaluate Real-world conditions

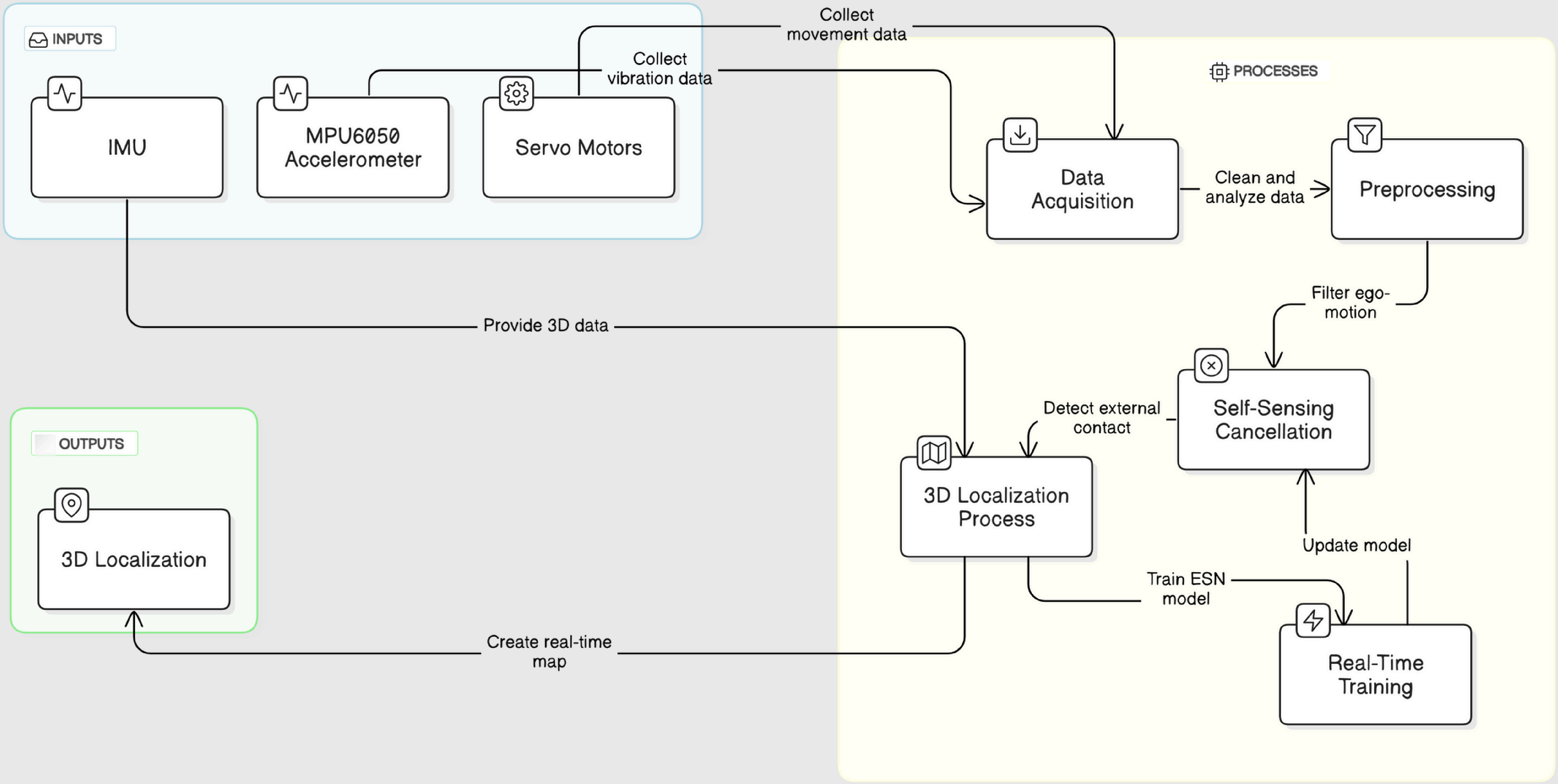
Data Analysis Methods

Raw Data From Sensors →

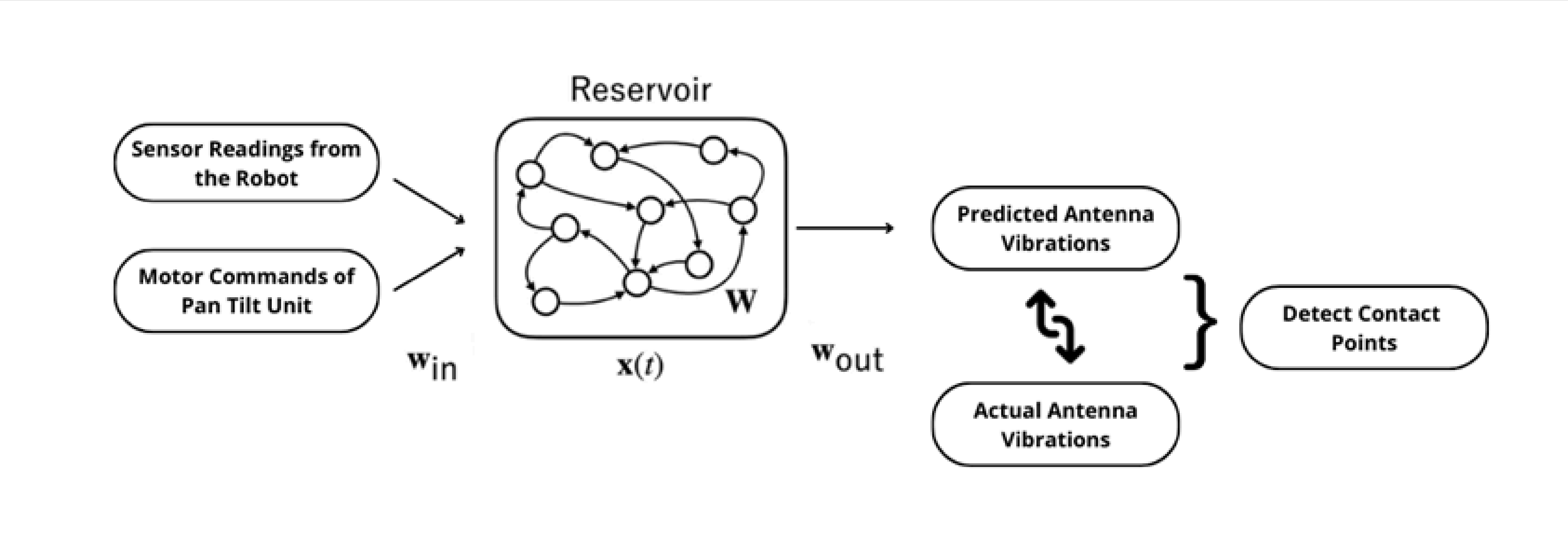
- **Kalman Filtering** – Noise reduction for motion data.
- **Fast Fourier Transform (FFT)** – Frequency domain analysis of vibration signals.
- **Low-Pass Filtering** – Removing high-frequency noise from sensor readings.

→ Pre – Processed Data

High Level Architecture



Echo State Network



- Predicts self-generated vibrations using motor commands and robot body sensor data.
- Isolates external contact events by subtracting predicted signals from raw data.

Google Cartographer SLAM Module

- Constructs 3D maps using IMU data and tactile inputs.
- Localizes the robot in real-time using loop closure and submap optimization.

Expected Results

Hypothesis

The proposed self-sensing cancellation framework will significantly reduce motion-induced noise, improving tactile data accuracy.

The integration of tactile-based SLAM will enable precise 3D localization in visually degraded environments.

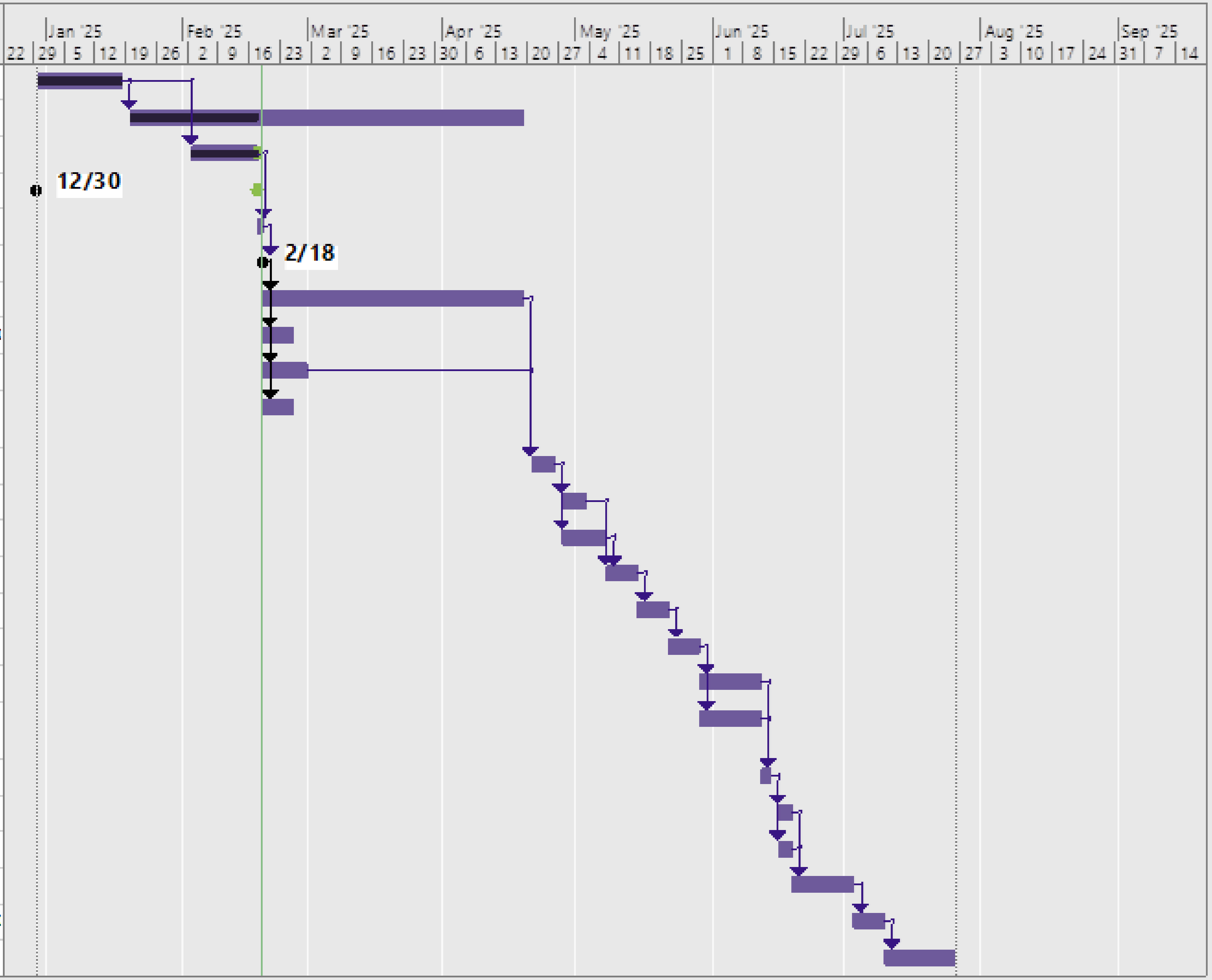
Potential Impact

Enhanced robotic navigation in low-visibility or cluttered environments.

Ego-motion cancellation can extend beyond vibration-based systems to vision-based and auditory systems, improving perception in dynamic environments.

Timeline

ID		ID	Task Name
1		1	Finalize Research Project
2		2	Literature review & Background Research
3		3	Creating LR Paper & Project Proposal
4		4	LR & Project Proposal Submisson
5		5	Creating the Proposal Presentation
6		6	Proposal Presentation
7		7	Finetuning High Level Architecture
8		8	Finalize Antenna Shape & Material Selecti
9		9	Design Pan-Tilt Mechanism
10		10	Setup Jetson Board & develop Initial Simulation with Sensors
11		11	Assemble Antenna Module
12		12	Create the Robot Navigation Interface
13		13	Finalize Circuit Design & Create PCB
14		14	Integrate Hardware Components
15		15	Perform Intergration Testing
16		16	Data Collection for the Offline Model Dev
17		17	Implement ESN Model
18		18	Develop Google Cartographer Algorithm to work with Tactile Data
19		19	Test Developed Software with Hardware
20		20	Validate Object Detection Accuracy
21		21	Validate Localization Accuracy
22		22	Optimized ML Models for Real Time Use
23		23	Final Validation with Different Envirnmnet
24		24	Finalize Research Paper and Report



Budget

CATEGORY	ITEM DESCRIPTION	AMOUNT	ESTIMATED COST
HARDWARE	POLY-ACRYLIC TUBE	1	RS. 1000.00
	MPU6050 ACCELEROMETERS	3	RS. 2,010.00
	THE ROBOTIC PLATFORM (4WD OMNI WHEEL ROBOT)	1	RS. 194,000.00
	MG90 SERVO MOTORS	4	RS. 2160.00
	JETSON NANO BOARD	1	RS. 77,500.00
	BATTERY PACK (NI-MH BATTERY 12V)	1	RS. 4000.00
	TOTAL		**RS. 280,670.00**

References

[1] Thierry Hoinville, Nalin Harischandra, A. F. Krause, and Volker Dürr, "Insect-Inspired Tactile Contour Sampling Using Vibration-Based Robotic Antennae," Lecture notes in computer science, pp. 118–129, Jan. 2014, doi: https://doi.org/10.1007/978-3-319-09435-9_11.

[2] N. Harischandra, A. F. Krause, and V. Dürr, "Stable phase-shift despite quasi-rhythmic movements: a CPG-driven dynamic model of active tactile exploration in an insect," Frontiers in Computational Neuroscience, vol. 9, Aug. 2015, doi: https://doi.org/10.3389/fncom.2015.00107.

[3] Nalin Harischandra and V. Durr, "A forward model for an active tactile sensor using Echo State Networks," pp. 103–108, Nov. 2012, doi: https://doi.org/10.1109/rose.2012.6402605.

REFERENCES LINK

Conclusion

Summary of Proposal

- The project aims to develop a robust tactile-based navigation system using bio-inspired sensors, self-sensing cancellation, and 3D localization.
- The system will be validated for real-world applications in challenging environments.

Approval for the project to proceed with hardware and experimental testing.

Thank you!