Chair of Robotics, Artificial Intelligence and Real-time Systems
TUM School of Computation, Information and Technology
Technical University of Munich

Active Tactile Exploration Based on Whisker-Inspired Sensory Array

Final Presentation, Bachelor's Thesis

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Outline

Outline

Introduction

Whisker Anatomy

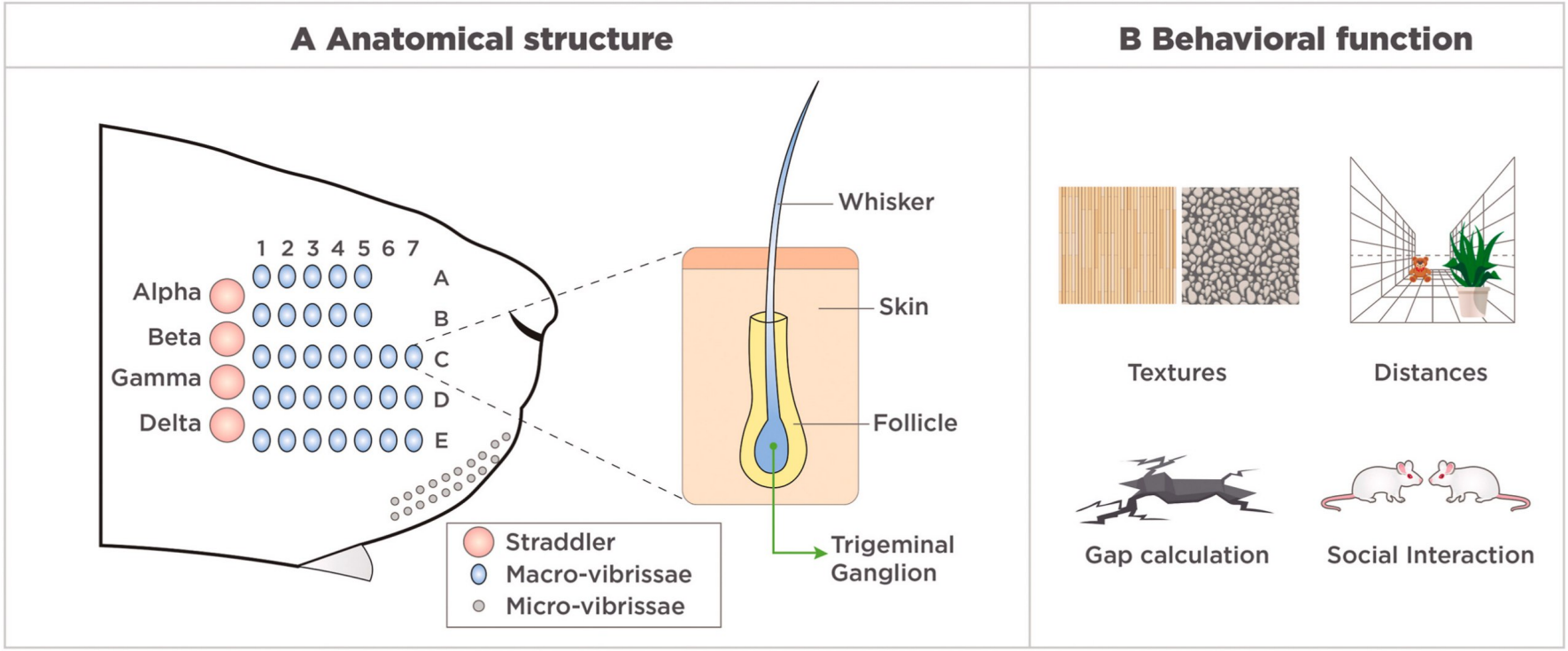


Figure: Representation of the vibrissae system and its function, from [IMG22]

Introduction

Robotic Whisker Sensors

- Strain gauge: bending →strain detection.
- Magnetic (Hall): bending →magnetic shift.
- Optical: deflection →light variation.

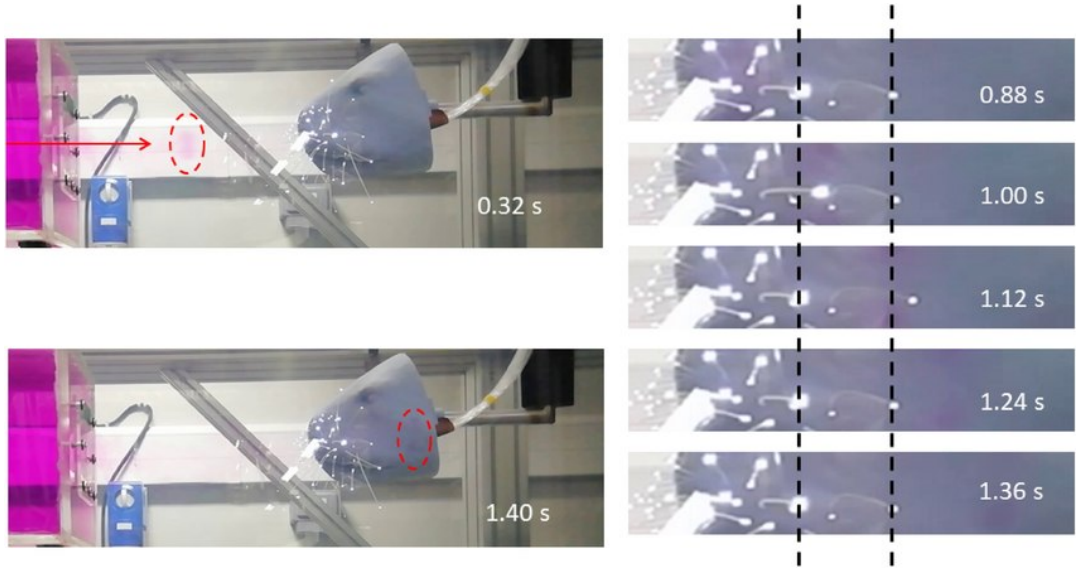


Figure: Picture of the 3D printed sea lion head with integrated optical whiskers, from [GMB22]

Introduction

Whisker Sensor Applications

Prominent applications according to [Say+22]:

- Biomimetic tactile: prosthetic feedback via impedance sensing.
- Robotic spatial sensing: 3D object localization and environmental mapping.
- Surface texture analysis: mapping surface details through whisking data.
- Navigation in dark: autonomous whisking for low-light environments.
- Underwater sensing: flow detection and vortex vibration control.

Outline

Related Work

3D Mapping of Underground Mining Environments

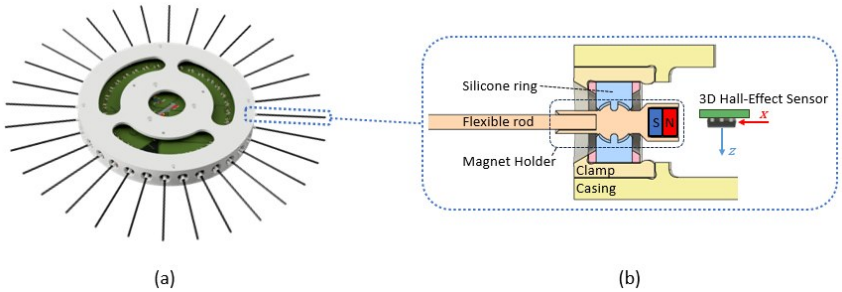


Figure: Whisker disk prototype. (a) The sensor comprises a circular array of 32 whiskers. (b) Detailed section view of a single whisker sensor, from [Gom+24]

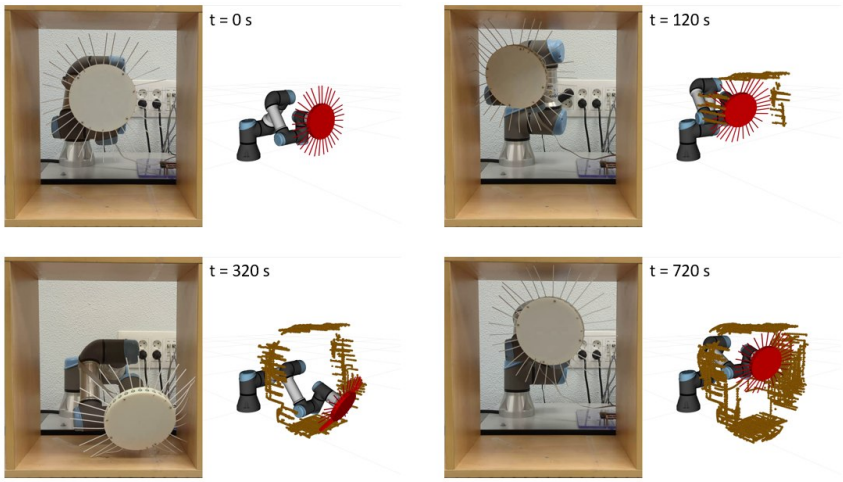


Figure: Environment reconstruction from the 3D-mapping experiment, from [Gom+24]

Related Work

Active Multiobject Exploration

Whisker sensors per se are passive sensors. →Active control is required.

Figure: Robot is using the tactile feedback from our developed whisker sensor to localize, and recognize the objects found during exploration, from [Xia+22]

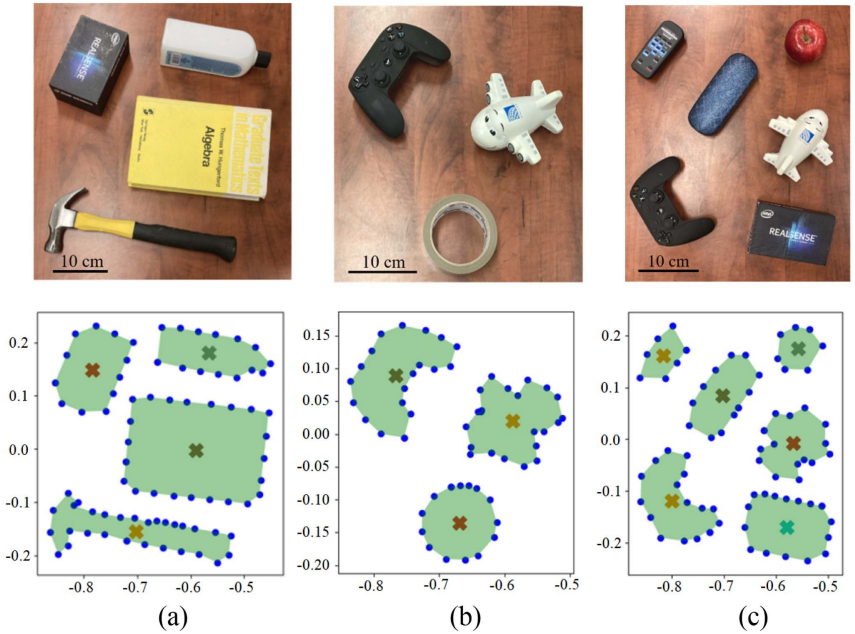
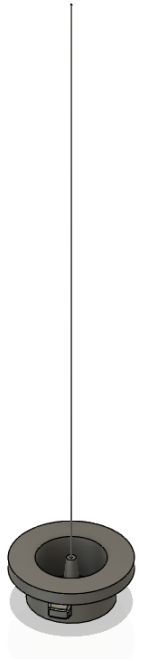


Figure: Results of active tactile exploration in real experiments., from [Xia+22]

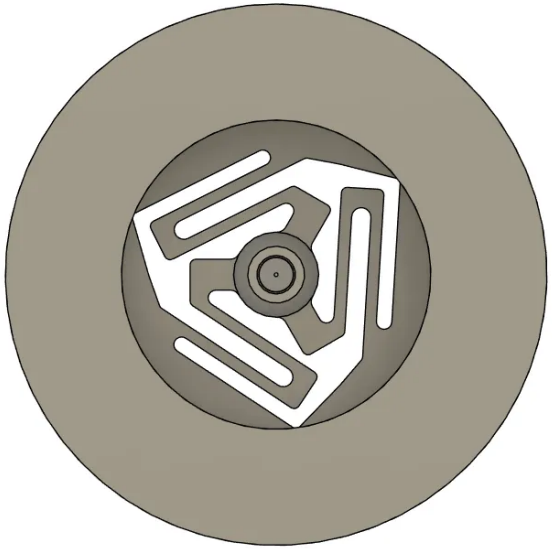
Outline

Hardware

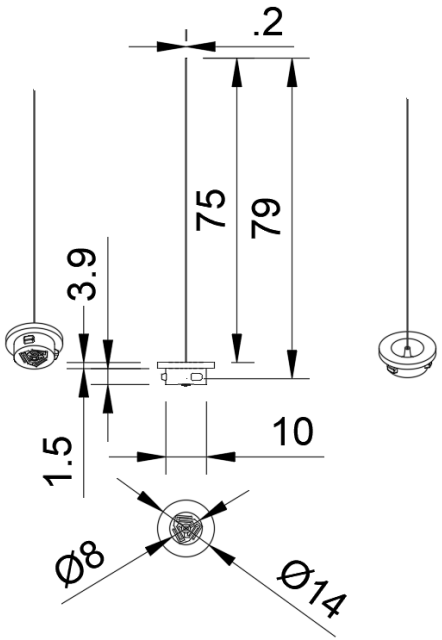
Magnetically Transduced Whisker Sensor



(a) Whisker Sensor,
Whisker shaft – a nitinol wire



(b) Suspension,
3D-printed with PLA



(c) Whisker sensor
dimensions

Hardware

Magnetically Transduced Whisker Sensor

- MLX90393 sensor is placed underneath the magnet glued to the suspension.
- Configured for measuring magnetic flux changes with a resolution of $0.15 \mu T / LSB$.
- The sensor uses I2C communication protocol, acting as a slave.
- If multiple sensors are used, they are connected in a daisy chain.

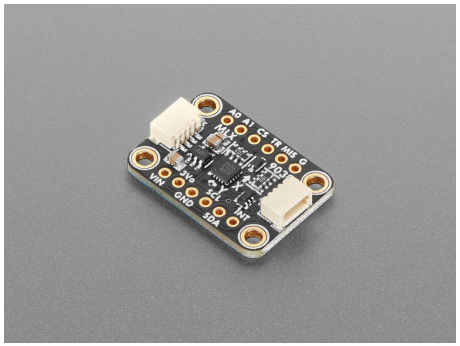


Figure: Adafruit MLX90393 sensor

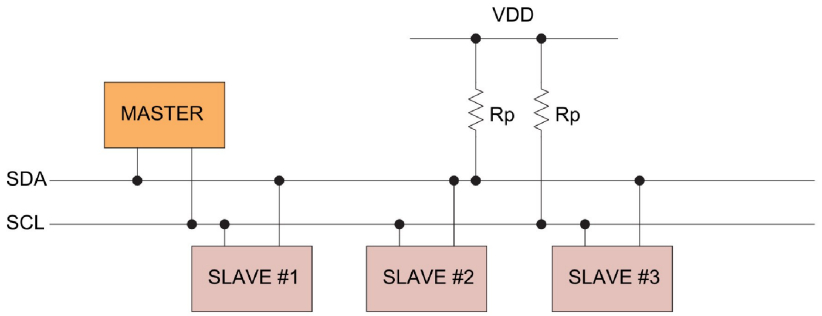


Figure: I2C communication

Hardware

Whisker Platform

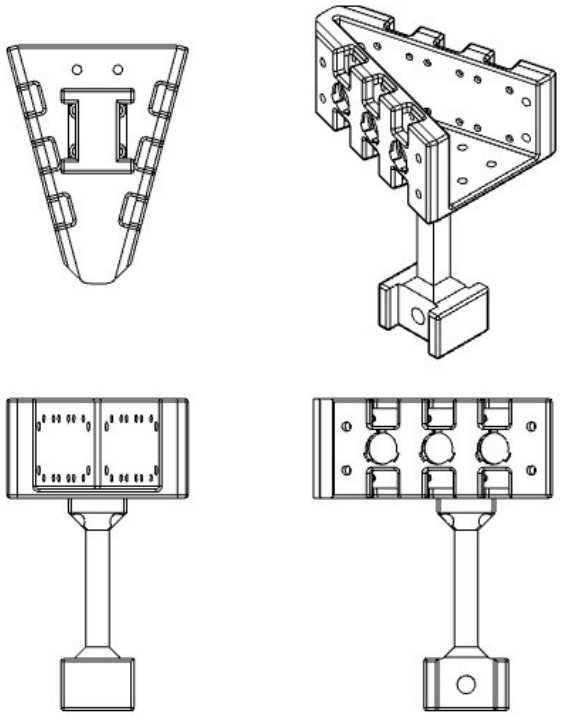


Figure: Platform sketch from below.

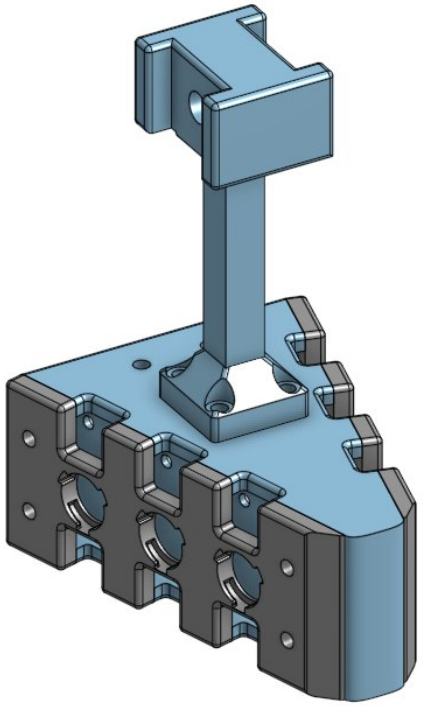


Figure: Platform CAD model.

Hardware

Whisker Platform

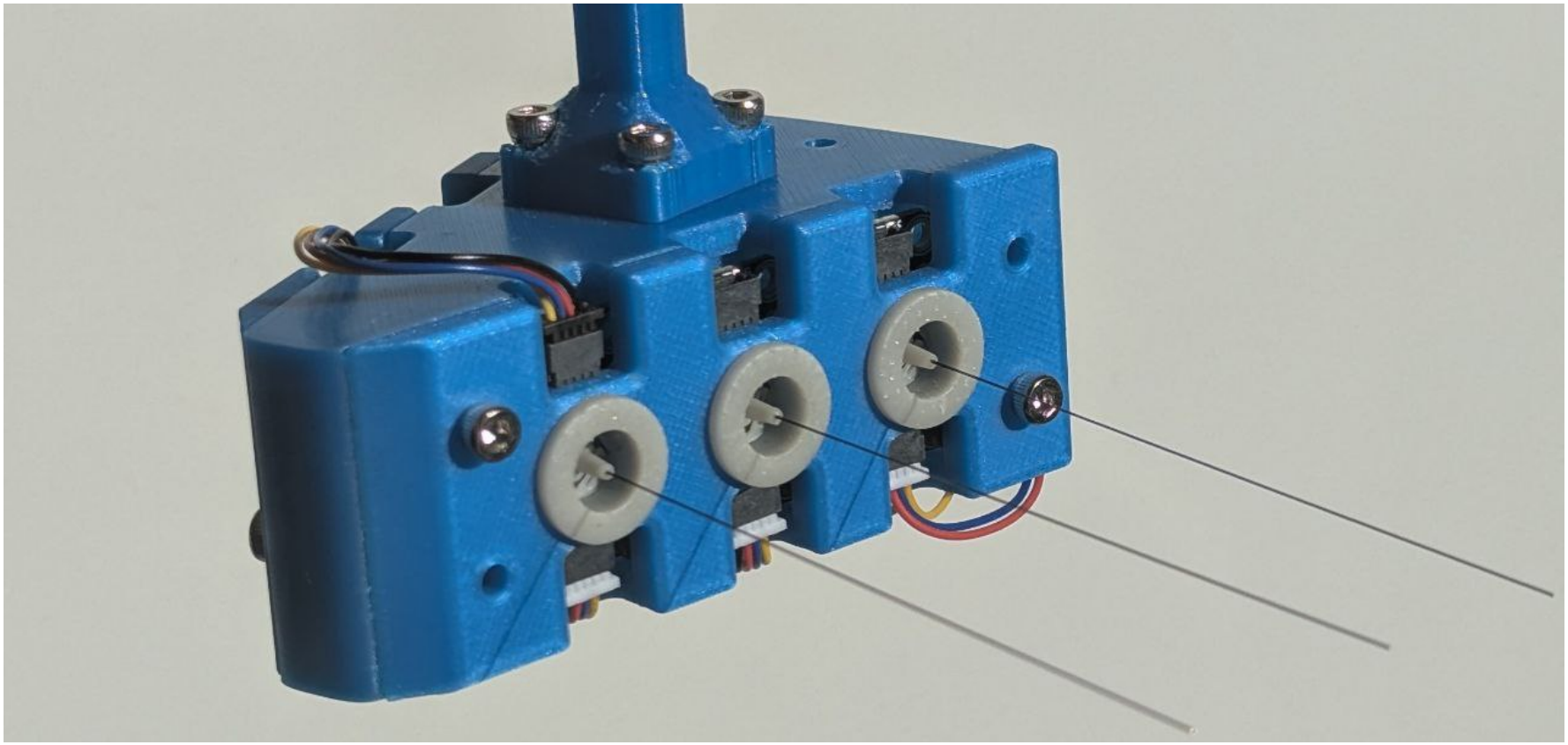


Figure: 3D-printed platform. Three whisker attached to the left side and robotic arm mounted at the top.

Outline

Problem Statement

Goals:

- Full contour capture
- Precise contour reconstruction
- Navigation in tunnels

Assumptions:

- Navigation and reconstruction in 2D
- Rigid stationary objects
- Contact at the tip
- Known whisker base position

Problem Statement

Goals:

- Full contour capture
- Precise contour reconstruction
- Navigation in tunnels

Assumptions:

- Navigation and reconstruction in 2D
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- Known whisker base position

Policies:

- Swiping Policy
- Retrieval Policy
- Tunneling Policy
- Governing Policy

Body Motion

Control Variables

Control Inputs:

- ${}^{\mathrm{w}}\boldsymbol{r}^{t}$ – platform position (world frame).
- ${}^{\mathrm{w}}\alpha^{t}$ – platform orientation (world frame).
- $\delta^{t}_{\mathrm{wsk,i}}$ – deflection of the i-th whisker.

Control Outputs:

- ${}^{\mathrm{w}}\boldsymbol{v}^{t}$ – platform velocity (world frame).
- ${}^{\mathrm{w}}\omega^{t}$ – platform angular velocity (world frame).

Body Motion

Control Algorithm

Algorithm Steer the Platform to Target Position and Orientation

1: Require ${}^{\mathrm{w}}\boldsymbol{r}^{t+1}$, ${}^{\mathrm{w}}\alpha^{t+1}$
2: ${}^{\mathrm{w}}\omega^{t+1} \leftarrow \mathrm{PID}({}^{\mathrm{w}}\alpha^{t+1} - {}^{\mathrm{w}}\alpha^{t})$
3: ${}^{\mathrm{w}}\boldsymbol{v}^{t+1} \leftarrow v_{\mathrm{total}} \cdot \dfrac{{}^{\mathrm{w}}\boldsymbol{r}^{t+1} - {}^{\mathrm{w}}\boldsymbol{r}^{t}}{\left\| {}^{\mathrm{w}}\boldsymbol{r}^{t+1} - {}^{\mathrm{w}}\boldsymbol{r}^{t} \right\|}$
4: Return ${}^{\mathrm{w}}\boldsymbol{v}^{t+1}$, ${}^{\mathrm{w}}\omega^{t+1}$

Algorithm Steer Whisker to Target Position and Orientation

1: Require ${}^{\mathrm{w}}\boldsymbol{r}_{\mathrm{wsk}}^{t+1}$, ${}^{\mathrm{w}}\alpha_{\mathrm{wsk}}^{t+1}$
2: $({}^{\mathrm{w}}\boldsymbol{v}^{t+1}, {}^{\mathrm{w}}\omega^{t+1}) \leftarrow \mathrm{steer\_body}({}^{\mathrm{w}}\boldsymbol{r}_{\mathrm{wsk}}^{t+1}, {}^{\mathrm{w}}\alpha_{\mathrm{wsk}}^{t+1})$
3: ${}^{\mathrm{w}}\boldsymbol{r}_{\mathrm{corr}} \leftarrow [0, 0, {}^{\mathrm{w}}\omega^{t+1}] \times \boldsymbol{r}_{\mathrm{wsk,body}}$
4: ${}^{\mathrm{w}}\boldsymbol{v}^{t+1} \leftarrow v_{\mathrm{total}} \cdot \dfrac{{}^{\mathrm{w}}\boldsymbol{v}^{t+1} + {}^{\mathrm{w}}\boldsymbol{r}_{\mathrm{corr}}}{\left\| {}^{\mathrm{w}}\boldsymbol{v}^{t+1} + {}^{\mathrm{w}}\boldsymbol{r}_{\mathrm{corr}} \right\|}$
5: Return ${}^{\mathrm{w}}\boldsymbol{v}^{t+1}$, ${}^{\mathrm{w}}\omega^{t+1}$

Swiping Policy

Control Algorithm

Algorithm Swiping Policy

If $|\delta^t_{\text{wsk}}| < \delta_{\text{wsk,thr}}$ Then
    Return ${}^{\text{w}}\boldsymbol{v}^t$, ${}^{\text{w}}\omega^t$
End If

${}^{\text{s}}\boldsymbol{r}^t_{\text{tip}} \leftarrow \text{wsk.defl\_model}(\delta^t_{\text{wsk}})$
${}^{\text{w}}\boldsymbol{r}^t_{\text{tip}} \leftarrow {}^{\text{w}}\boldsymbol{r}^t + {}^{\text{w}}\boldsymbol{r}_{\text{wsk,body}} + \boldsymbol{R}^2_{xy}({}^{\text{w}}\alpha^t_{\text{wsk}}) \cdot {}^{\text{s}}\boldsymbol{r}^t_{\text{tip}}$
wsk.spline.add_keypoint(${}^{\text{w}}\boldsymbol{r}^t_{\text{tip}}$)
If not wsk.spline.has_enough_points() Then
    Return ${}^{\text{w}}\boldsymbol{v}^t$, ${}^{\text{w}}\omega^t$
End If

Swiping Policy

Control Algorithm

Algorithm Swiping Policy

11: ${}^{\mathrm{w}}\boldsymbol{\tau}^{t}_{\mathrm{spline}} \leftarrow \dfrac{\mathrm{wsk.spline}(u{=}u_{k1}) - \mathrm{wsk.spline}(u{=}u_{k0})}{\|\mathrm{wsk.spline}(u{=}u_{k1}) - \mathrm{wsk.spline}(u{=}u_{k0})\|}$

12: ${}^{\mathrm{w}}\theta^{t}_{\mathrm{spline}} \leftarrow \arctan2({}^{\mathrm{w}}\boldsymbol{\tau}^{t}_{\mathrm{spline}})$

13: ${}^{\mathrm{s}}\boldsymbol{r}^{t}_{\mathrm{tip,target}} \leftarrow \mathrm{wsk.defl\_model}\big(\delta_{\mathrm{wsk,target}} \cdot \mathrm{sgn}(\delta^{t}_{\mathrm{wsk}})\big)$

14: $\Delta\boldsymbol{r}^{t}_{tip} \leftarrow \boldsymbol{R}^{2}_{xy}({}^{\mathrm{w}}\alpha^{t}_{\mathrm{wsk}}) \cdot ({}^{\mathrm{s}}\boldsymbol{r}^{t}_{\mathrm{tip,target}} - {}^{\mathrm{s}}\boldsymbol{r}^{t}_{\mathrm{tip}})$

15: ${}^{\mathrm{s}}\boldsymbol{r}_{\mathrm{tip,neutral}} \leftarrow \mathrm{wsk.defl\_model}(0)$

16: $w^{t}_{\mathrm{defl}} \leftarrow \dfrac{\|\Delta\boldsymbol{r}^{t}_{\mathrm{tip}}\|}{\|{}^{\mathrm{s}}\boldsymbol{r}^{t}_{\mathrm{tip,target}} - {}^{\mathrm{s}}\boldsymbol{r}_{\mathrm{tip,neutral}}\|}$

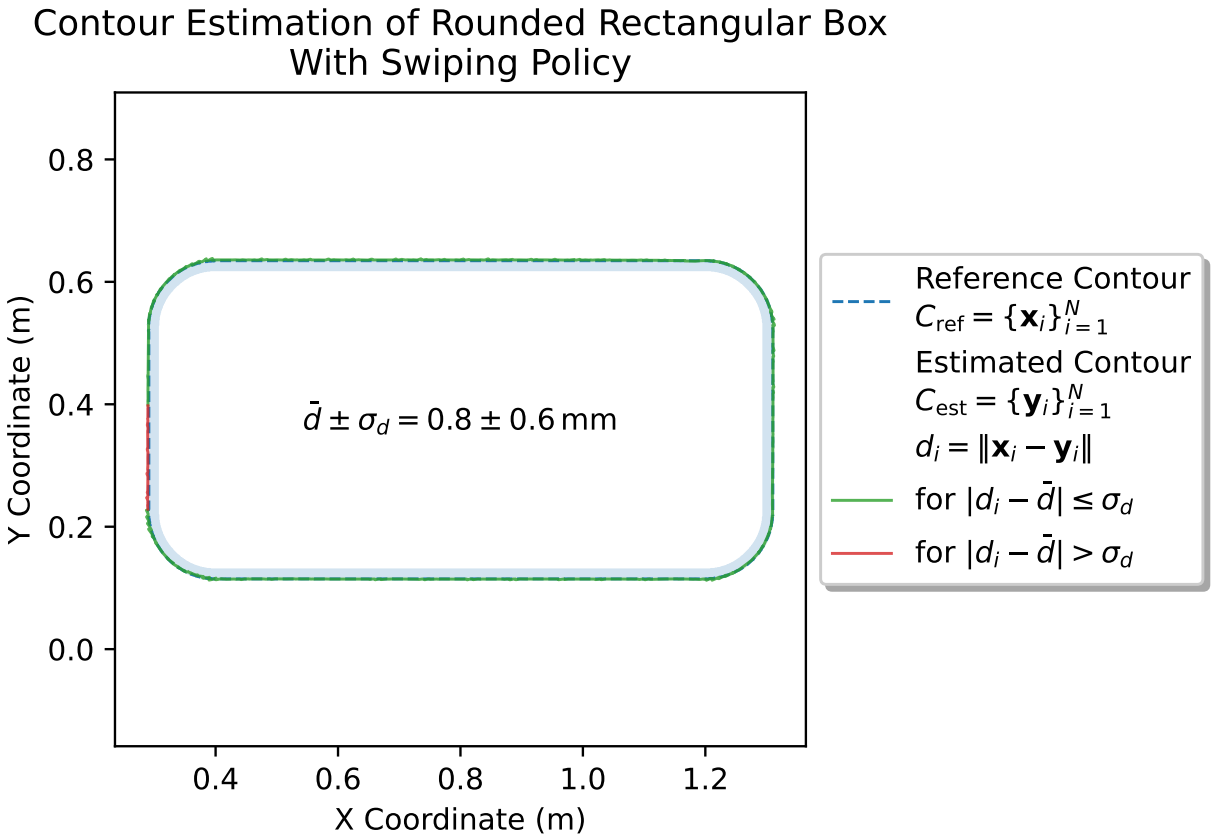
17: ${}^{\mathrm{w}}\boldsymbol{r}^{t+1}_{\mathrm{wsk}} \leftarrow {}^{\mathrm{w}}\boldsymbol{r}^{t}_{\mathrm{wsk}} + w^{t}_{\mathrm{defl}} \cdot \dfrac{-\Delta\boldsymbol{r}^{t}_{\mathrm{tip}}}{\|\Delta\boldsymbol{r}^{t}_{\mathrm{tip}}\|} + (1 - w^{t}_{\mathrm{defl}}) \cdot \dfrac{{}^{\mathrm{w}}\boldsymbol{\tau}^{t}_{\mathrm{spline}}}{\|{}^{\mathrm{w}}\boldsymbol{\tau}^{t}_{\mathrm{spline}}\|}$

18: $({}^{\mathrm{w}}\boldsymbol{v}^{t+1}, {}^{\mathrm{w}}\omega^{t+1}) \leftarrow \mathrm{steer\_wsk}({}^{\mathrm{w}}\boldsymbol{r}^{t+1}_{\mathrm{wsk}}, {}^{\mathrm{w}}\theta^{t}_{\mathrm{spline}})$

19: Return ${}^{\mathrm{w}}\boldsymbol{v}^{t+1}, {}^{\mathrm{w}}\omega^{t+1}$

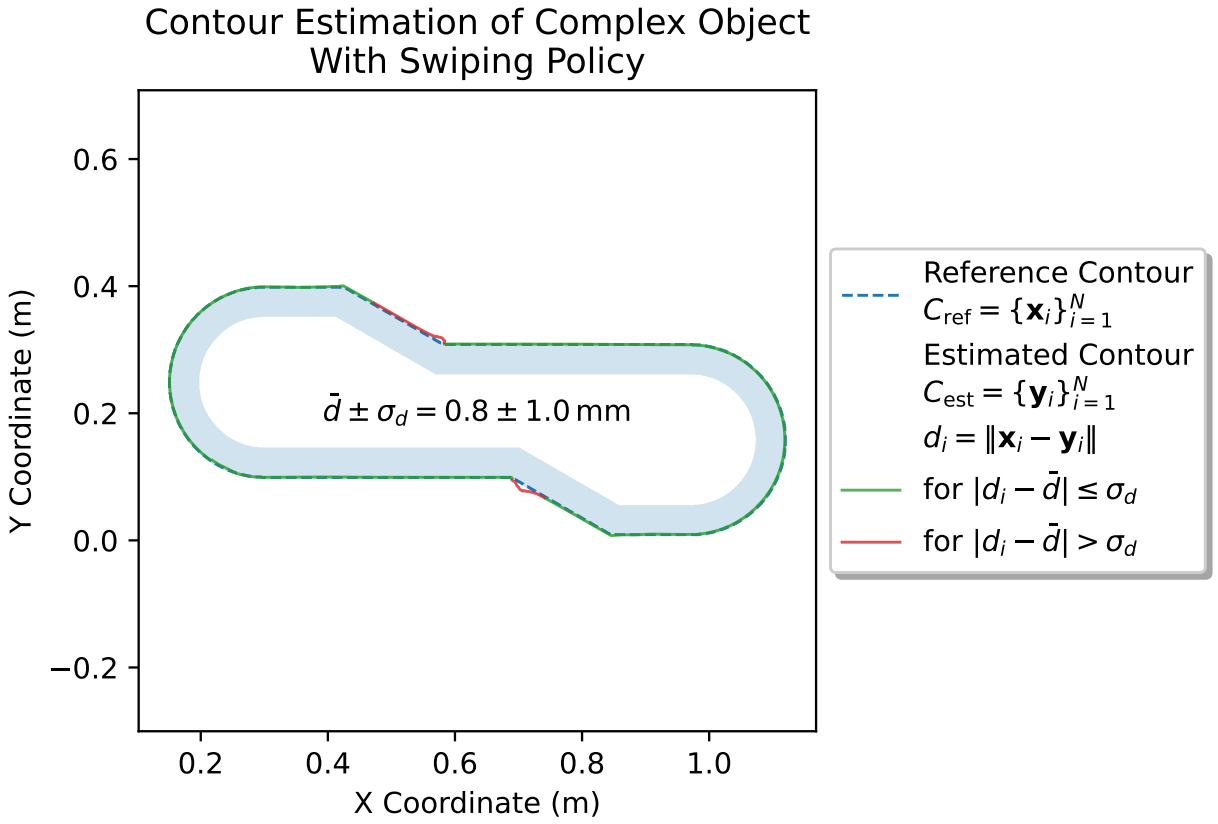
Swiping Policy

Simulation Results



Swiping Policy

Simulation Results



Retrieval Policy

Motivation

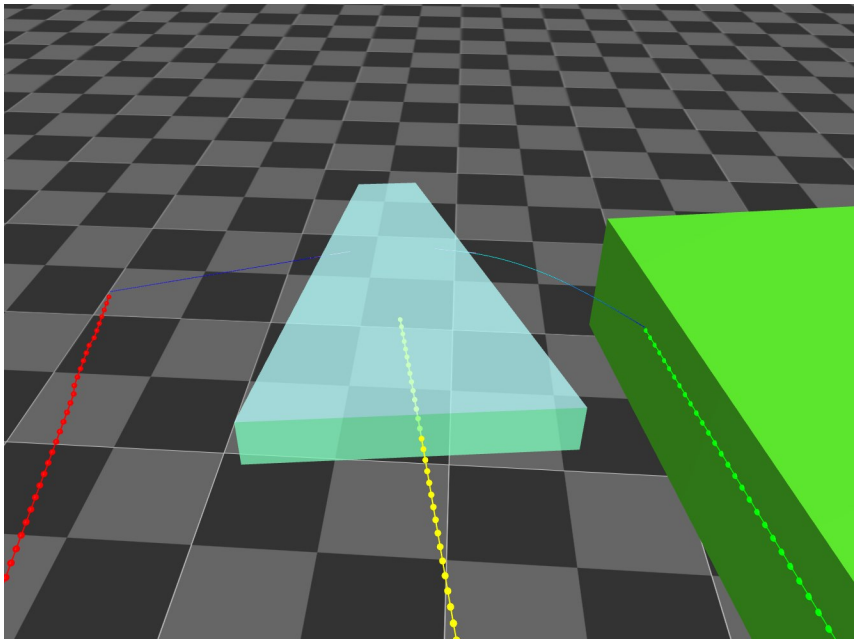


Figure: **(0.1) Initial situation**
Swiping along the side of the object.

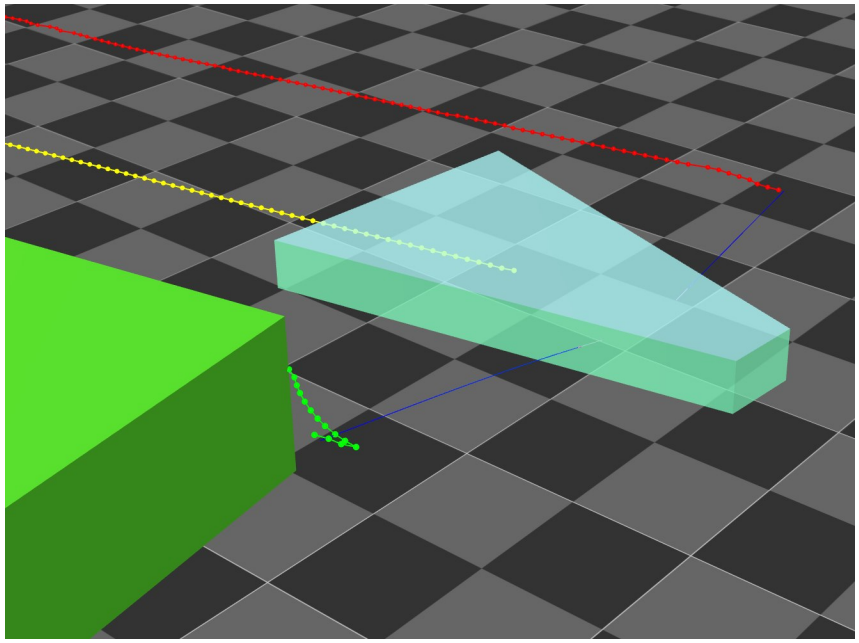


Figure: **(0.2) Disengagement**
Whisker has detached.

Retrieval Policy

Angle Resolution

1. **Angle Resolution**
   - 1.1 Construct a circle of potential contact points
   - 1.2 Move to the first candidate point
   - 1.3 Move sequentially from one candidate point to another until the contact is established
   - 1.4 Calculate the edge angle

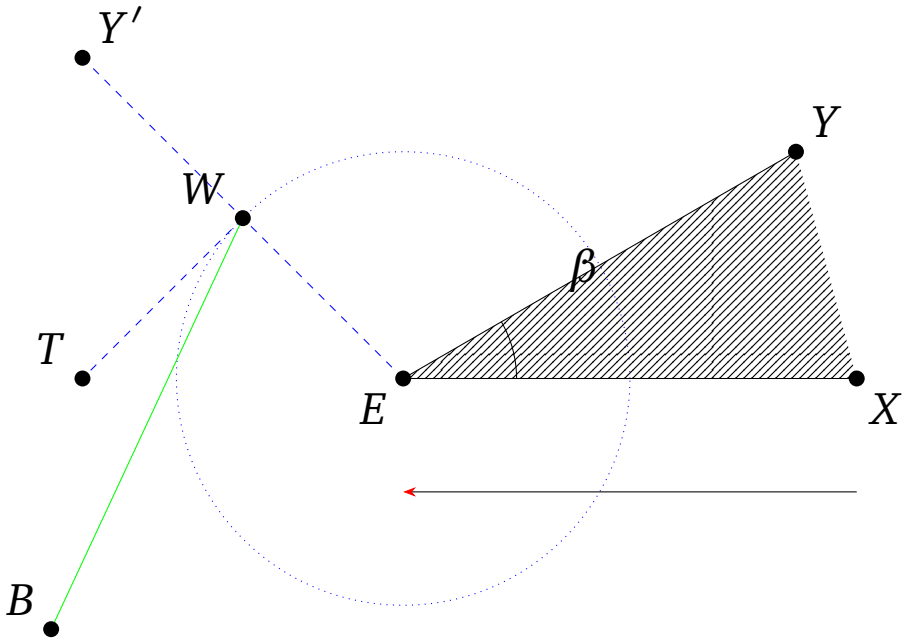


Figure: Angle Resolution at Edge E
Black $[XE]$, $[EY]$ — object surface,
Green $[BW]$ — the whisker.

Retrieval Policy

Angle Resolution

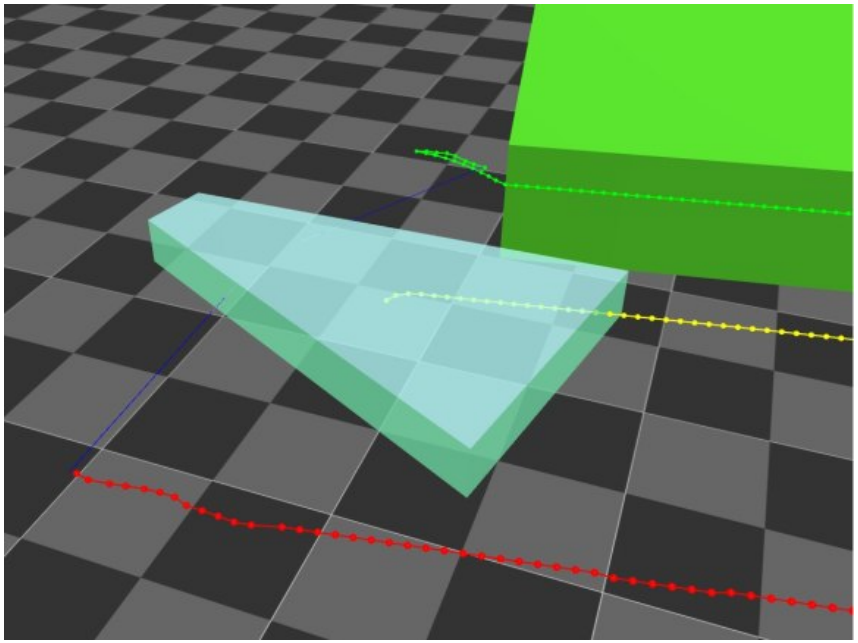


Figure: **(1.1) Rotation**
Whisker is rotating around the edge.

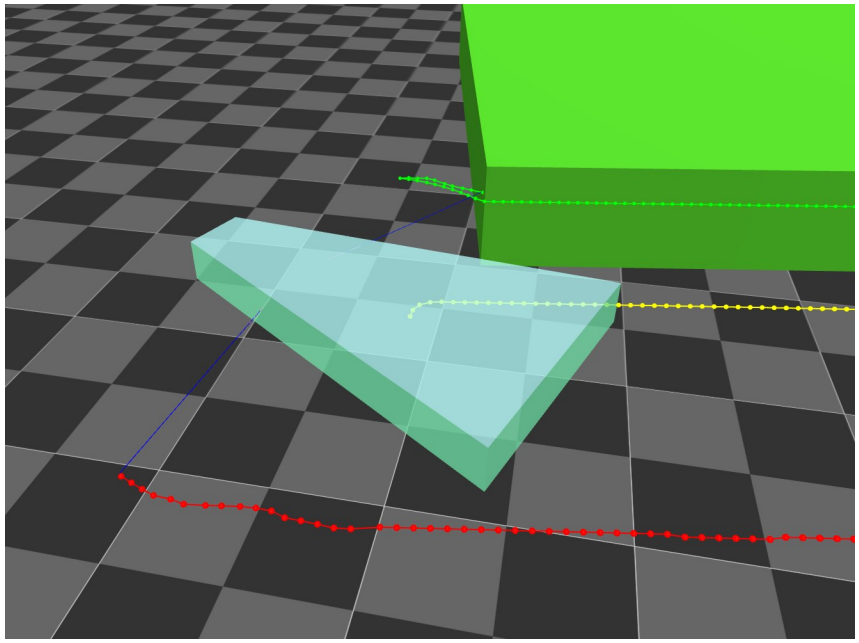


Figure: **(1.2) Retrieval**
Whisker has retrieved the contact.

Retrieval Policy

Whisking and Transition to Swiping

2. **Whisking Back to the Edge**

   2.1 Move back along the opposite side of the edge

   2.2 Disengage the whisker at the edge

3. **Transition to Swiping**

   3.1 Reposition the whisker with a slight overshoot

   3.2 Move towards the object until the contact is re-established

   3.3 Transfer control to the exploration policy

Retrieval Policy

Whisking and Repositioning

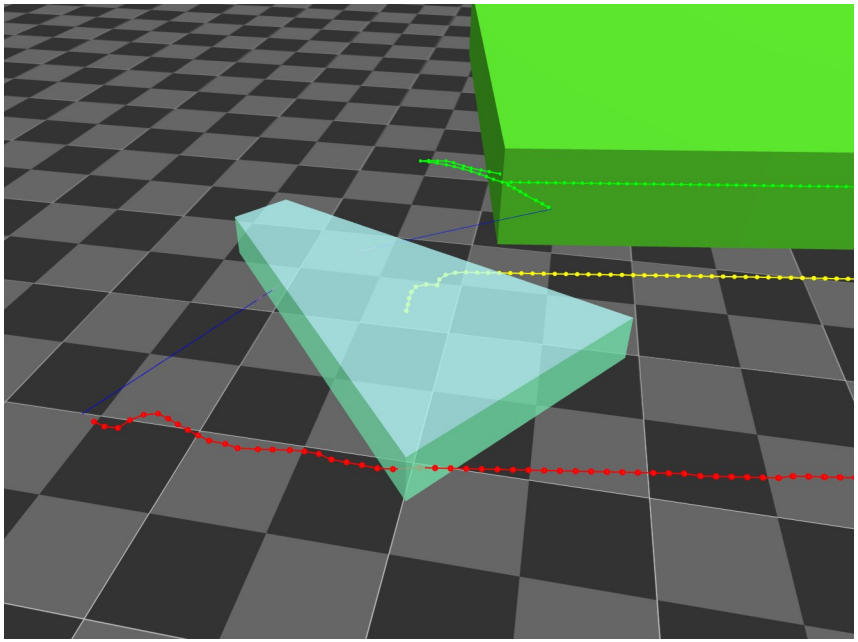


Figure: **(2) Whisking**
Moving back along the opposite side of the edge.

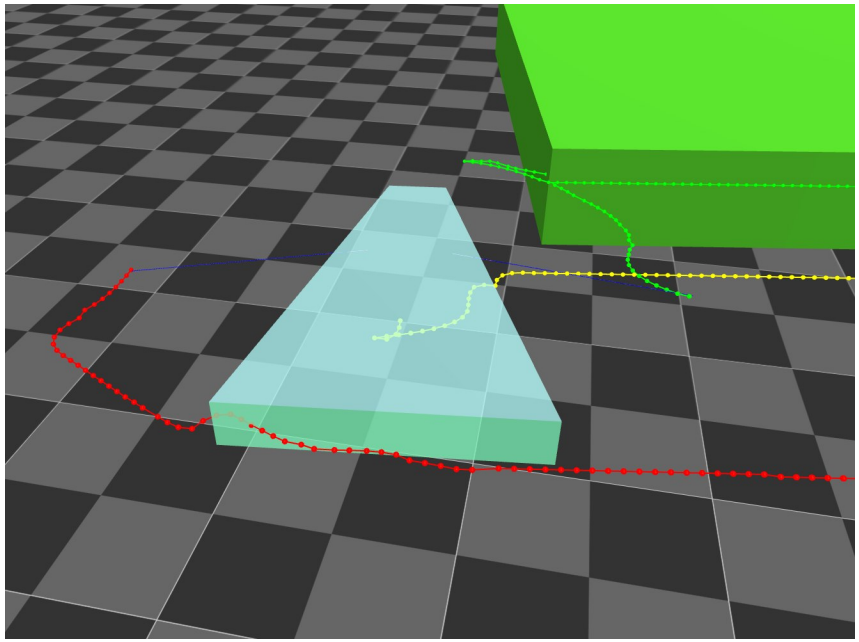


Figure: **(3.1) Repositioning**
Assuming an optimal position for approach.

Retrieval Policy

Final Steps

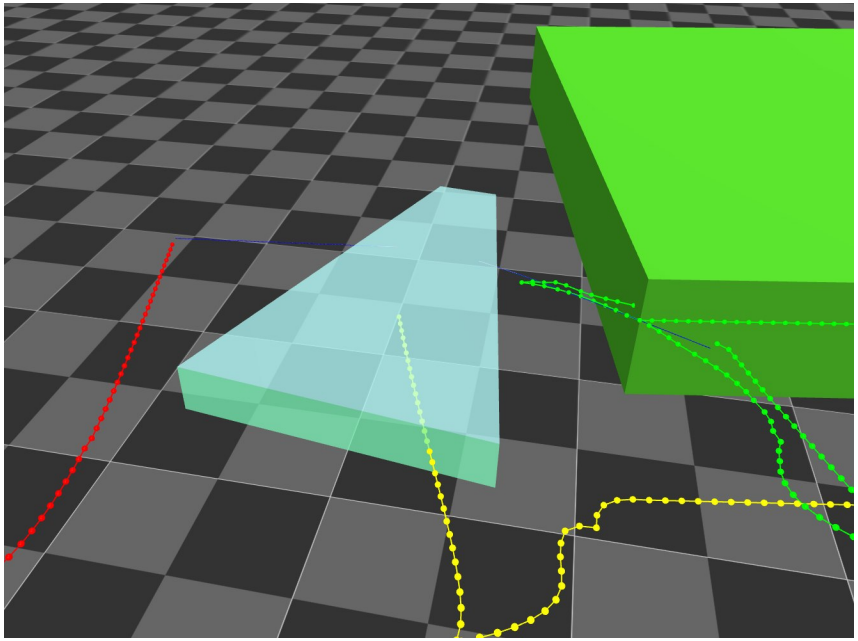


Figure: **(3.2) Approach**
Moving towards the object.

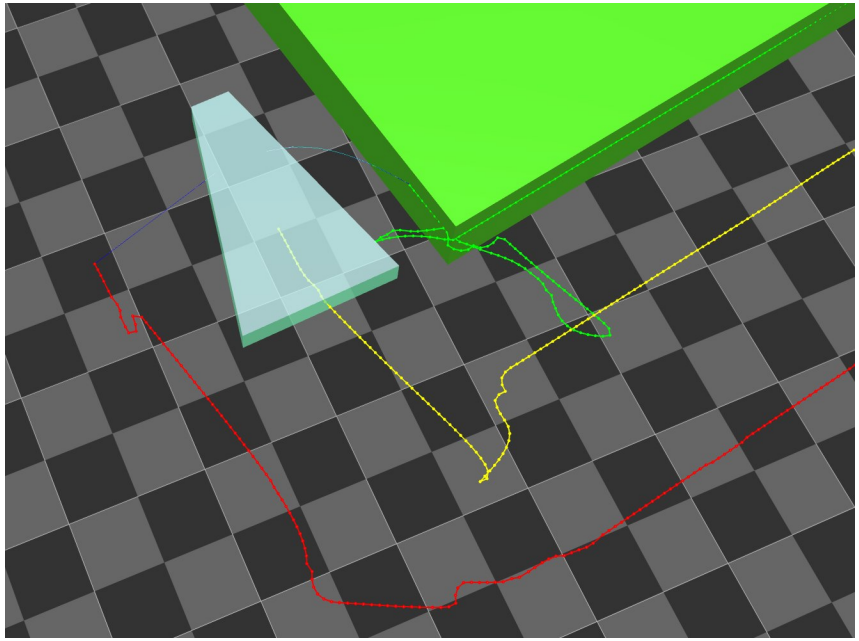
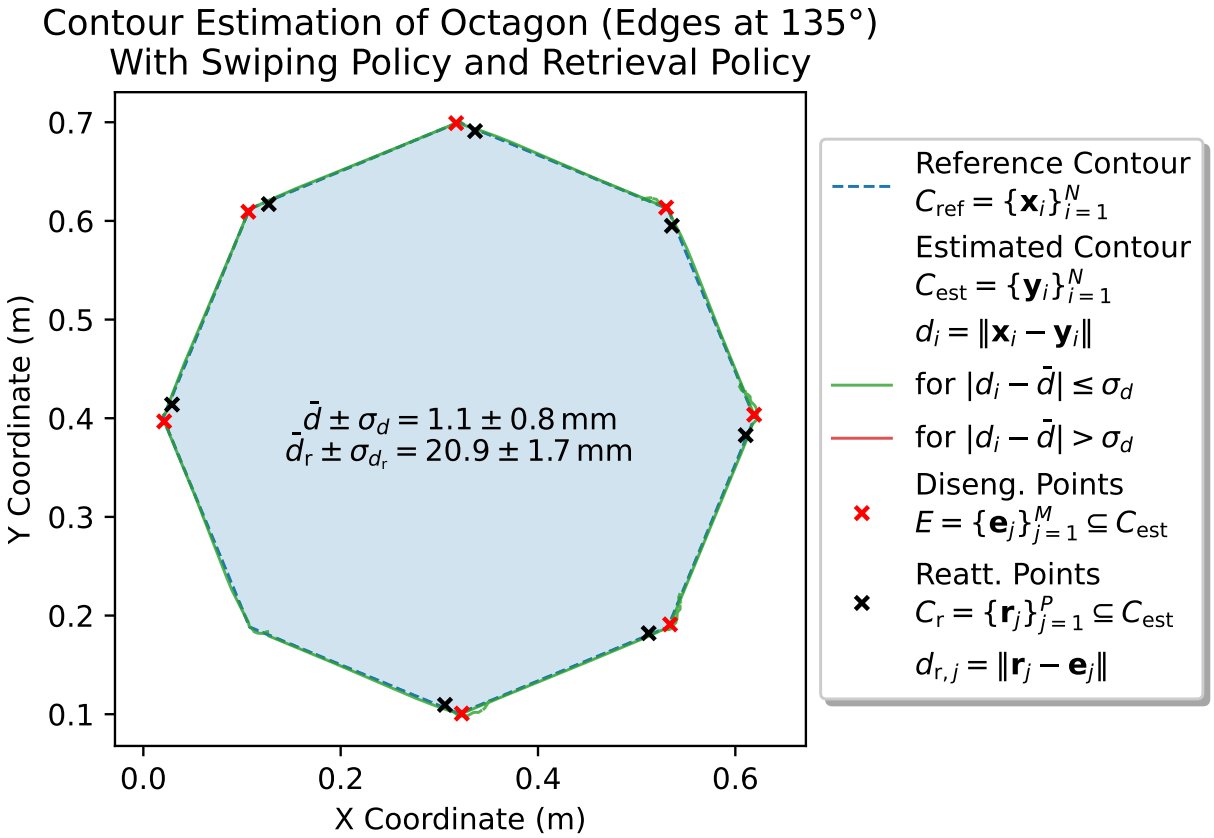


Figure: **(3.3) Transition to Swiping**
Transferring control to the Swiping Policy.

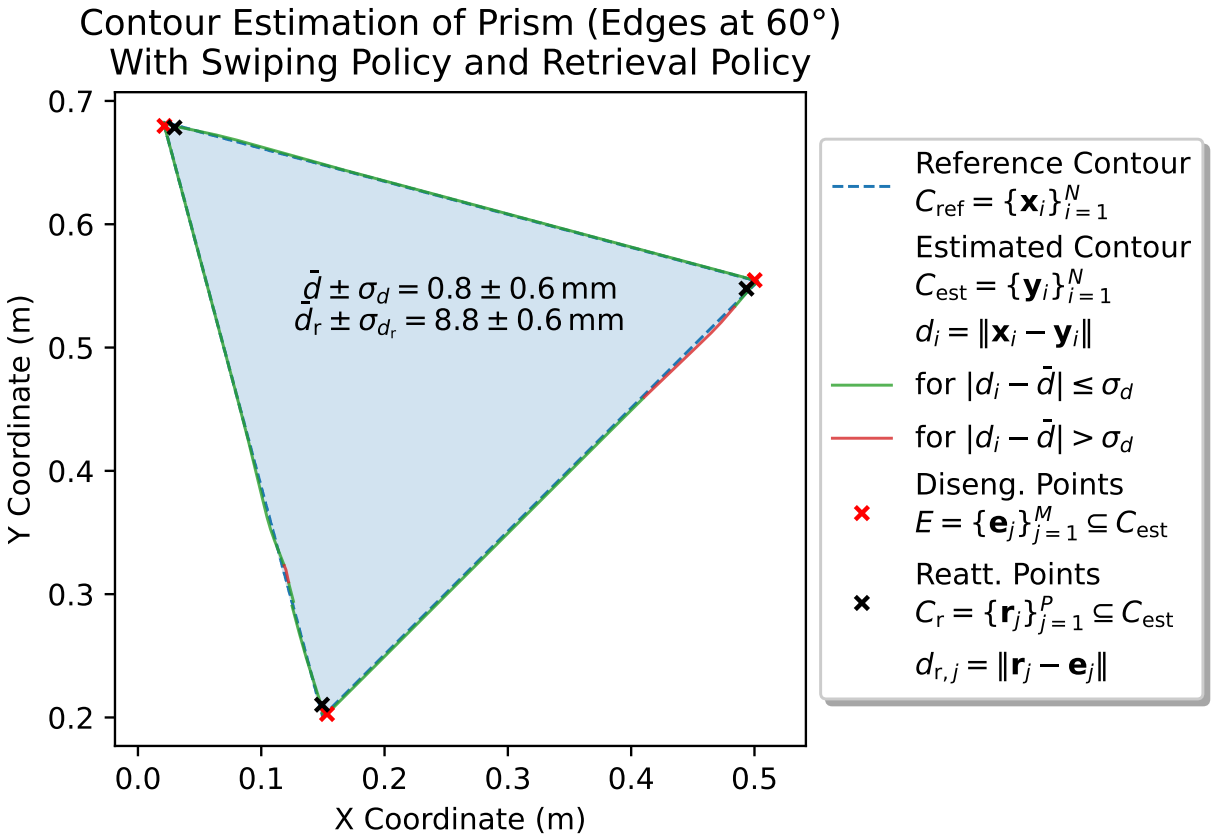
Retrieval Policy

Simulation Results



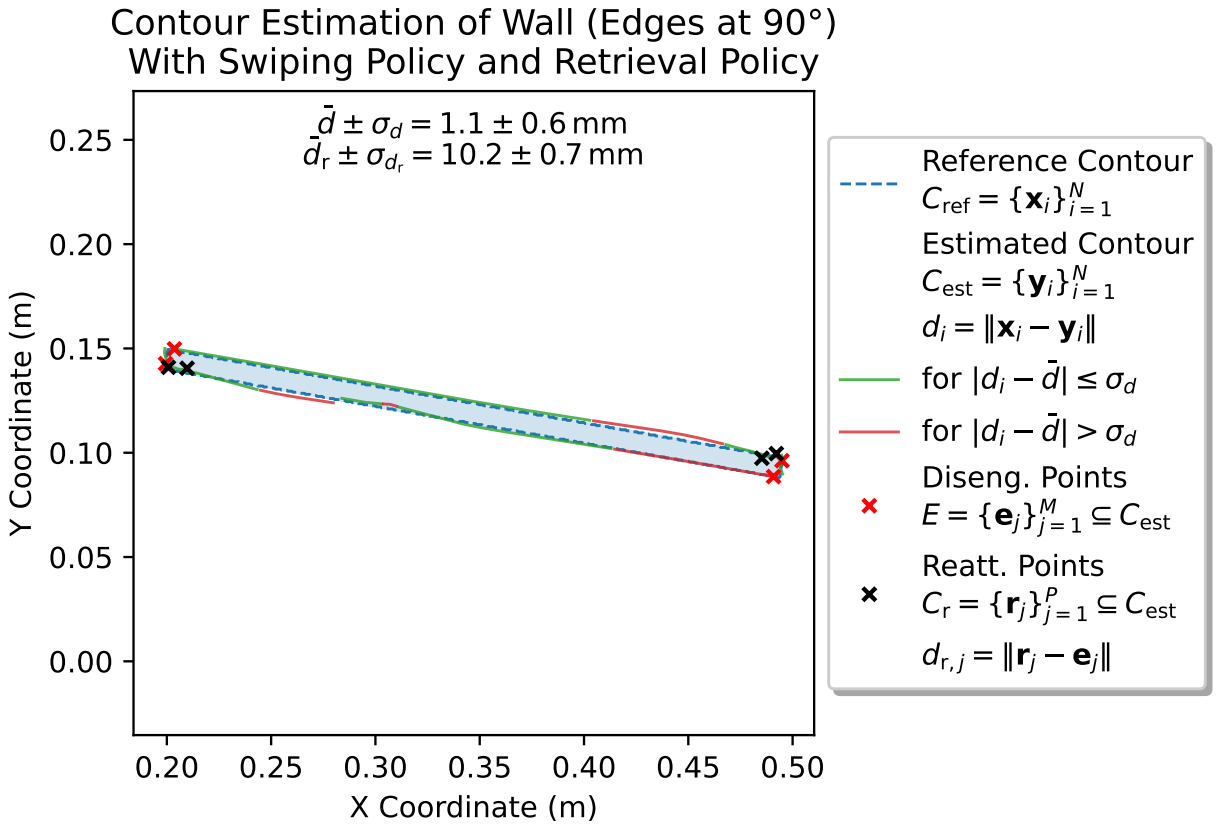
Retrieval Policy

Simulation Results



Retrieval Policy

Simulation Results



Tunneling Policy

Control Algorithm

Algorithm Tunneling Policy Control

1: ${}^{\mathrm{w}}\boldsymbol{r}^{t}_{\mathrm{tip,r}} \leftarrow {}^{\mathrm{w}}\boldsymbol{r}^{t} + {}^{\mathrm{w}}\boldsymbol{r}_{\mathrm{r,body}} + \boldsymbol{R}^{2}_{xy}({}^{\mathrm{w}}\alpha^{t}_{\mathrm{r}}) \cdot \mathrm{r.defl\_model}(\delta^{t}_{\mathrm{r}})$

2: ${}^{\mathrm{w}}\boldsymbol{r}^{t}_{\mathrm{tip,l}} \leftarrow {}^{\mathrm{w}}\boldsymbol{r}^{t} + {}^{\mathrm{w}}\boldsymbol{r}_{\mathrm{l,body}} + \boldsymbol{R}^{2}_{xy}({}^{\mathrm{w}}\alpha^{t}_{\mathrm{l}}) \cdot \mathrm{l.defl\_model}(\delta^{t}_{\mathrm{l}})$

3: $\mathrm{midpoint\_spline.add\_keypoint}\big(({}^{\mathrm{w}}\boldsymbol{r}^{t}_{\mathrm{tip,r}} + {}^{\mathrm{w}}\boldsymbol{r}^{t}_{\mathrm{tip,l}})/2\big)$

4: If not midpoint_spline.has_enough_points Then Return ${}^{\mathrm{w}}\boldsymbol{v}^{t}$, ${}^{\mathrm{w}}\omega^{t}$ End If

5:

6: ${}^{\mathrm{w}}\boldsymbol{\tau}^{t}_{\mathrm{spline}} \leftarrow \mathrm{midpoint\_spline}(u{=}1) - \mathrm{midpoint\_spline}(u{=}0)$

7: ${}^{\mathrm{w}}\boldsymbol{n}^{t}_{\mathrm{spline}} \leftarrow \boldsymbol{R}^{2}_{xy}(\pi/2 \cdot orient^{t}_{\mathrm{r}}) \cdot {}^{\mathrm{w}}\boldsymbol{\tau}^{t}_{\mathrm{spline}}$

8: ${}^{\mathrm{w}}\theta^{t}_{\mathrm{spline}} \leftarrow \arctan2({}^{\mathrm{w}}\boldsymbol{\tau}^{t}_{\mathrm{spline}})$

9: $\mathrm{pull}_{\mathrm{total}} \leftarrow \mathrm{clip}\big(\frac{\delta^{t}_{\mathrm{r}} - \delta_{\mathrm{r,target}}}{\delta_{\mathrm{r,target}}} - \frac{\delta^{t}_{\mathrm{l}} - \delta_{\mathrm{l,target}}}{\delta_{\mathrm{l,target}}}, \mathrm{min}{=}-1, \mathrm{max}{=}1\big)$

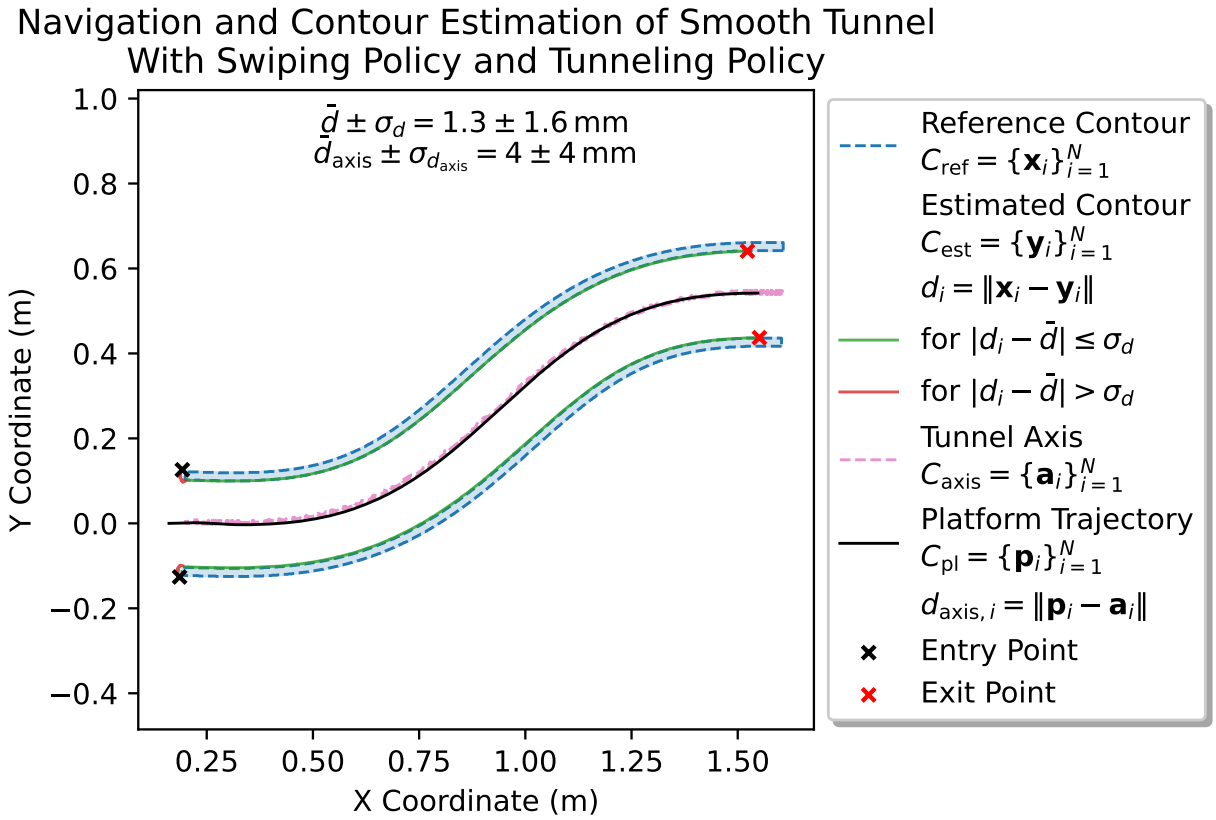
10: ${}^{\mathrm{w}}\boldsymbol{r}^{t+1} \leftarrow {}^{\mathrm{w}}\boldsymbol{r}^{t} + {}^{\mathrm{w}}\boldsymbol{\tau}^{t}_{\mathrm{spline}} + \mathrm{pull}_{\mathrm{total}}/2 \cdot {}^{\mathrm{w}}\boldsymbol{n}^{t}_{\mathrm{spline}}$

11: $({}^{\mathrm{w}}\boldsymbol{v}^{t+1}, {}^{\mathrm{w}}\omega^{t+1}) \leftarrow steer\_body({}^{\mathrm{w}}\boldsymbol{r}^{t+1}, {}^{\mathrm{w}}\theta^{t}_{\mathrm{spline}})$

12: Return ${}^{\mathrm{w}}\boldsymbol{v}^{t+1}$, ${}^{\mathrm{w}}\omega^{t+1}$

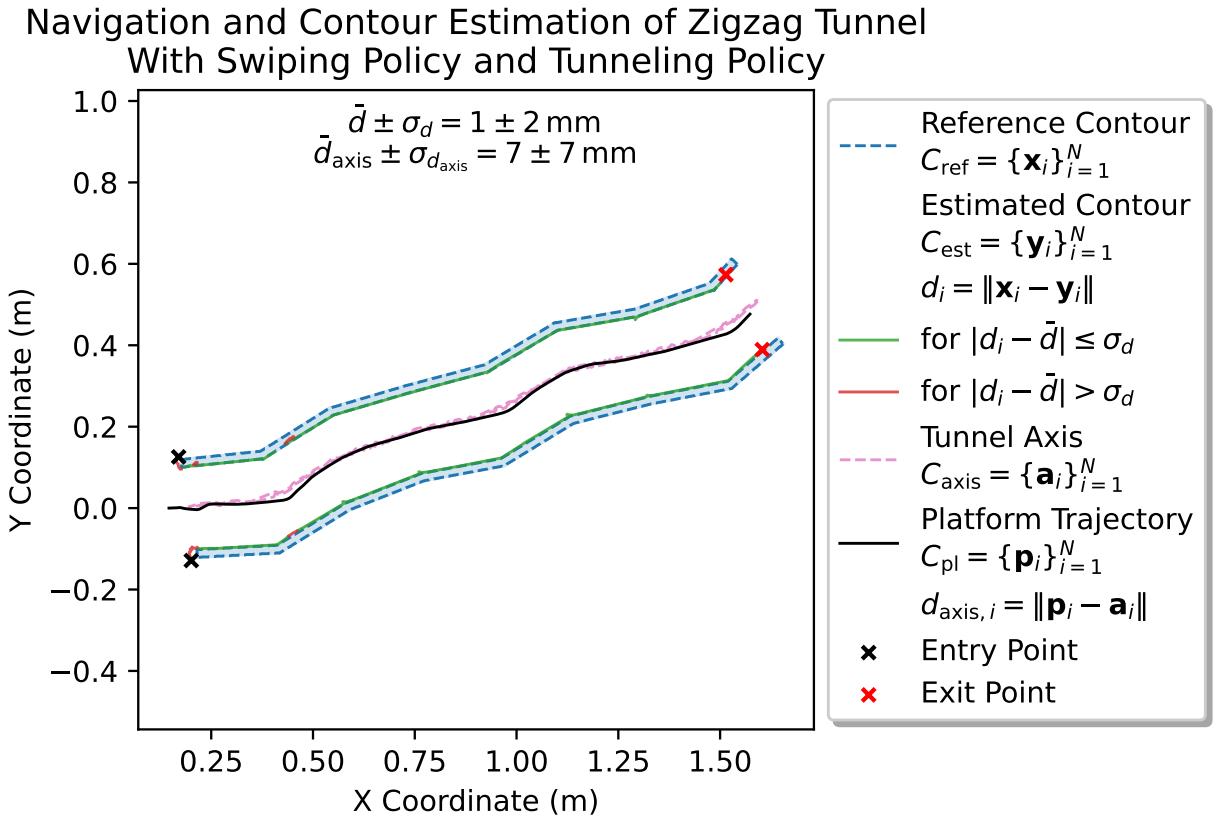
Tunneling Policy

Simulation Results



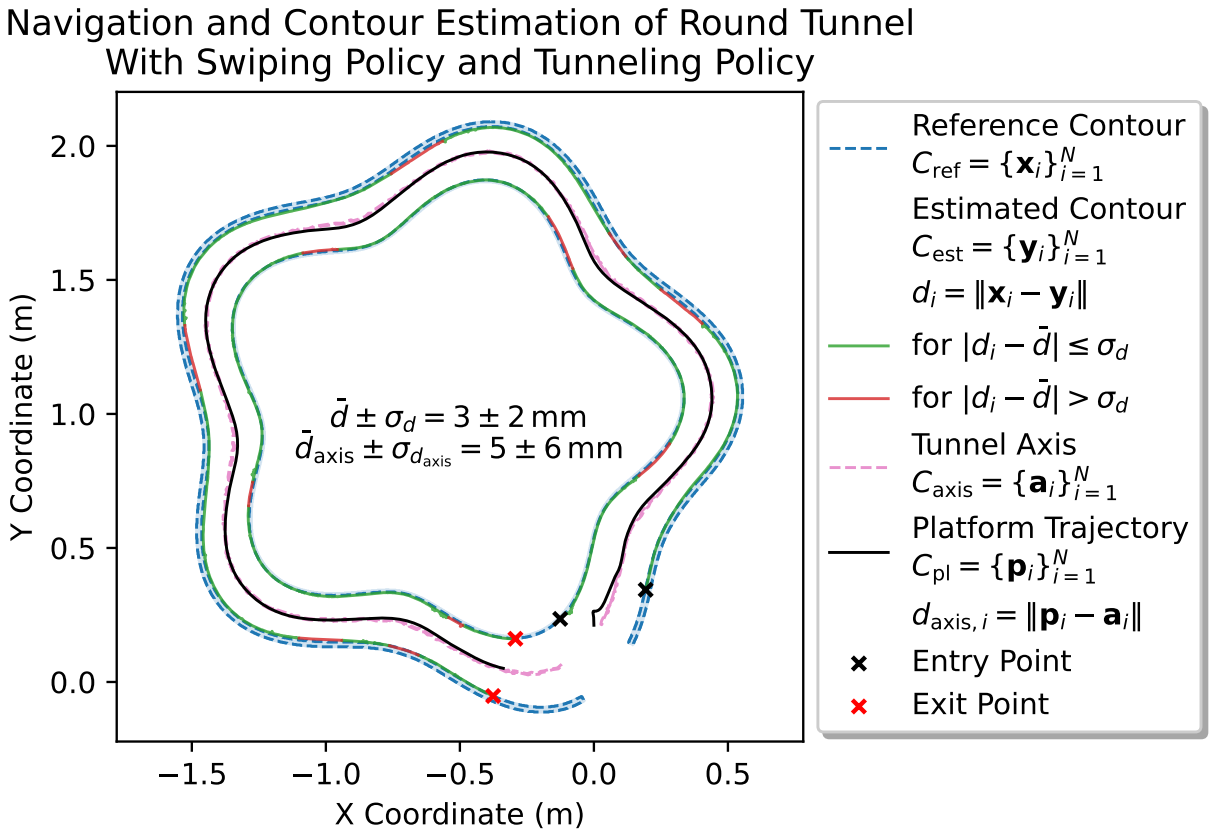
Tunneling Policy

Simulation Results



Tunneling Policy

Simulation Results



Governing Policy

Finite State Machine

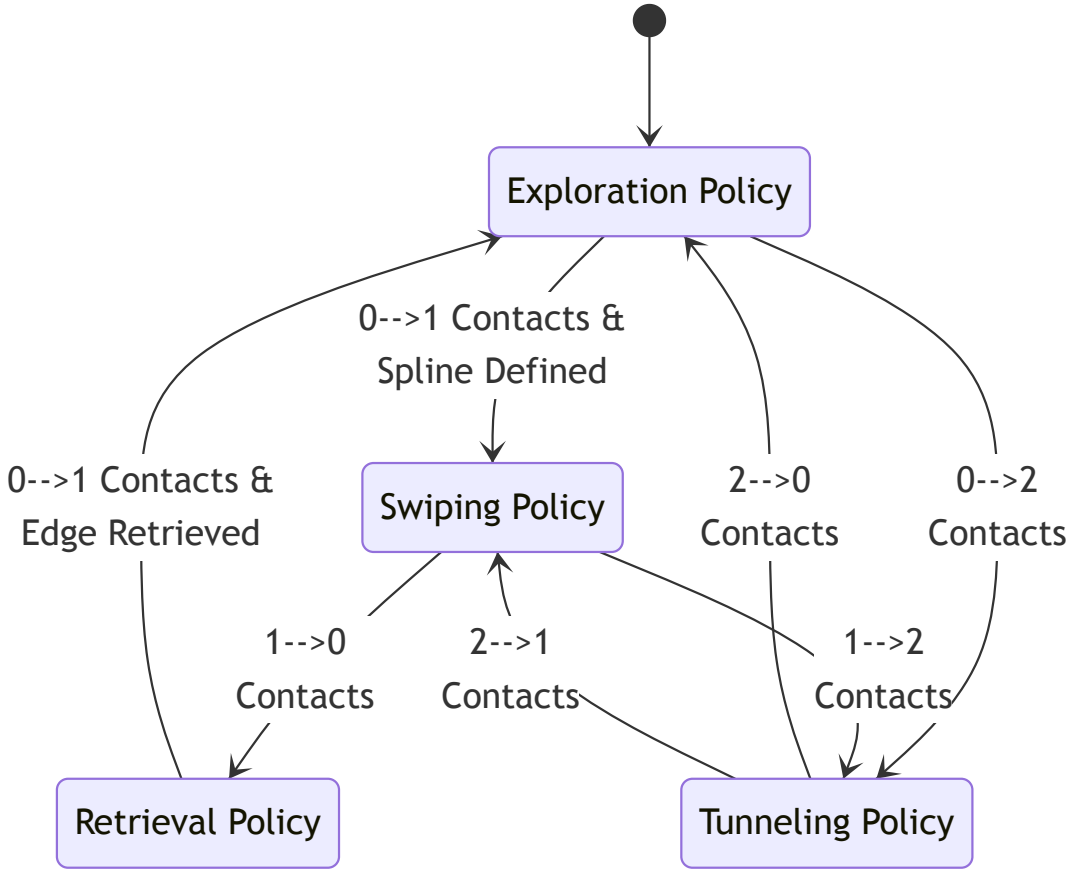


Figure: FSM diagram of the whisker control system.

Outline

Infrastructure

System Overview

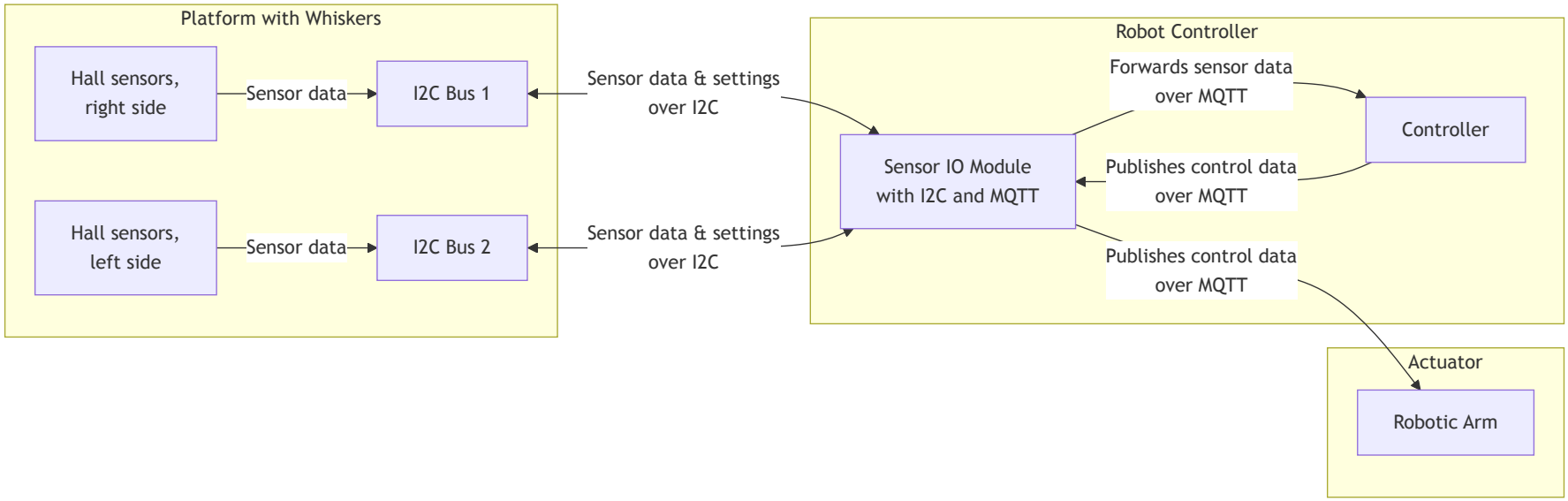


Figure: Data flow in the system infrastructure.

Infrastructure

Robot Controller Overview

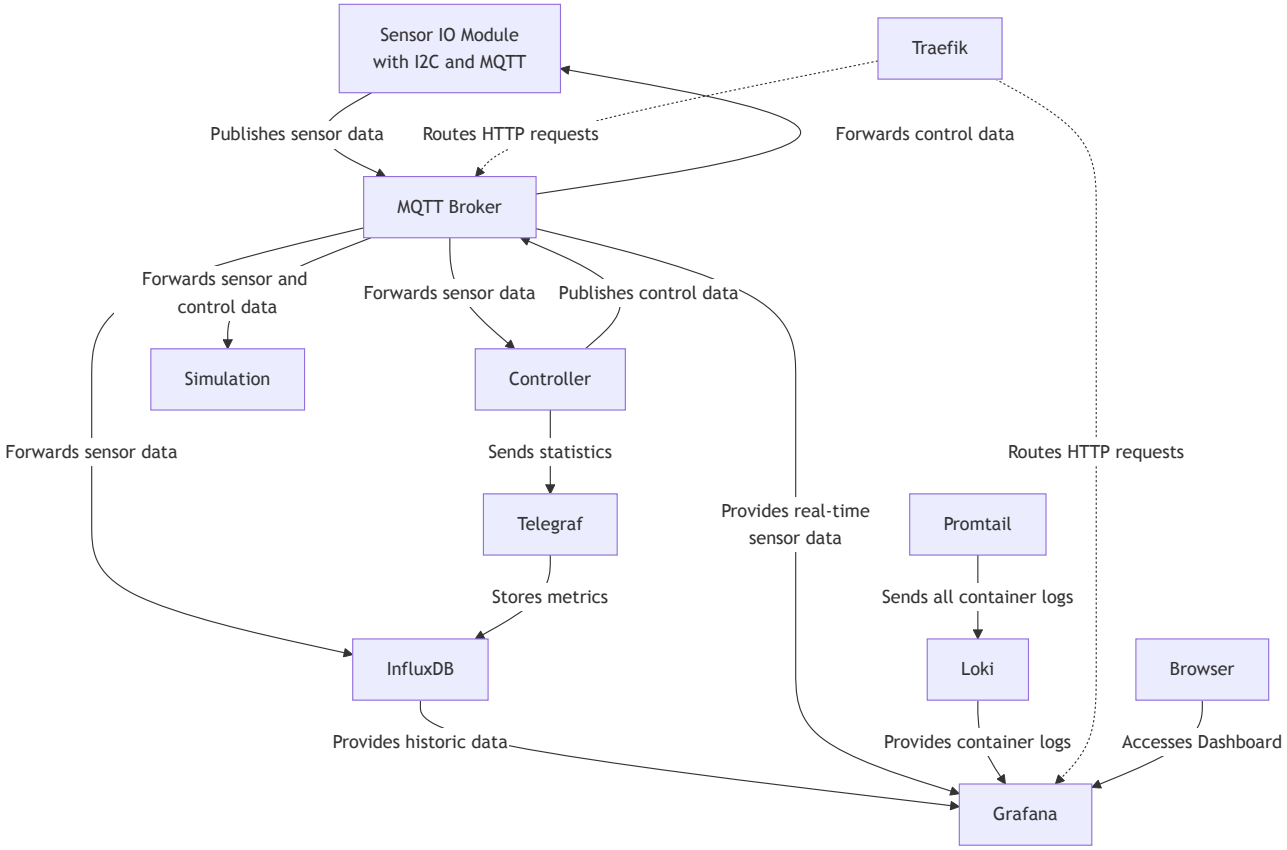


Figure: Data flow in the robot controller infrastructure.

Infrastructure

Data Visualization

Figure: Sensor data visualization in real time using Grafana.

Outline

Future Work

- Testing of the whisker control system with the Franka Emika Panda robotic arm
- Addition of more whiskers to each side of the platform
- Active exploration of unstructured environments
- SLAM for navigation in cluttered environments
- Integration of the whiskers into the robotic rat

Outline

Conclusion

1. A **whisker array platform** for active tactile exploration was designed and assembled
2. Control algorithms were implemented for:
   - Contour reconstruction
   - **Object retrieval**
   - **Navigation in tunnels**
3. A **test framework with physics simulation** was developed for the whisker control system
4. A **system infrastructure** was developed for real-time sensor data visualization and evaluation

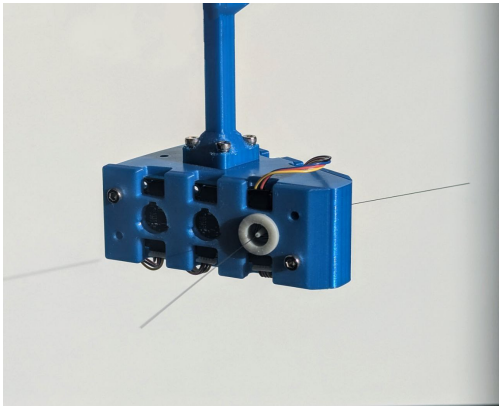


Figure: Platform with left and right whiskers

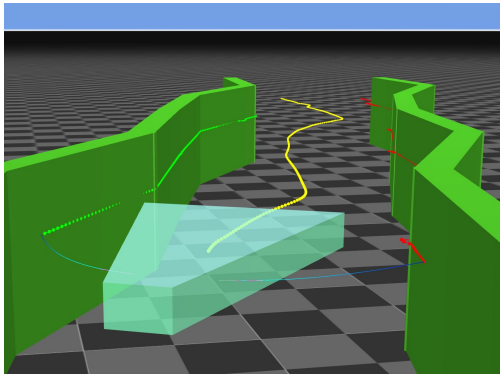


Figure: Simulation: platform navigating in a tunnel

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Active Tactile Exploration Based on Whisker-Inspired Sensory Array

Final Presentation, Bachelor's Thesis

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March 28, 2025

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