PatrolKnight

Intelligent Patrol Security Robotics System

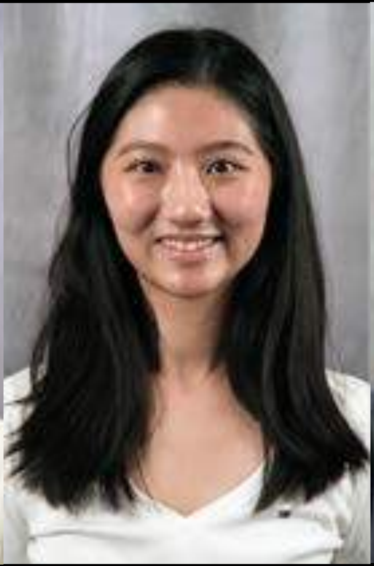
Team E: Sam Dong, Po-Ting Ko, Leo Xu, Pin-Wen Wang, Joshua Tsai

Our Team

Sam Dong

Po-Ting Ko

Leo Xu



Pin-Wen Wang

Joshua Tsai

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Project Description

User needs

- $50/hr → $3/hr
- $758K → $7000
- Efficient and reliable patrol coverage in large environments
- Reduced manual workload for security personnel
- Real-time awareness of abnormal activities

Proposed Method

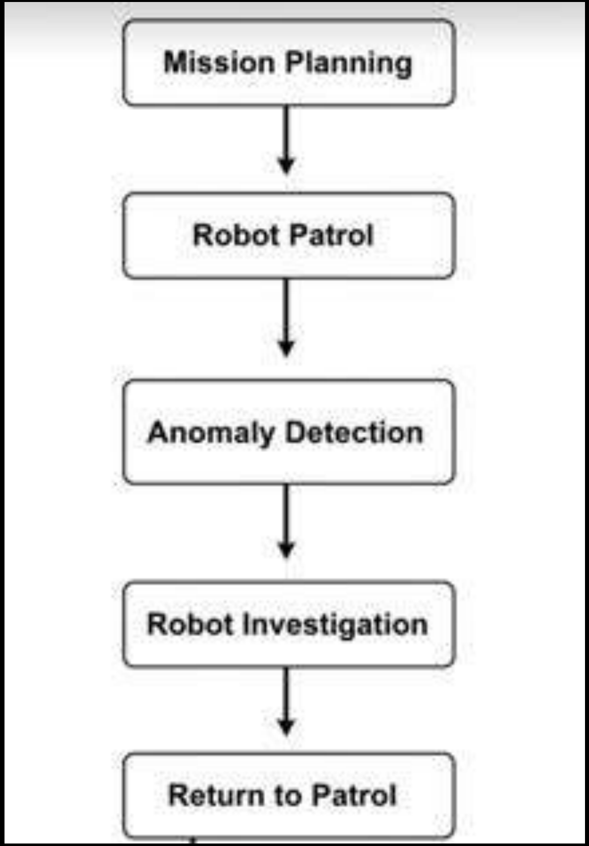
- AI-assisted waypoint recommendation for efficient patrol coverage
- Autonomous robot patrol with minimal human intervention
- Real-time monitoring and anomaly alerts to operators
- Dynamic response to incidents with human-in-the-loop control

Use Case

Use cases

Workflow

1. Operator opens dashboard and reviews suggested waypoints
2. Operator confirms or edits patrol route
3. Robot autonomously patrols environment
4. System monitors and detects anomalies
5. Robot is redirected to investigate if needed
6. Operator verifies alerts and system resumes patrol



System-level Requirements

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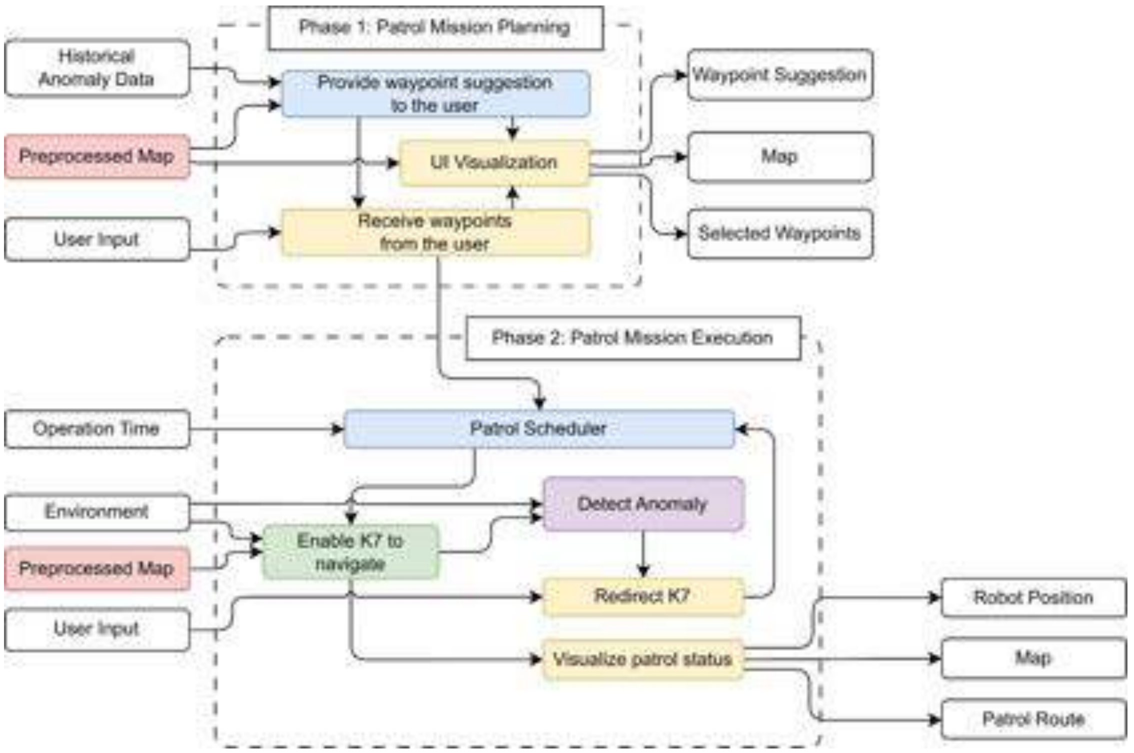
IDs	Functional Requirement
F.R.1	Provide waypoint suggestion to the user
F.R.2	Receive waypoints from the user
F.R.3	Enable K7 to navigate
F.R.4	Visualize patrol status
F.R.5	Detect anomaly
F.R.6	Redirect K7
F.R.7	Support alarm verification

System Architecture

Functional Architecture

- Two Phases
  - Mission Planning
  - Mission Execution
- Anomaly Handling
- Human-in-the-loop



Functional Architecture

- Two Phases
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  - Mission Execution
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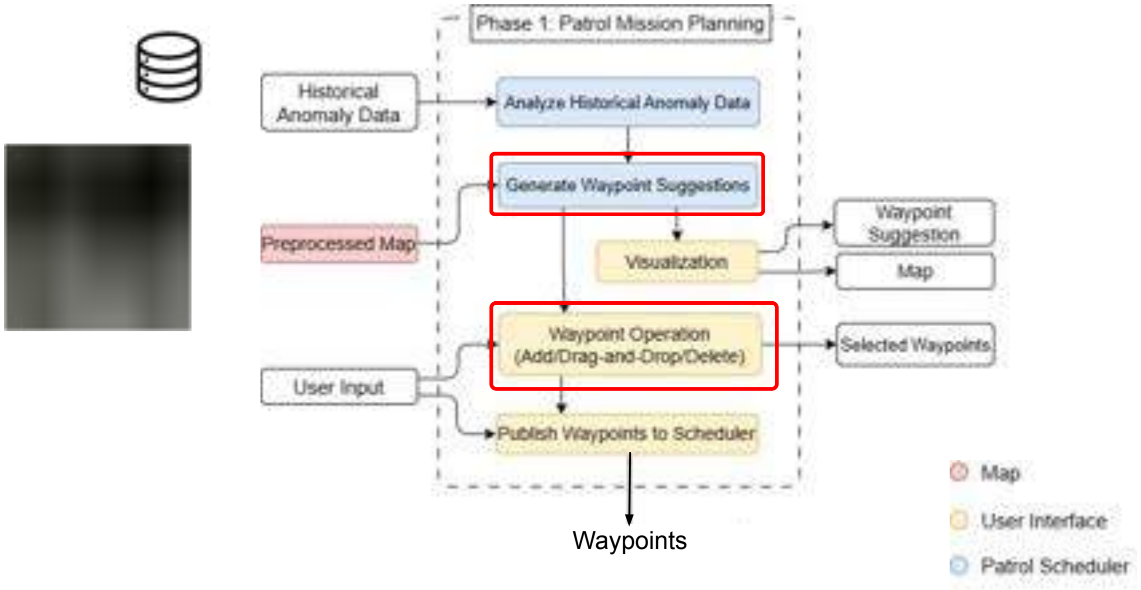
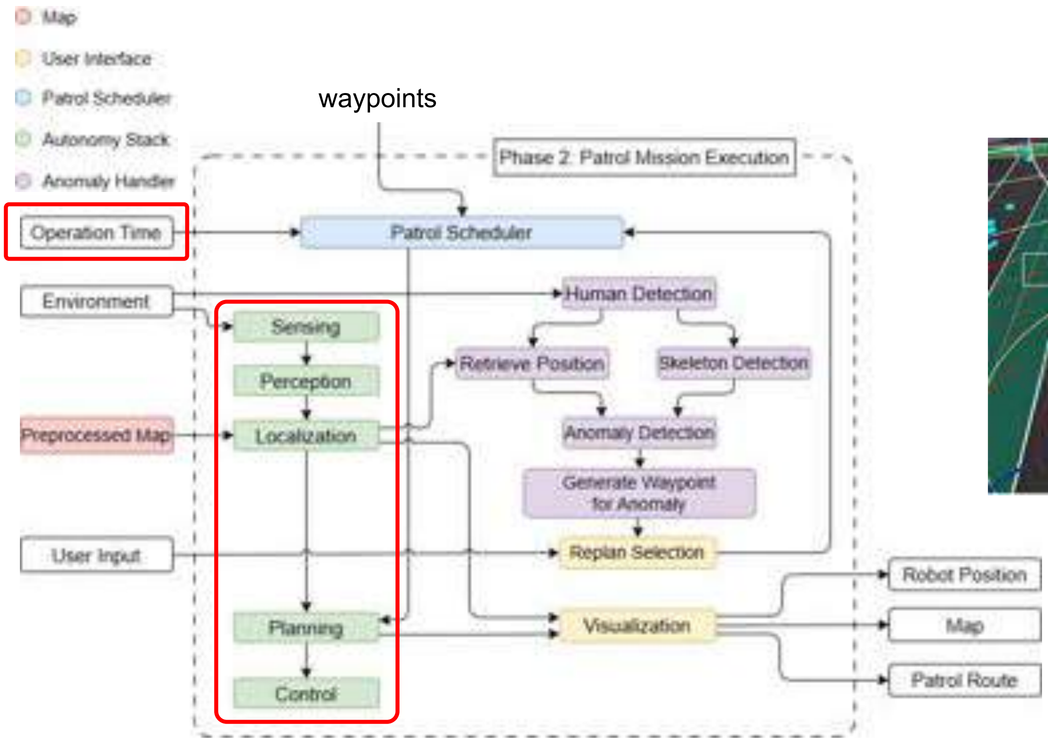
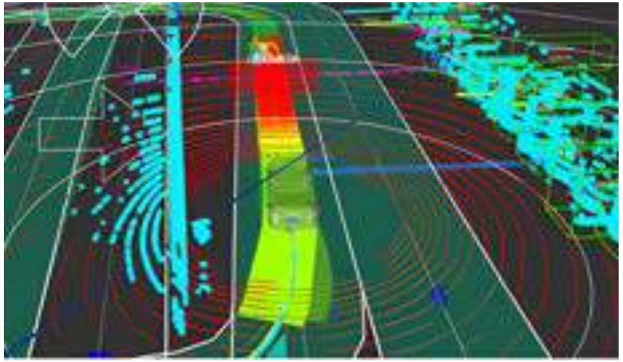
- Human-in-the-loop

Patrol Mission Planning

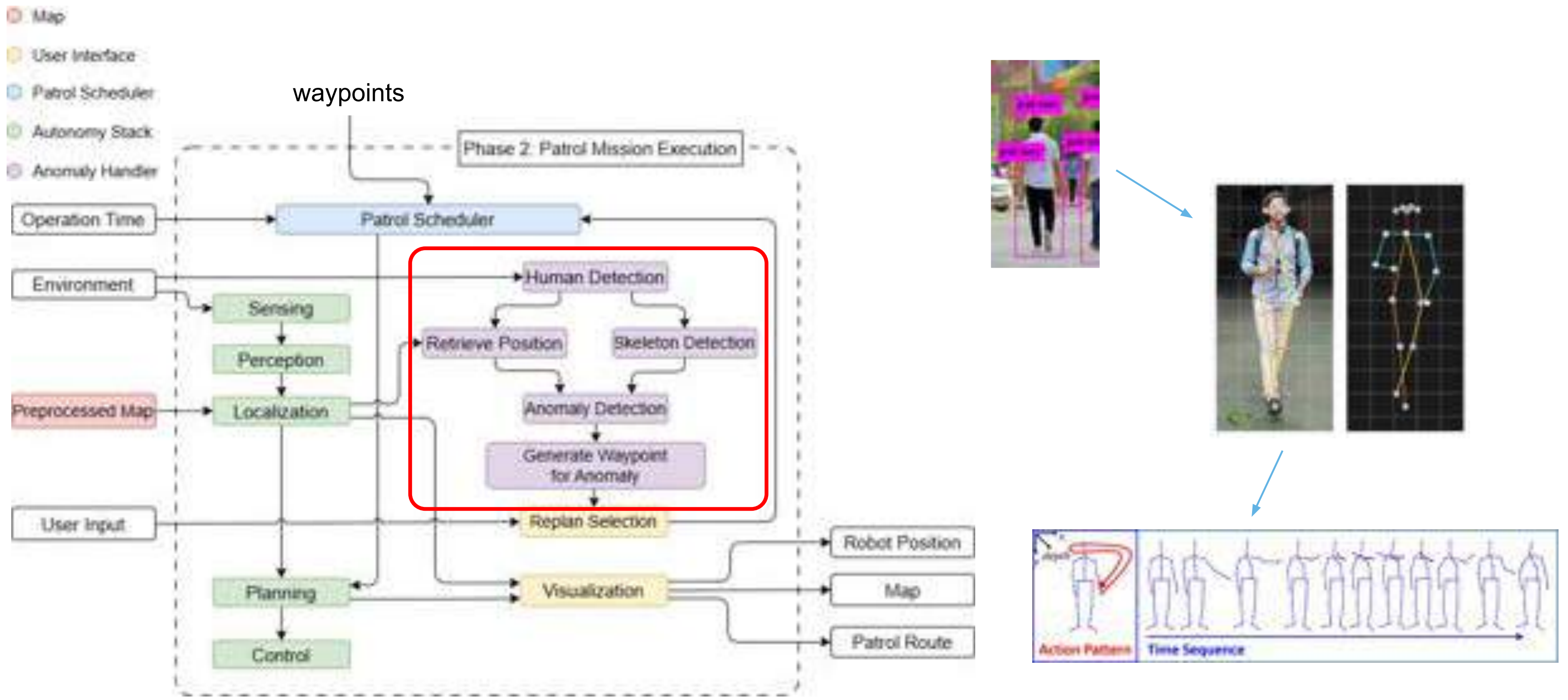


Patrol Mission Execution

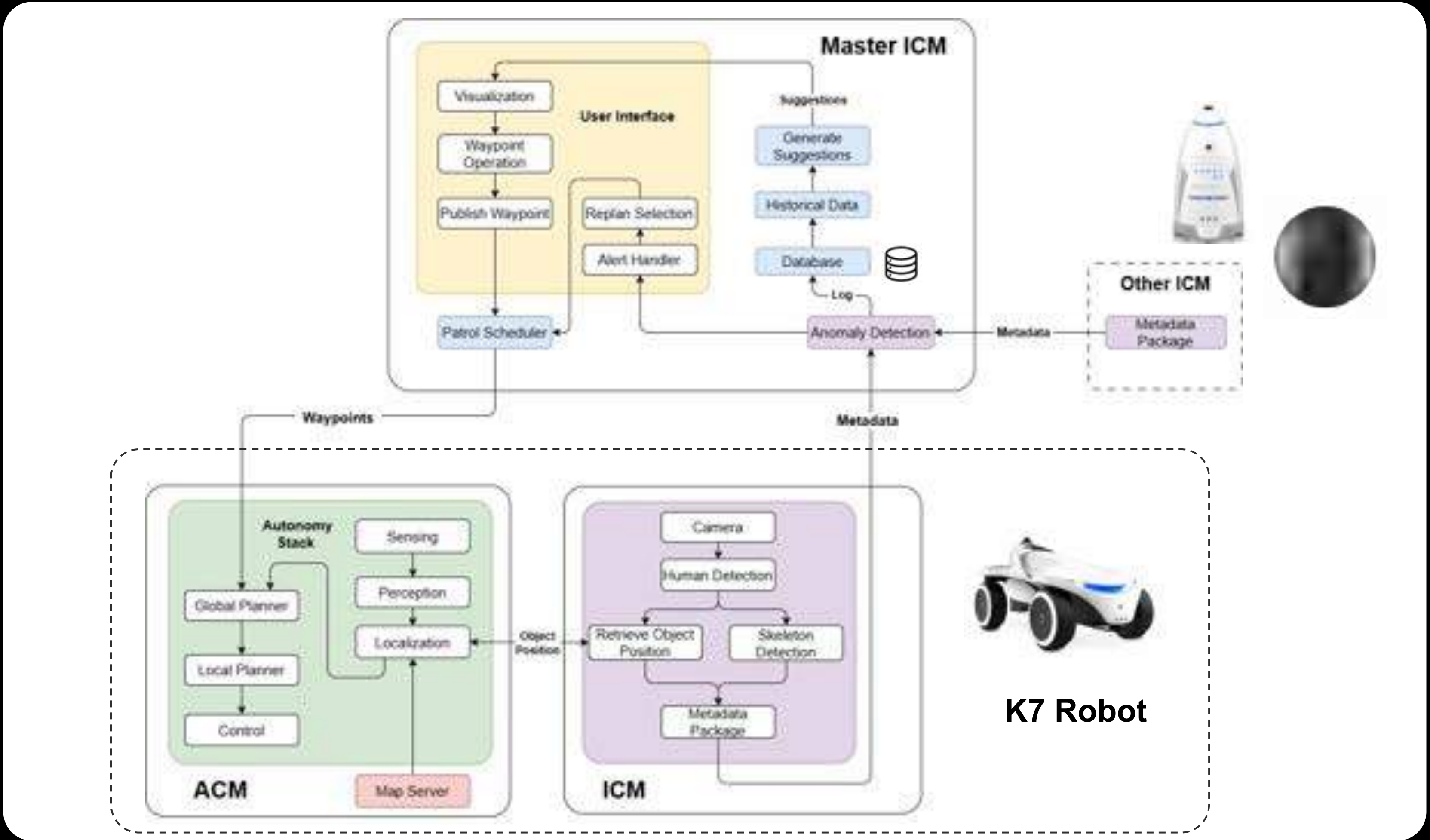




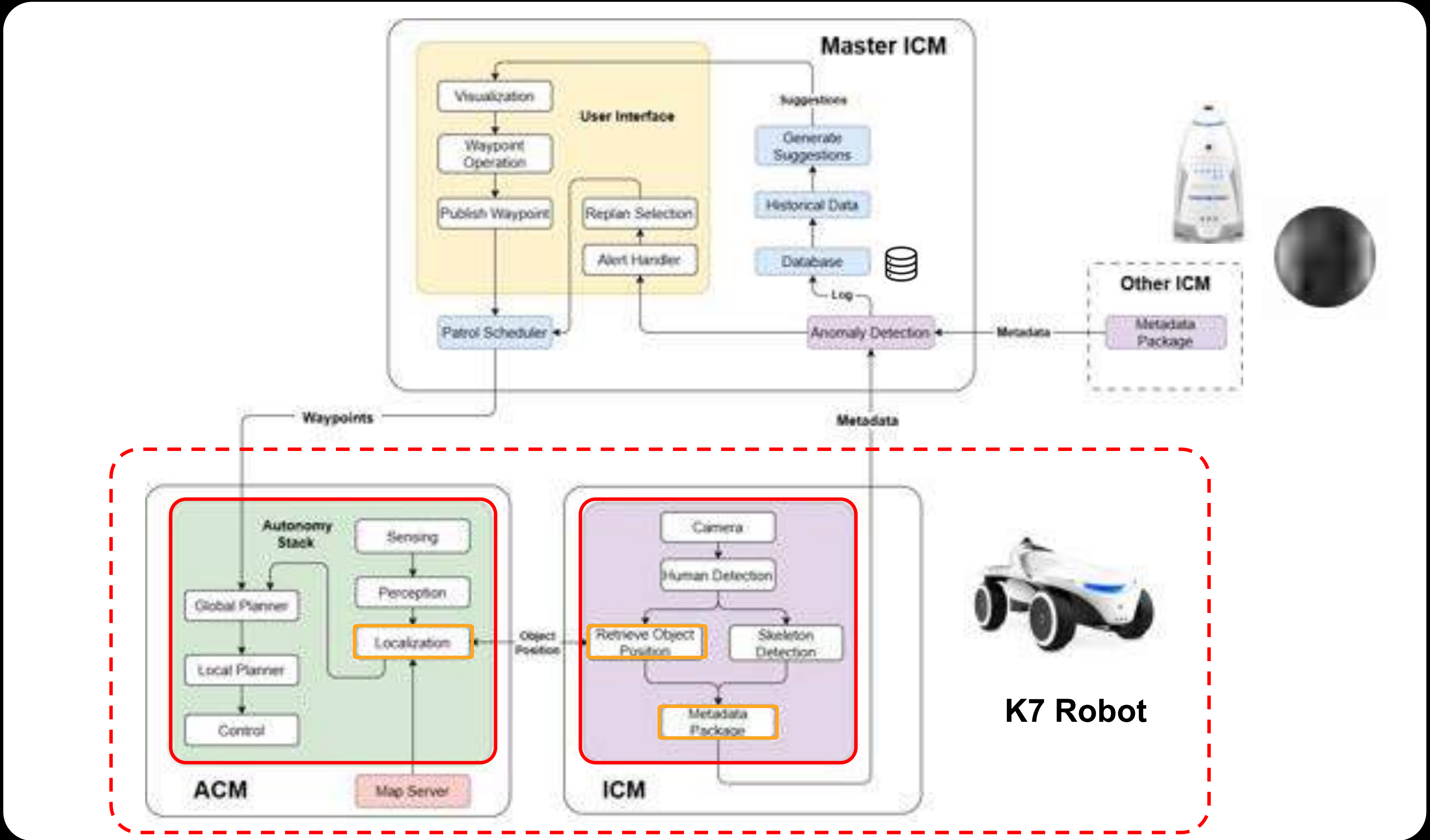
Patrol Mission Execution



Cyberphysical Architecture

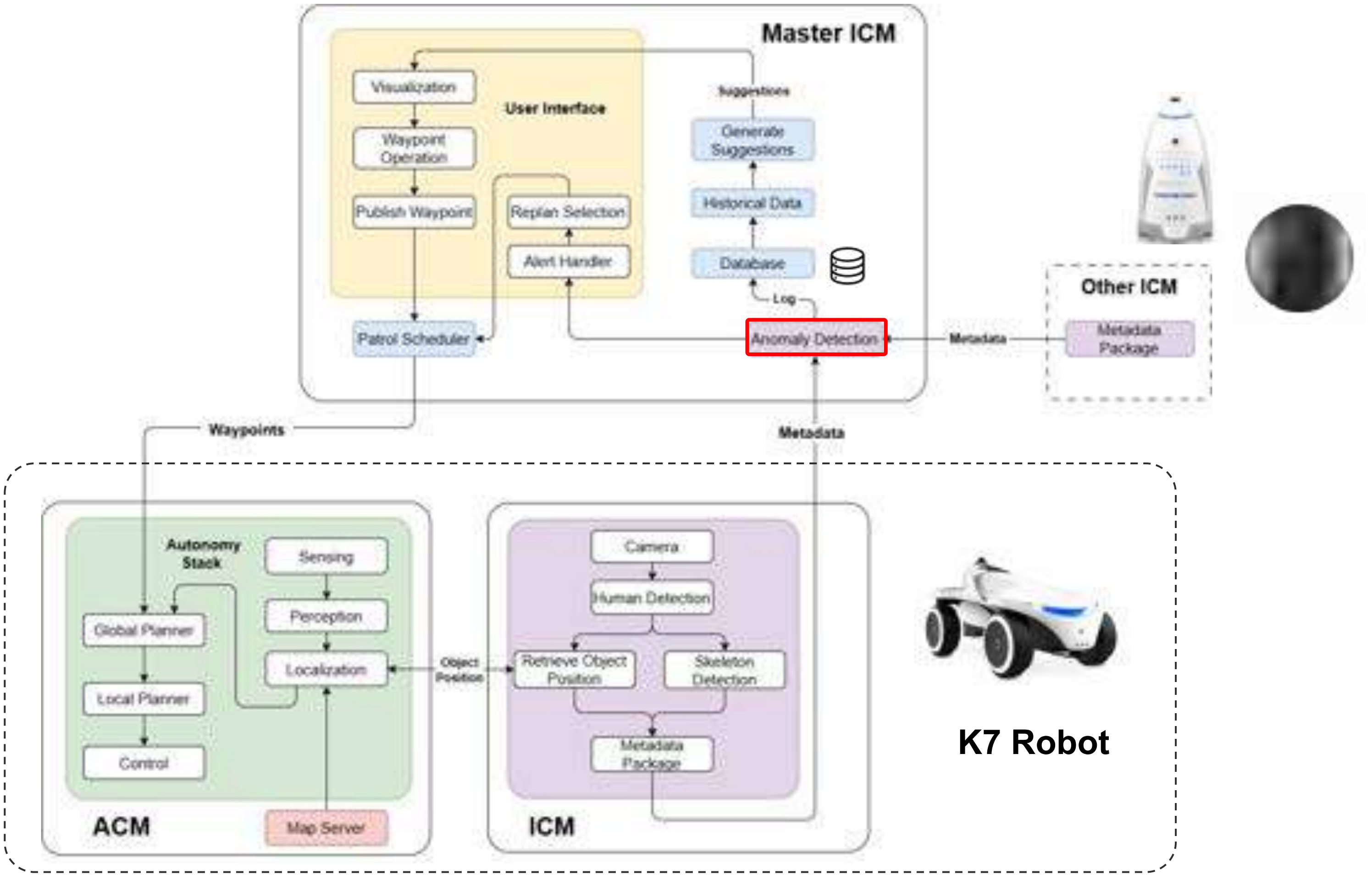


Cyberphysical Architecture

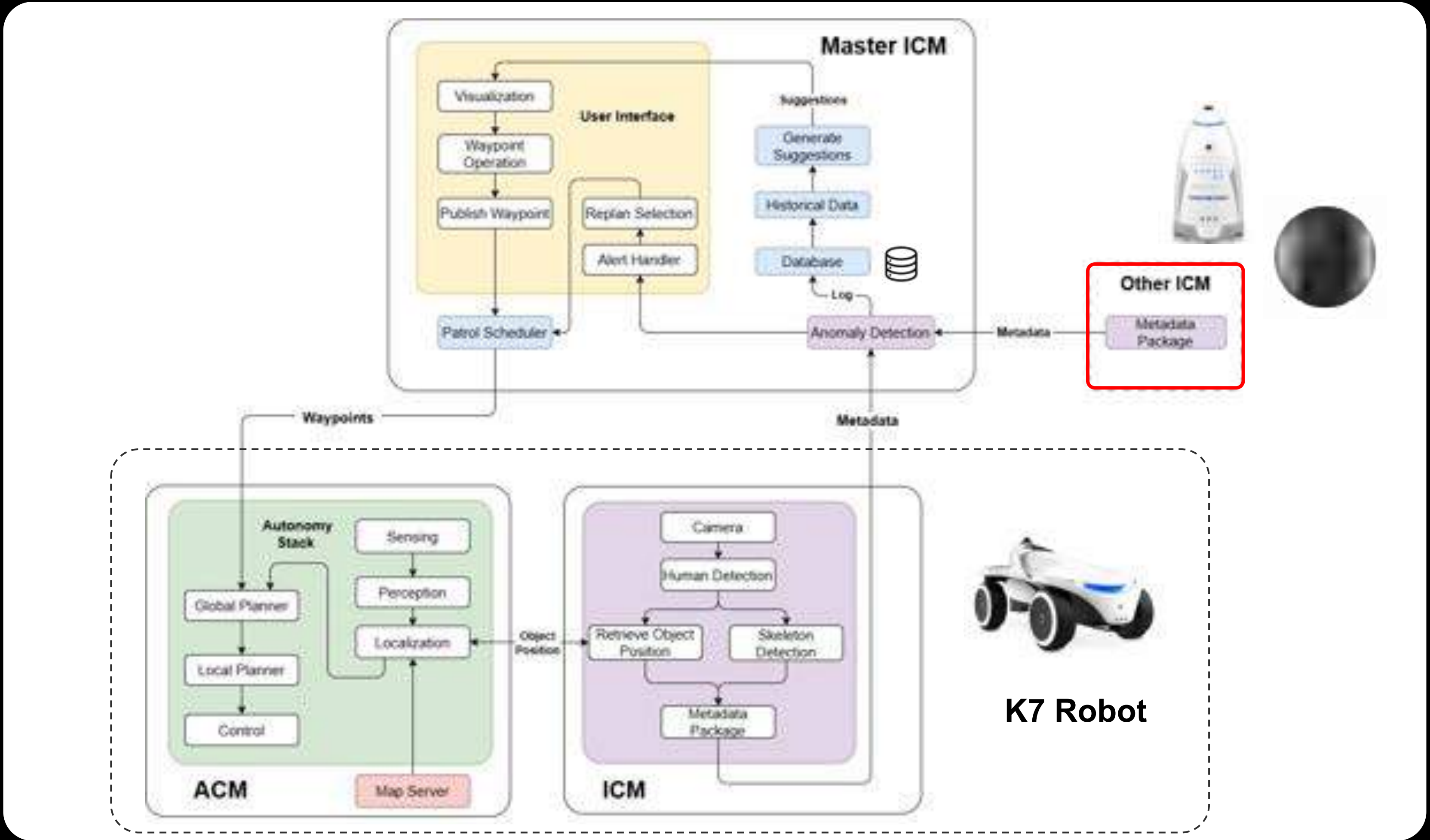


Cyberphysical Architecture

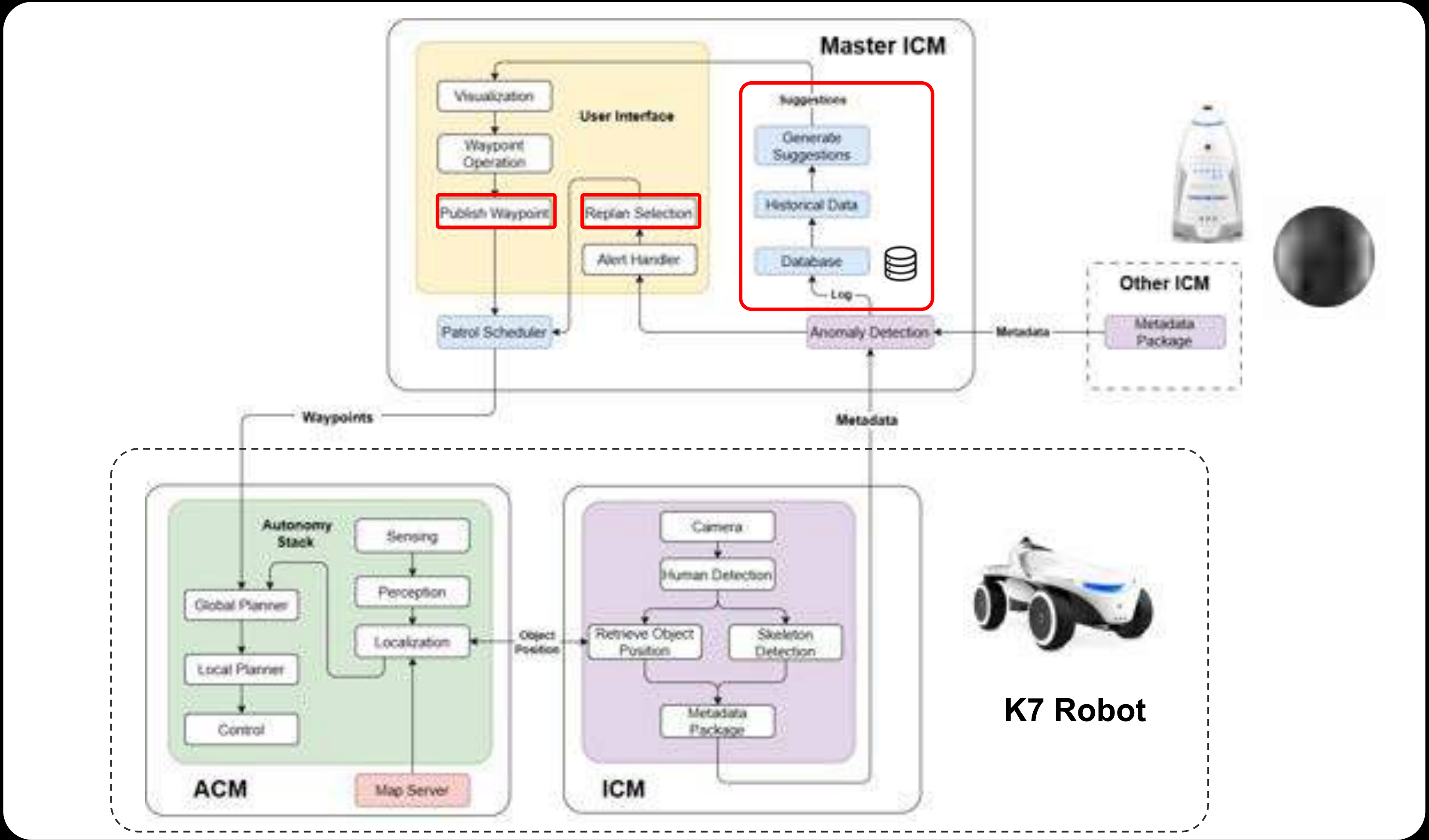
KNIGHTSCOPE



Cyberphysical Architecture



Cyberphysical Architecture



Current System Status

Targeted Requirements

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User Interface Subsystem

- Frontend Server
- Bridge Node
- Communication

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Autonomy Subsystem

- F1TENTH
- Simulation

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- Frontend Server
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- Communication

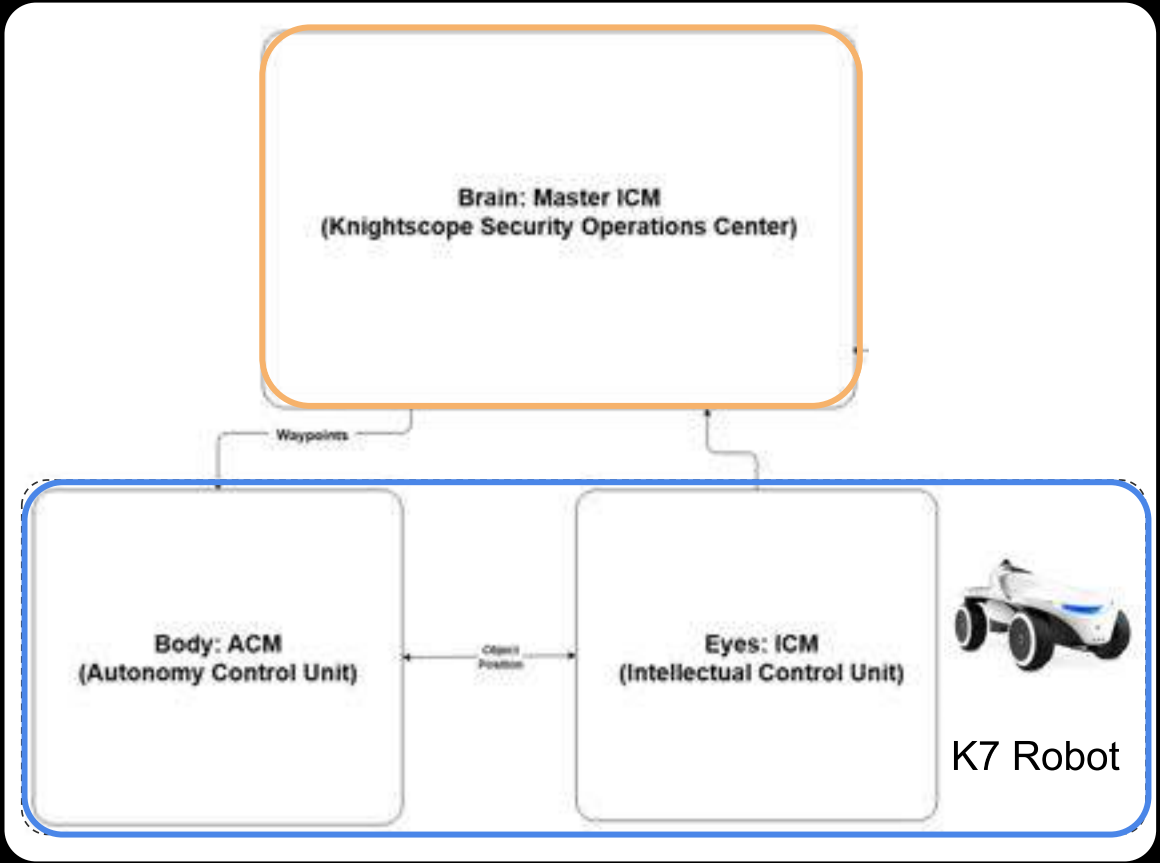
Autonomy Subsystem

- F1TENTH
- Simulation

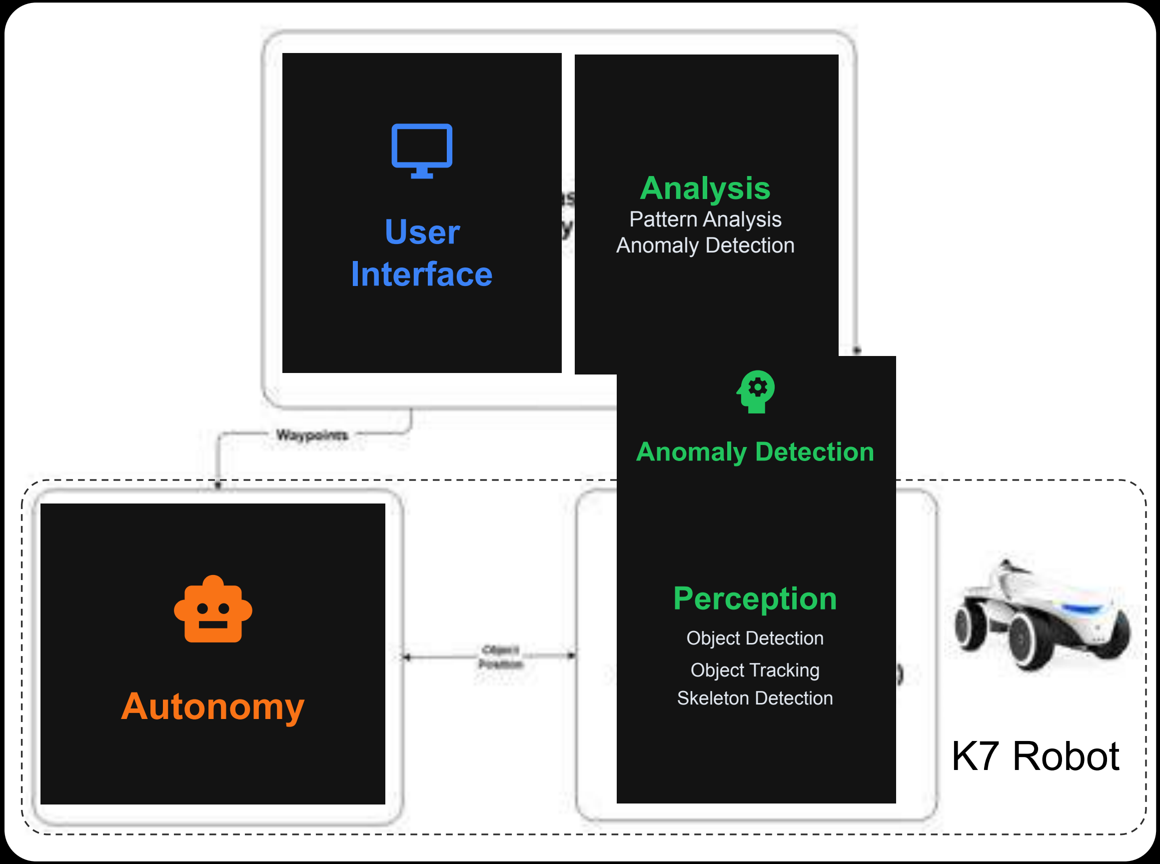
Anomaly Detection Subsystem

- RealSense D435i
- Skeleton Detection
- Anomaly Detection

Overall System Depiction



Overall System Depiction



Prototype Recap

Prototype 1: F1TENTH

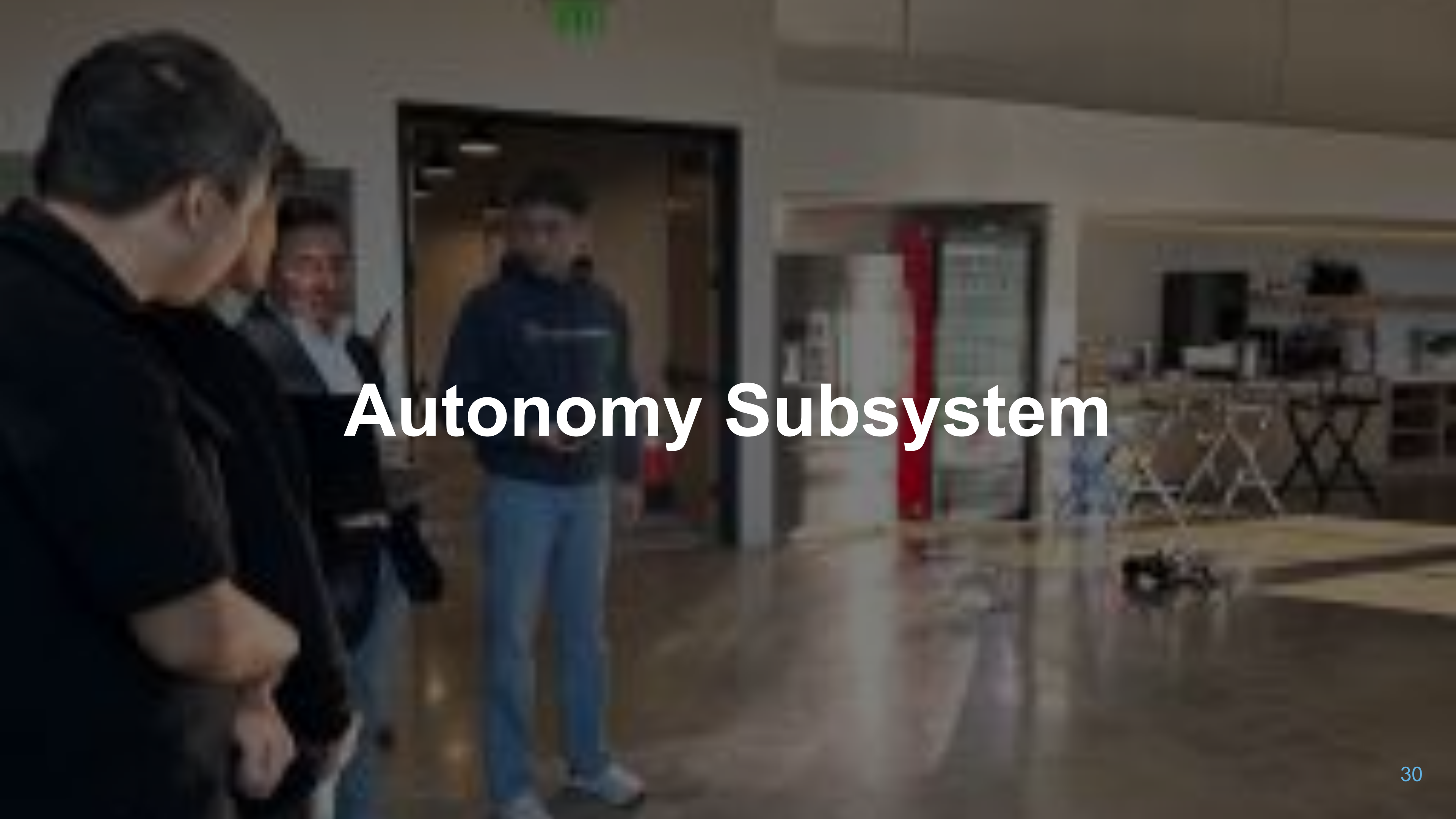
Scale Autonomous Racing Platform

Prototype 2: LSV

Low-Speed Vehicle Platform

Prototype 3: K7

Knightscope Autonomous Security Robot



Autonomy Subsystem

Subsystem Description

F1TENTH Autonomy Pipeline (PDR Progress)

Offline SLAM
SLAM_Toolbox map build & preprocessing

→

Localization
Particle Filter based on built map

→

Path Planning
Waypoint planning with shortcutting & smoothing

→

Pure Pursuit
Controller tracking the generated path

Implementation Details:

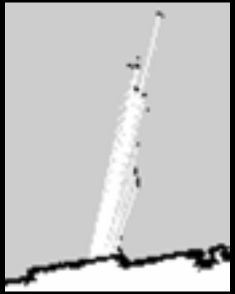
- SLAM Toolbox provides offline map generation followed by map preprocessing
- Particle Filter utilizes robot odometry (/scan, /odom) and the point map for robot localization.
- Planning unit consumes user waypoints to output a smoothed path for the controller.
- Pure Pursuit Controller manages vehicle-specific steering and velocity to track the trajectory.

Mapping

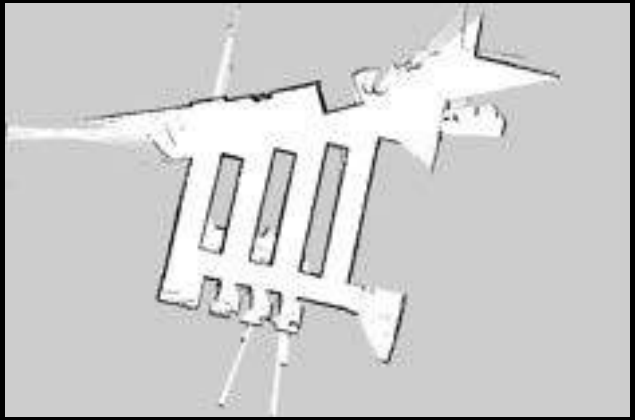
Acceptance Criteria:

- Offline map preprocessing
- Ensure map consistency with no structural misalignment, dynamic obstacles, and outliers.

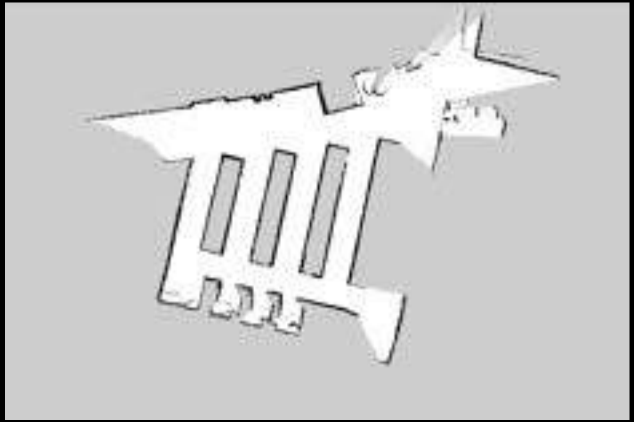
Dynamic Object, Outlier



Point Behind Wall



Raw Map

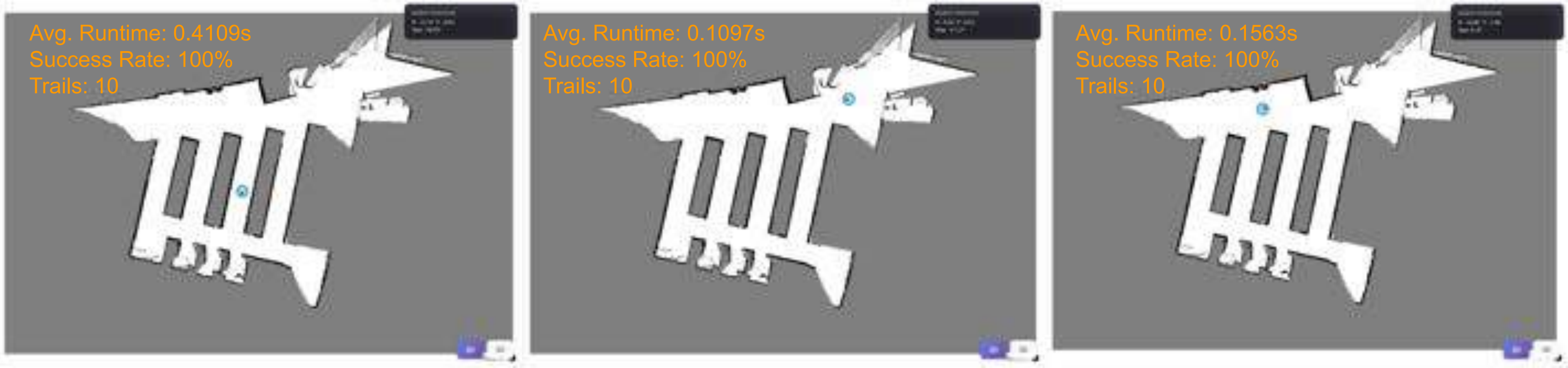


Static Map

Initialization / Localization

Acceptance Criteria:

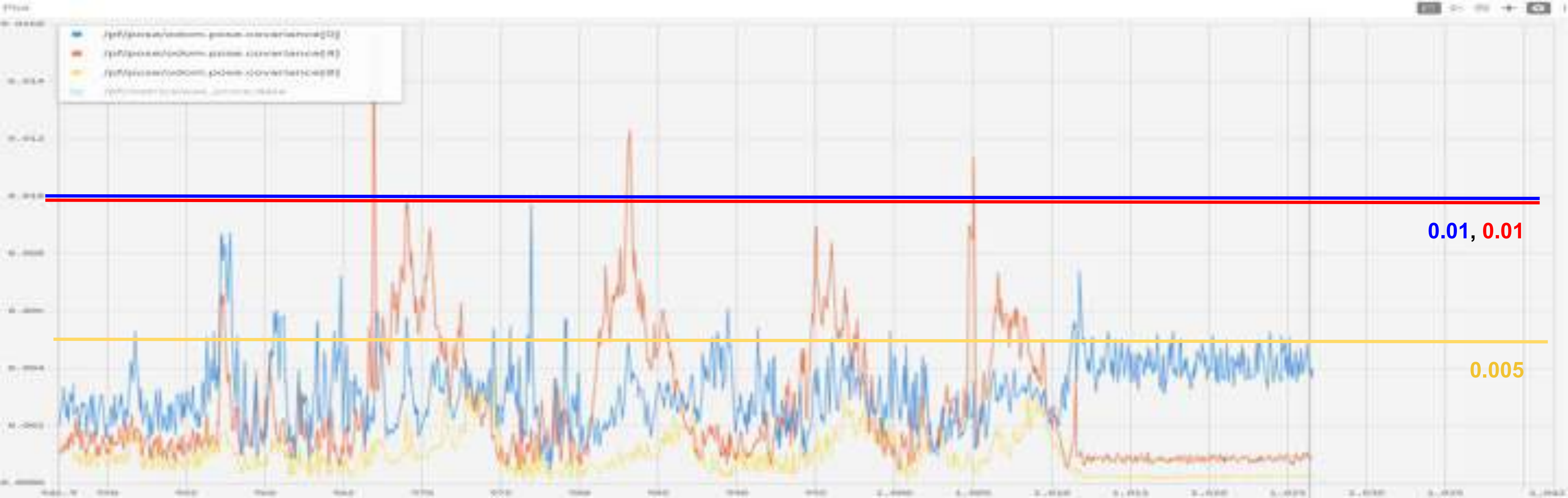
Initialize F1TENTH with a success rate > 90% at multiple locations.



Initialization / Localization

Acceptance Criteria:

- Localize F1TENTH with x and y covariance < 0.01
- Localize F1TENTH with yaw covariance < 0.005



Planning

Acceptance Criteria:

- Plan a collision-free and geometrically trackable path whose 95th-percentile curvature is below the vehicle limit 1.55.

$$L = 0.30\ \mathrm{m}$$
$$\delta_{\max} = 25^\circ$$

$$\kappa_{\max} = \frac{\tan(25^\circ)}{0.30} \approx 1.55\ \mathrm{m}^{-1}.$$

F1TENTH Curvature Limitation

$$\theta_i = \arccos\left(\frac{\mathbf{v}_1 \cdot \mathbf{v}_2}{\|\mathbf{v}_1\|\|\mathbf{v}_2\|}\right)$$

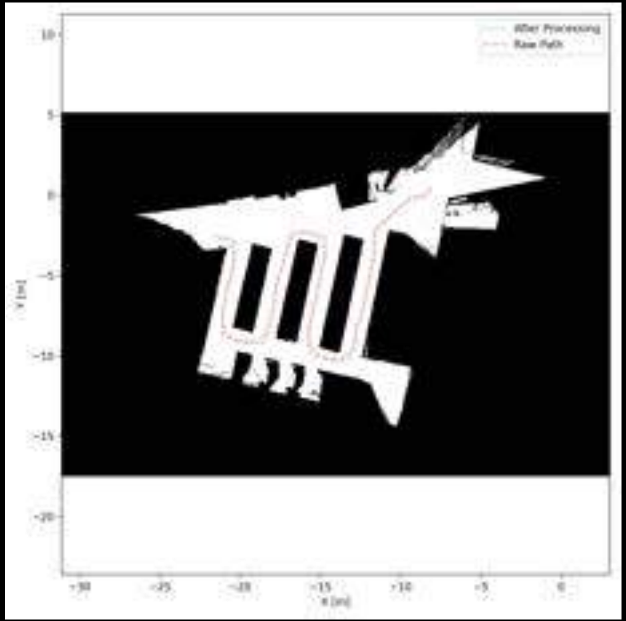
$$\Delta s_i = \frac{\|p_i - p_{i-1}\| + \|p_{i+1} - p_i\|}{2}$$

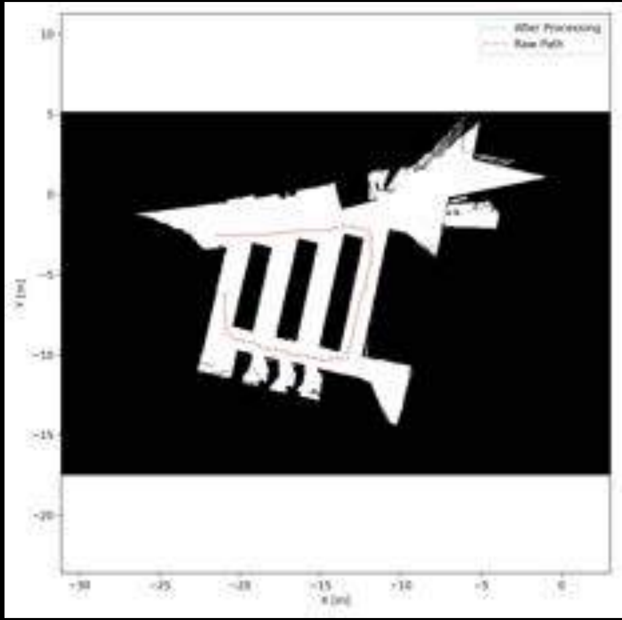
$$\kappa_i \approx \frac{\theta_i}{\Delta s_i}$$

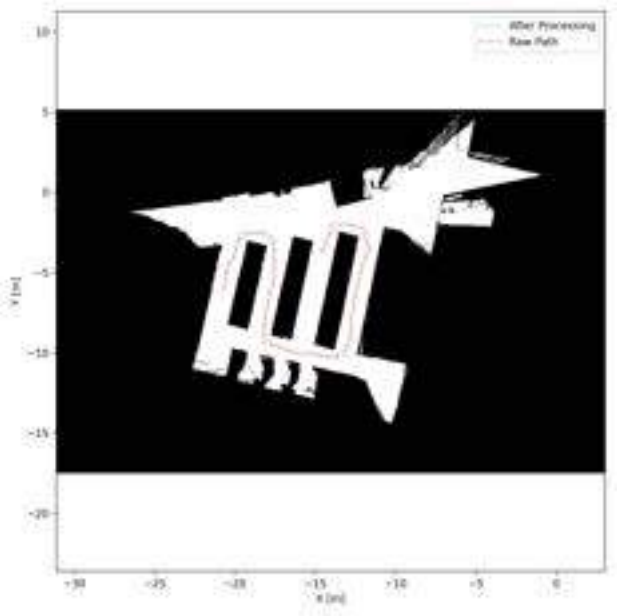
Discrete Curvature for Path With Requirement:

$$P_{95}(|\kappa|) = \text{95th percentile of curvature}, \quad P_{95}(|\kappa|) \leq 1.55\ \mathrm{m}^{-1}$$

Planning







Path	Length	Curv95
Raw	42.50	5.81
Smooth	39.38	1.14

Path	Length	Curv95
Raw	29.12	5.81
Smooth	27.46	0.97

Path	Length	Curv95
Raw	30.55	5.81
Smooth	27.97	1.24

Pure Pursuit Controller

Acceptance Criteria:

- Patrol along the path with Cross-Track Error (CTE) < 5cm. (Straight Line)
- Patrol along the path with Cross-Track Error (CTE) < 50cm. (Turning)

Reason: CTE when turning is way larger than tracing straight line.

Autonomy Control Module (ACM)

Limitations of F1TENTH in real-world deployment

- Requires full autonomy stack (mission / behavior / local planning)
- Needs behavior tree / state machine for robust execution
- Requires scalable SLAM (e.g., LIO-SAM, NDT)

Migration to ACM (Knightscope)

- Provides production-level autonomy capabilities
- Enables scalable and real-world-ready system design

Current focus: simulation

- Physical robot not yet available
- Develop and validate system using simulation environment (RViz2)


D
2 | 2
24
79 m
12 sec

User Interface Subsystem

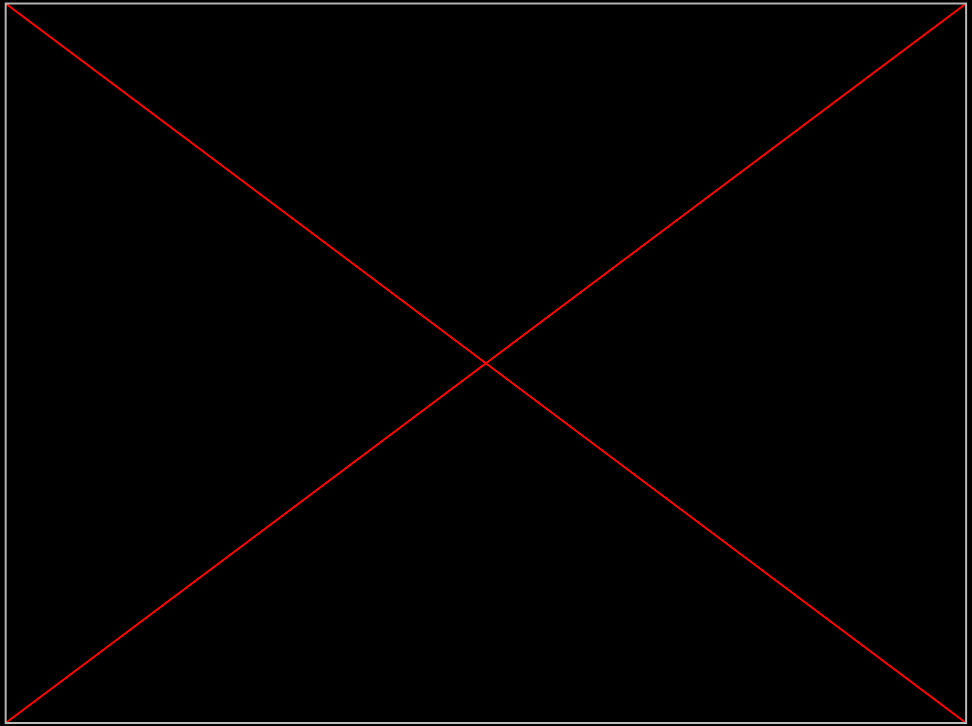
Subsystem Description

Capabilities

- Operate waypoint
  (add / delete/ drag-and-drop)
- Visualize path
- Visualize robot status

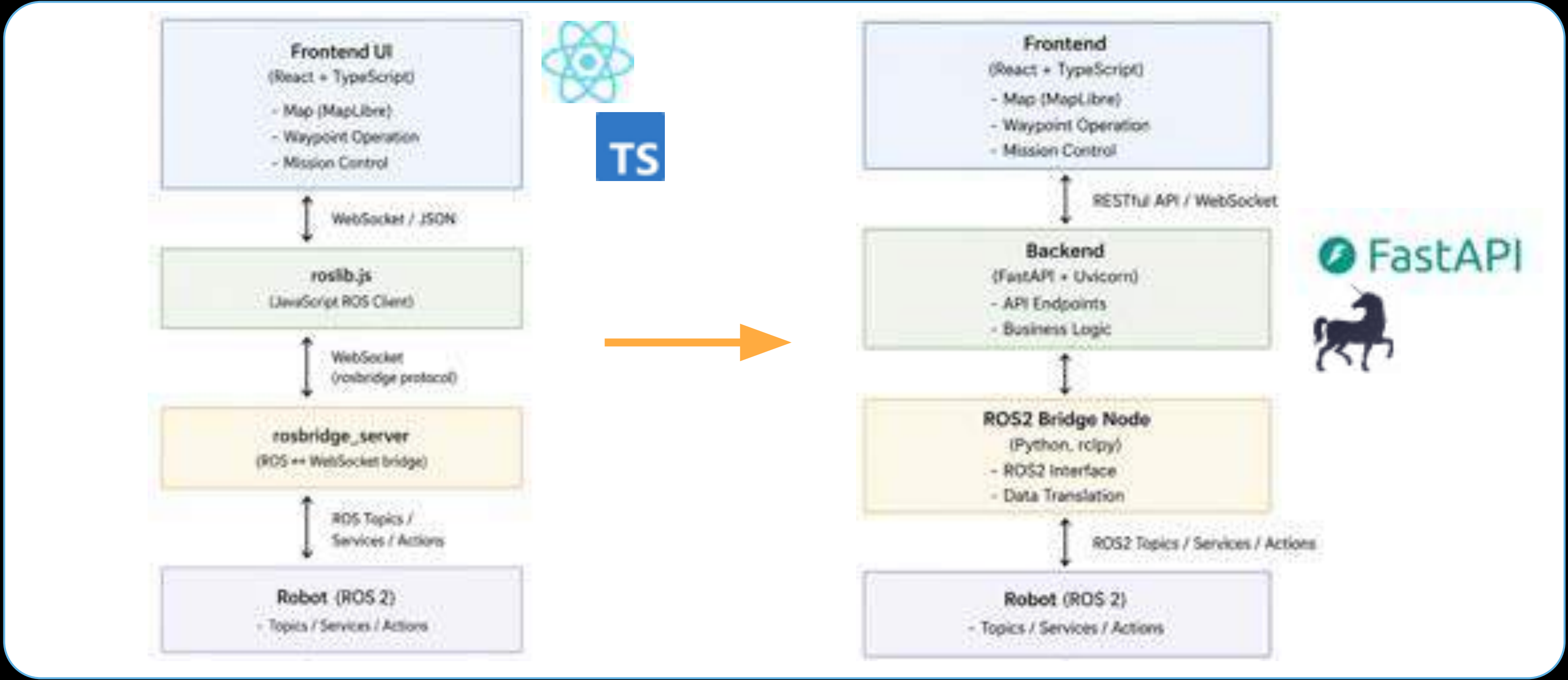
F1TENTH Interface

- Manually Initialization
- Occupancy Map



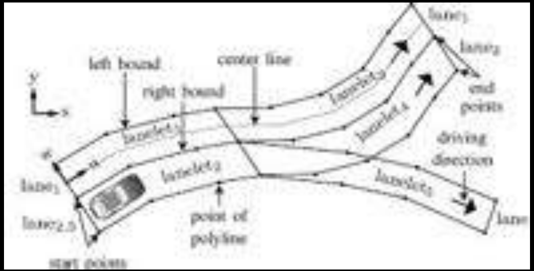
User Interface Migration

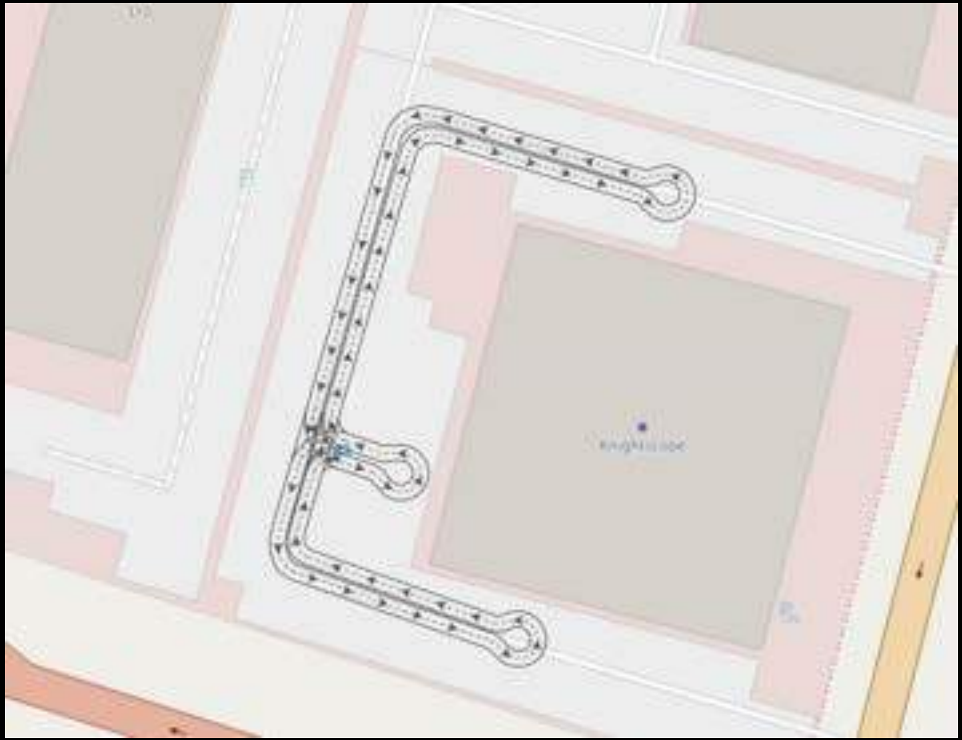
- Enable scalable and stable system architecture
- Support future extensions (scheduler, AI modules, database integration)



Lanelet Map

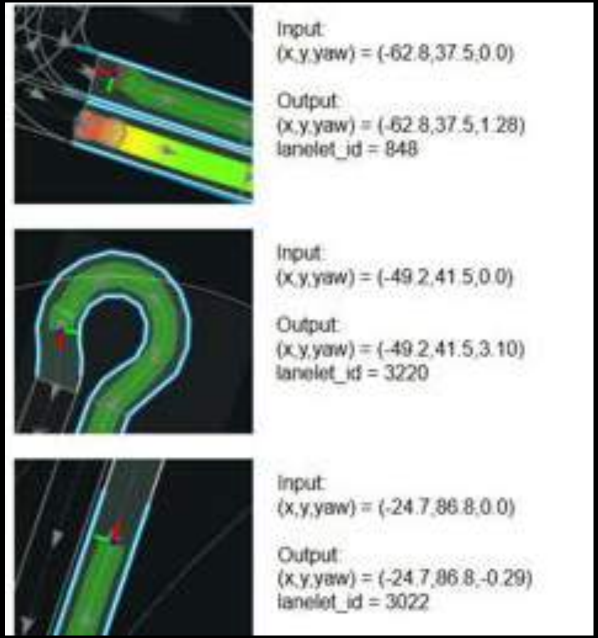
- Transition from occupancy maps to lanelet-based maps
- Enable lanelet-based route planning
- Provide route-level information (distance, ETA)



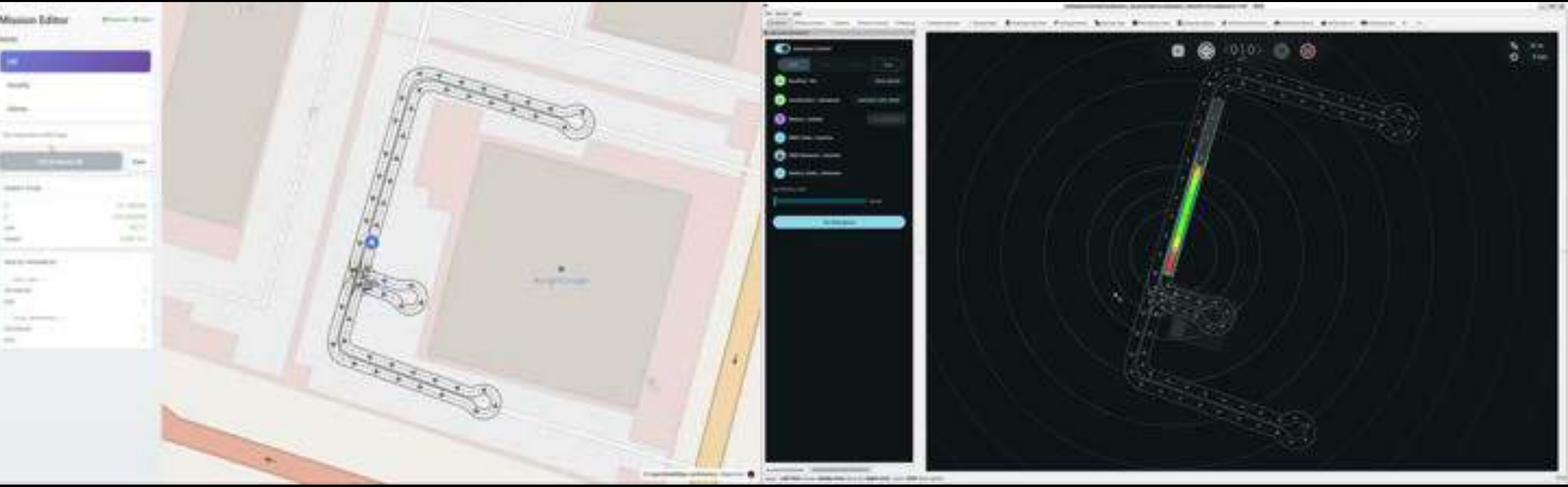


Heading Assignment & Waypoint Scheduler

- Infer waypoint orientation from lanelet geometry (given position-only input)
- Develop a sequential mission scheduler with integrated state management



Demo

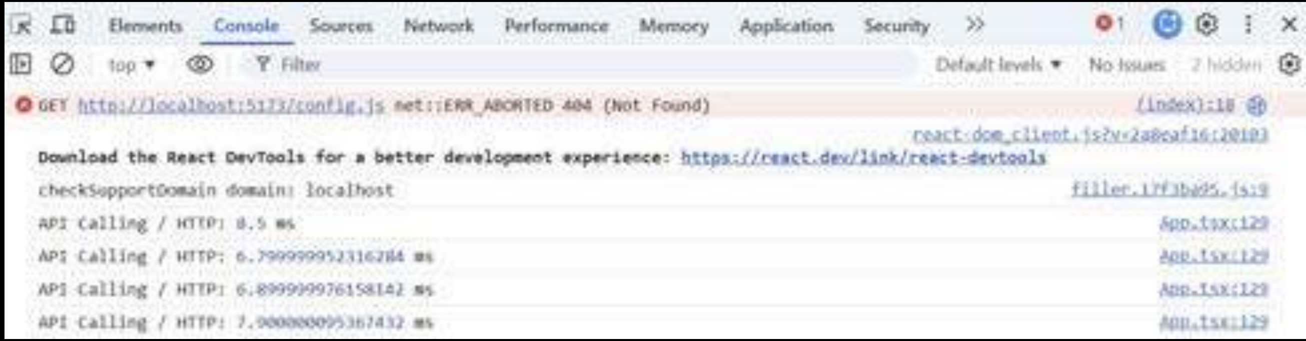


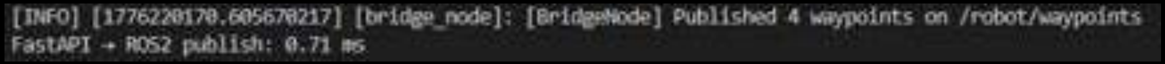
Performance Evaluation

Acceptance Criteria:

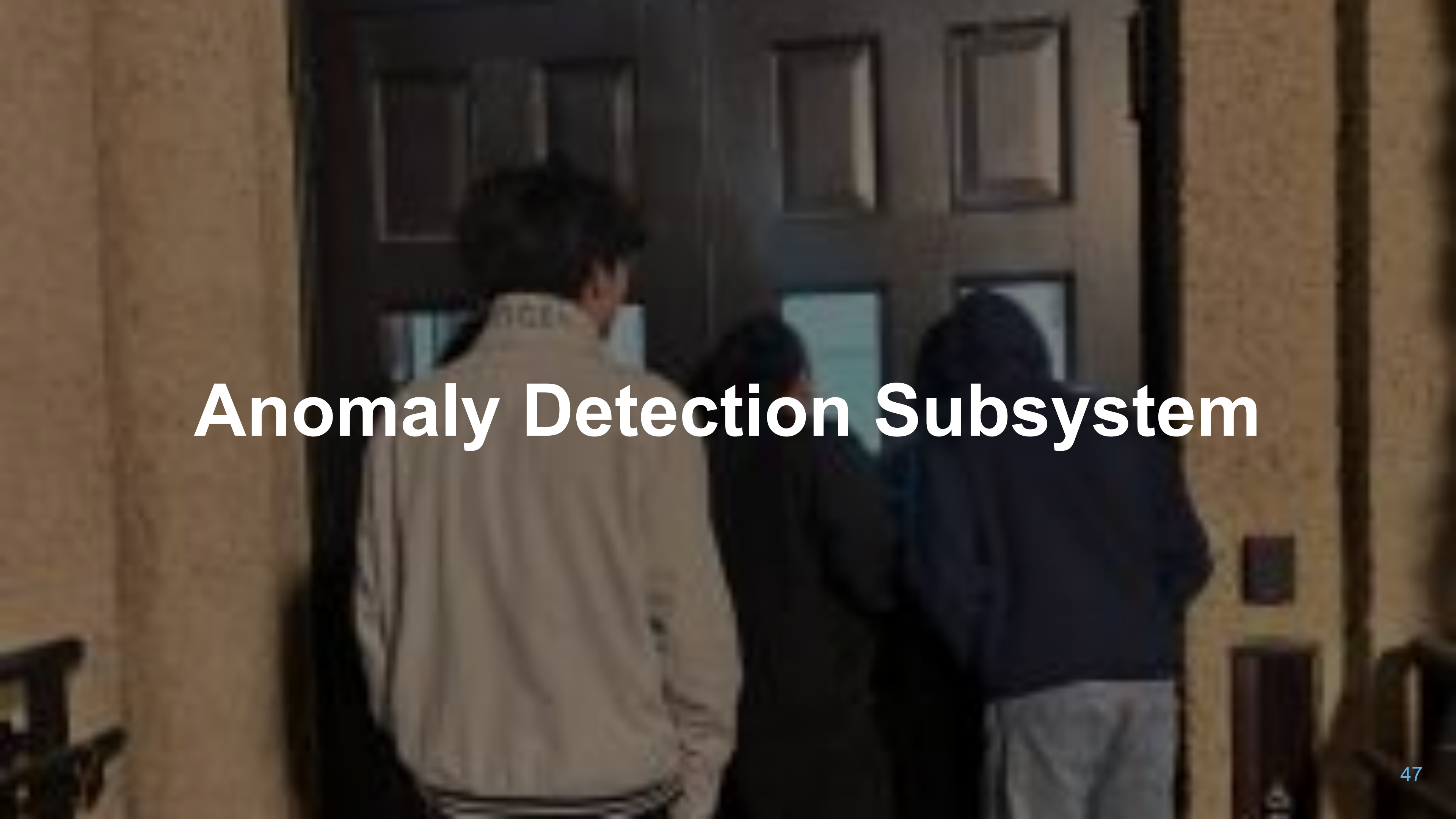
✓ User interface can real-time display robot status.

✓ The waypoint publishing should execute within 50 ms.





Frontend to Backend	Bridge Node	ROS2 Execution	Total
7.6 ms (average)	0.78 ms (average)	2.1 ms (average)	10.48 ms (average)



Anomaly Detection Subsystem

Subsystem Description

Live Skeleton Detection

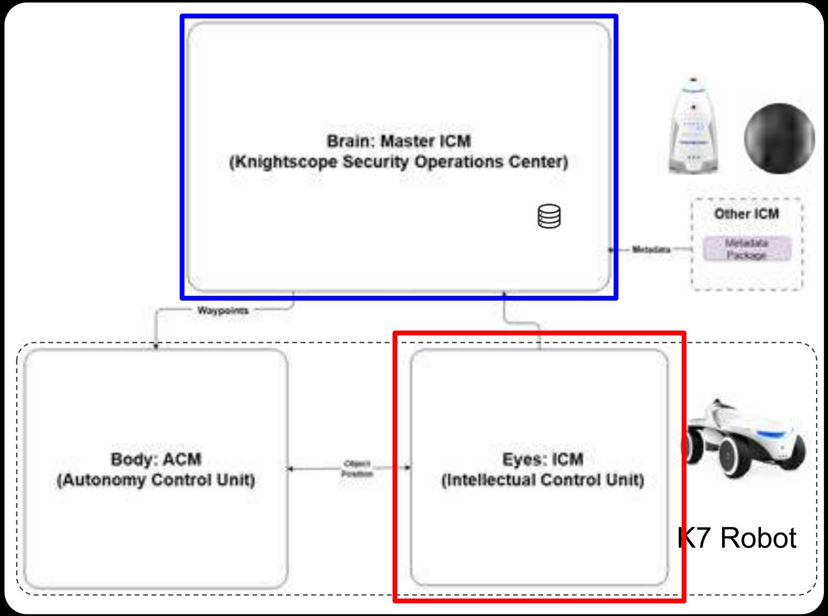
Real-time tracking of human joints and connections

Anomaly Analysis

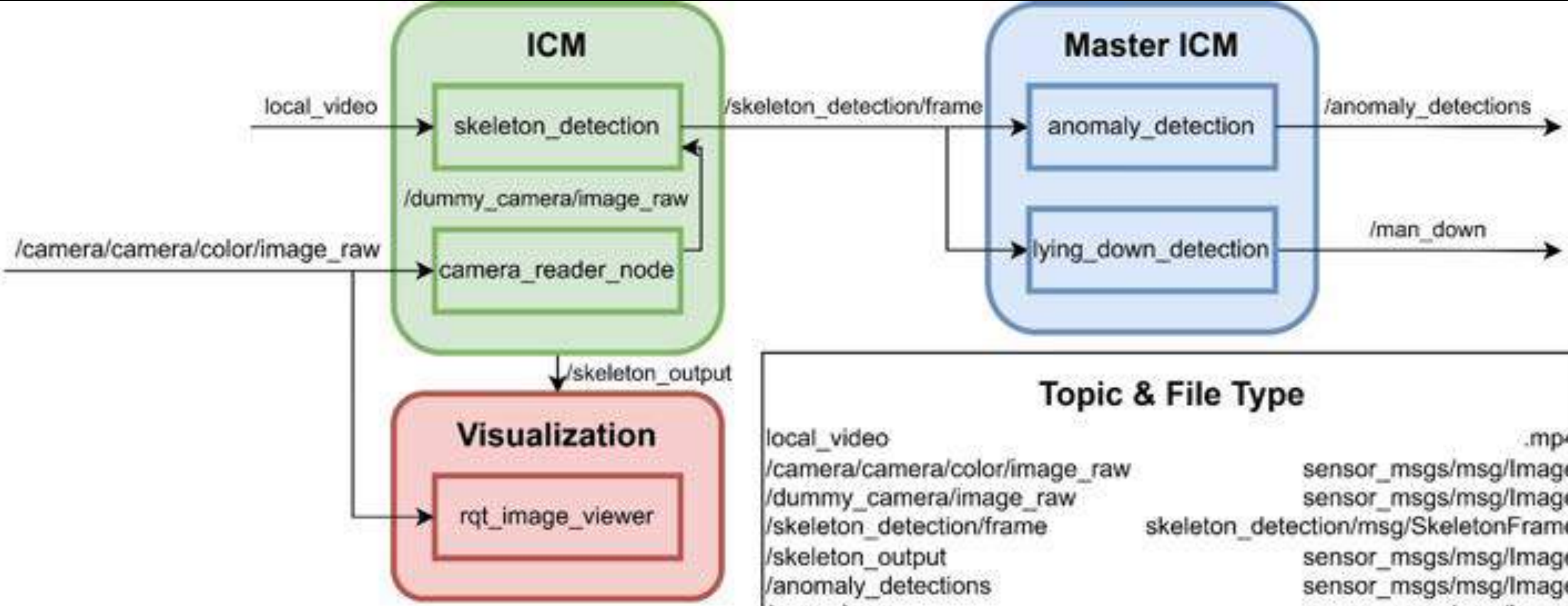
- Fighting detection
- Trespassing alerts
- Falling incident detection
- …

Lying Down Detection

Specific identification of person lying on the ground.



Subsystem Description



Topic & File Type

local_video	.mp4
/camera/camera/color/image_raw	sensor_msgs/msg/Image
/dummy_camera/image_raw	sensor_msgs/msg/Image
/skeleton_detection/frame	skeleton_detection/msg/SkeletonFrame
/skeleton_output	sensor_msgs/msg/Image
/anomaly_detections	sensor_msgs/msg/Image
/man_down	sensor_msgs/msg/Image

Model Selection (Skeleton Detection)

Top-down Pose Estimation Method: bounding box → joints

The most accurate but become slower as the number of people in the frame increases.

Bottom-up Pose Estimation Method: joints → person

Speed is constant regardless of how many people are in the scene.

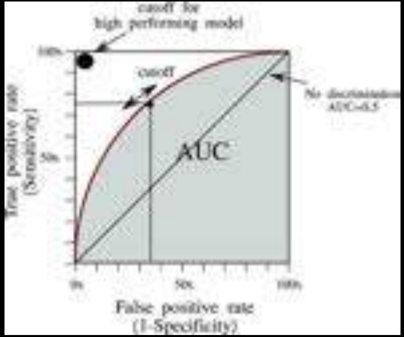
Model Selection (Skeleton Detection)

Evaluation Criteria	Weight	OpenPifPaf	OpenPose	HigherHRNet	MoveNet
Far-Field / Low-Res Accuracy	40%	5	3	4	2
Handle Occlusion	20%	5	4	3	2
Inference speed	20%	4	2	2	5
Deployment Difficulty (API compatability)	20%	4	3	3	4
Total Weighted Score	100%	4.6	3	3.2	3

Model Selection (Anomaly Detection)

- Dataset: HR-Shanghai Tech
  - Defined anomaly actions are likely happened around campus, meeting the needs of our use case
- Stage 1: Graph Jigsawed Conditioned
  Diffusion model
  Anomaly score
- Stage 2: Bart-large-mnli
  Zero-shot LLM
  Anomaly classification

AUROC: Area under curve

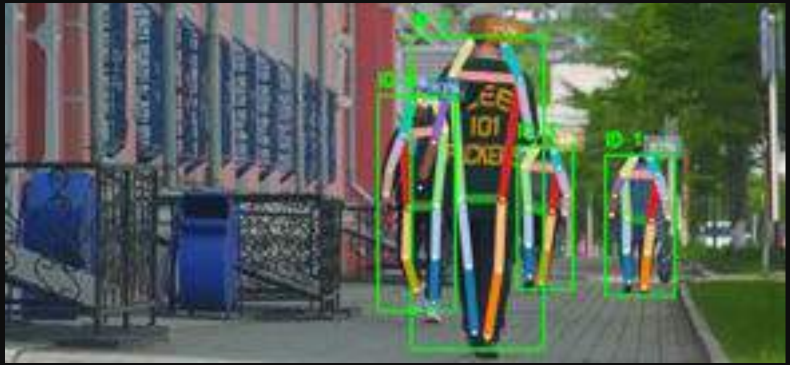


Method	Params	AUROC
AED-SSMTL◇ [12]	>80M	61.3
TimeSformer◇ [3]	121M	68.6
TrajREC	4.9M	68.0
MoCoDAD	142K†	68.3†
GiCiSAD	**82.6K**	**68.6**

Testing (Skeleton Detection)

1. Command line output

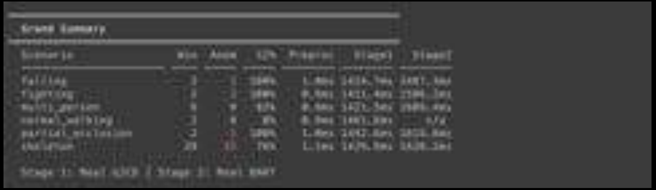
2. Single frame image

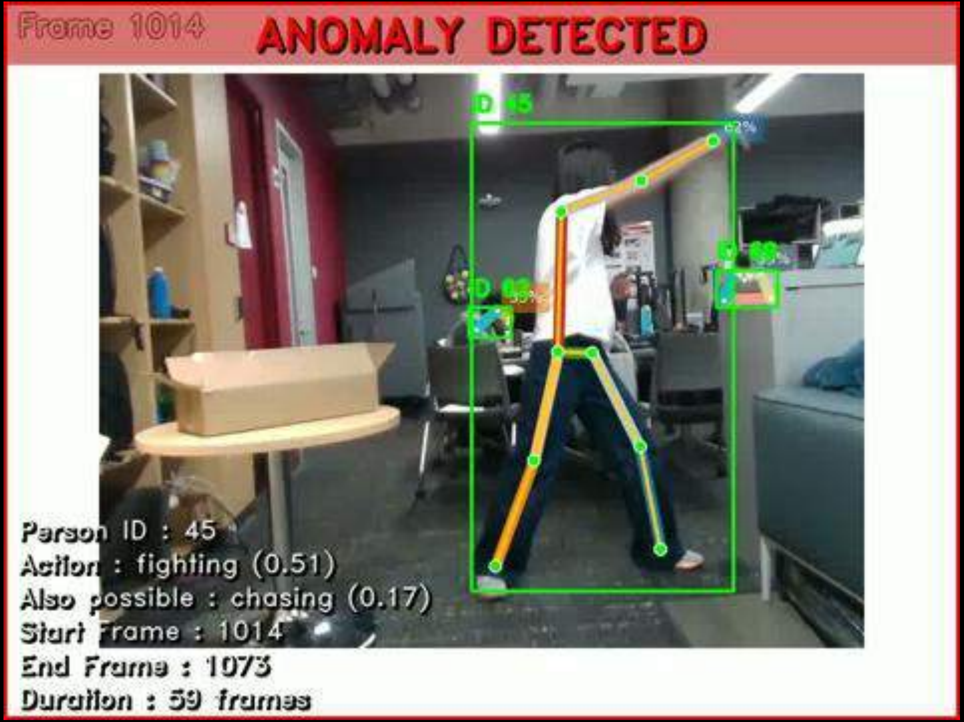


3. Local video

4. Live video

Testing (Anomaly Detection)





Performance Evaluation against SVD

Acceptance Criteria:

- ✓ Successfully detect > 95% of non-occluded human skeletons (joints & connections). (F.R.5)
- ✓ Generated bounding boxes accurately enclose a valid human subject. (F.R.5)
- ✓ Re-identify and maintain tracking of a human target even when occluded < 50 frames.(F.R.5)
- ✓ Detect people lying on the ground (width > height). (F.R.5)
- × Flag actions, throwing object, jumping, pushing, biker, fighting, chasing, loitering, hiding, playing with ball, are an anomaly action > 50% of the time. (F.R.5)

Conclusion (Autonomy)

Strong:

- Modular system architecture
- Scalable design for future real-world deployment
- ACM provides robust navigation and execution capabilities

Weak:

- No physical robot validation yet
- Simulation fidelity constraints (RViz2 vs real environment)

Area to refine:

❑ Integrate real robot platform for deployment validation

Conclusion (User Interface)

Strong:

- Clear separation between frontend, backend, and ROS2 interface
- Backend abstraction enables system scalability and extensibility

Weak:

- Still relies on simulation environment (no real-world latency)
- No persistent data layer (no database integration yet)

Area to refine:

- [ ] Add database layer for mission history and analytics
- [ ] Optimize real-time performance under larger system scale

Conclusion (Anomaly Detection)

Strong:

- Skeleton detection performs accurately on live non-occluded people
- Lying down detection is quick and accurate.

Weak:

- Skeleton detection still has high inference latency
- Person tracking is inaccurate when passing behind other people.
- Anomaly detection has high latency and low accuracy

Area to refine:

❏ Skeleton detection speed
❏ Person tracking accuracy
❏ Split anomaly detection

Project Management

Work Breakdown Structure

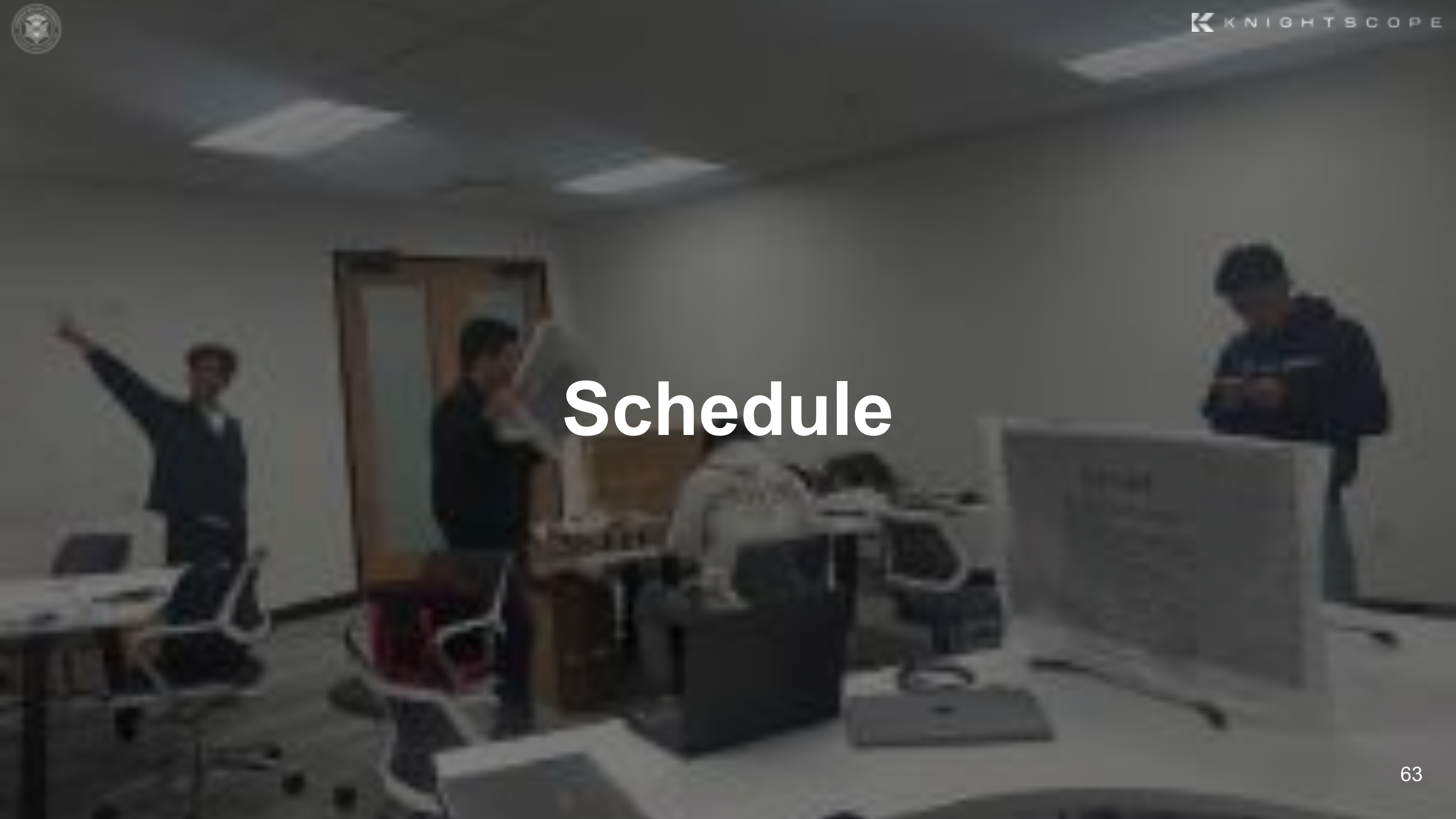
Work Breakdown Structure (WBS)

Work Breakdown Structure (WBS)

Complete

Simulation Only

To Do



Schedule

Schedule Status

Major Milestones:

- **SVD (Done):** All major spring milestones completed ahead of SVD
- **Robot Platform (September):** Build robot(s) with full ACM/ICM capabilities
- **FVD (November):** Finalize system to meet FVD goals

Current Status:

- Achieved most promised goals for SVD
- Robot Platform delay due to contract agreement issues

Plan to Improve:

- Use alternative robots (F1TENTH, Husky, ...) and integrate required ACM/ICM functionalities

Test Plan

Fall Test Plan

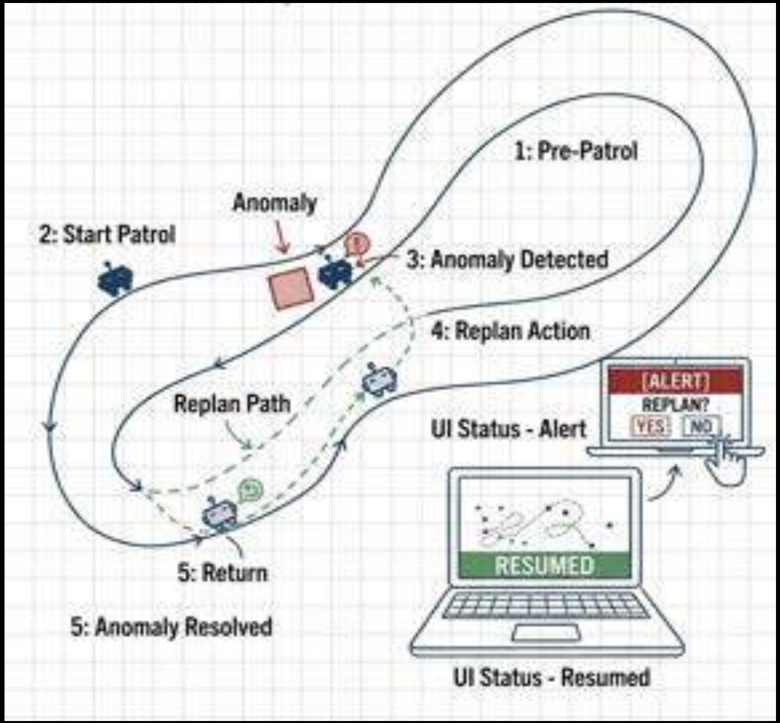
	Month	Milestones	Tests
P.R.7	Early September	Internal network	Internal network test
P.R.8	Mid September	Anomaly action classification AI route optimizer	Anomaly classification test Waypoint suggestion test
P.R.9	Early October	UI alert LSV modification	UI test LSV in car test
P.R.10	Mid October	Integration	LSV in car test
P.R.11	Mid November	Full system test	Integration test
P.R.12	Late November	All system integrated and functioning	FVD

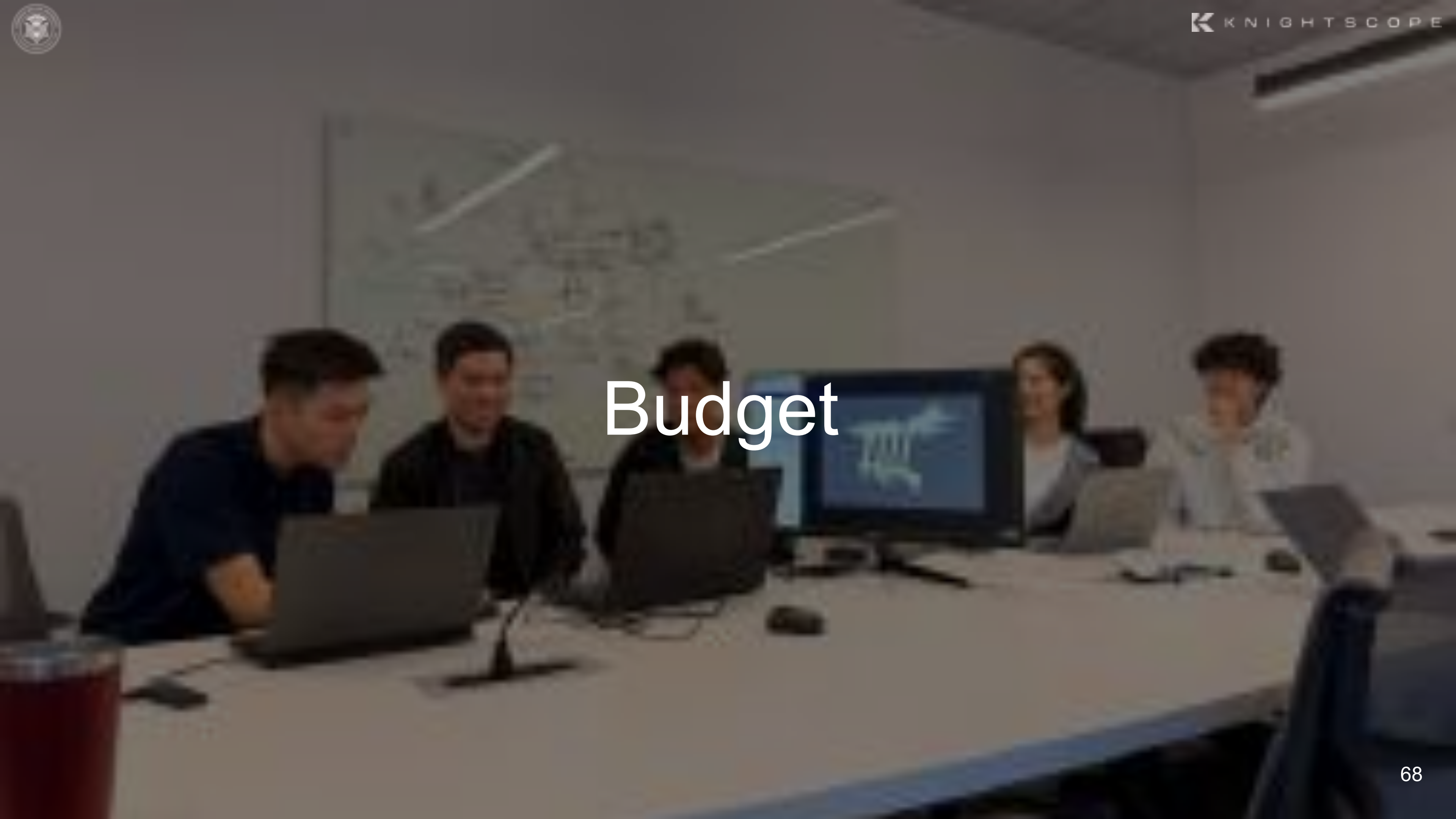
FVD

Location: NSH front porch, KSHQ
Equipment: LSV, K7

Demo:
1. Generates suggested waypoints.
2. Accesses UI via laptop to manage and modify waypoints by the user.
3. Monitors for anomalies. If an anomaly occurs, the robot will ask the user for replan.
4. Calculates a new route and updates the UI based on the alert.
5. Returns to original route after solving the alert.

Objectives:
The system must identify anomalies with correction > 90%.
The system must suggest 3 efficient patrol waypoints to the user.
The system must demonstrate the robot's ability to change its path dynamically when an alert is triggered within 2 secs.





Budget

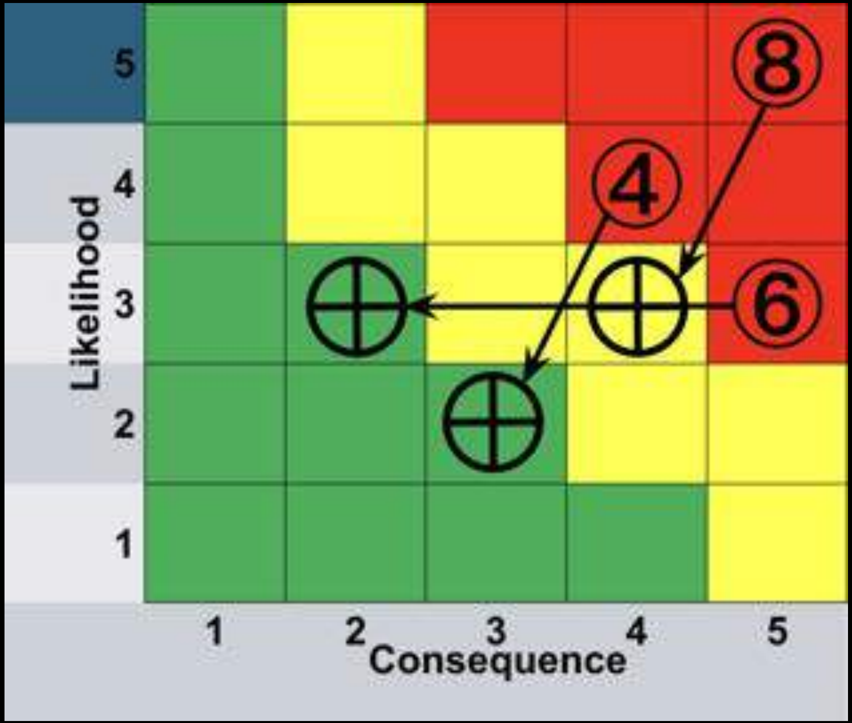
Budget

- Total Budget: 15,000
- Mostly for traveling
- PCB spent $20.27
- About 40% were spent

pay date	desciption	pay by		receipt status	amount
02/05/26	tickets (PIT - SJC)	Maddie	Travell...	full rec...	881.05
02/05/26	AirBnB	Maddie	Accom...	full rec...	900
02/15/26	AirBnB	Maddie	Accom...	full rec...	1143
02/28/26	checked bag	Joshua	Travell...	full rec...	35
03/01/26	uber	Joshua	Travell...	full rec...	69.98
03/01/26	car rental	Maddie	Travell...	full rec...	591.84
03/01/26	lunch	Joshua	Food	full rec...	75.45
03/01/26	dinner	Joshua	Food	full rec...	111.92
03/01/26	dinner	Maddie	Food	full rec...	19
03/01/26	grocery	Joshua	Food	full rec...	42.56
03/01/26	grocery	Joshua	Food	full rec...	61.03
02/06/26	tickets (SJC - PIT)	Maddie	Travell...	full rec...	841
03/02/26	lunch	Maddie	Food	full rec...	55.38
03/02/2026	dinner	Maddie	Food	full rec...	139.51
03/03/26	lunch	Maddie	Food	full rec...	15.06
03/03/26	dinner	Maddie	Food	full rec...	330.78
03/04/26	dinner	Maddie	Food	full rec...	410.75
03/05/26	gasoline	Maddie	Travell...	full rec...	26.55
03/05/26	checked bag	Maddie	Travell...	full rec...	35
03/05/26	breakfast	Maddie	Food	full rec...	53.18
03/05/26	lunch	Maddie	Food	full rec...	83.08
03/06/26	uber	Joshua	Travell...	full rec...	112.67
03/30/26	PCB	Koko	PCB	full rec...	20.27

Risk Management

Risk-Consequence Matrix



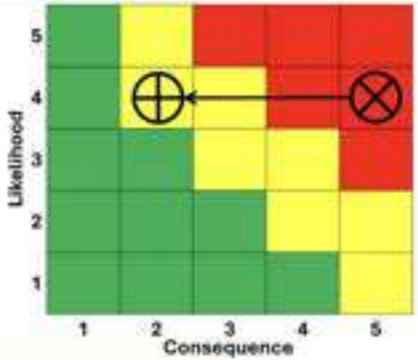
Key Risks:

R4 - Insufficient Features for Prediction Model
R6 - System Integration Blockage
R8 - LSV Late Arrival

2:42 PM
Yes. There is controversy I am working through right now on ownership.

R1: K7 Availability Issue

Risk ID	Risk Title	Risk Owner
R1	K7 Availability Issue	Leo Xu



Description

The LSV Patrol Robot in Fantom Robotics may not be available due to ownership conflicts and scheduling constraints.

Date Added: 11/26/2025

Consequence

No platform available for testing our system.

Date Updated: 04/17/2026

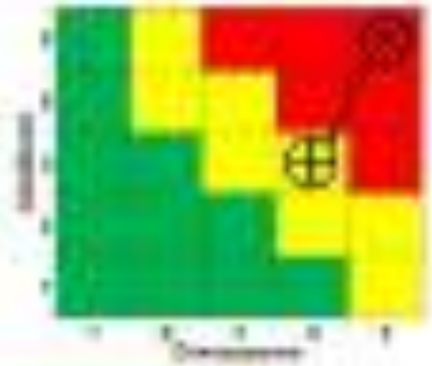
Risk Reduction Plan Summary

Risk Type: Schedule, Cost

Action/Milestone	Success Criteria	Date Planned	Date Implemented
Use other prototypes (F1 Tenth, Golf Cart) for onboard testing.	Successfully run our system on the prototype.	11/28/2025	02/05/2026
Use simulators (CARLA, Gazebo, Rviz) for offline testing.	Successfully test developed features on the simulator.	11/28/2025	02/15/2026

Comments

R2: Incompatible between Environment & Platform



R3: Can not Access Company Training Data

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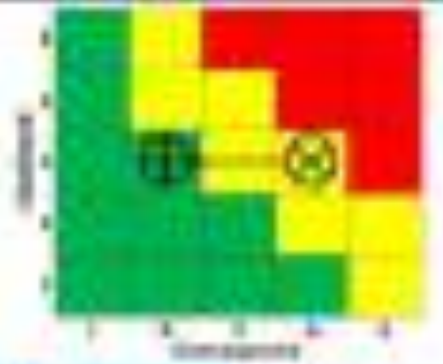

[illegible]		[illegible]	Technical
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	
[illegible]		[illegible]	
[illegible]			

R4: Insufficient Log Data Features for Prediction Model

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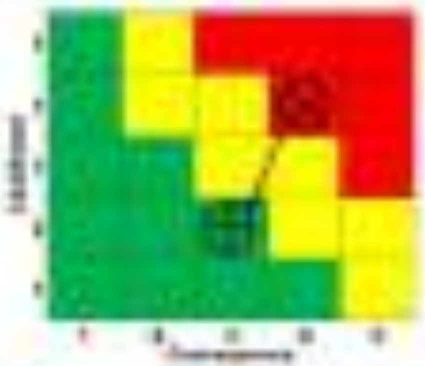

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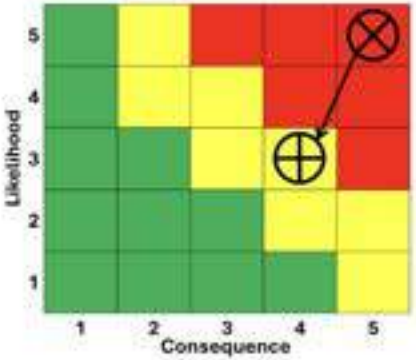
R5: Schedule Conflict Between Knightscope and CMU

Risk ID	Risk Title	Risk Owner
R5	Schedule Conflict between Knightscope and CMU	Sam Dong

Description	Date Added
Scheduling misalignment between Knightscope's availability (for meetings, reviews, and demo) and the CMU team's academic schedule (course deadlines, project milestones, and travel constraints).	11/29/2025

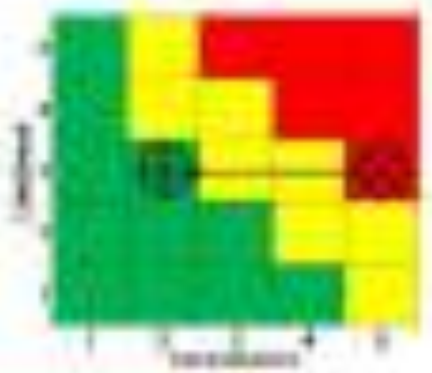
Consequence	Date Updated
Key deliverables may delay due to mismatched schedules. Also, lack of timely feedback from Knightscope cause the team to move in a suboptimal direction and later need revisions.	02/02/2026



Risk Reduction Plan Summary		Risk Type:	Schedule
Action/Milestone	**Success Criteria**	**Date Planned**	**Date Implemented**
Set a weekly meeting with Knightscope with agenda and meeting notes to ensure efficient communication.	Most of action items are completed or updated before the next meeting.	11/30/2025	02/02/2026
Align project milestones early and allocate time buffer to absorb possible communication delays.	Most of milestones are achieved on or before the buffered deadline.	11/30/2025	02/02/2026

Comments

R6: System Integration Blockage by Incomplete Modules



R7: F1TENTH Platform Malfunctioning

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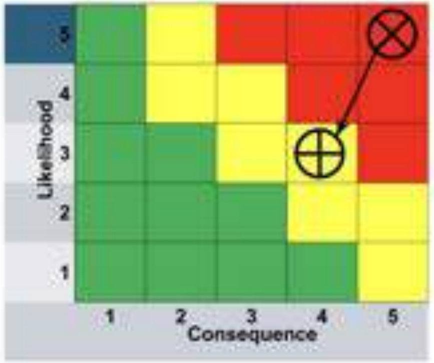
KNIGHTSCOPE

R8: LSV Late Arrival

Risk ID	Risk Title	Risk Owner
R8	LSV late arrival	Joshua Tsai
Description		**Date Added**
Due to ownership conflict and scheduling issue, the golf cart LSV might not arrive on time, blocking the development timeline		04/26/2026
Consequence		**Date Updated**
We might not have physical platform to implement and test our system; resulting in no delivery in FVD. And it will be hard to immigrate our final prototype		04/26/2026



Risk Reduction Plan Summary		Risk Type:	Technical
Action/Milestone	**Success Criteria**	**Date Planned**	**Date Implemented**
Use different platform (Husky) and change the final delivery to demonstrating on that platform.	Platform can successfully work on the current ACM module.	04/26/2026	04/26/2026
Contact with Fantom Robotics and do the testing there.	Access the golf car LSV.	04/26/2026	04/26/2026

Comments

Conclusion

Conclusion (Lessons Learned)

Technical:

1. Pretrained model → ✓ starting point ✗ final model
2. Lack of unit tests in anomaly detection
3. ROS2 communication (DDS & QoS)

Systems engineering and project management:

1. Plan ahead
2. Task assignment based on each team member's working style

Conclusion (Future Plan)

1. Skeleton detection optimization
2. Tracking method replacement
3. Anomaly add action
4. Waypoint suggestion model development
5. Local Area Network (LAN)
6. LSV wiring
7. ACM deployment
8. Redirection development
9. Alert verification UI development
10. RealSense depth location transformation

IDs	Status	Functional Requirement
F.R.1	TODO	Provide waypoint suggestion to the user
F.R.2	Done	Receive waypoints from the user
F.R.3	Simulation Only	Enable K7 to navigate
F.R.4	Done	Visualize patrol status
F.R.5	Need to Speed Up & Split Model	Detect anomaly
F.R.6	TODO	Redirect K7
F.R.7	TODO	Support alarm verification

Thank You

Appendix