PhD-FSTM-2026-037
March 20, 2026

Ph.D. Thesis Defense

Enhancing Robots' Situational Awareness using Imperceptible Artificial Landmarks

by **Ali Tourani** (ali.tourani@uni.lu)

Defence Committee:

- **Prof. Holger Voos**, SnT, University of Luxembourg, Luxembourg
- **Prof. Jan Lagerwall**, DPMS, University of Luxembourg, Luxembourg
- **Prof. Rafael Munoz-Salinas**, DCNA, University of Cordoba, Spain
- **Dr. Martin R. Oswald**, Universiteit van Amsterdam, the Netherlands
- **Dr. Jose Luis Sanchez-Lopez**, SnT, University of Luxembourg, Luxembourg

Agenda

- Preface
- Background & Literature Review
- Research Objectives
- Thesis Contributions
- Closing Remarks
    - Achievements
    - Open Challenges

Preface

Framing the scope and boundaries of the project

TRANSCEND

UNIVERSITÉ DU LUXEMBOURG

- An **interdisciplinary** project, funded by the Institute for Advanced Studies (IAS)

[WP#1] Design & Fabrication of
Human-Imperceptible Robotic Landmarks

[WP#2] Sensing and Detection **Framework**

ROS inside!

[WP#3] Robotic **Integration** & Perception

[WP#4] Real-World **Deployment** in Robotics

SnT, Automation and Robotics Group

Department of Physics and Materials Science

Background and Literature Review

Background concepts & state-of-the-art research

Fiducial Markers

- Artificial **visual landmarks** as references for perception systems

Objectives:

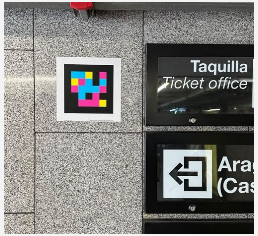
- Robust **detection** (highly distinctive patterns)
- Accurate **pose estimation** (as stable visual anchors)
- Enabling precise 3D→2D **correspondence**
  - Mapping world coordinates and image projections

Why do they matter?

- Enhance perception in **textureless/feature-sparse** environments
- References for sensor **calibration**

Berlin U-Bahn, Germany

Auchan, Luxembourg



Barcelona Metro, Spain

Photos by the author

Fiducial Markers

- **General Procedure of Marker Recognition**

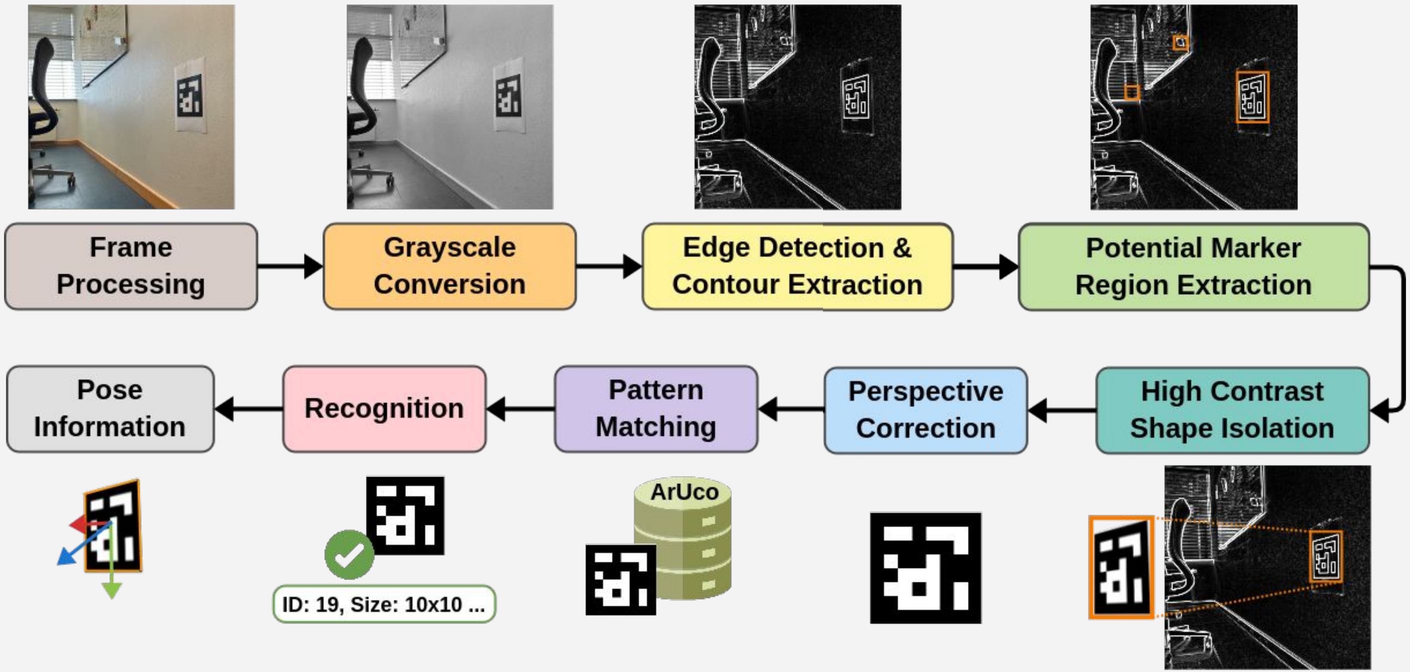
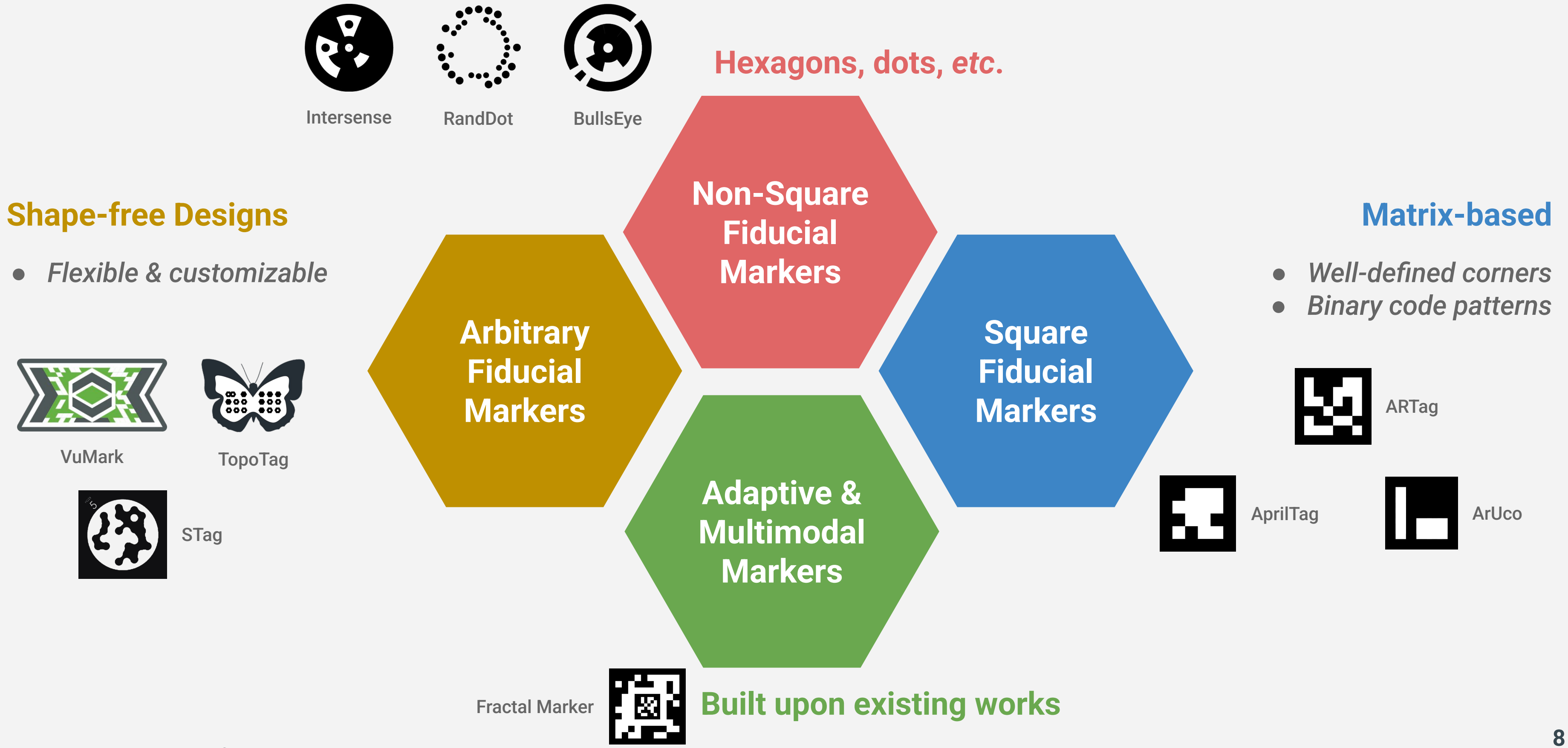


Illustration by the author

Fiducial Markers (Classic Approaches)



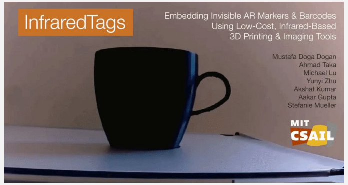
Fiducial Markers (Blended/Unobtrusive Approaches)

Hiding Markers for Security & Aesthetics

BrightMarker [4]

Embedding data into objects using a **NIR-fluorescent filament**

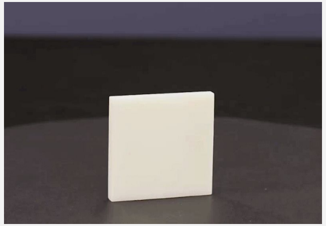
InfraredTags [3]



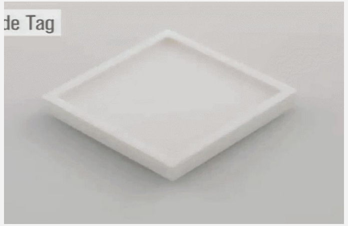
Embedding data during the 3D printing, detectable in IR spectrum

AirCode [2]

Tagging physically fabricated objects using **air pockets**



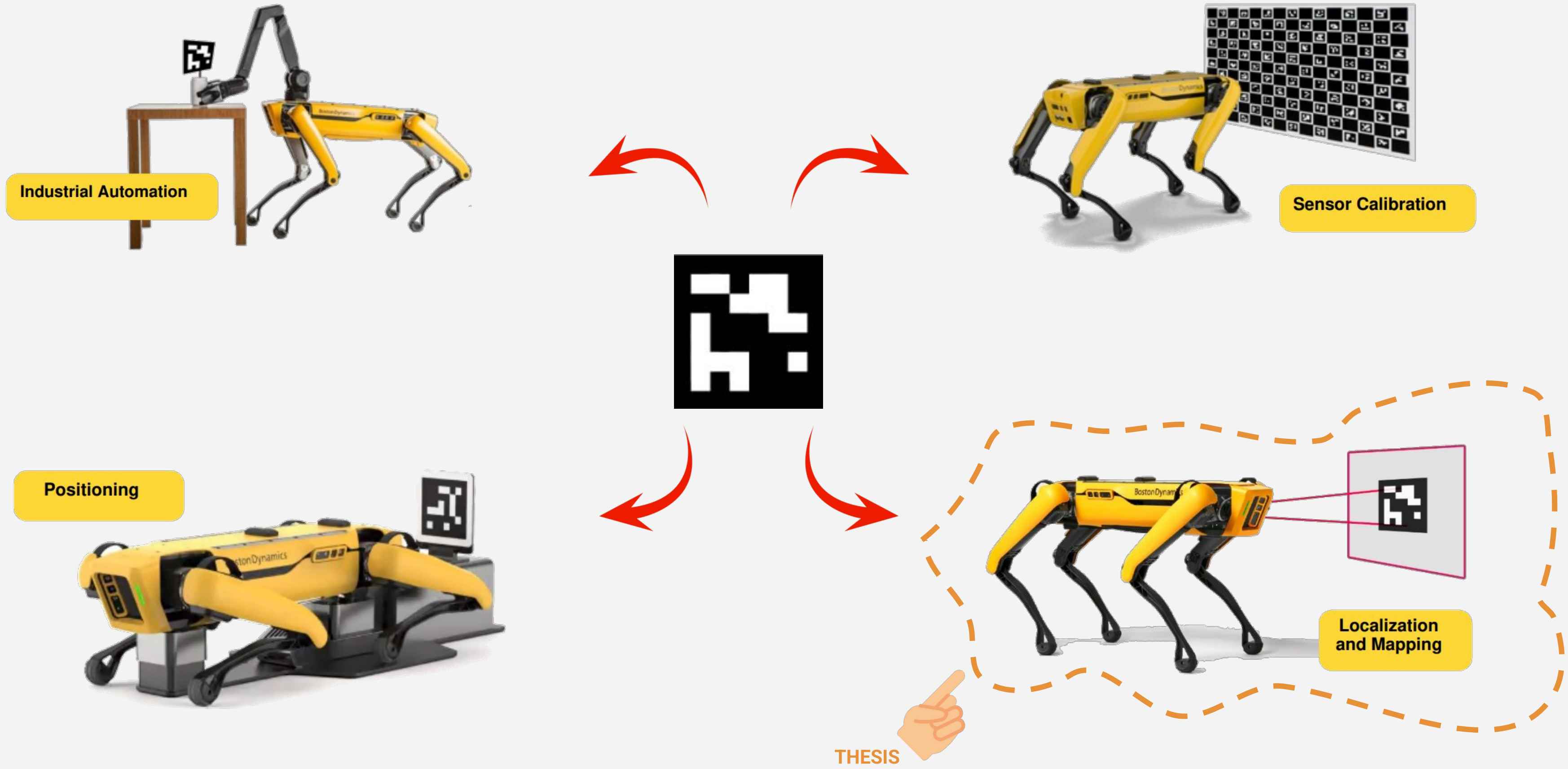
InfraStructs [1]



Embedding information inside digitally fabricated objects for imaging in THz

[1] Willis et al. (2013) InfraStructs: Fabricating information inside physical objects for imaging in the terahertz region.
[2] Li et al. (2017) Aircode: Unobtrusive physical tags for digital fabrication.
[3] Dogan et al. (2022). Infraredtags: Embedding invisible AR markers and barcodes using low-cost, infrared-based 3d printing and imaging tools.
[4] Dogan et al. (2023) Brightmarker: 3d printed fluorescent markers for tracking.

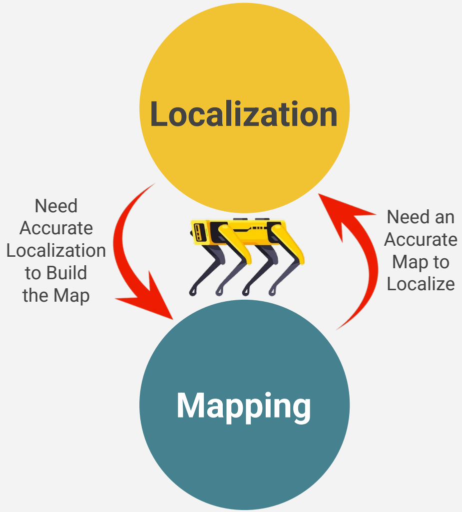
Markers in Robotics

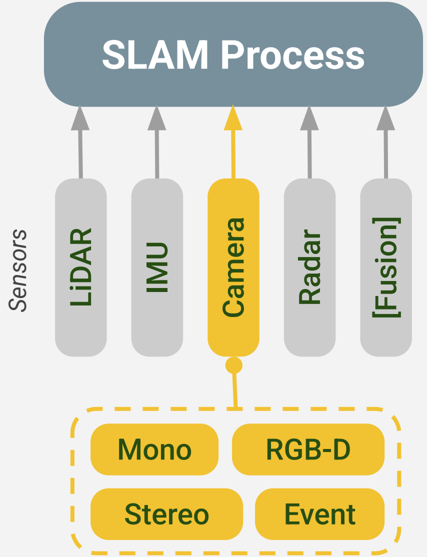


Markers in Robotics: SLAM

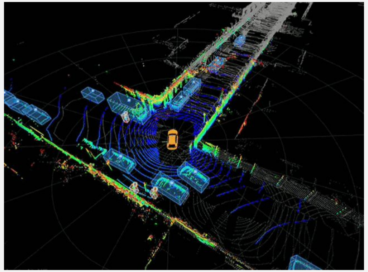
Simultaneous Localization and Mapping (SLAM)

- Concurrent mapping and self-localization by autonomous agents (robots)
    - Building the surrounding map while estimating robot pose

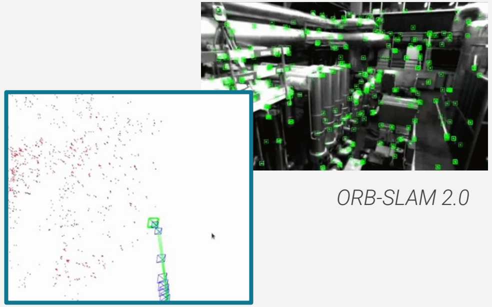




Vision Sensors

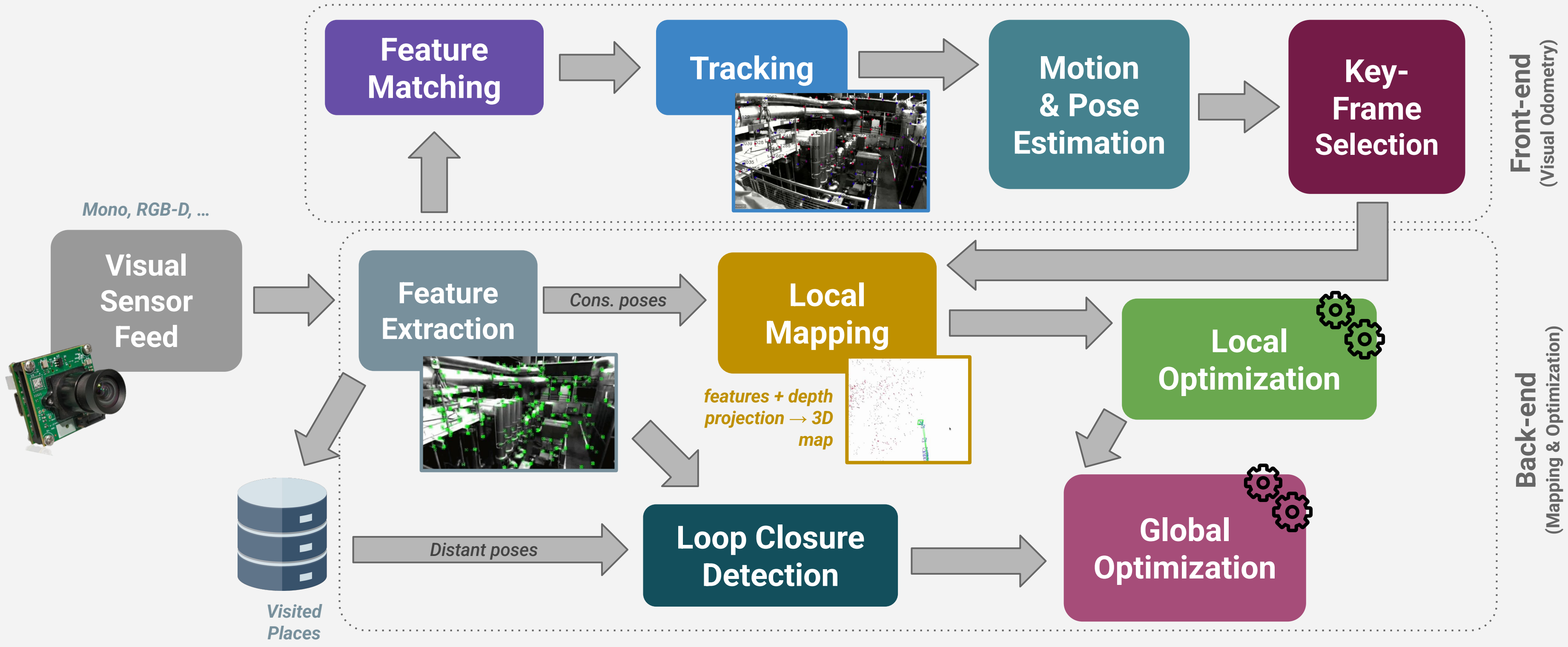


LSD (LiDAR SLAM & Detection)



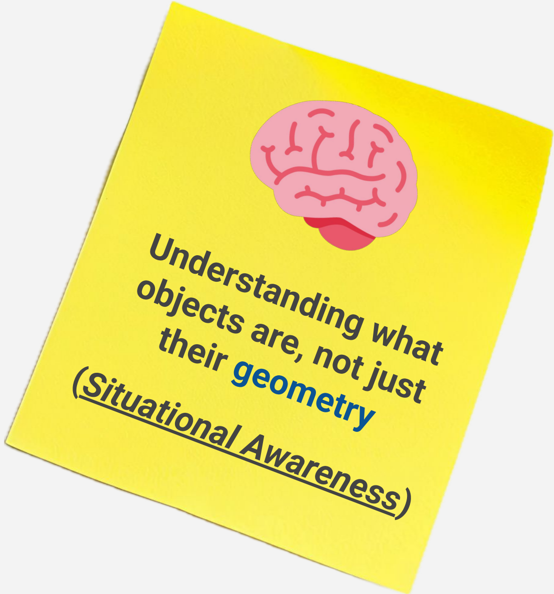
ORB-SLAM 2.0

Visual SLAM (VSLAM)



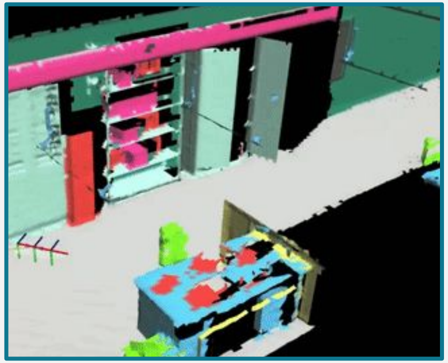
Note: the slide is focused on indirect (feature-based) VSLAM; front-end/back-end definitions may vary across VSLAM approaches.

Visual SLAM Map Representation



Semantic Maps

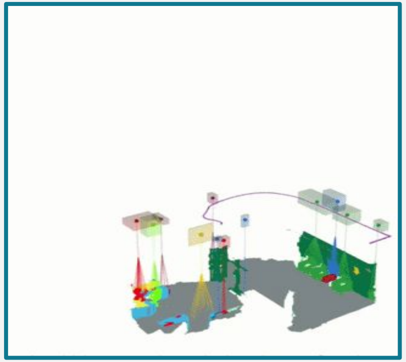
- *Object **landmarks***
    - *Voxels*
- ***Semantic** point clouds*



Kimera Semantics [2]

Scene Graphs

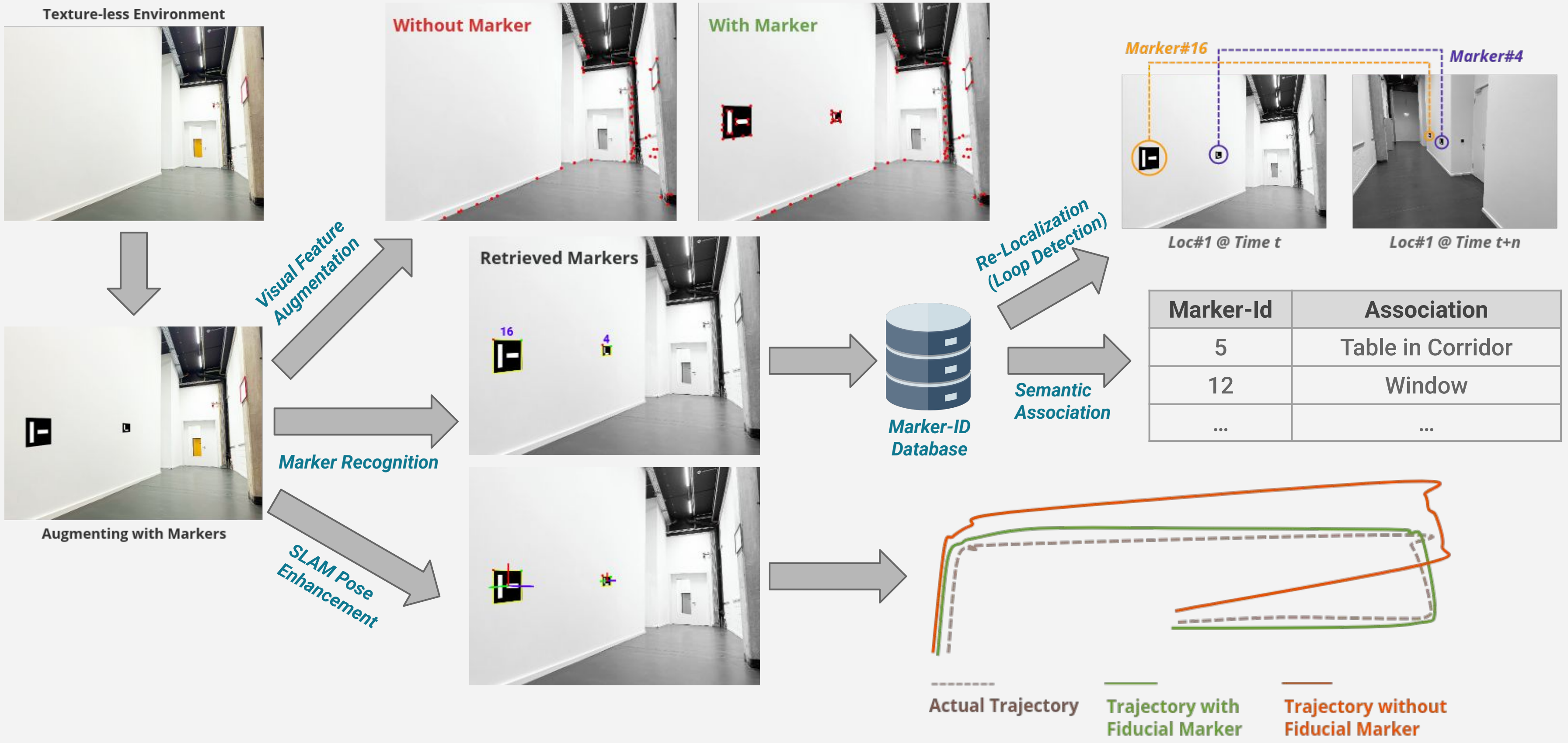
- ***Nodes** (landmarks / objects)*
- ***Edges** (topology)*
- ***Structured** environment*
- *Keep **spatial relationship***



Hydra [3]

[1] Mur-Artal & Tardós (2017) ORB-SLAM2: An open-source slam system for monocular, stereo, and rgb-d cameras.
[2] Rosinol et al. (2020) Kimera: an open-source library for real-time metric-semantic localization and mapping.
[3] Hughes et al. (2022) Hydra: A real-time spatial perception system for 3D scene graph construction and optimization.

Visual SLAM with Markers



Marker-Id	Association
5	Table in Corridor
12	Window
...	...

Research Objectives

Clarifying the aims and boundaries of the research

Research Motivation

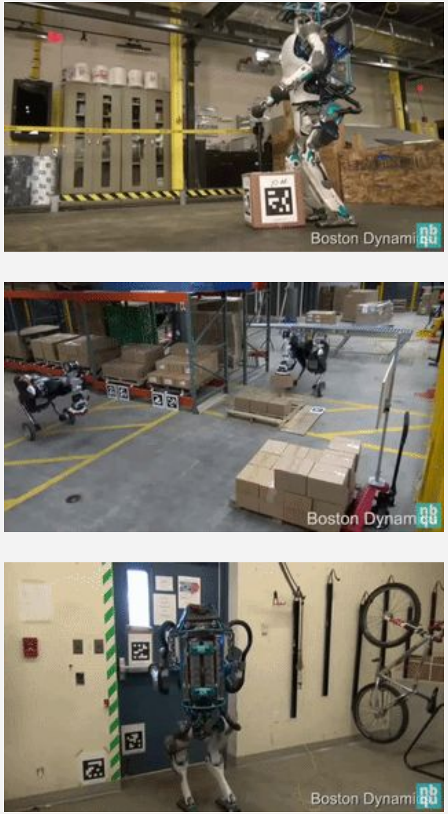
- Robots in **complex** and **dynamic** environments
  - *Examples*: warehouse logistics

Goal: achieve reliable perception with:

- Reasonable computational cost
- Balanced performance and cost trade-off

Opportunity: markers to label objects for

- Fast semantic grounding
- Reduced perception complexity



Videos from Boston Dynamics

Research Motivation

[Q] What if we deploy visible fiducial markers at large scale?

Illustrations by the author

g/worry-free-automation/

- Visually cluttered
- Aesthetically degraded
- No functional value to humans!

Research Objectives

RQ#1
Human-friendly, Robot-detectable Markers?

RQ#2
Can Markers Boost VSLAM Performance?

RQ#3
Can Human-friendly Markers Perform Like Printed Ones?

RQ#4
Landmarks: Essential or Supplementary for S.A.?

Thesis Contributions

Summary of key scientific and technical contributions

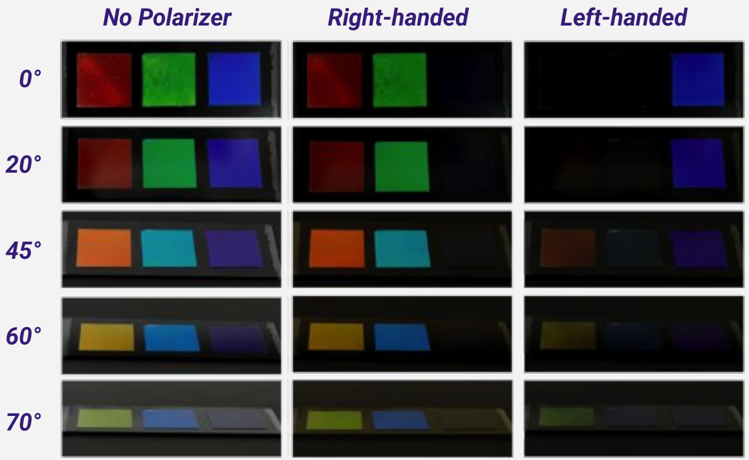
RQ#1:

Human-friendly, Robot-detectable Markers?

Motivation

- **Cholesteric Liquid Crystals (CLCs)**
  - Made of **molecules** that self-organize into a “***helix***” structure
  - What makes them **unique**?
    - ***Selective Reflection***: only for specific light **wavelengths** (thus colors)
      - Covering **near-infrared (NIR)**, **visible**, and **near-ultraviolet (NUV)** ranges
    - ***Circular Polarization***: only reflect **circularly-polarized** light with the same **handedness (R/L)**

Department of Physics and Materials Science



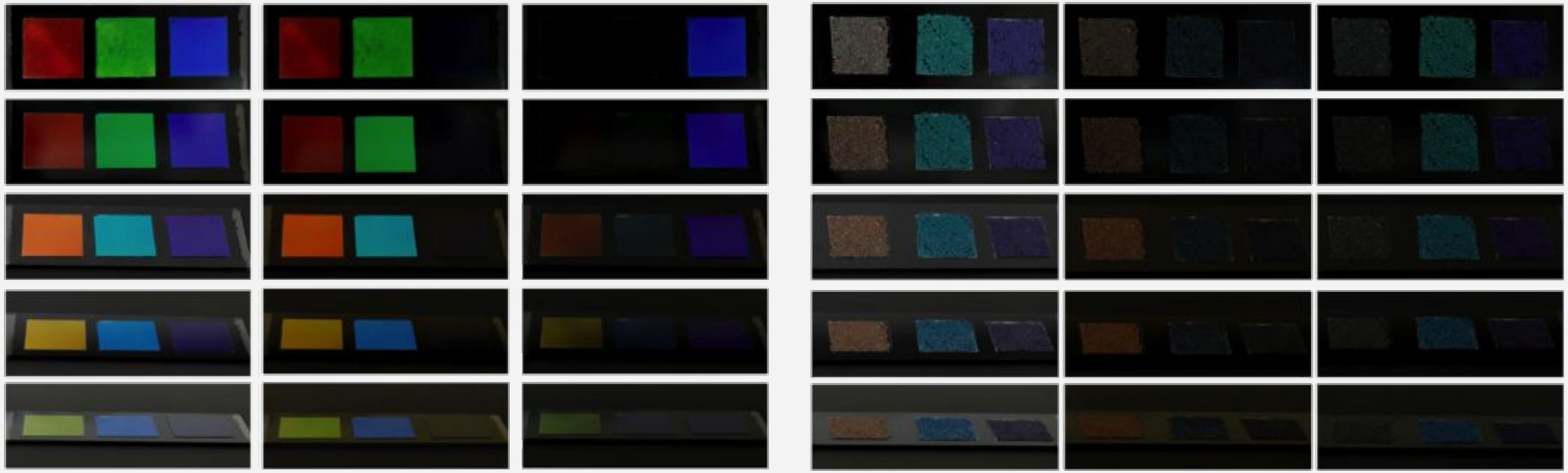
Unclonable Human-invisible Machine Vision Markers Leveraging the Omnidirectional Chiral Bragg Diffraction of Cholesteric Spherical Reflectors

Agha *et al.*, Light: Science & Application, (2022)

Motivation

- **Cholesteric Spherical Reflectors (CSRs)**
  - Microscopic **droplets** of CLCs
  - What makes them **unique w.r.t.** CLCs?
    - *Omnidirectional Reflection*: reflect light directly back to its source, regardless of the angle

Department of Physics and Materials Science



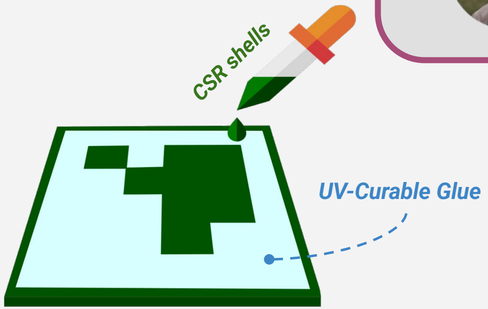
Flat CLC Films

Densely Packed CSRs

Imperceptible Markers (iMarkers)

- **Core Material:** Cholesteric Spherical Reflectors (CSRs)

Department of Physics and Materials Science



Fabrication Procedure

a. Pick a fiducial marker pattern (*e.g.*, ArUco)

b. Replicate pattern and borders with CSR shells

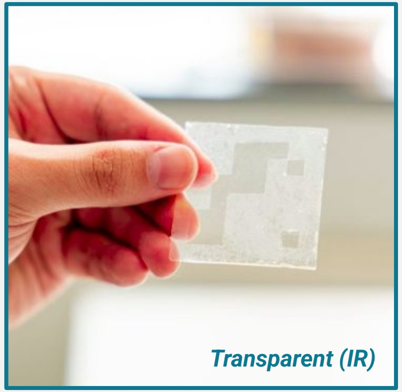
c. Fill the rest with transparent resin to keep shape

Core Question: how can iMarkers be reliably detected by robots?

Unveiling the Potential of iMarkers: Invisible Fiducial Markers for Advanced Robotics

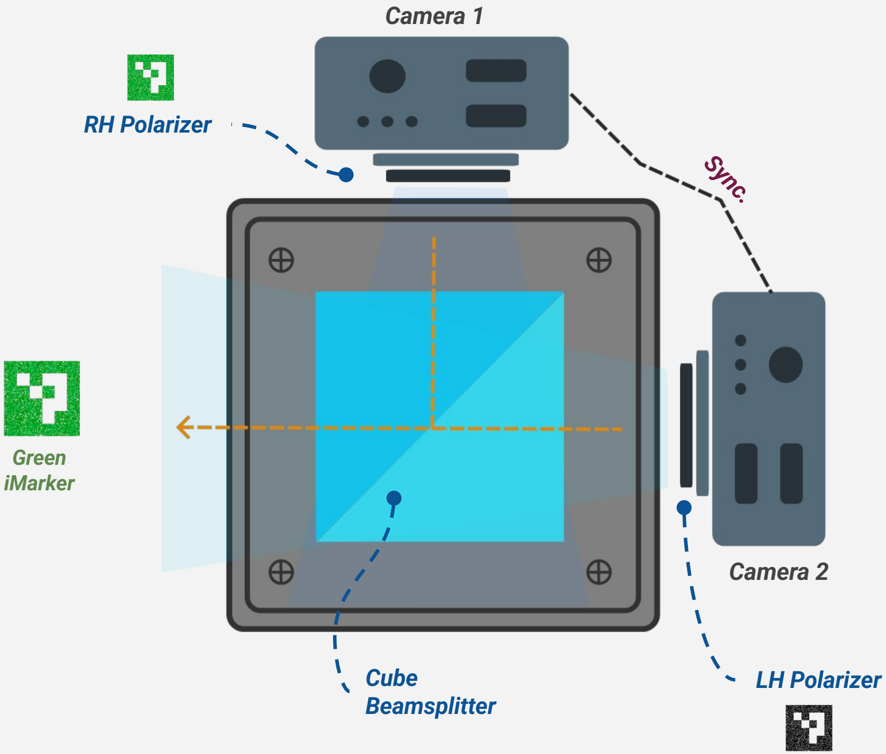
Tourani *et al.*, IEEE RA-M, (2026)

Camouflage (visible)

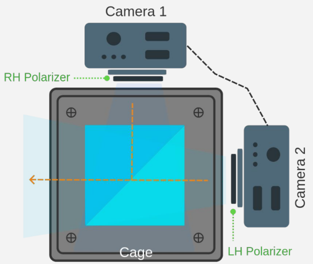


iMarker Detection Solutions

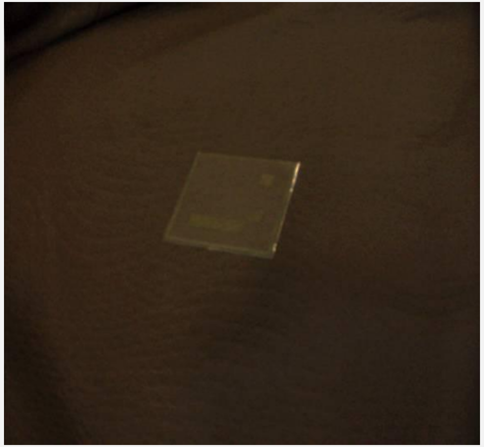
Solution I. Dual-vision Setup



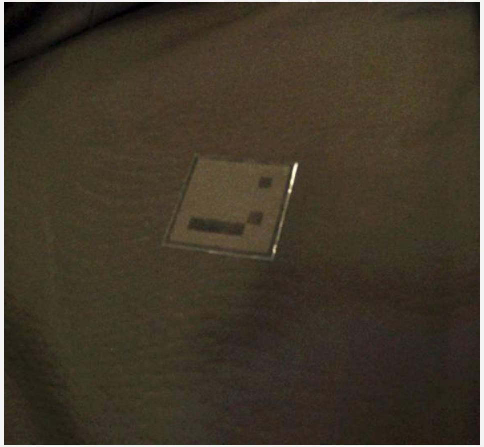
iMarker Detection Solutions



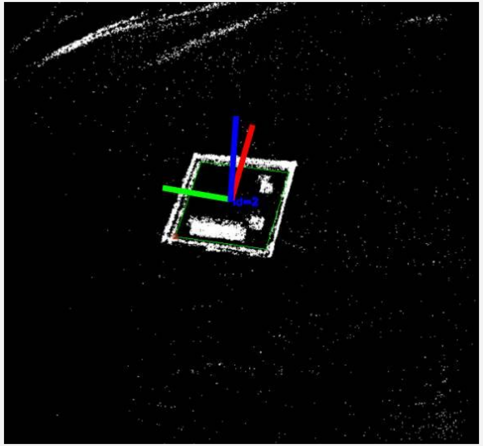
Solution I. Dual-vision Setup



A green **visible-range** iMarker in low-light condition, capture by **camera#1** with **right-handed** circular polarization.



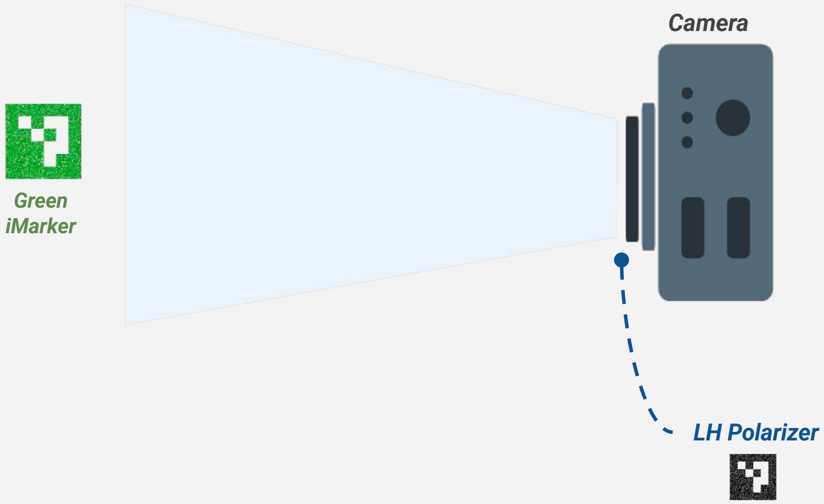
The same scene captured by **camera#2** with **left-handed** circular polarization, blocking the CSR regions of the iMarker.



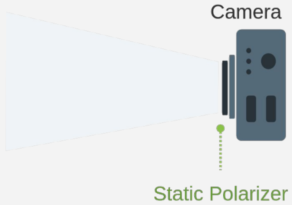
The final detection result using **spatial subtraction**.

iMarker Detection Solutions

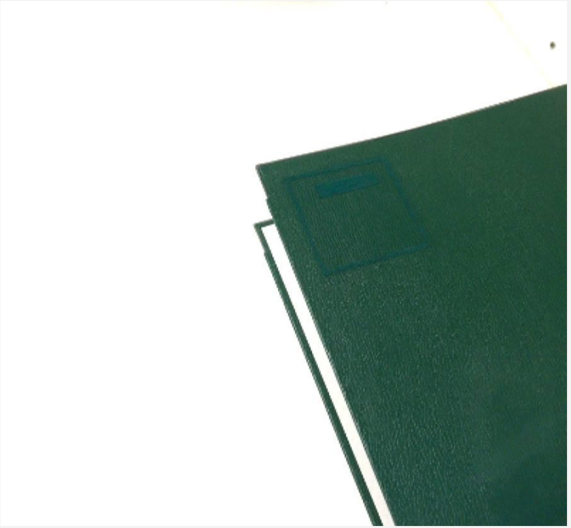
Solution II. Single-vision Setup with Static Polarizer



iMarker Detection Solutions

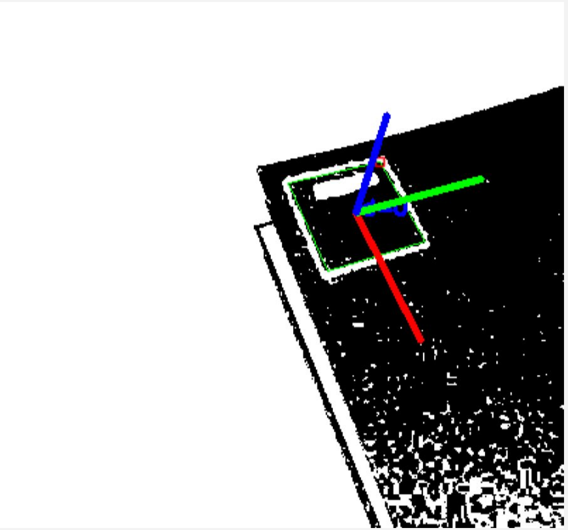


Solution II. Single-vision Setup with Static Polarizer



A green **visible-range** iMarker **camouflaged** in a same-color background.

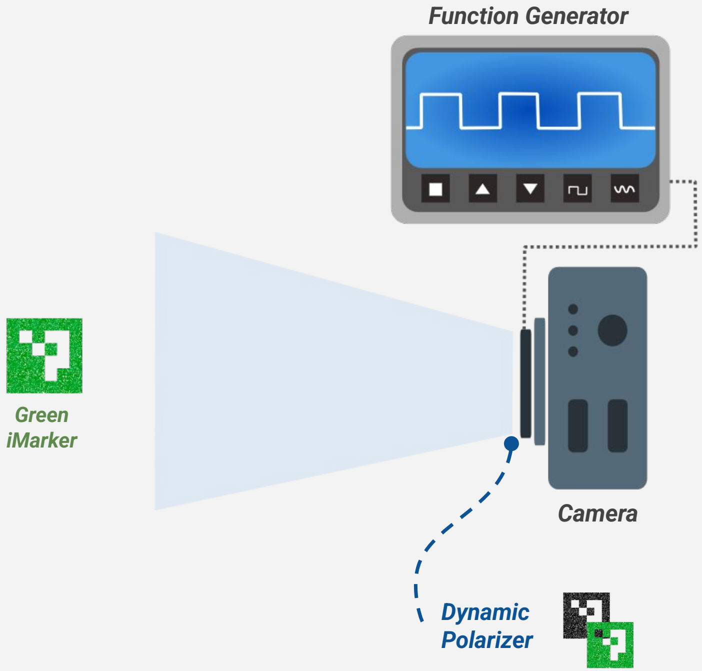
Blocked CSR regions of the iMarker using the static polarizer reveals the patterns.

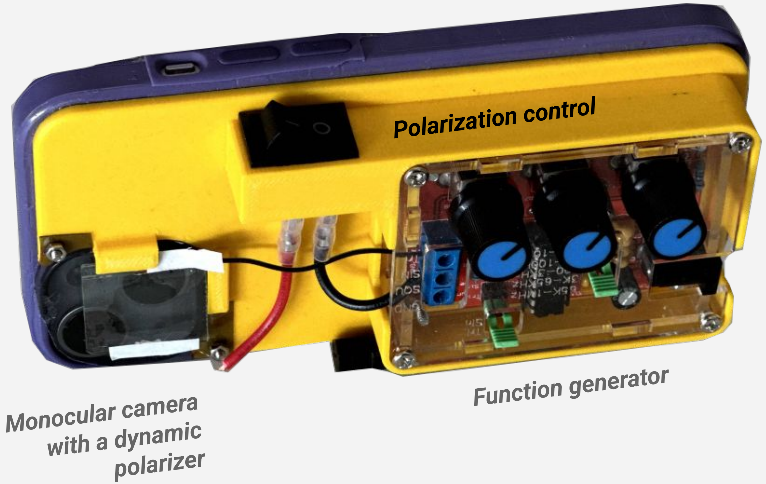


The detection result can be achieved using **color masking** (green).

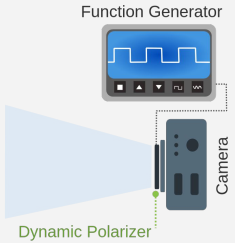
iMarker Detection Solutions

Solution III. Single-vision Setup with Dynamic Polarizer





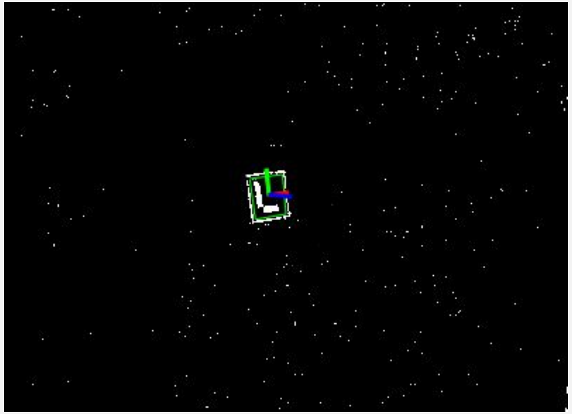
iMarker Detection Solutions



Solution III. Single-vision Setup with Dynamic Polarizer

A **visible-range** iMarker **camouflaged** in an outdoor environment, capture by sensor with **off-phase** circular polarization.

The same scene captured in the **next frame** using **on-phase** circular polarization, revealing the marker presence.

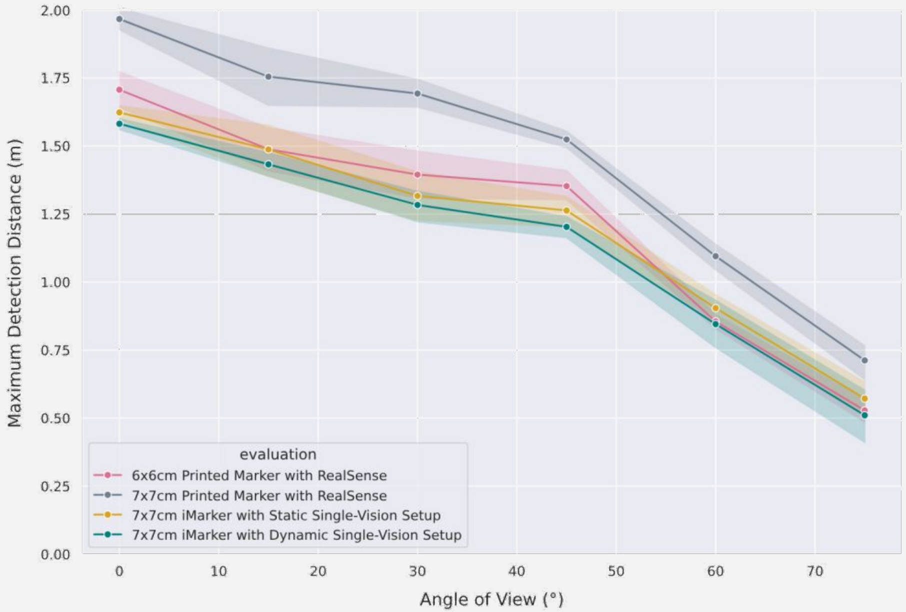


The final detection result using **temporal subtraction**.

Benchmarking

> **Unveiling the Potential of iMarkers: Invisible Fiducial Markers for Advanced Robotics**
>
> Tourani *et al.*, IEEE RA-M, (2026)

I. Detection Range & Pose Accuracy



Mean pose estimation error (meters) of 7×7 markers.

	Printed	iMarker (Static SV)	iMarker (Dynamic SV)
0º	0.155	0.160	0.161
15º	0.191	0.196	0.194
30º	0.208	0.211	0.214
45º	0.214	0.218	0.220
60º	0.228	0.231	0.234
75º	0.235	0.238	0.241

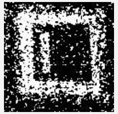
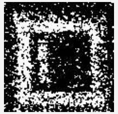
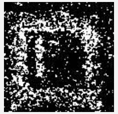
Near-comparable detection with **aesthetic invisibility**.

Pose accuracy comparable to printed ones.

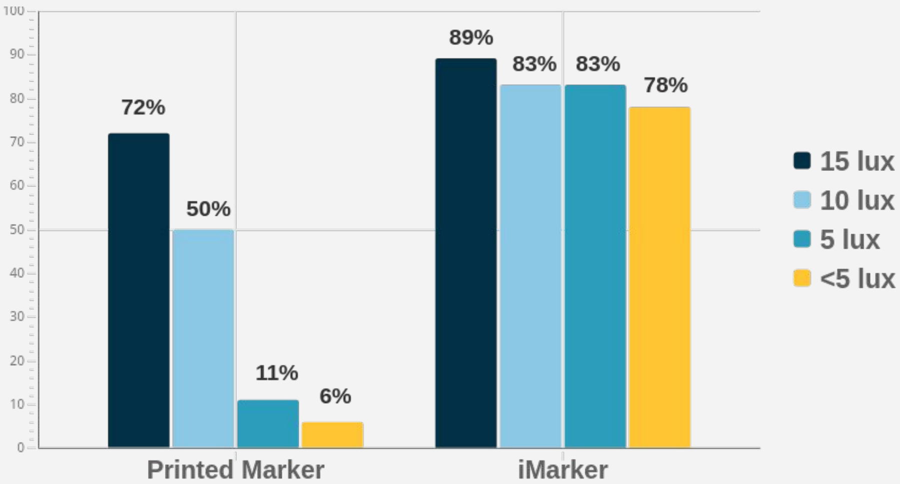
Benchmarking

> **Unveiling the Potential of iMarkers: Invisible Fiducial Markers for Advanced Robotics**
>
> Tourani *et al.*, IEEE RA-M, (2026)

II. Degraded Visual Conditions Analysis

	15 lux	10 lux	5 lux	≤ 5 lux
Printed Marker				
IR-range iMarker				

Detection Rate (percentage) over 18 frames



Reliable detection under **challenging illumination** ⇒ robust perception **beyond aesthetic** benefits.

Thesis Contributions

Summary of key scientific and technical contributions

RQ#2:

Can Fiducial Markers Boost VSLAM Performance?

Motivation: Marker-based VSLAM

- **Existing Works**
  - Markers for improved **perception** and **localization**
    - Reduced **tracking loss**
  - Enhanced **geometric mapping** quality
  - Enable **re-localization** and **loop closure** detection

UcoSLAM [1]

Research Gap

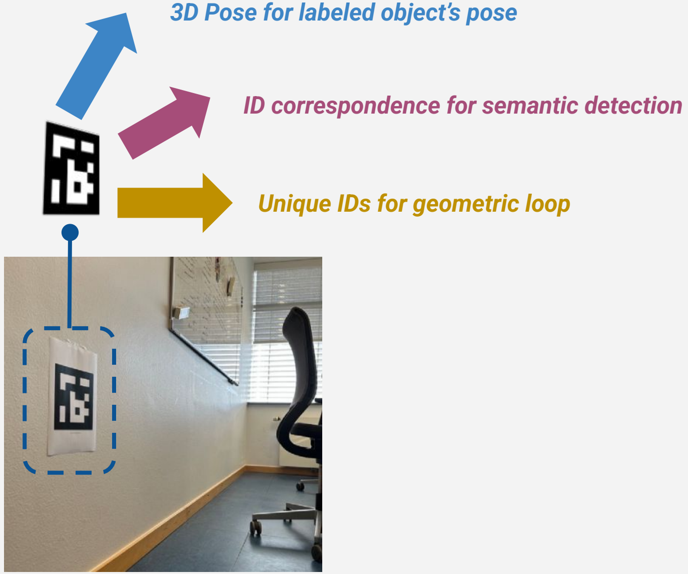
- Markers for purely geometric constraints
- Limited exploitation of markers as **semantic references**
  - **Potential** for semantic-aware mapping
  - **Strategically locating** instead of random distribution

[1] Munoz-Salinas, R., & Medina-Carnicer, R. (2020). UcoSLAM: Simultaneous localization and mapping by fusion of keypoints and squared planar markers.

Proposed: Semantic UcoSLAM

> **Marker-Based Visual SLAM Leveraging Hierarchical Representations**
>
> Tourani *et al.*, IROS 2023

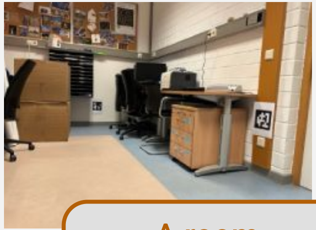
- **Core Idea**
  - Fetching **Semantic Information** from fiducial markers
  - Extracting (and showing) their **topological relationships**
- **Proposed**
  - Built upon **UcoSLAM** (monocular)
  - Inspired by **LiDAR-based S-Graphs**
    - Generating <u>hierarchical representations</u>
      - Detecting walls, corridors, and rooms



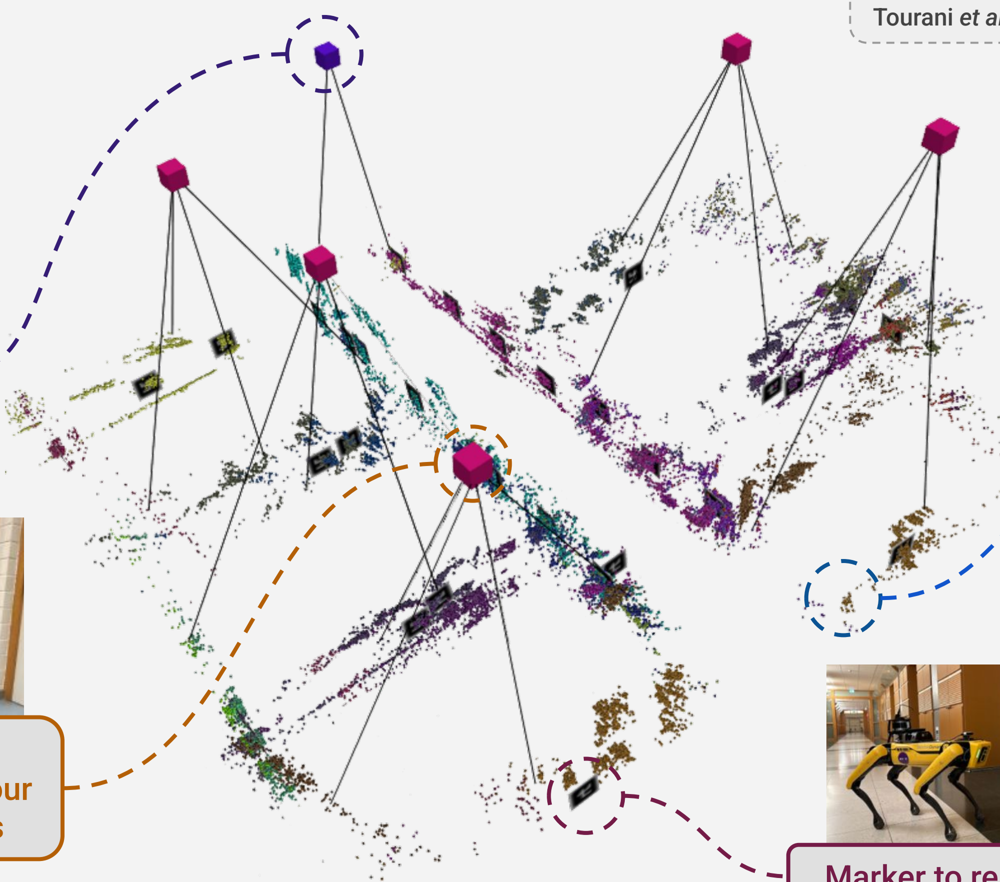
Semantic UcoSLAM – Overall

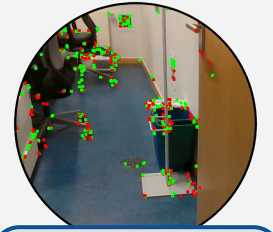
> **Marker-Based Visual SLAM Leveraging Hierarchical Representations**
>
> Tourani *et al.*, IROS 2023

A corridor detected by two facing walls



A room comprising four facing walls



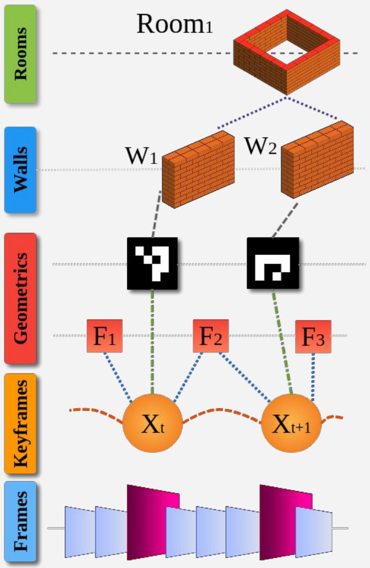


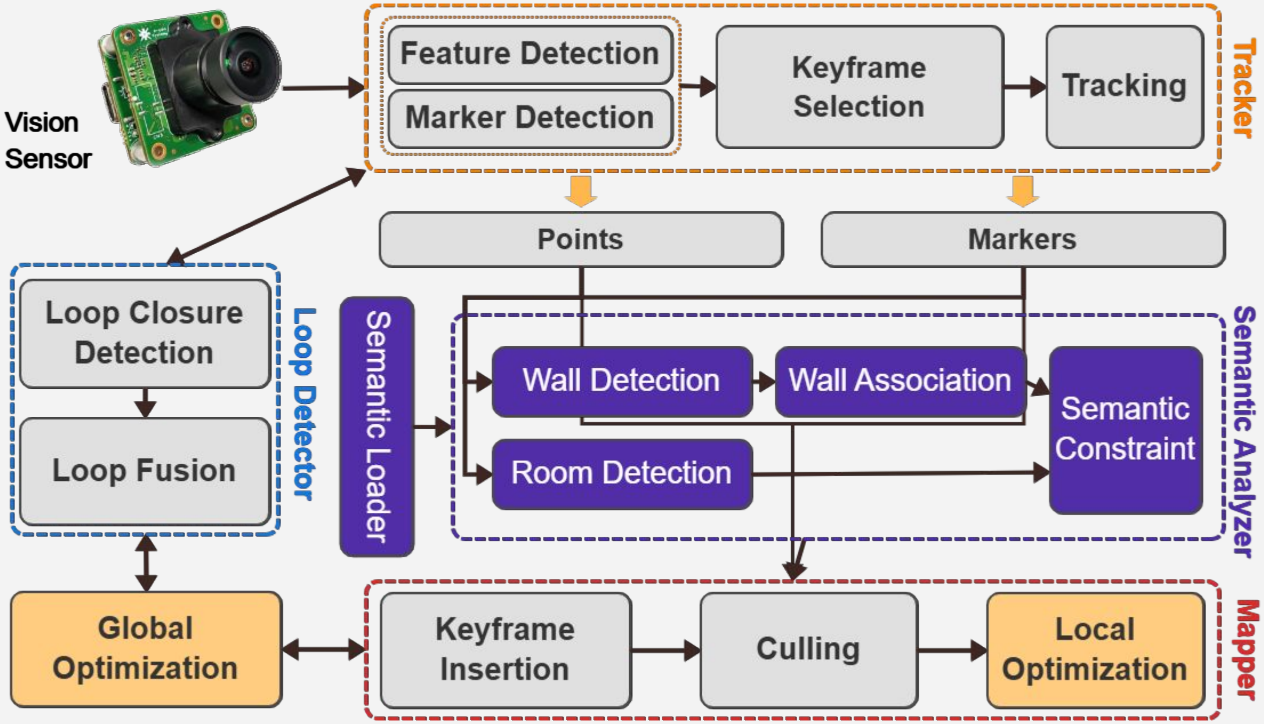
3D Map Points (visual features) laying on the same wall

Marker to represent a wall

Semantic UcoSLAM – Architecture

> **Marker-Based Visual SLAM Leveraging Hierarchical Representations**
>
> Tourani *et al.*, IROS 2023



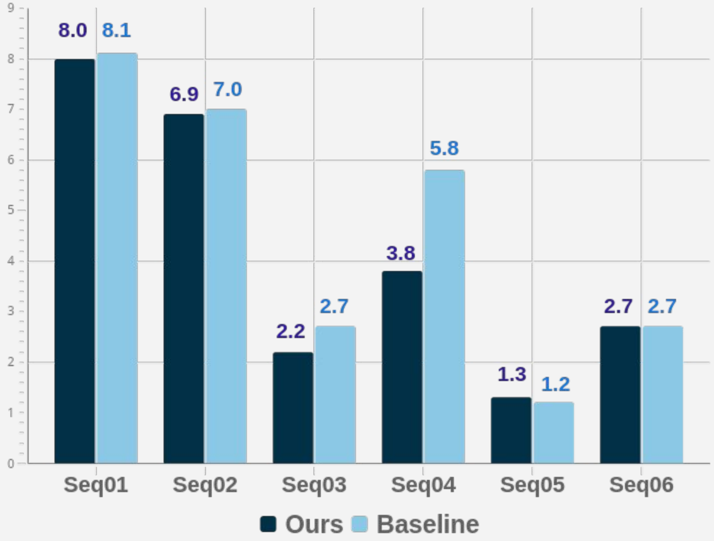


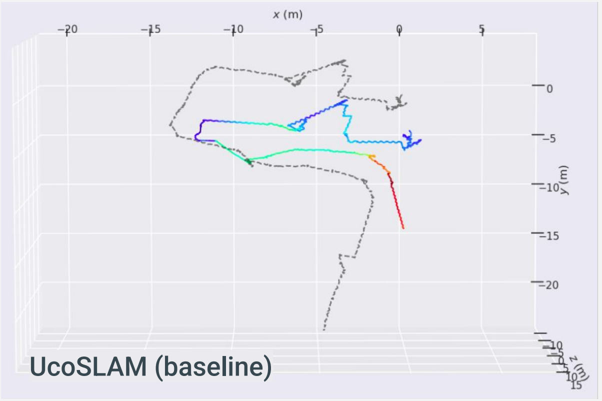
From the baseline | Modified | Added

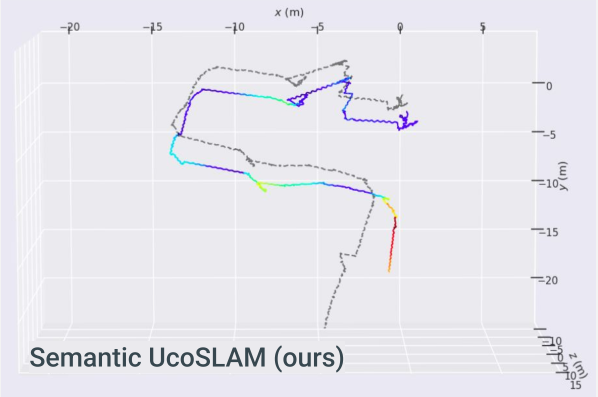
Evaluations – RMSE

Marker-Based Visual SLAM Leveraging Hierarchical Representations

Tourani *et al.*, IROS 2023





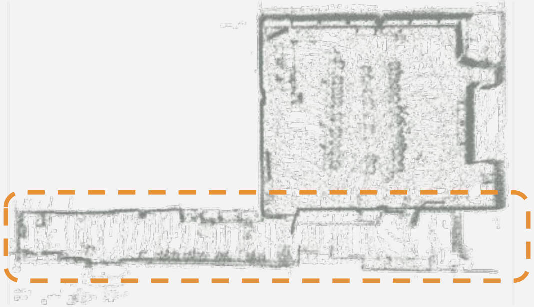


Outperforming the baseline in trajectory estimation
(due to semantic mapping and association)

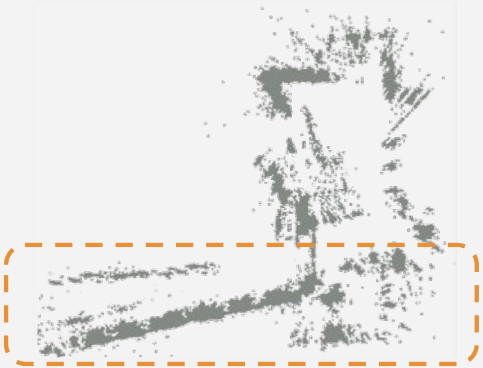
Evaluations – Mapping

Marker-Based Visual SLAM Leveraging Hierarchical Representations

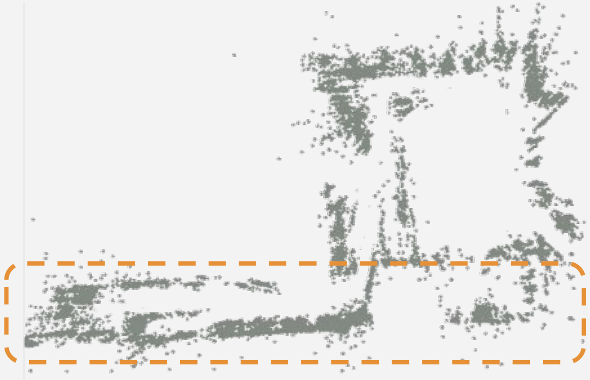
Tourani *et al.*, IROS 2023



Ground-Truth (S-Graphs)



Baseline (UcoSLAM)



Ours (Semantic UcoSLAM)

Enhancing **map reconstruction** by imposing more semantic constraints to ensure **global consistency**

Thesis Contributions

Summary of key scientific and technical contributions

RQ#3:

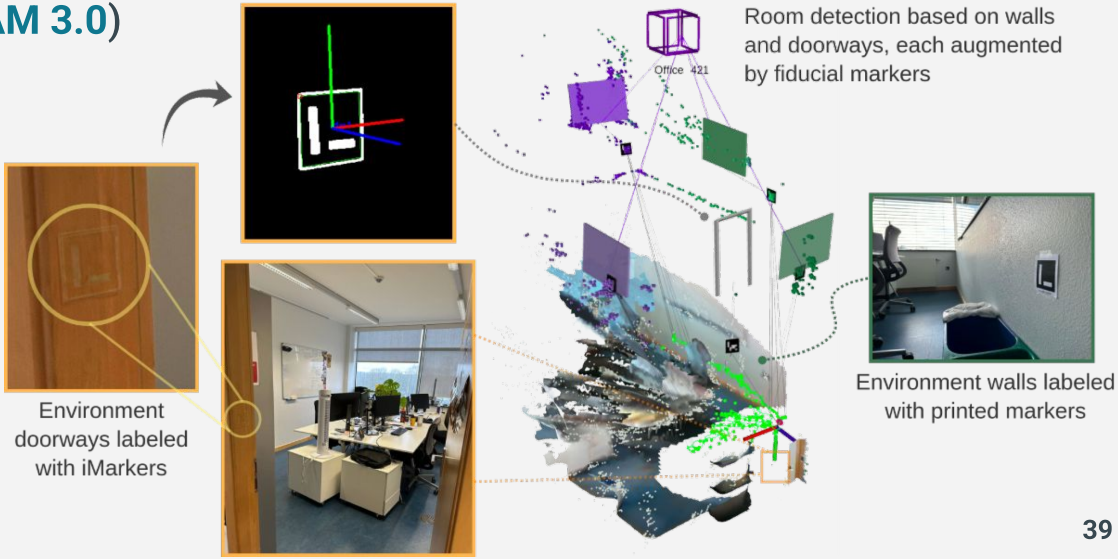
Can iMarkers Compete with Printed Markers in VSLAM?

Motivation

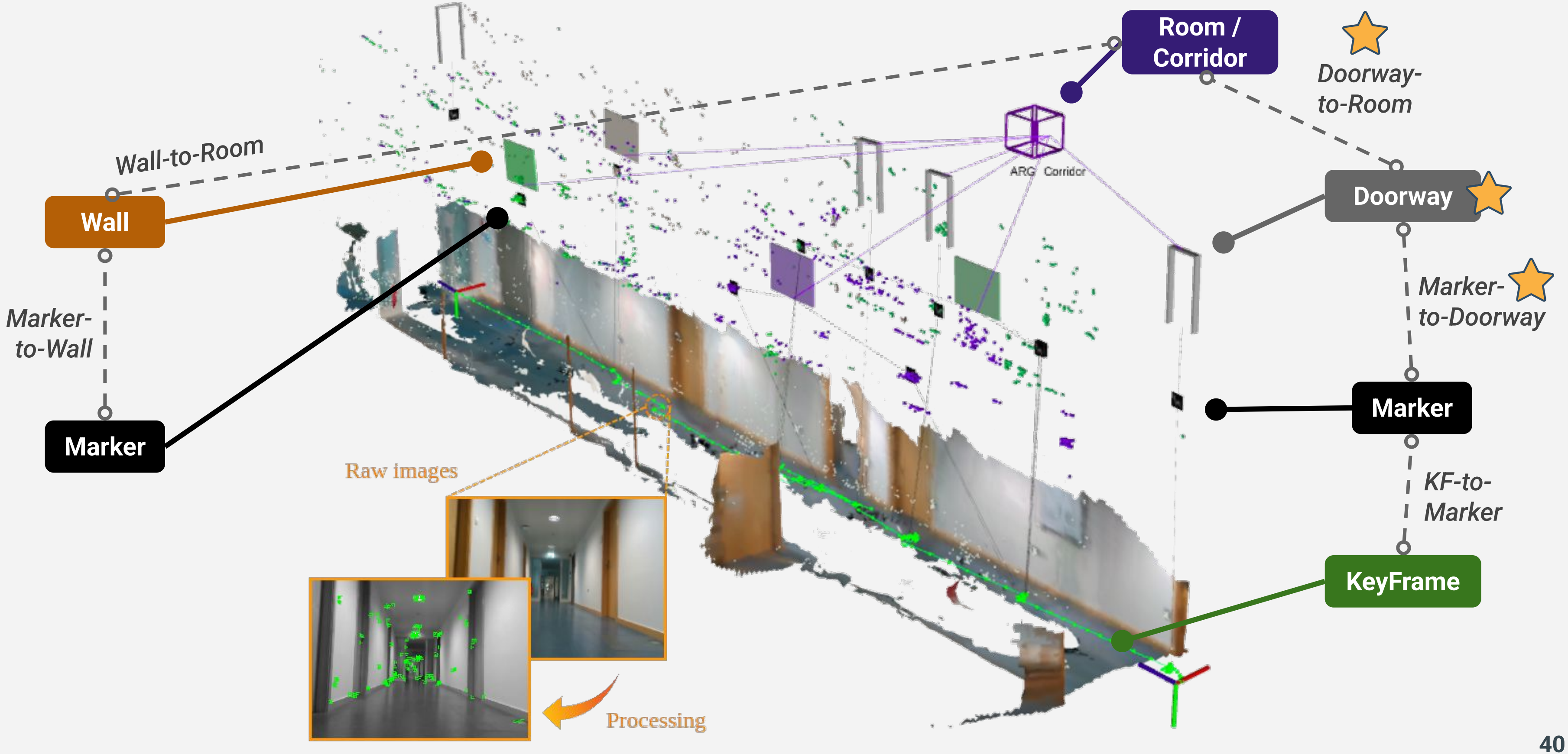
- Prototyping **iMarkers** alongside **printed markers**
  - **iMarkers** to **label complicated entities** (e.g., doorways)

- Revisiting the baseline (**ORB-SLAM 3.0**)
  - Actively maintained SOTA
  - **Extension capabilities** (IMU)

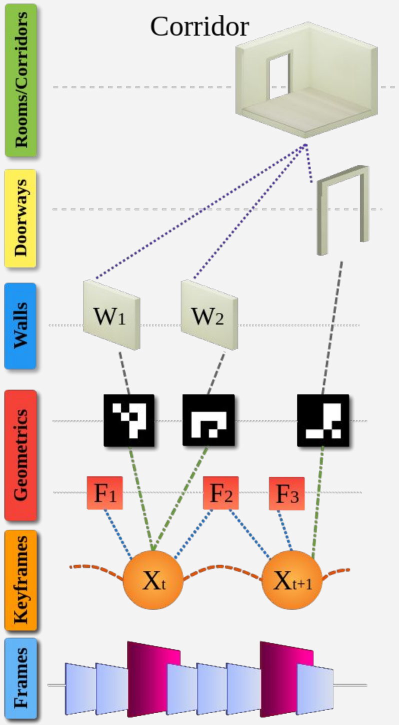
> **Vision-based Situational Graphs Exploiting Fiducial Markers for the Integration of Semantic Entities**
>
> Tourani *et al.*, (2024) Robotics.

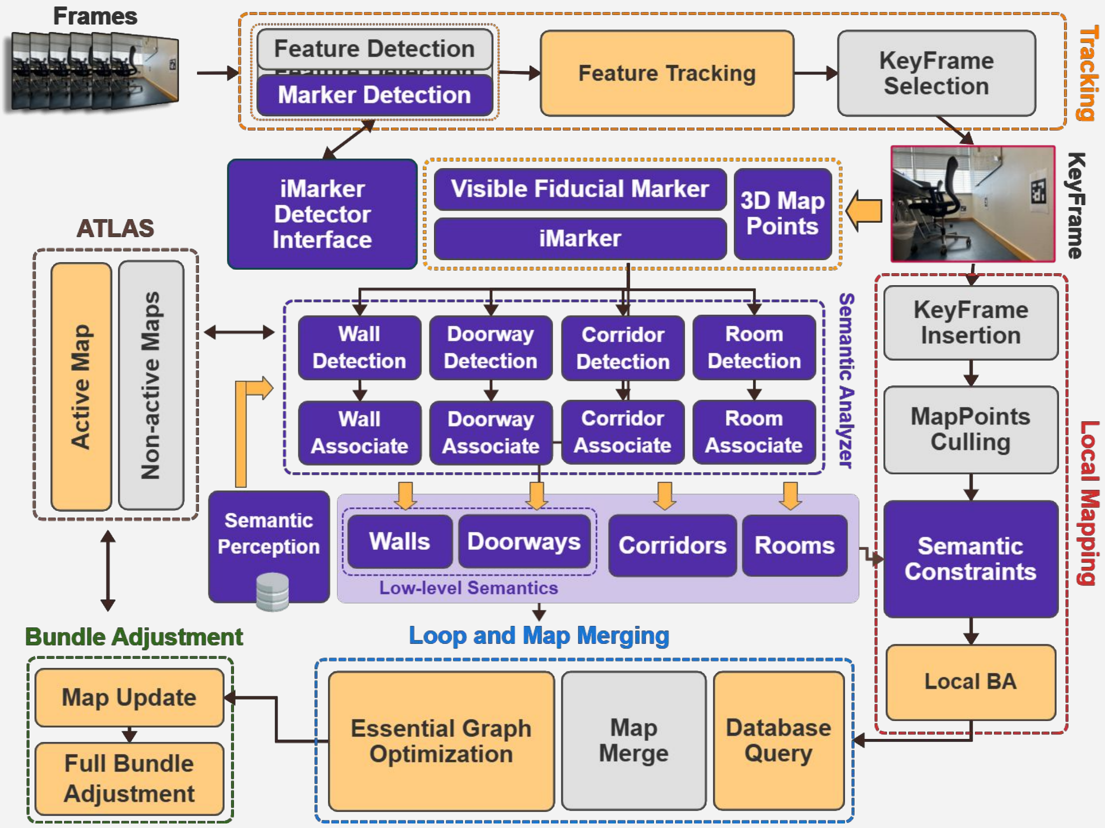


Marker-based ORB-SLAM 3.0 – Overall



Marker-based ORB-SLAM 3.0 – Structure



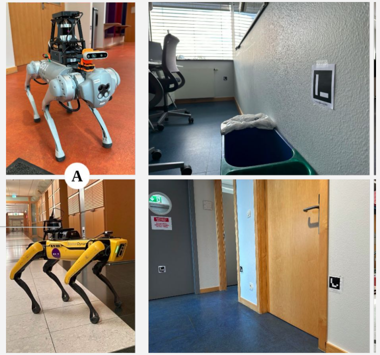


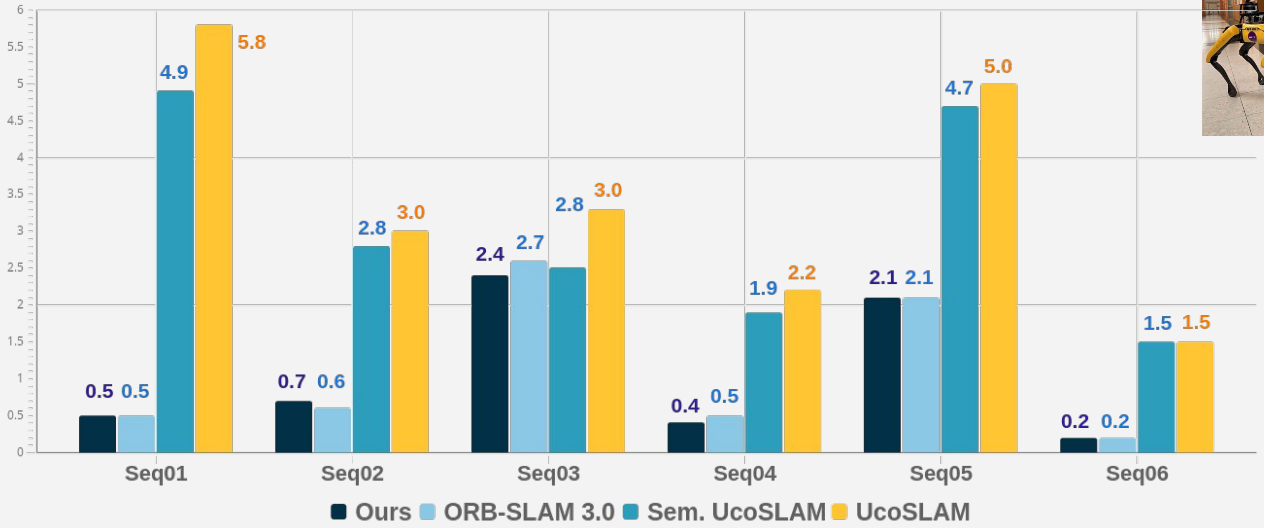
From the baseline Added Modified

Evaluations – RMSE Evaluations

Vision-based Situational Graphs Exploiting Fiducial Markers for the Integration of Semantic Entities

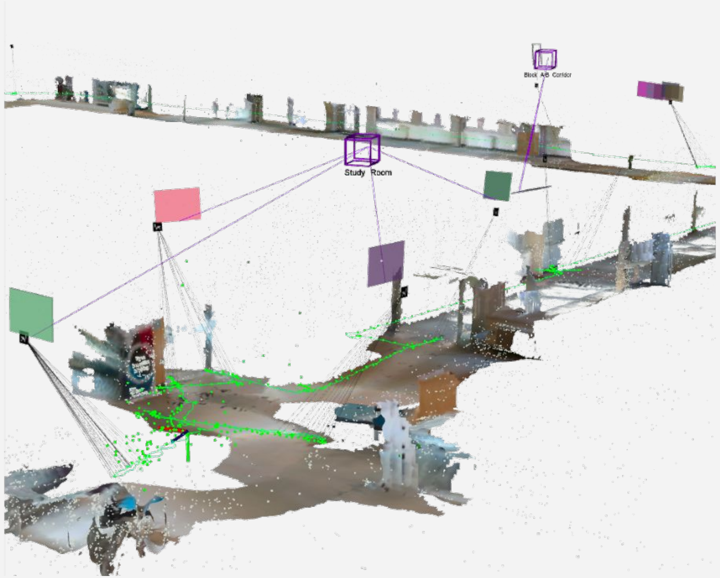
Tourani *et al.*, (2024) Robotics.

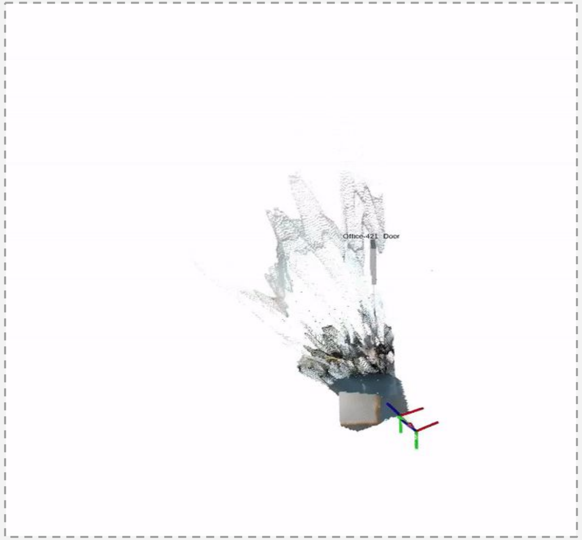




Outperforming the baseline (ORB-SLAM 3.0) and Semantic UcoSLAM

Qualitative Evaluations





Vision-based Situational Graphs Exploiting Fiducial Markers for the Integration of Semantic Entities

Tourani *et al.*, (2024) Robotics.

”

Semantic map and 3D Scene Graph generation in real-time given printed marker or iMarker

Thesis Contributions

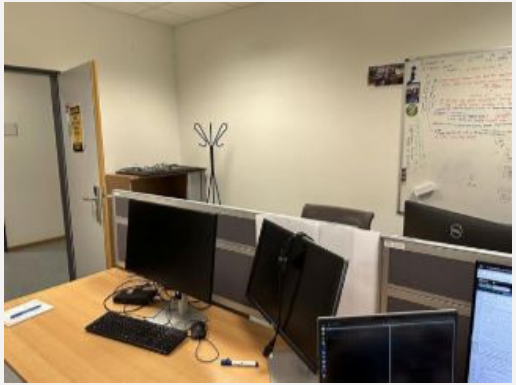
Summary of key scientific and technical contributions

RQ#4:

Landmarks: Essential or Supplementary for Situational Awareness?

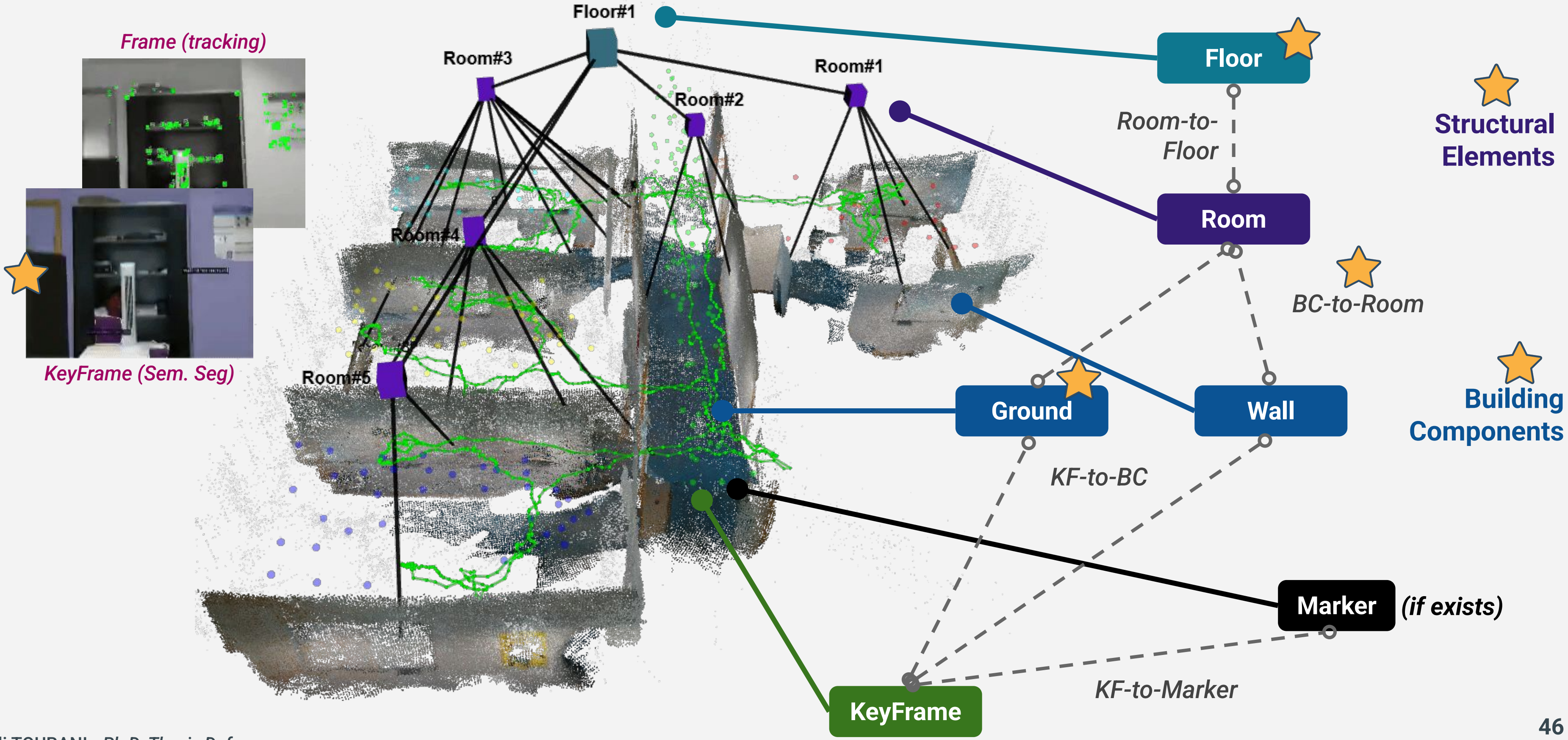
Motivation

- Can we consider markers as **strategic anchors**?
  - Deployed **selectively** at key locations
  - Serve as **supplementary** localization cues
  - Enhance robustness without **heavy reliance** on infrastructure
  - System **remains robust** with sparse marker availability



Visual S-Graphs (vS-Graphs)

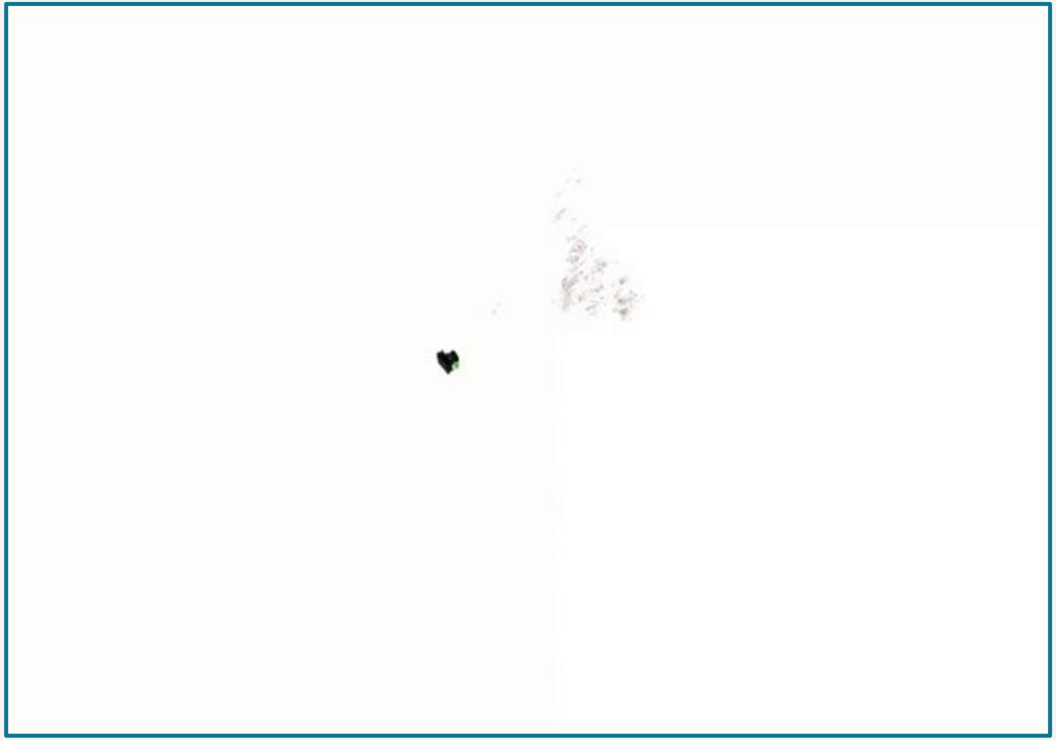
> **vS-Graphs: Tightly Coupling Visual SLAM and 3D Scene Graphs Exploiting Hierarchical Scene Understanding**
>
> Tourani *et al.*, (2025) RA-L (Under Review).



vS-Graphs – Overall

vS-Graphs: Tightly Coupling Visual SLAM and 3D Scene Graphs Exploiting Hierarchical Scene Understanding

Tourani *et al.*, (2025) RA-L (Under Review).

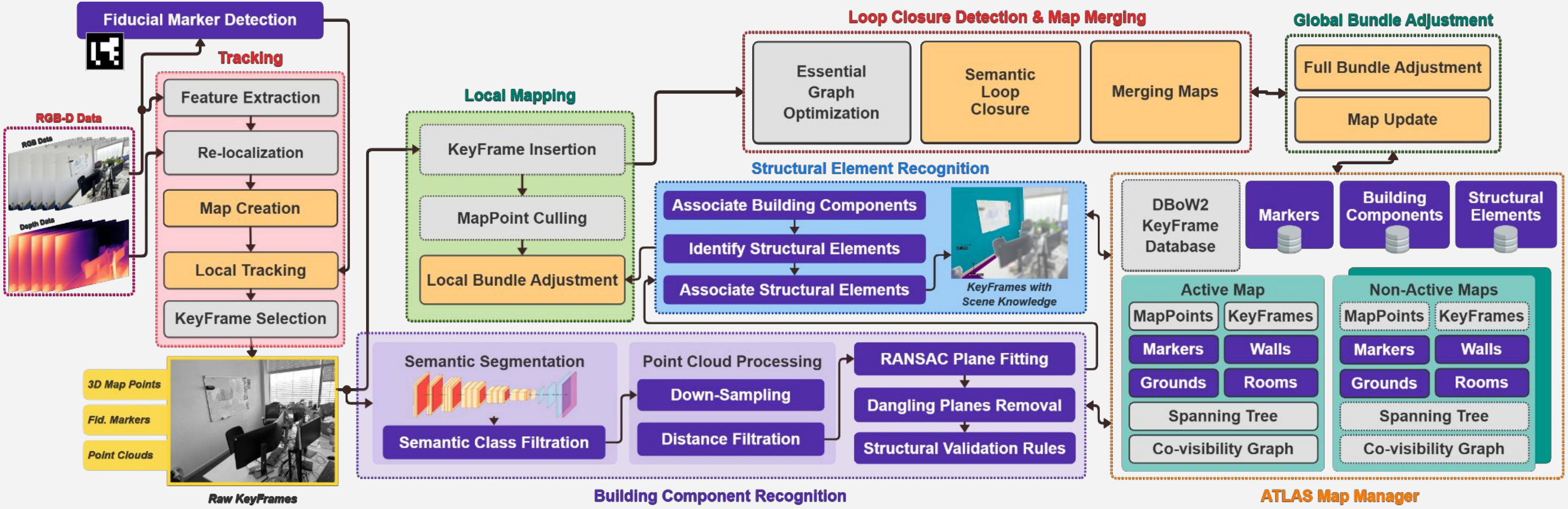


Technical Details

- Continuation of the previous work
- **Integrated panoptic segmentation**
  - YOSO and pFCN
- **RGB-D sensor**
- **ROS-2 Jazzy**
- Open Source

vS-Graphs – Architecture

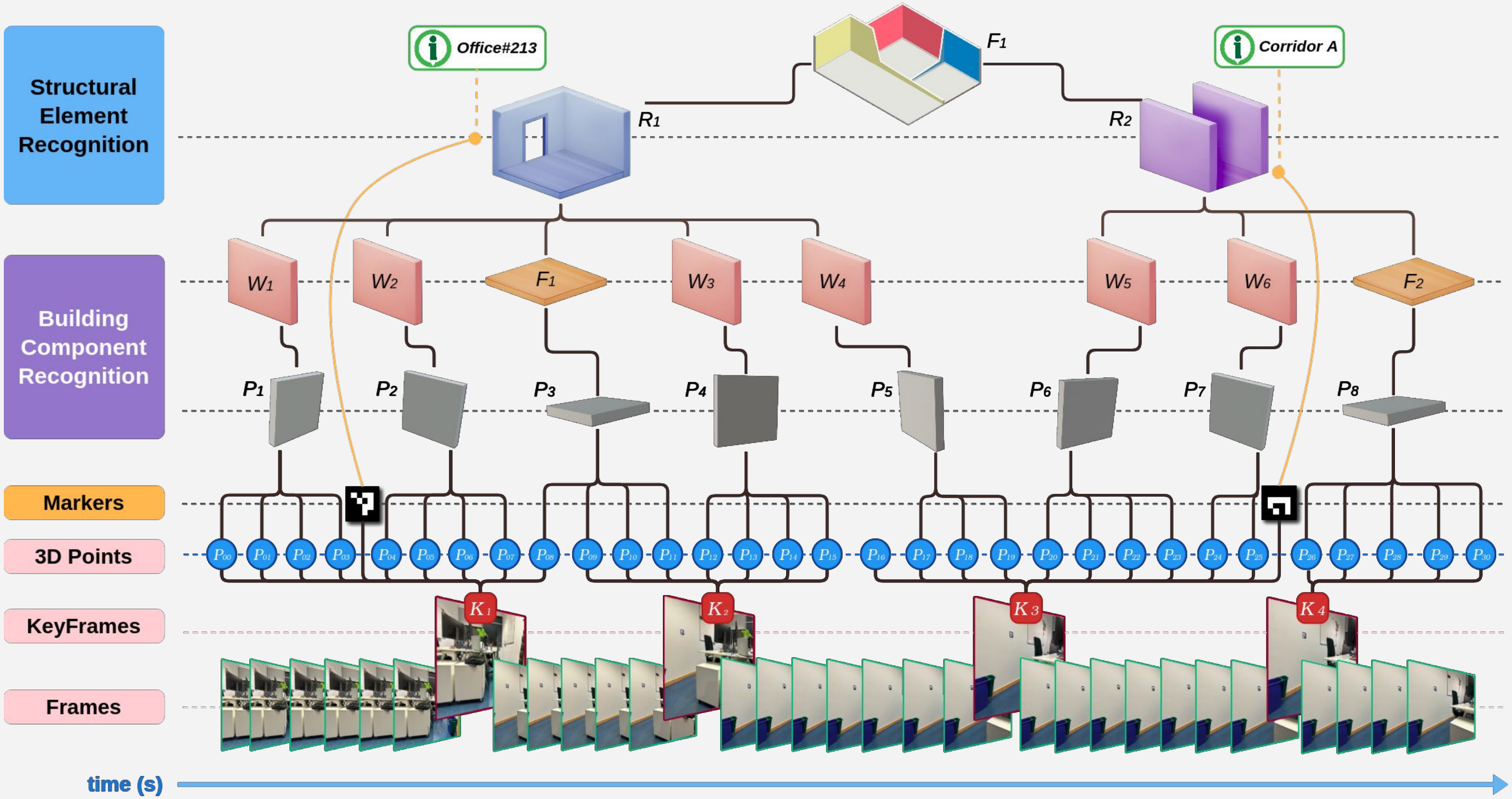
> **vS-Graphs: Tightly Coupling Visual SLAM and 3D Scene Graphs Exploiting Hierarchical Scene Understanding**
>
> Tourani *et al.*, (2025) RA-L (Under Review).



From the baseline — Modified — Added

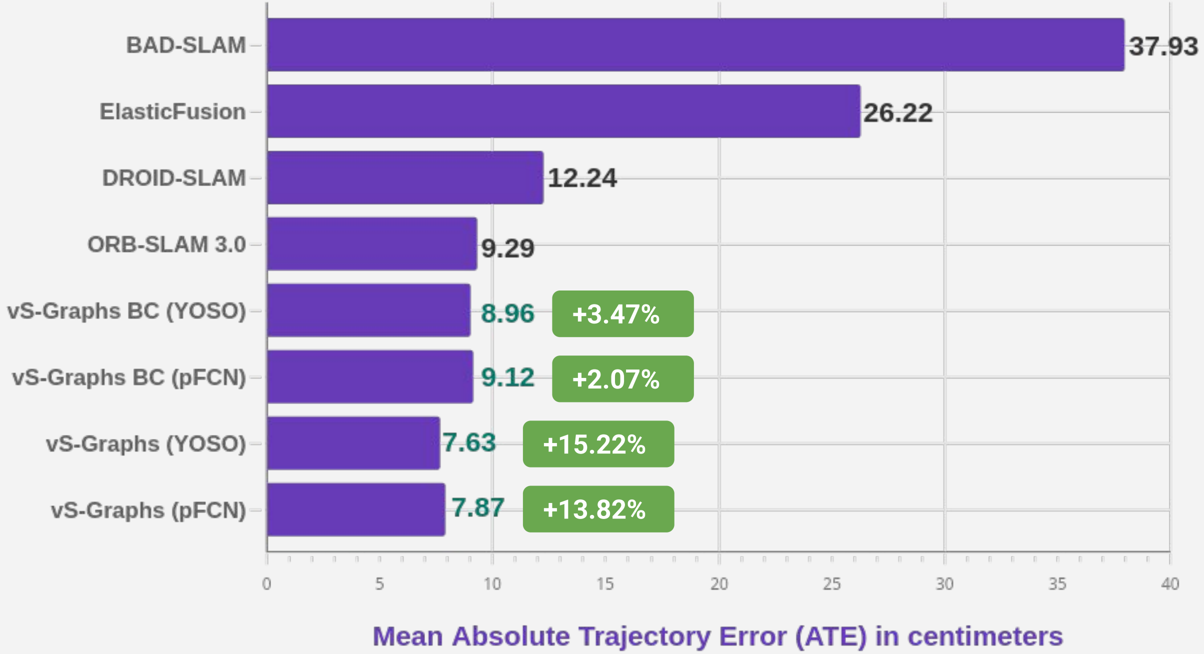
vS-Graphs – Architecture

> **vS-Graphs: Tightly Coupling Visual SLAM and 3D Scene Graphs Exploiting Hierarchical Scene Understanding**
>
> Tourani *et al.*, (2025) RA-L (Under Review).



vS-Graphs – RMSE Evaluations

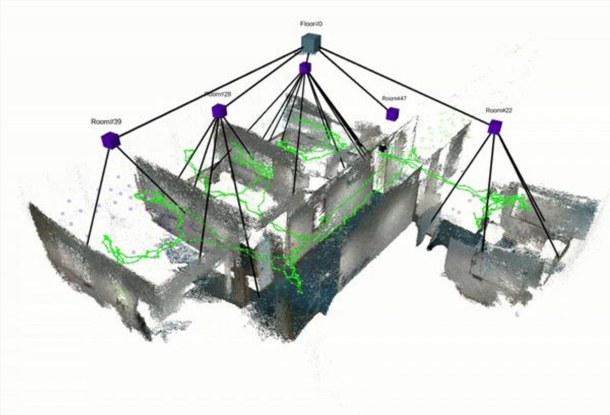
*Over five datasets with **total duration of ~44 minutes** and the **trajectory length of ~620 meters**.*



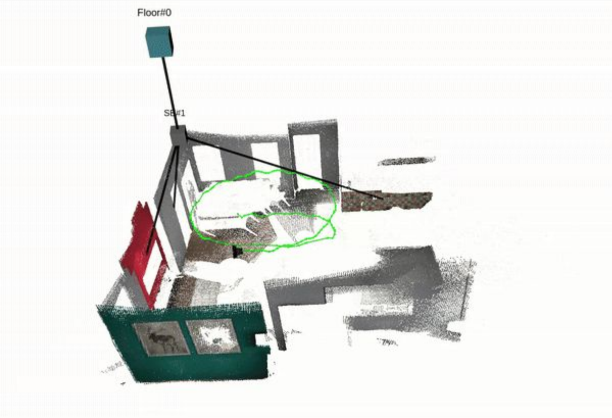
Enhanced **trajectory accuracy** due to **imposing more constraints** in the optimizable 3D scene graph

vS-Graphs – 3D Scene Graphs

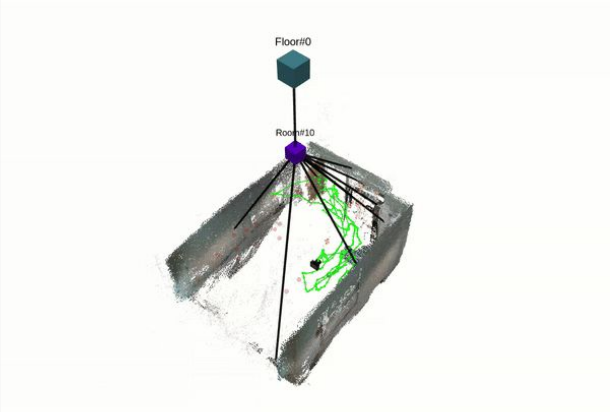
MR03



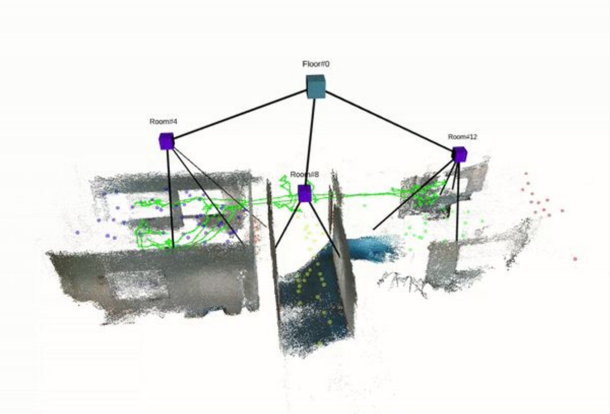
ICL-MAVF



SR01



SR03



Closing Remarks

Takeaways and concluding insights

Achievements (Scientific Papers)

International Conferences

ICRA 2023 (w) — 1st Author — A*
1x Presented

IROS 2023 — 1st Author — A
1x Presented

IROS 2024 (w) — 1st Author — A
1x Presented

ICUAS 2024 — B
1x Presented

	First Author			Co-Author	
	Published	Accepted	Under Review	Published	Under Review
Journal	4	1	1	3	2
Conference	3	-	-	1	-
Total	9			6	

Peer-Reviewed Journals

nature — *Light: Science & Applications* — top-2%
1x Published (2022)

IEEE RA-L — 1st Author — top-3%
1x Published (2025 as co-author), 2x Under Review (2026, one as first author, one as co-author)

IEEE — *IEEE Access* — 1st Author — top-10%
1x Published (2025)

MDPI — *Sensors* — top-12%
2x Published (2022 as first author, 2023 as co-author)

ELSEVIER — *JINT* — 1st Author — top-14%
1x Published (2026)

IEEE RA-M — 1st Author — top-16%
1x Conditionally Accepted (2026)

MDPI — *Robotics* — 1st Author — top-18%
1x Published (2024)

Achievements (Open-Source Code Contributions)

License: GPL-3.0

vS-Graphs

License: SnT Academic

iMarker Detector (standalone)

License: SnT Academic

iMarker Detector (ROS-enabled)

License: GPL-3.0

Semantic Scene Segmentation

License: GPL-3.0

Robot Suite

License: GPL-3.0

SMapper

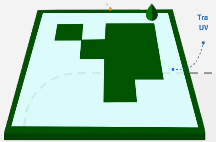
** **GPL-3.0**: strong copyleft license requiring derivatives to remain open source; **SnT Academic:** academic-only permissive license; research use allowed, commercial use restricted. **

Conclusions

- Introduced **iMarkers**, imperceptible landmarks for robotics
  - **Fabrication** considerations
  - Detection **sensors** and **algorithms**

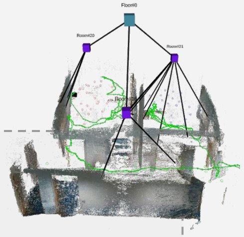
- Three **Visual SLAM** frameworks
  - **Semantic UcoSLAM**: markers for semantic information extraction
  - **Marker-based ORB-SLAM 3.0**: integrating traditional markers and iMarkers
    - Further semantic entities mapping
  - **vS-Graphs**: the ultimate framework to integrate geometry, semantics, and 3D scene graphs
    - Standalone semantic entity extraction
    - Supplementary (i)marker role to improve situational awareness

Discussions & Open Challenges



iMarkers

- Detection and transparency **trade-off**
- Robotics **integration** beyond VSLAM
  - Low-light drone landing, grasping, *etc*.
- Further iMarker **outperforming** scenarios



Visual SLAM

- **Computational** considerations for real-time operation
  - Lightweight **perception models**
- Dependency on **segmentation** quality
  - Propagation to **3D reconstruction**
- Further exploitation of **iMarkers**
  - Mirrors, glass walls, windows, *etc*.


Thank You!

Thank You!

Thesis Defence

Enhancing Robots' Situational Awareness using Imperceptible Artificial Landmarks

Ali TOURANI (ali.tourani@uni.lu)