ROYAL MILITARY ACADEMY - 3D PERCEPTION LAB
Charles HAMESSE, Research Engineer

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3D Perception Systems for the Modern Battlefield

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Agenda

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The 3D Perception Lab

We're a research unit from the Belgian Royal Military Academy (RMA):

- "University of Defence" in Belgium: responsible for the academic and military **training** of officers
- Scientific and technology **research** for military applications (often dual-use)
- Areas of **expertise** in multiple engineering domains
- Frequent **collaboration** with other universities and industry

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The 3D Perception Lab

We work on the following topics:

1. **Sensor fusion**: critical for 3D perception, we research and develop novel sensor fusion strategies for portable systems (e.g., camera, LiDAR, IMU) and applications (e.g., mapping)

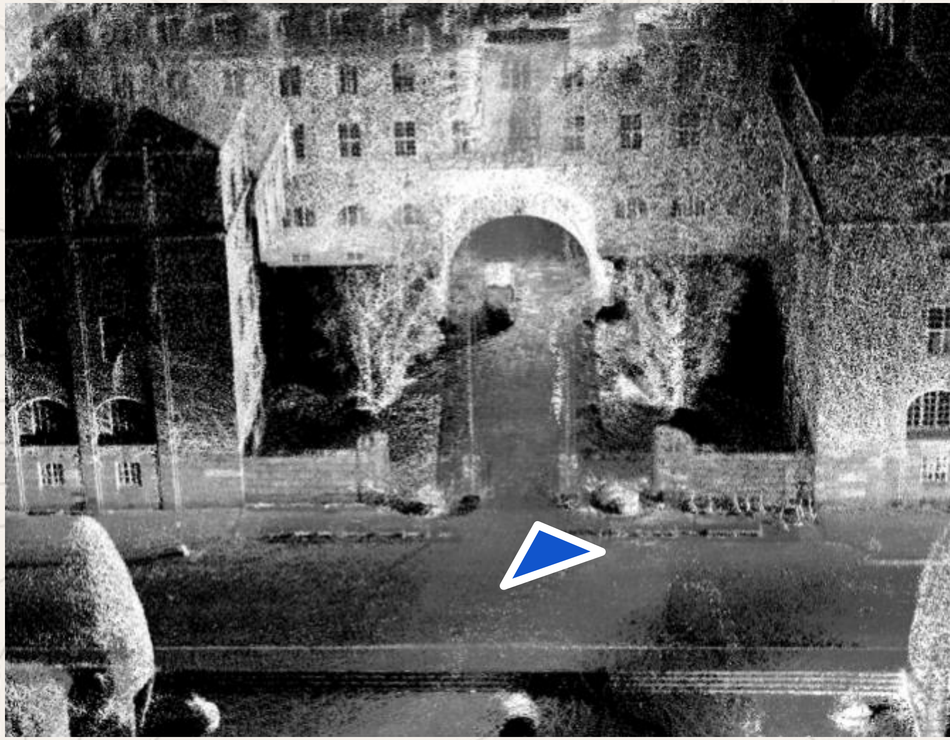
2. **Multi- or hyperspectral image processing**: we develop various applications using infrared multi- or hyperspectral imaging (robust 3D perception in adversarial weather, mine detection, etc.)

3. **Multi-agent robotic systems**: we research clever strategies to fuse the outputs of multiple (heterogeneous) sensor systems

3D Perception Systems for the Modern Battlefield

Focus on the fundamental components of 3D perception: localization and mapping

- **First layer of situational awareness:** where am I? what is around me?
- **Downstream applications:** mission planning, line of sight calculation, blast damage calculation, change detection, etc.
- **Performance metrics:** accuracy, SWaP-C efficiency, real-time capability, 3D map representation, etc.
- **No one-size-fits-all system**



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3D Perception Systems for the Modern Battlefield

Modern battlefield scenarios create new constraints:

- **Multi-level operations:** super-surface, surface, and sub-surface environments
- **Urban combat:** complex urban terrains, repetitive structures, indoors and outdoors
- **GNSS challenges:** navigation and positioning systems need to be resilient to jamming and spoofing
- **No prior information:** we cannot rely on existing satellite pictures, 3D scans, etc
- **Enemy detection:** need for stealth techniques to evade enemy sensors

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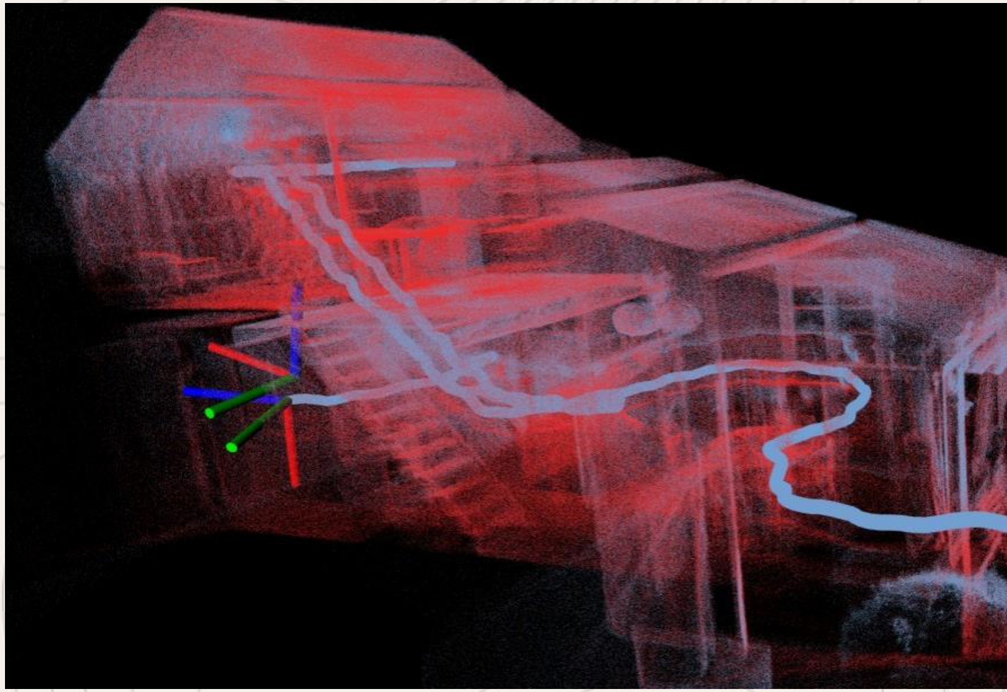
3D Perception Systems for the Modern Battlefield

Therefore, self-sufficient perception systems are required:

- Need for **Simultaneous Localization and Mapping** (SLAM) systems
- SLAM exists in **many variants**, although the most commonly used sensors are LiDAR, camera, and IMU
- Depending on the sensors and the scenario, SLAM can be considered solved or still in an early stage of development (active field of research)



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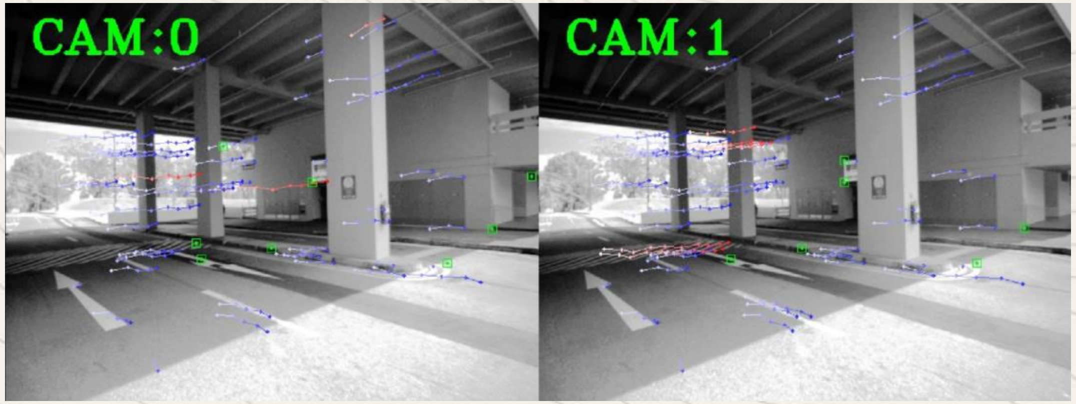
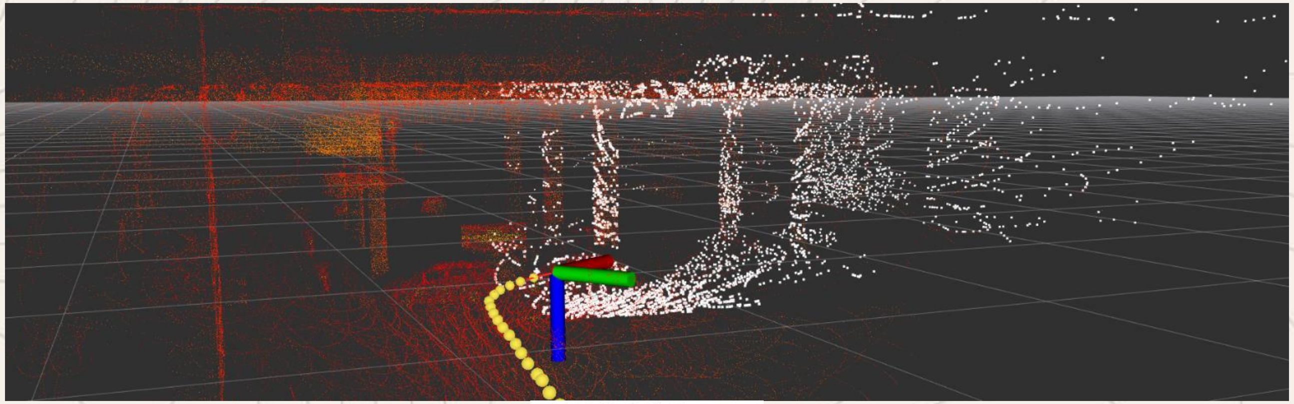
Principles of 3D Localization and Mapping

Common SLAM approaches rely on sensor fusion:

- **Inertial Measurement Unit:** provides high-frequency accelerometer and gyroscope data.
- **Camera:** used for visual tracking (low accuracy, high robustness, passive).
- **LiDAR:** used for scan-to-map alignment (high accuracy, low robustness, active).





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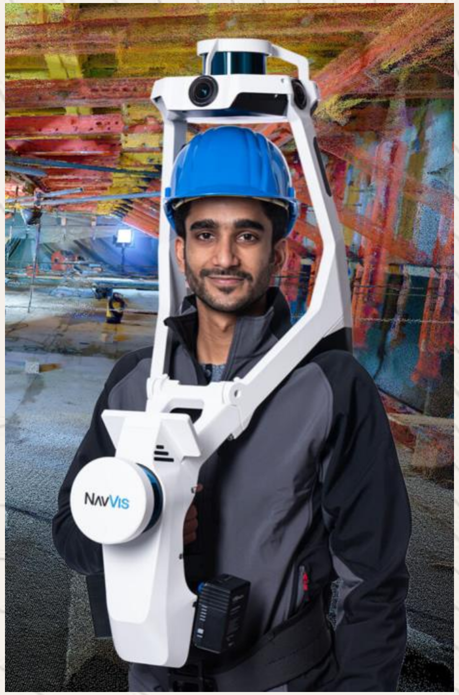
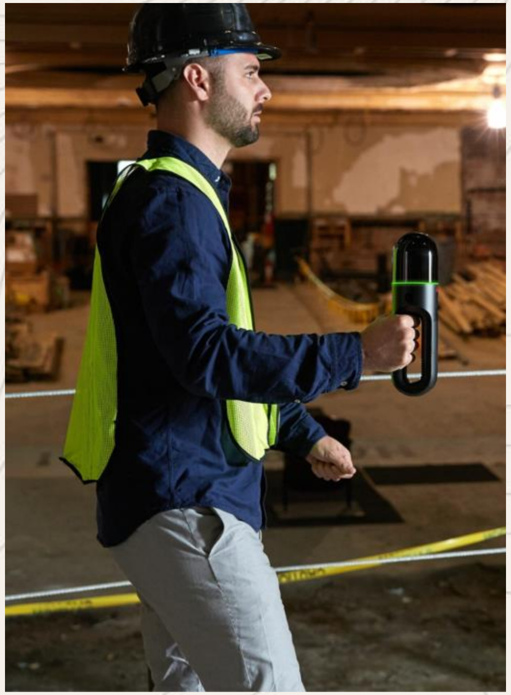
Principles of 3D Localization and Mapping

Some existing commercial SLAM systems:





NavVis VLX3

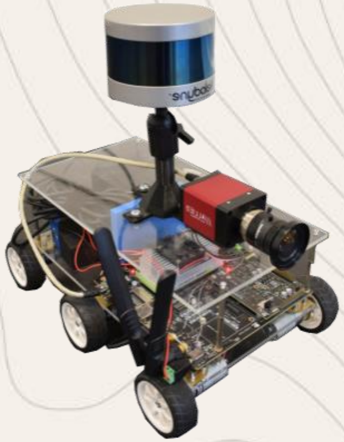
Leica BLK2GO

GeoSLAM Discovery

& Horizon

Principles of 3D Localization and Mapping

Of course, SLAM systems are often found on robots:



UGV

Photogrammetry drone

LiDAR drone

Overview of 3D SLAM Systems

The previous SLAM systems offer very good performance, but can difficulty be used in battlefield conditions.

In the following slides, we present our own developments towards military SLAM systems.

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Portable LiDAR-Inertial System

Concept:

- Baseline portable SLAM system using a Livox Avia (drone LiDAR)
- Hand-held setup, computer and battery in backpack

Advantages:

- Lightweight (sensors < 500g, computer + battery: 2kg)
- Dense map

Drawbacks:

- Active system: LiDAR's IR pulses can be picked hundreds of meters away

Portable LiDAR-Inertial System

Hands-Free Dual LiDAR-Inertial System

Concept:

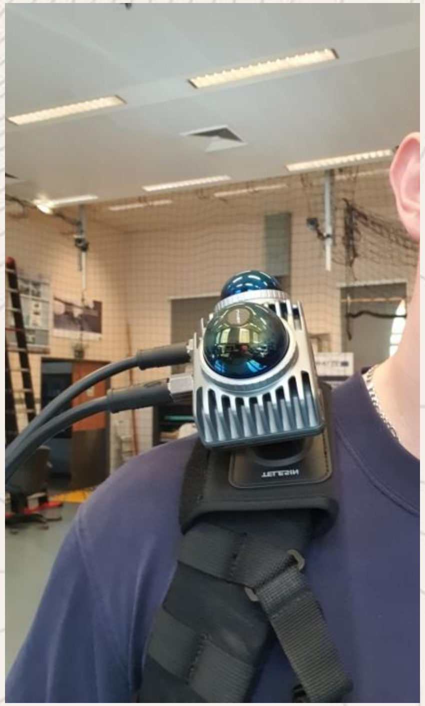
- Combining two 360° HFoV LiDARs to increase VFoV
- Shoulder mount
- Running in real-time, on micro-computer with battery pack

Advantages:

- Lightweight (sensors < 500g, computer + battery: 2kg), hands-free
- Robust SLAM

Drawbacks:

- Active system: LiDAR's IR pulses can be picked hundreds of meters away



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C. Hamesse, T. Fréville, J. Saarinen, M. Vlaminck, H. Luong and R. Haelterman,
"Development of Ultra-Portable 3D Mapping Systems for Emergency Services"
IEEE ICRA Workshop on Field Robotics 2024

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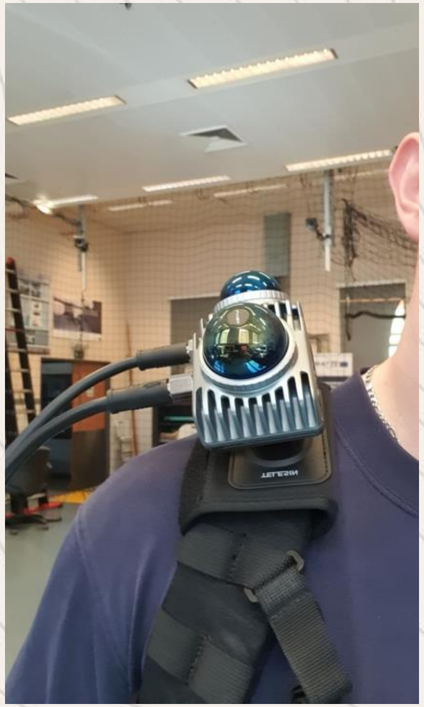
Dual LiDAR-Inertial System



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Depth-Visual-Inertial (DVI) Mapping System

Concept:

- Combining all sensors of a DVI sensor mounted on helmet
- In-house developed sensor fusion scheme

Advantages:

- Lightweight (sensor < 500g, computer + battery: 2kg), hands-free
- Low-power (USB powered)

Drawbacks:

- Active system: Time-of-Flight camera's IR pulses can be picked up (although much less than LiDAR)
- Limited range (<10m)

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C. Hamesse, M. Vlaminck, H. Luong and R. Haelterman
"Depth-Visual-Inertial (DVI) Mapping System for Robust Indoor 3D Reconstruction"
IEEE Robotics and Automation Letters 2024, doi: 10.1109/LRA.2024.3487496.

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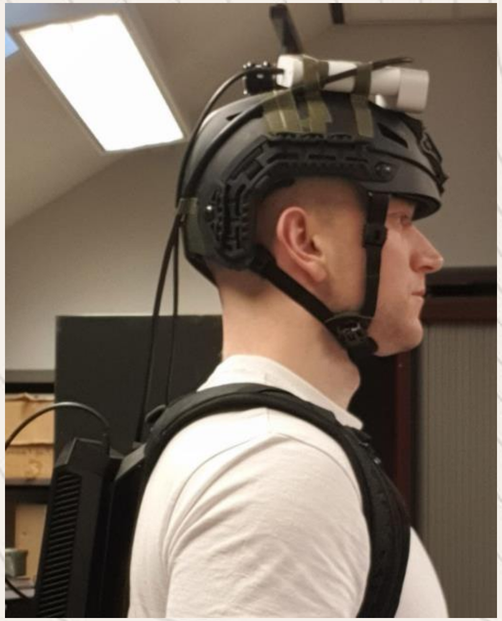
Depth-Visual-Inertial Mapping System



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Multi-Spectral Inspection UGV

Concept:

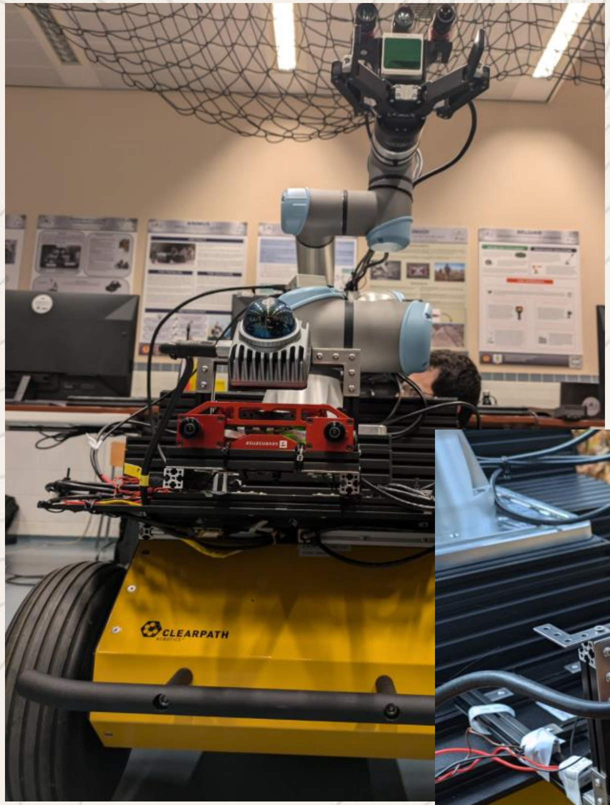
- UGV platform: 360° LiDAR + multi-camera visual-inertial sensor for robot situational awareness
- Robotic arm: RGB + SWIR + thermal LWIR cameras for advanced robustness and mine detection

Advantages:

- Rapidly deployed system
- Robust 3D perception, extended with the arm sensors

Disadvantages:

- UGV has limited motion and terrain traversability capacity



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Multi-Spectral Inspection UGV

Platform sensors:

Robust forest mapping

Multi-Spectral Inspection UGV

Arm sensors:

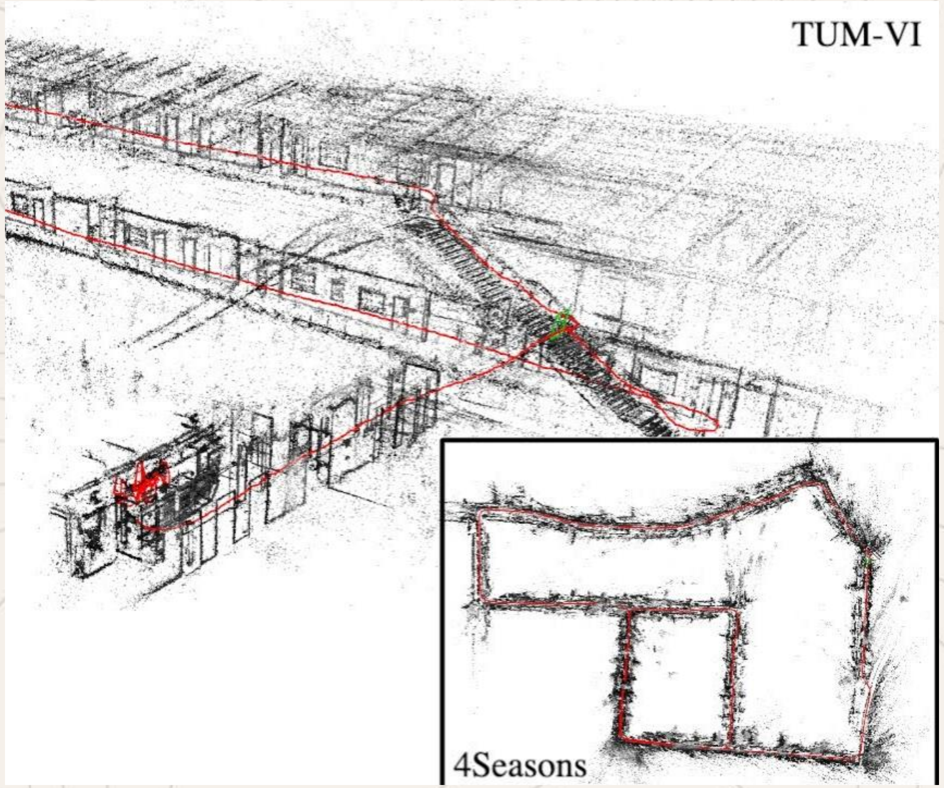
Mine detection

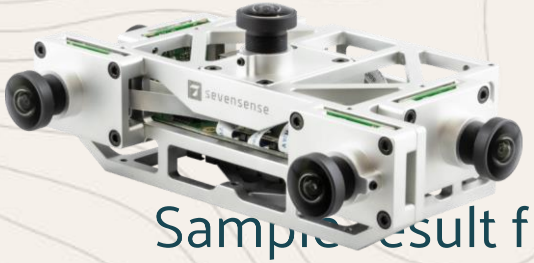
Image to be inserted

Way Ahead: 3D Mapping with Passive Sensors

Camera-based perception allows to map in a covert manner, unlocking many military use cases.

- Cameras are cheap, small and consume very little energy
- But currently, LiDAR mapping is significantly more accurate and dense
- There is a lot of **ongoing research** on visual-inertial mapping, very important potential





Sample result from DM-VIO

Sevensense Core Research sensor

Conclusion

Throughout the years, we have developed numerous prototype SLAM systems for various scenarios. Our main observations are:

- Sensor miniaturization is unlocking many, many SLAM use cases
- In most military scenarios, SLAM still requires extensive research efforts
- There is a big future for visual-inertial (passive) SLAM

Thank you for your interest!

Get in touch: charles.hamesse@mil.be

Questions?

Back-up slides

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Ultra Wideband (UWB) Localization System

Concept:

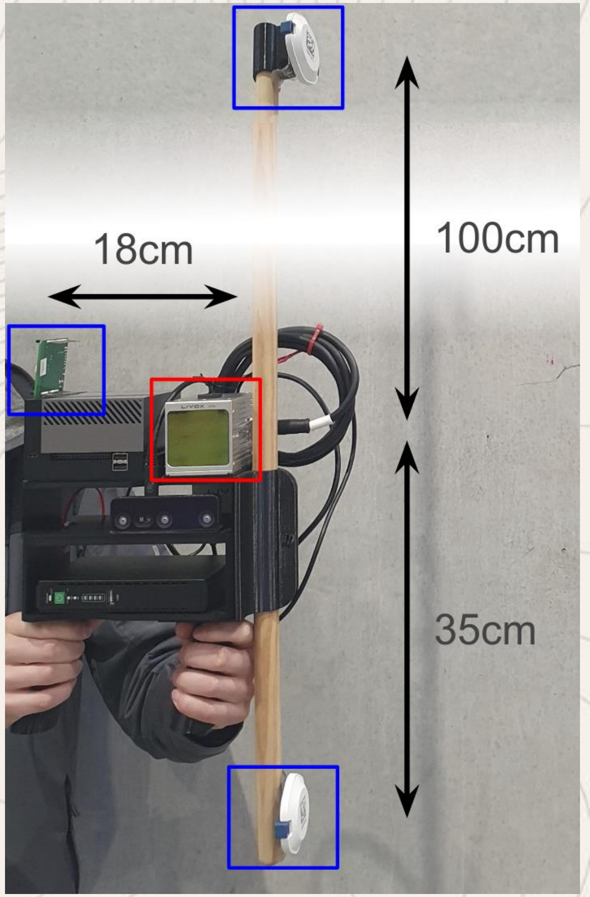
- Use a LiDAR-inertial SLAM system to set up a UWB localization system
- After that, only UWB tags are needed for real-time positioning (cheap, lightweight, low-power)

Advantages:

- UWB tags are cheap, lightweight and consume extremely low power
- Can localize many agents / systems with new UWB tags

Disadvantages:

- More complex setup



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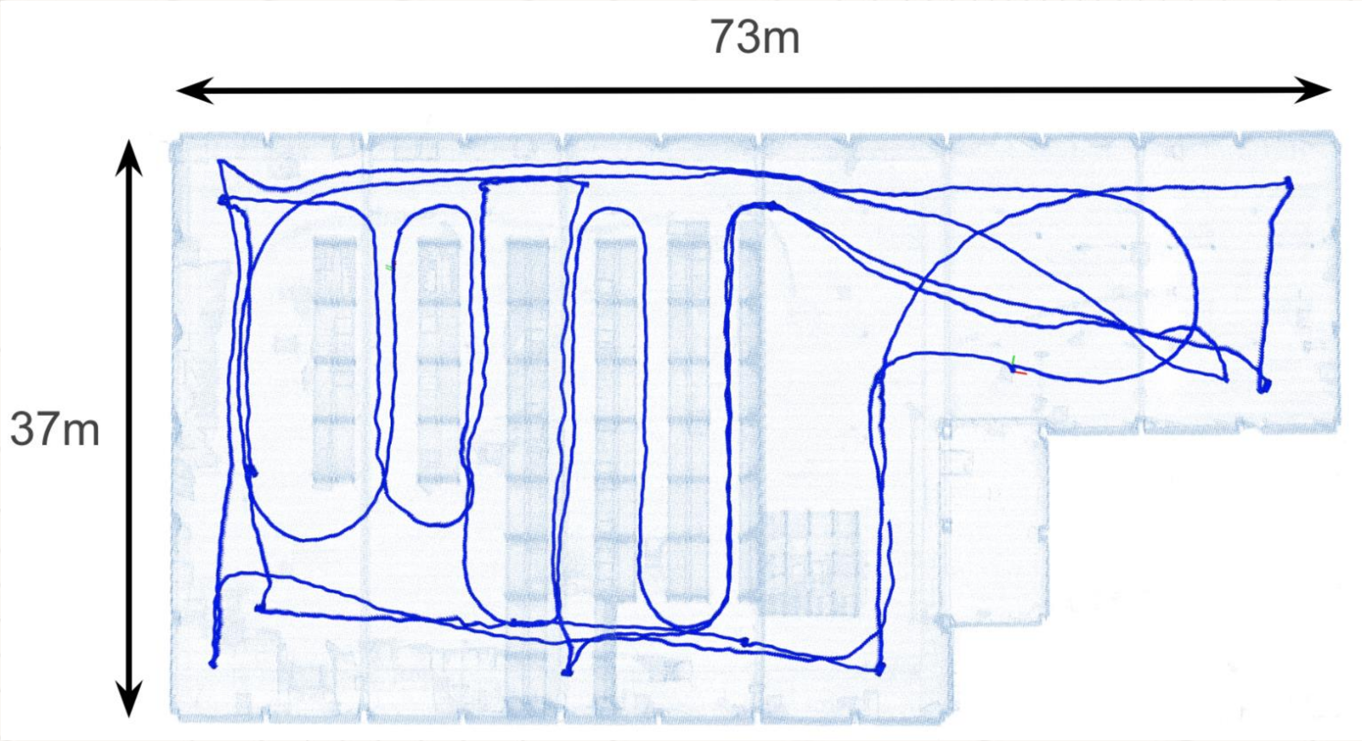
C. Hamesse, R. Vleugels, M. Vlaminck, H. Luong and R. Haelterman,
"Fast and Cost-Effective UWB Anchor Position Calibration Using a Portable SLAM System"
IEEE Sensors Journal, 2024, doi: 10.1109/JSEN.2024.3419261

Ultra Wideband (UWB) Localization System



Test warehouse

Trajectory estimated
from the UWB system

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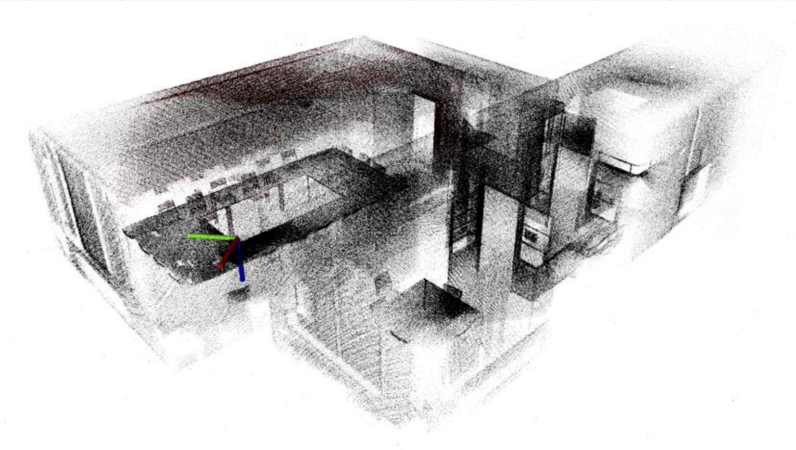
Principles of 3D Localization and Mapping

SLAM systems will incrementally output:

- **Trajectory:** set of (timestamped) position and orientation data
- **Map:** can be the final output or a means to an end

Elevation (or 2.5D)



Mesh

Point cloud

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Towards Ultra-Portable Mapping Systems

Recently, miniaturization of cameras and LiDAR sensors has enabled the development of wearable 3D mapping systems for emergency responders.

- Solid-state LiDARs weigh less than 300g, consume less than 10W
- Cameras can be smaller than a die

https://www.livoxtech.com/mid-360

https://www.ximea.com/en/products/subminiature-cameras

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Ultra-Portable Mapping Systems

State-of-the-art mapping algorithms work in real-time or “faster”. The key components are:

- Sliding window-based optimization for sensor fusion
- Appropriate 3D data structures for fast 3D point association and scan-to-map alignment
- Parallelism

All of the experiments shown in the rest of this presentation show results obtained in real-time or faster, using computers such as Intel NUCs (no GPU):

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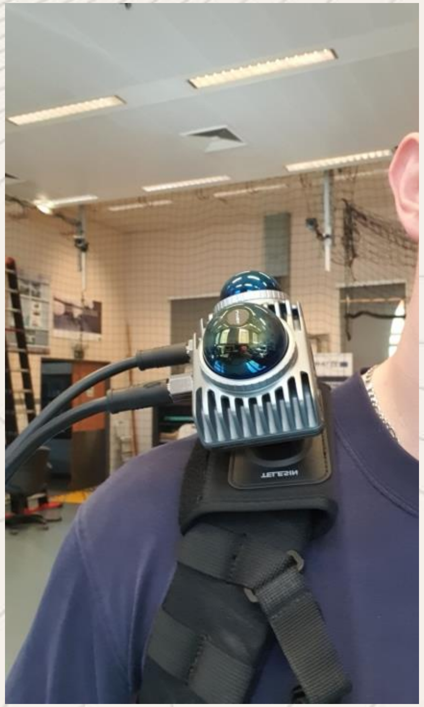
Towards Ultra-Portable 3D Mapping Systems

Our research is focused on integrating this latest hardware in portable systems:



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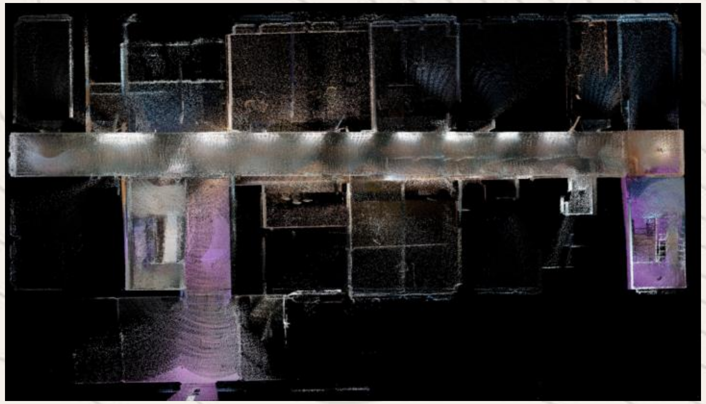
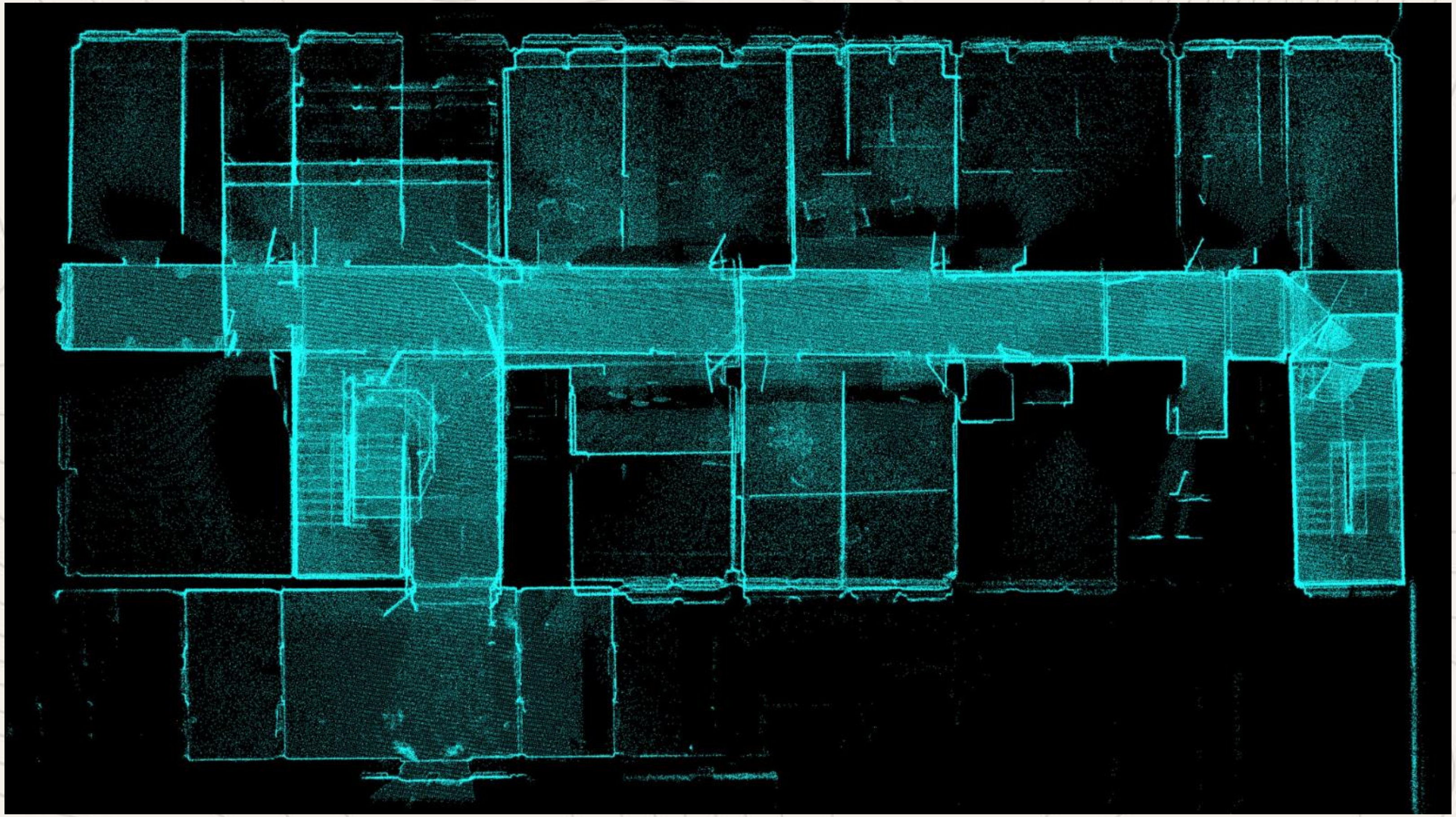
Sample Results

Sample Results





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Sample Results

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3D Modelling of the Battlefield

Modelling the geometric properties of the battlefield represents a significant opportunity to enhance military applications such as:

- Situational awareness
- Mission planning
- Line of sight calculation
- IED damage simulation
- Change detection
- ...Many others!

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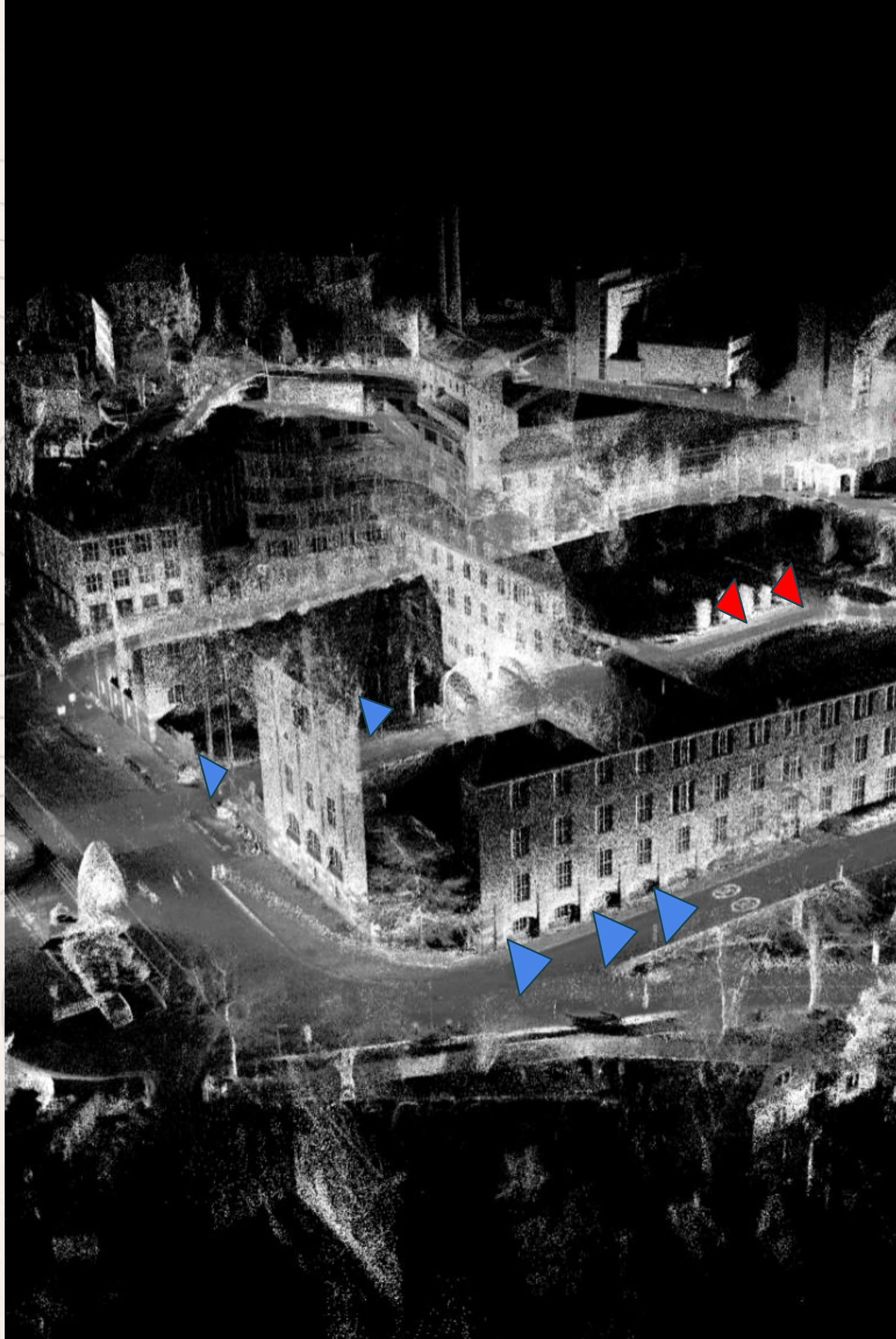

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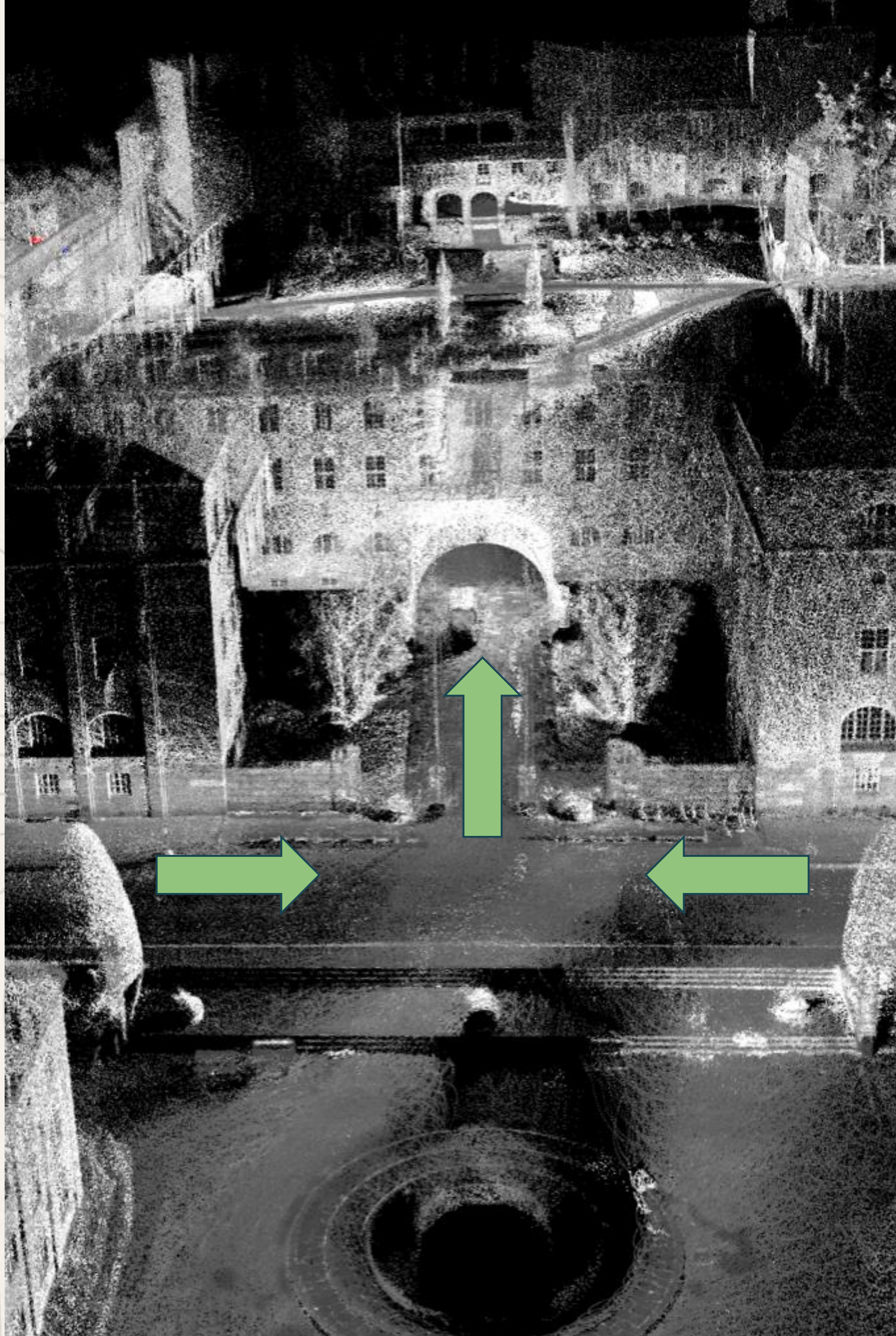

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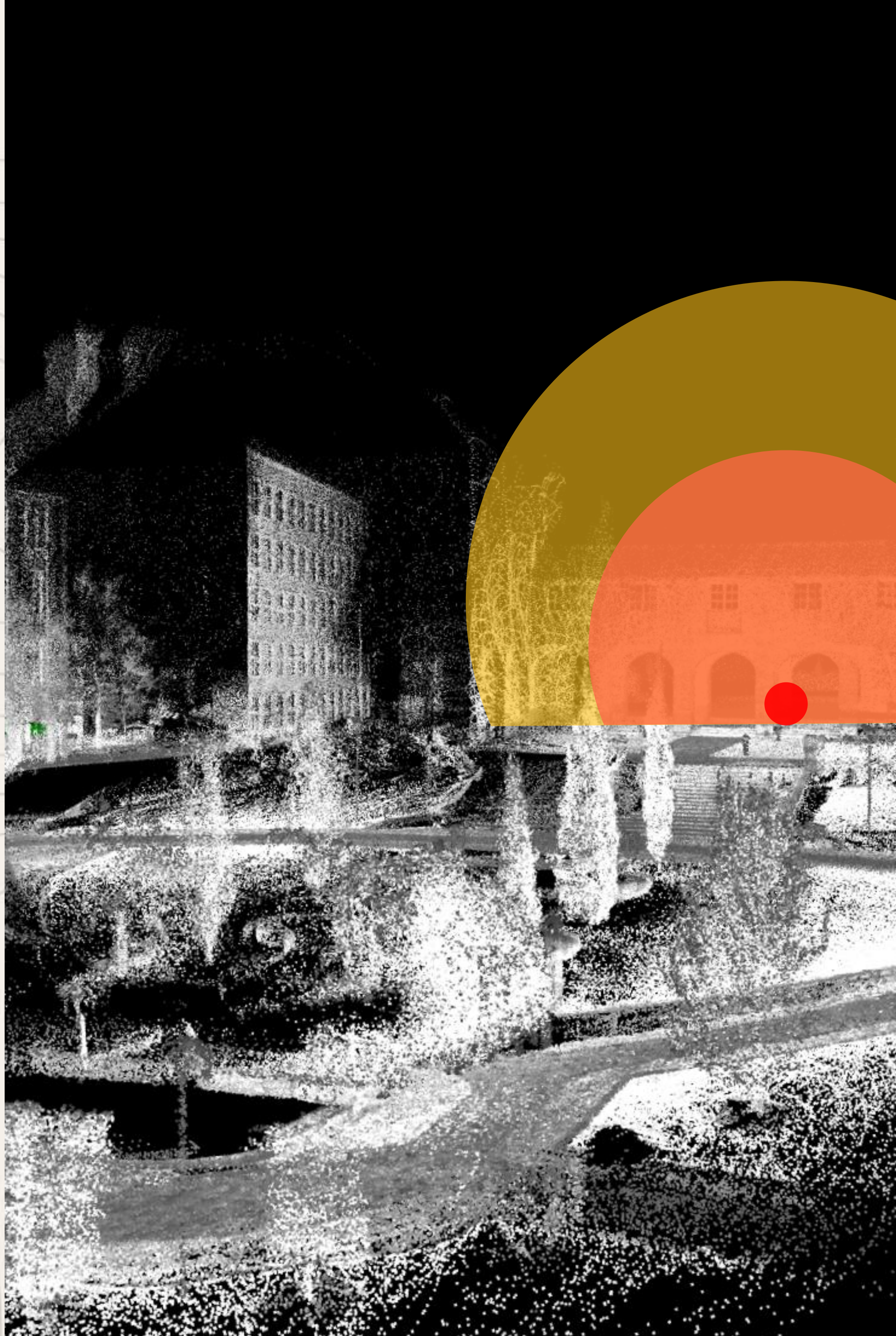

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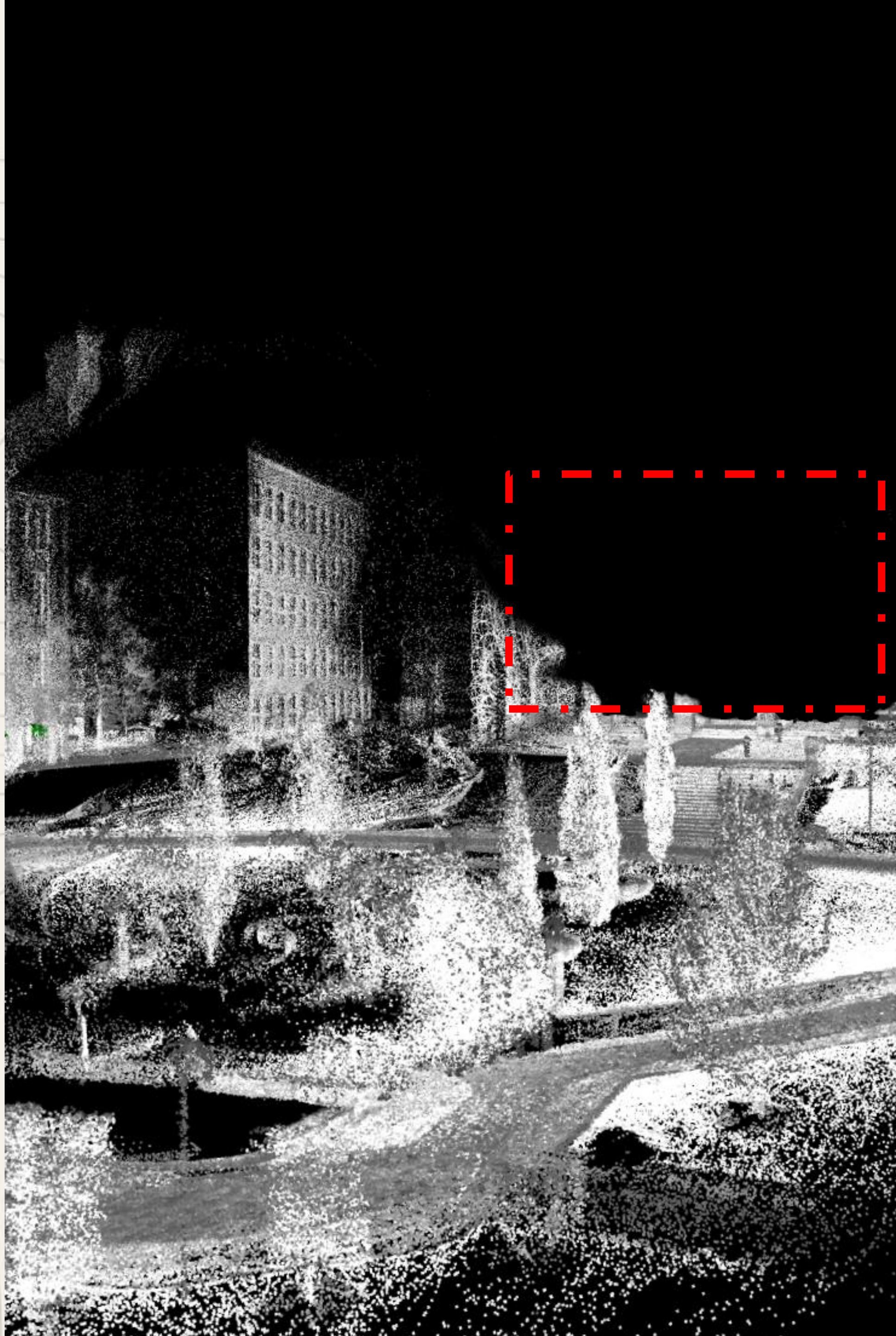

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Principles of 3D Mapping

The pose estimation and mapping “problems” are intertwined:

- To build a map from your observations, you need to anchor these observations in some reference frame linked to your position and vice-versa.
- Very often, the 3D mapping problem is solved as:
  1. Pose (trajectory estimation)
  2. Reprojection of observed data in the global map

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