Multi-Dimensional Structural Assessment with a Mobile Scanning Device

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Computer Vision for Smart Structure

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Outline

1. Background
2. Challenges
3. Proposed Methodology
4. Experiment and Results

Background: Visual Inspection

Various Structural Inspection manuals have a recommendation for inspection frequencies every 24 months

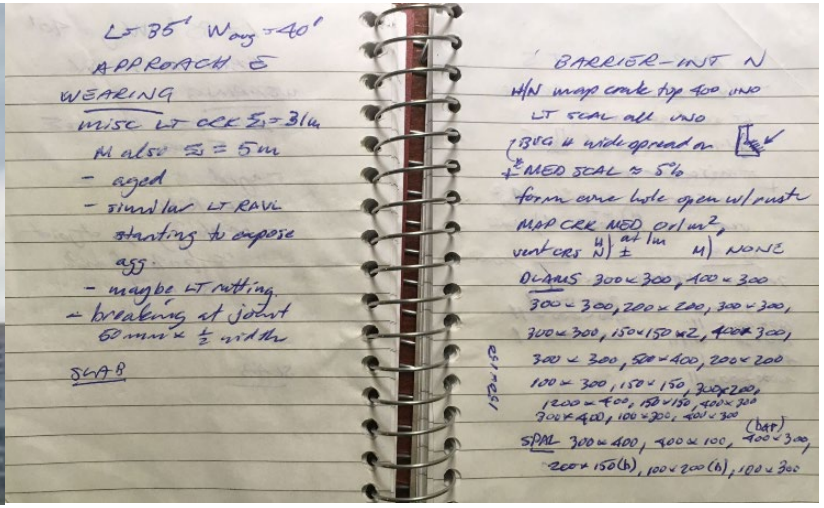
- British Columbia, Canada
- Ontario, Canada
- Michigan, USA
- Massachusetts, USA

"It is expected that in order to adequately assess the condition of all elements, the inspector should plan to spend at least 2 to 3 hours at a typical bridge site. For large bridges, this time will increase."

Ontario Structure Inspection Manual (OSIM)

Background: Current Inspection Practices

a. Preparations for Inspection



b. Typical Inspection Notes

Limitations

- Time-consuming
- Inaccurate
- Expensive
- Inaccessible regions
- Inefficient
- Dangerous

“In many cases, the inspection should be conducted within arms length of the element, possibly involving tapping with a hammer or making measurements by hand. ”

Ontario Structure Inspection Manual (OSIM)

Challenges: Multi Dimension Measurements using Sensors

Severity	
Light	- Spalled area measuring less than 150 mm in any direction or less than 25 mm in depth.
Medium	- Spalled area measuring between 150 mm to 300 mm in any direction or between 25 mm and 50 mm in depth.
Severe	- Spalled area measuring between 300 mm to 600 mm in any direction or between 50 mm and 100 mm in depth.
Very Severe	- Spalled area measuring more than 600 mm in any direction or greater than 100 mm in depth.

from OSIM

Infrared (IR) Depth Sensors

Mode	Resolution	FoI	FPS	Operating range*	Exposure time
NFOV unbinned	640x576	75°x65°	0, 5, 15, 30	0.5 - 3.86 m	12.8 ms
NFOV 2x2 binned (SW)	320x288	75°x65°	0, 5, 15, 30	0.5 - 5.46 m	12.8 ms
WFOV 2x2 binned	512x512	120°x120°	0, 5, 15, 30	0.25 - 2.88 m	12.8 ms
WFOV unbinned	1024x1024	120°x120°	0, 5, 15	0.25 - 2.21 m	20.3 ms
Passive IR	1024x1024	N/A	0, 5, 15, 30	N/A	1.6 ms

320x288	75°x65°	0, 5, 15, 30	0.5 - 5.46 m

Q1: Are these sensors sufficiently accurate?

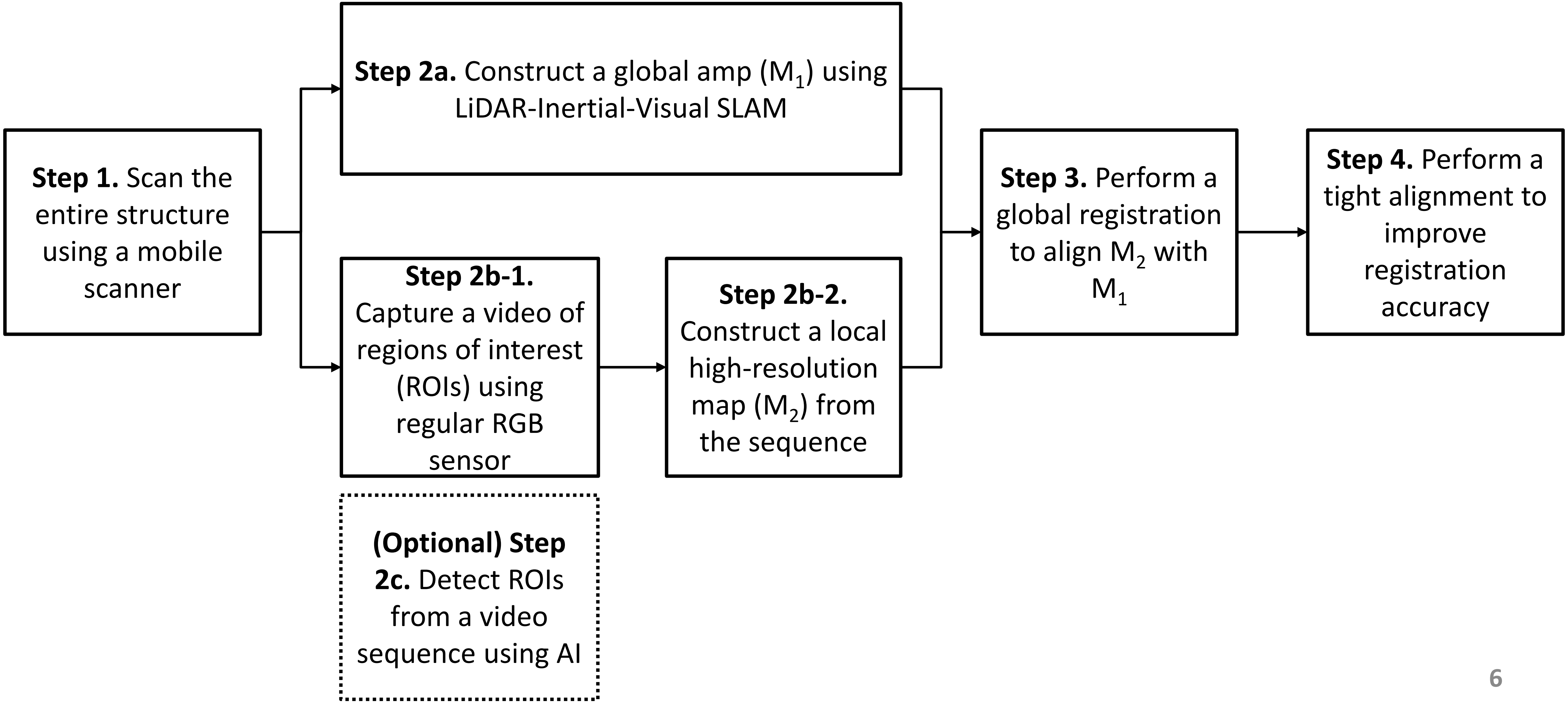
Q2: Do these sensors have enough range?

LiDAR

Range Precision (1σ @ 20m)	2 cm[1]

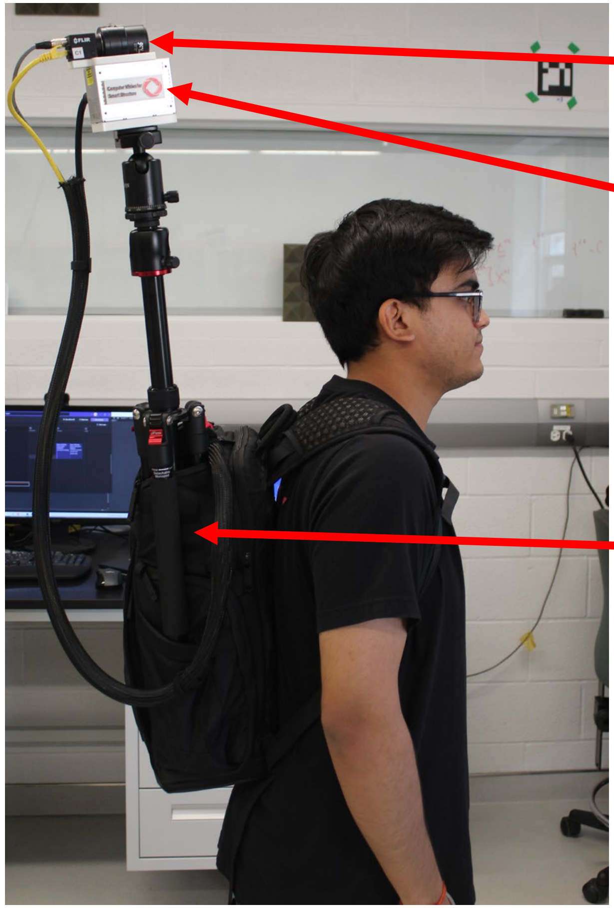
Accuracy-range trade-off

Proposed Methodology: Multi-Resolution Mapping Routine



Step 1. Data Collection: Hardware Setup and Cost Efficiency of High-fidelity Mobile Scanner

HARDWARE SETUP



Backpack Configuration

Flir Blackfly Ethernet Camera (330 USD)

Livox Avia (1600 USD)
-Solid state lidar
-Integrated IMU
-Non-repetitive circular scanning

Intel NUC (680 USD)
-Mobile Computer

Mapping Software: R3Live (Open Source)
github.com/hku-mars/r3live

Total Cost ~ 2600 USD

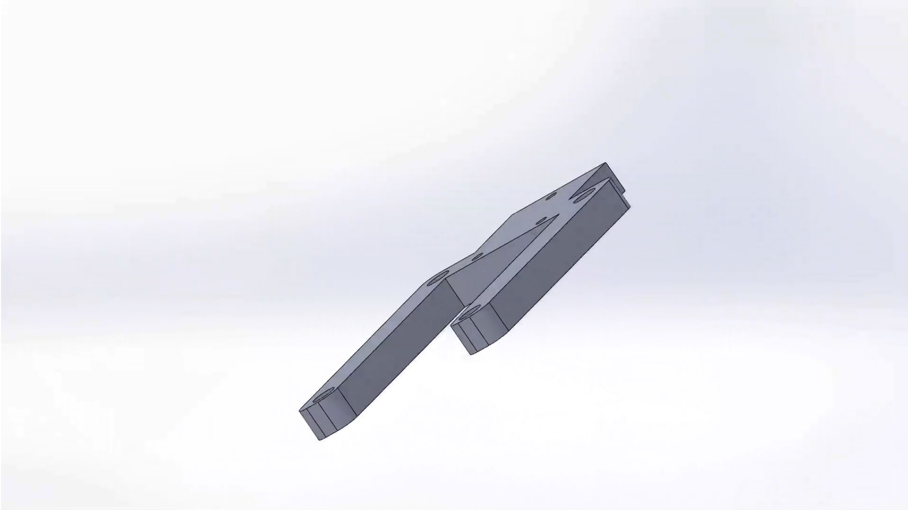
The scanner is a self-contained piece of equipment that uses tightly coupled *LiDAR-Inertial-Visual* state estimation to perform spatial mapping.

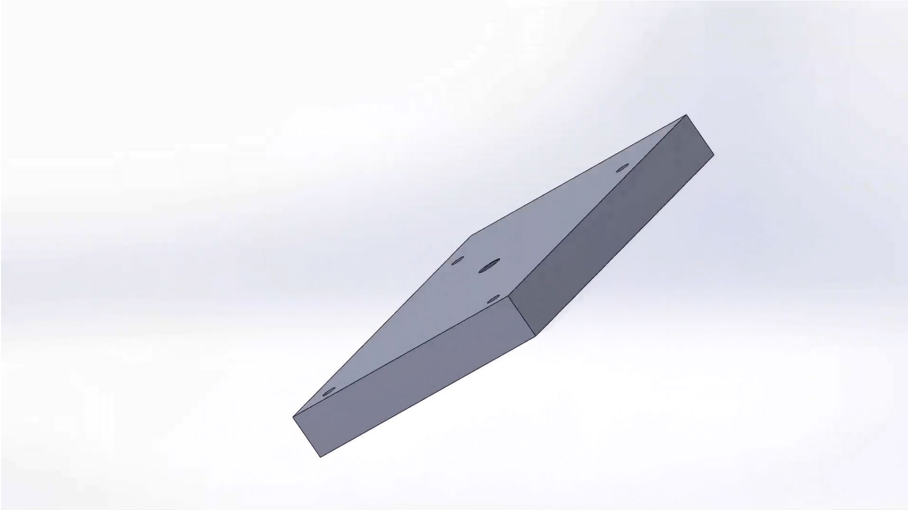
Step 1. Data Collection: Design a High-fidelity Mobile Scanner

Handle Configuration

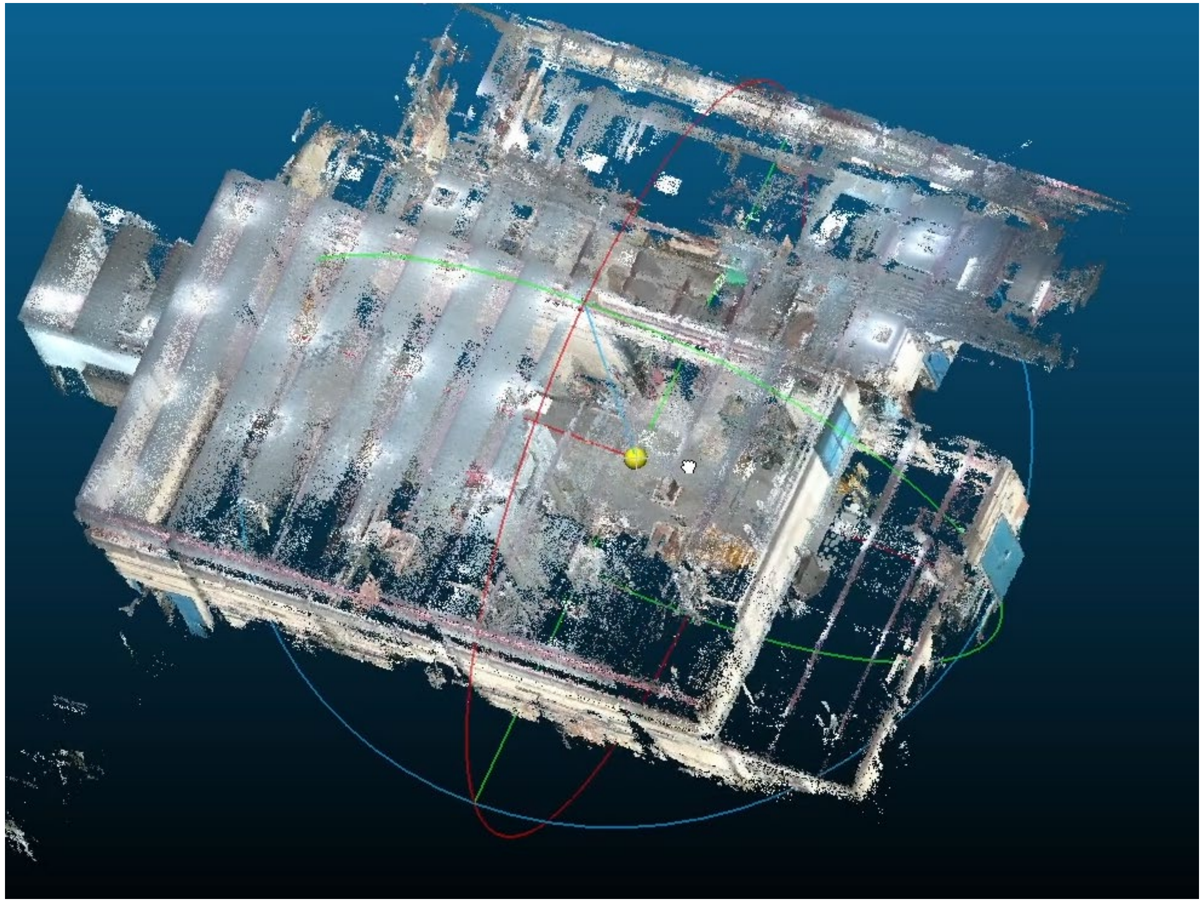
3D Printed Camera-LiDAR connector

3D Printed LiDAR-Handle connector

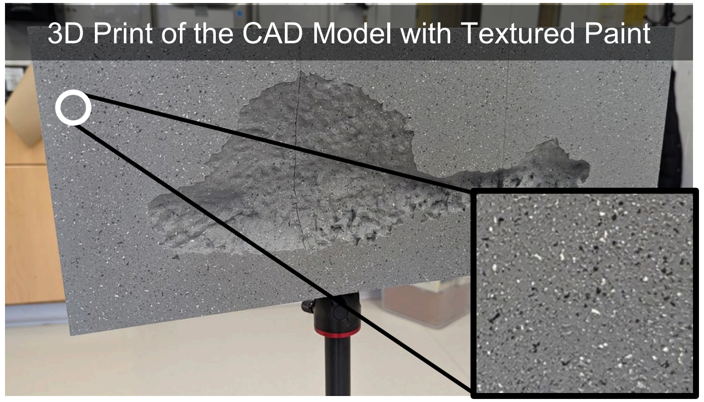


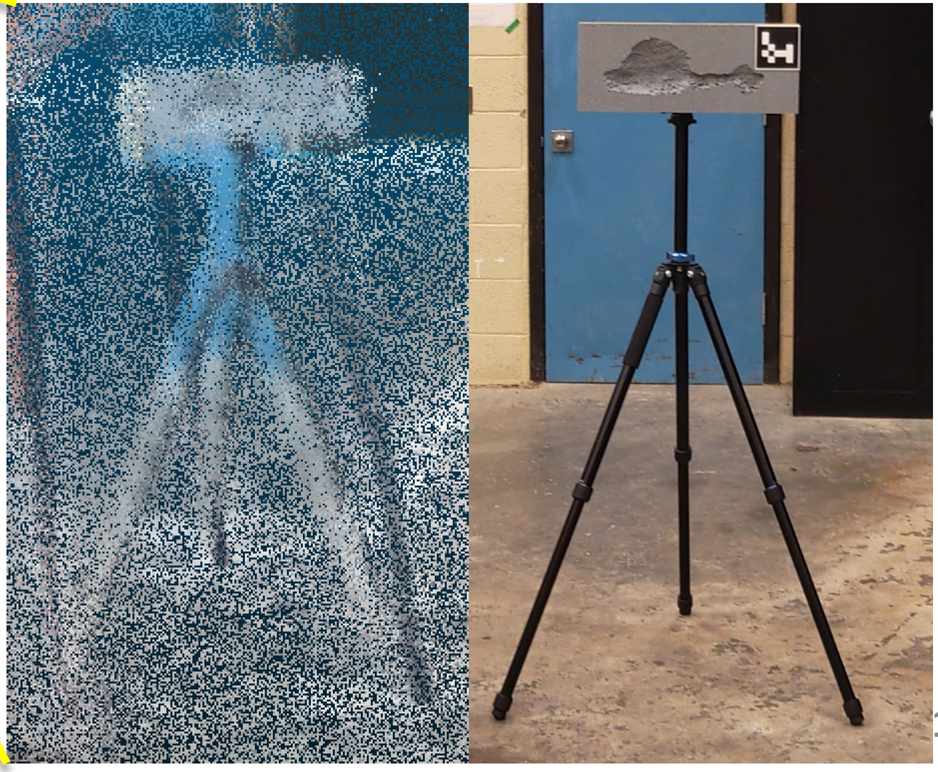


Step 2a. Create Global Map (M_1): Scanning with our Mobile Scanner



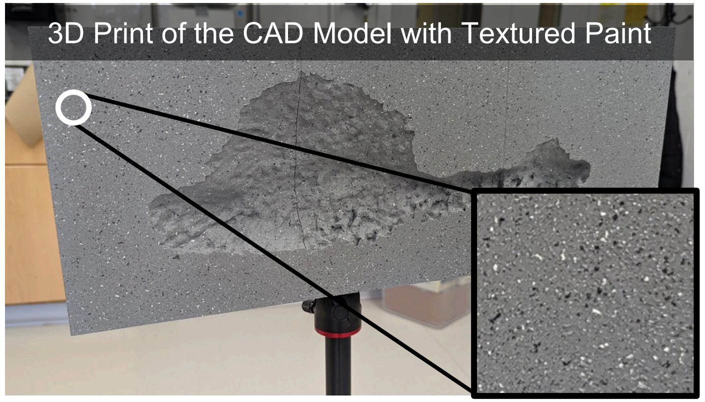
Step 2a. Create Global Map (M_1): Insufficient Resolution of the ROI

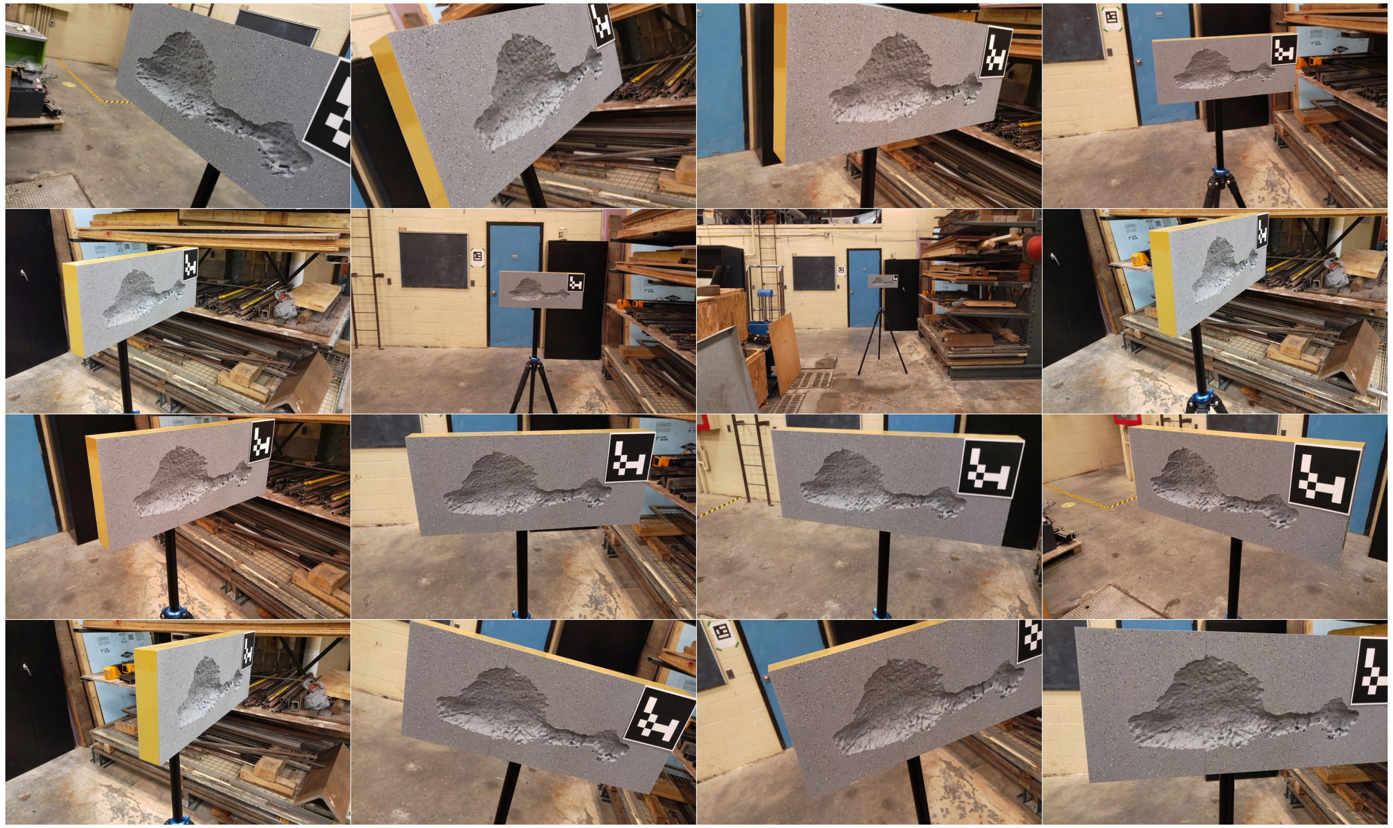




Step 2b-1. Record a Close-Range Video of ROIs

- Fabricate artificial spalling damage using 3D printing
- Collect a video data using a Microsoft Hololens2 (Mixed Reality Device)
- Note that the proposed methodology is **platform and technique agnostic for local mapping**



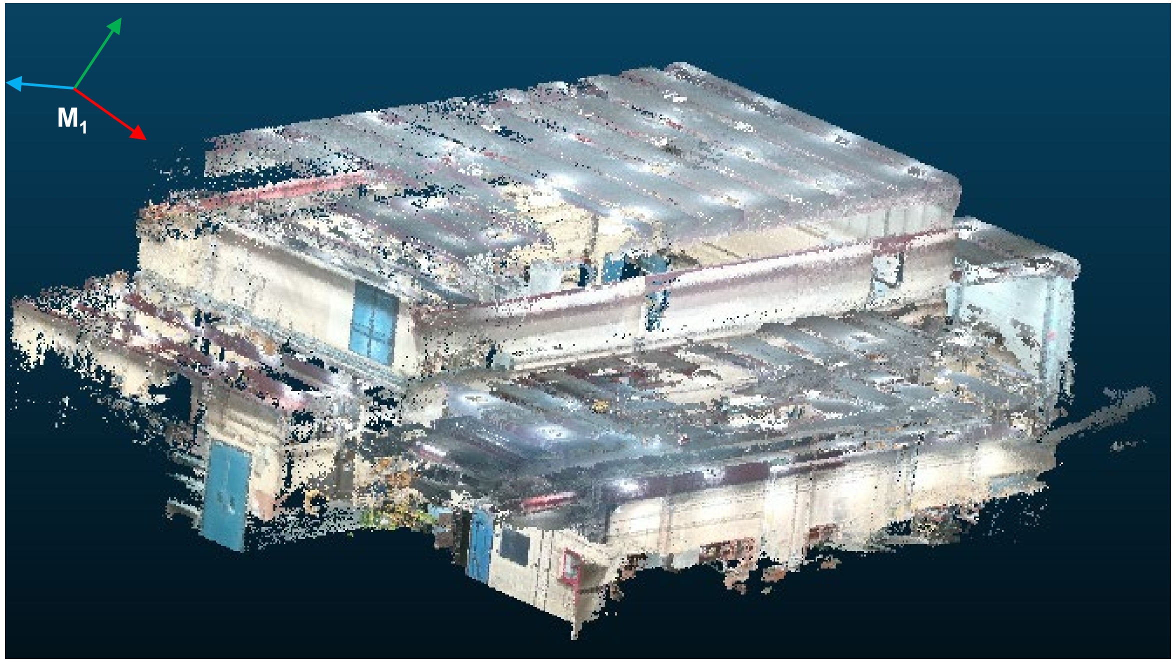


Step 2b-2. Reconstruct ROI in a 3D Space (M_2)

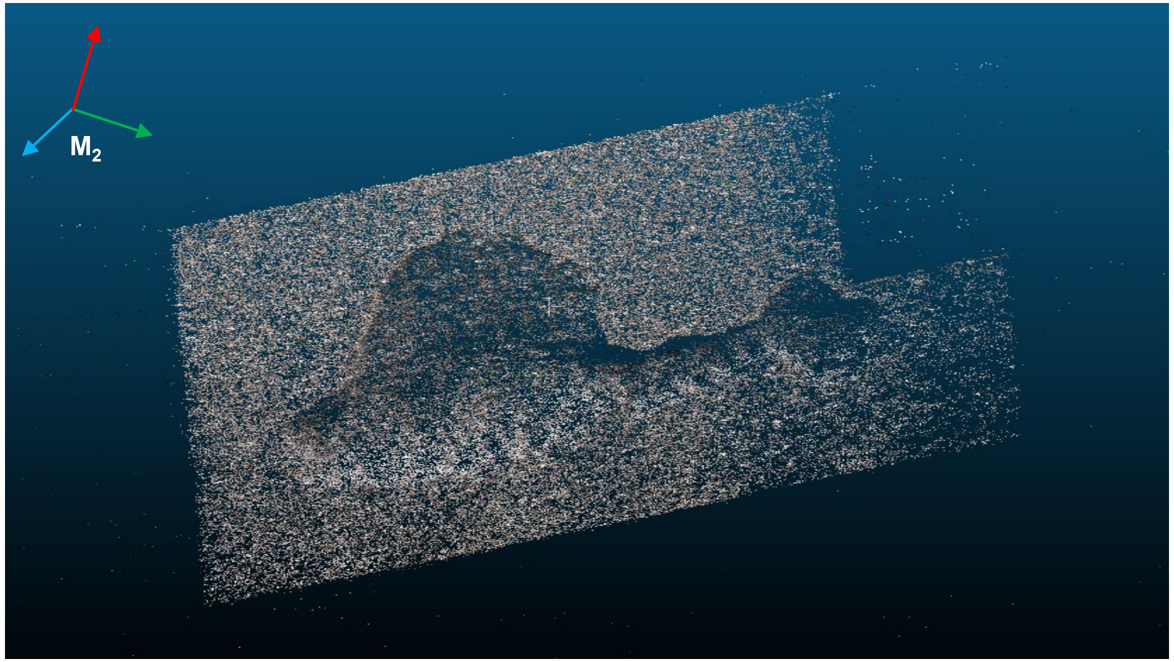
- Perform Structure from Motion (SfM) using images of the ROI
- Using open-source software: openMVG (https://github.com/openMVG/openMVG)
- SfM reconstruction provides higher detail and enables quantification ability for damages [1]

[1] Bajaj, R., Al-Sabbag, Z. A., Yeum, C. M., & Narasimhan, S. (2022). " Volumetric Damage Quantification For Visual Inspection", *8th World Conference on Structural Control and Monitoring*, Orlando, Florida, USA, 2022.

Step 3. Perform Global Registration: Maps with Different Resolutions



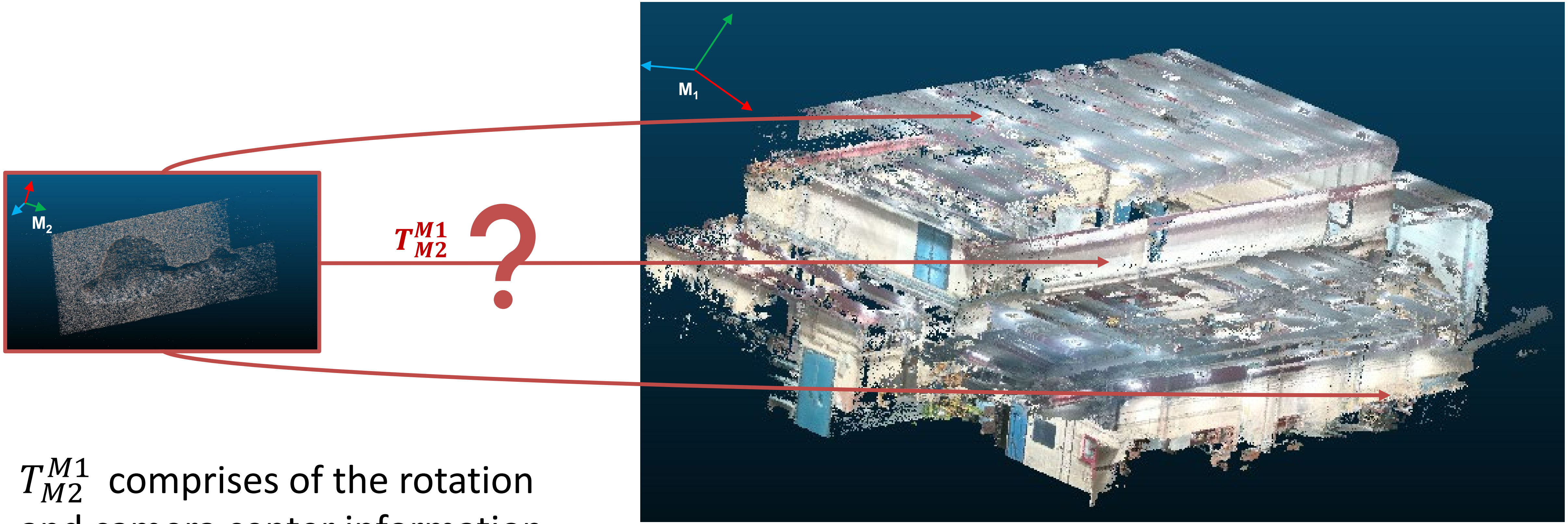
M_1: A larger 3D map from LiDAR+Camera data



M_2: Higher resolution 3D Reconstruction of ROI

Step 3. Perform Global Registration: Problem Statement

- The goal here is to **register the higher resolution damage map** (M_2) on the global map (M_1) which will enable the spatial map alignment.



T_{M2}^{M1} comprises of the rotation and camera center information

Step 3. Perform Global Registration: Localization Algorithm

Encode a **global map image** (I_1) to a fixed size vector: $f(I_1)$ using NetVLAD [2] utilizing image features points (p_1) and bag-of words pooling

Encode a **query map image** (I_2) to a fixed size vector: $f(I_2)$ using NetVLAD [2] utilizing image feature points (p_2) and bag-of words pooling

Use Euclidean distance between $f(I_1)$ and $f(I_2)$ to perform visual search and retrieve closest images to I_2 amongst all I_1

Using image features (p_1) and depth information in M_1 **create 3D points (X_1)**

cv2.solvePnPRansac(X_1,p_2,K_2) to solve for position of query images (I_2) in global map (M_1): T_{C2}^{M1}

T_{C2}^{M1}: Location of query images captured by camera C_2 in Global Map coordinates (M_1)

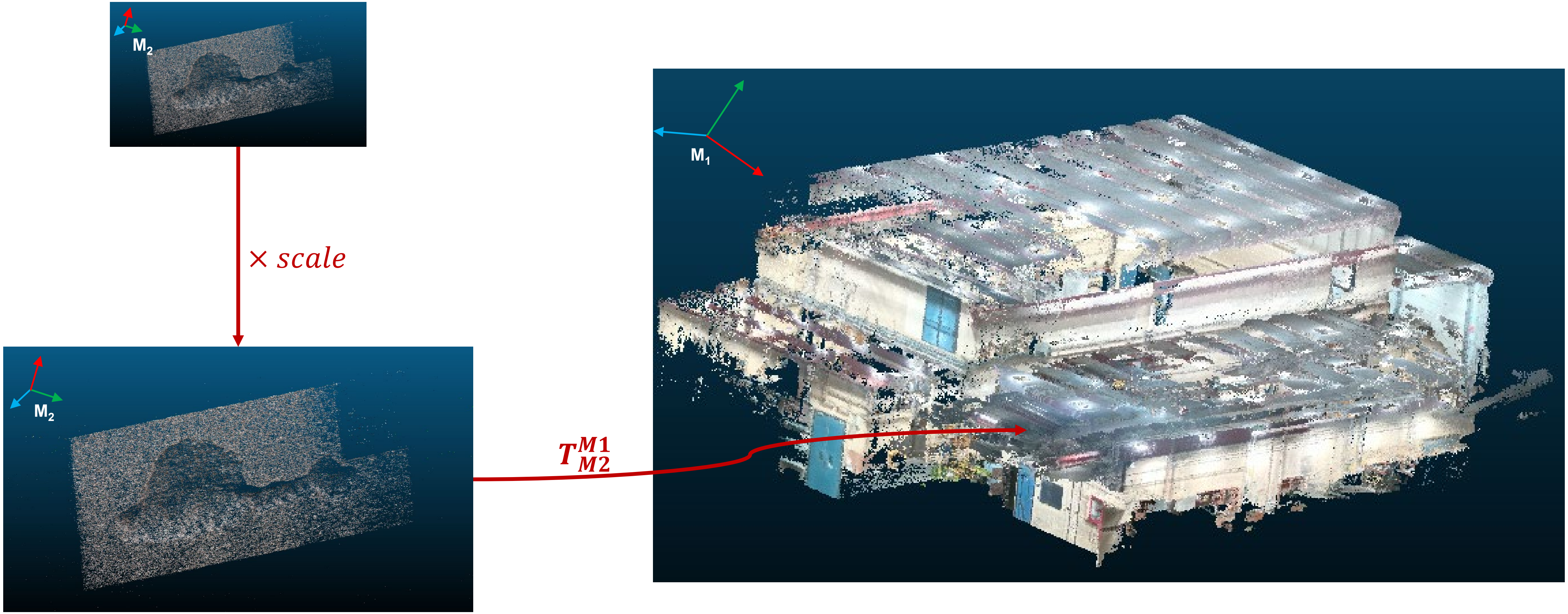
D_1:Distance between ROI camera centers in M_2: From T_{C2}^{M2}
D_2:Distance between ROI camera centers in M_1: From T_{C2}^{M1}
$scale = \frac{D_1}{D_2}$

$$\boldsymbol{T_{M2}^{M1}} = T_{C2}^{M1} \times {T_{C2}^{M2}}^{-1}$$

[2] R. Arandjelović, P. Gronat, A. Torii, T. Pajdla, J. Sivic. "NetVLAD: CNN architecture for weakly supervised place recognition", CoRR, abs/1511.07247, 2015

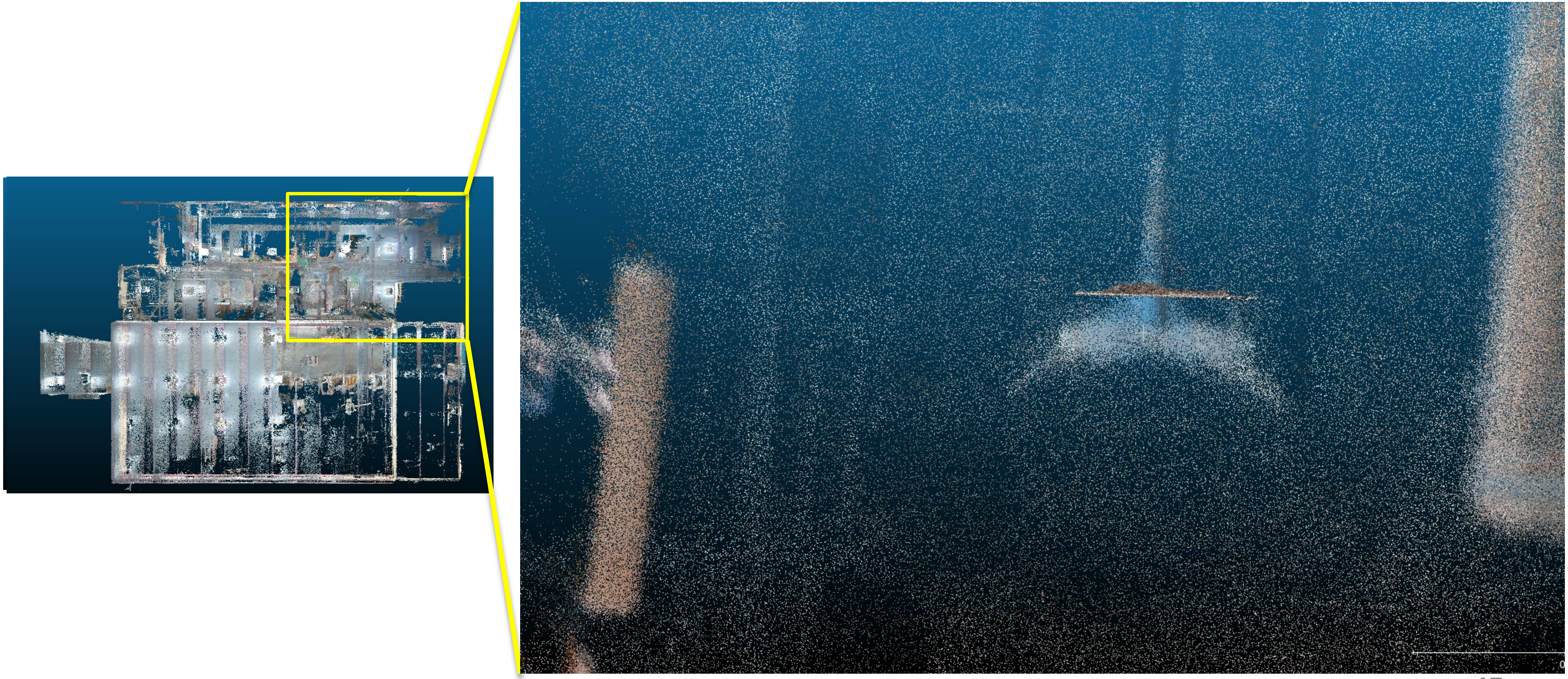
Step 3. Perform Global Registration: Intended Outcome

- Using the transformation T_{M2}^{M1} we can know where the ROI in M_2 is placed in M_1 ⟶ Global registration



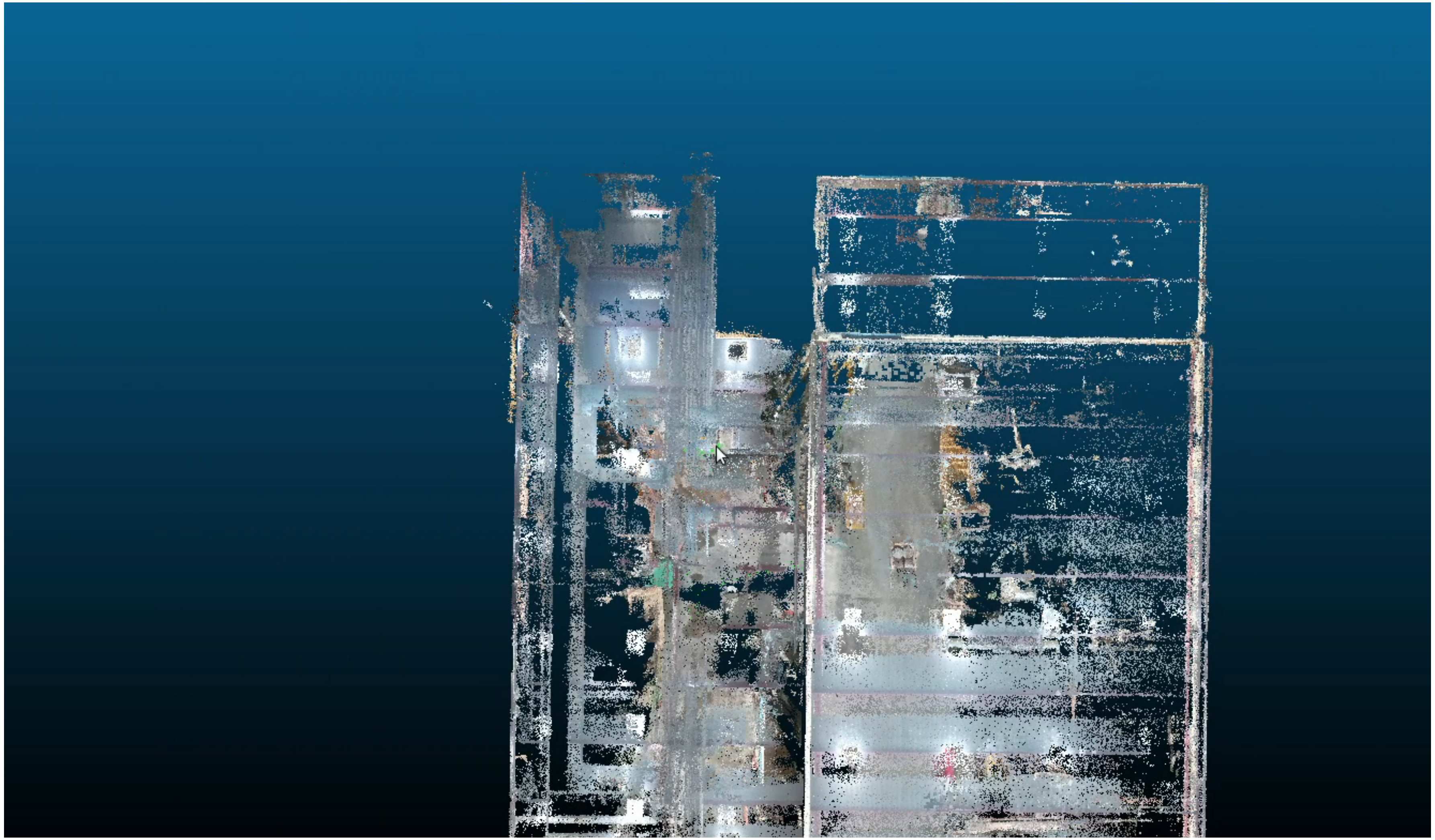
Step 3. Perform Global Registration: Result

Local Map (M_2) registered to Global Map (M_1) **after localization** (Global Registration)

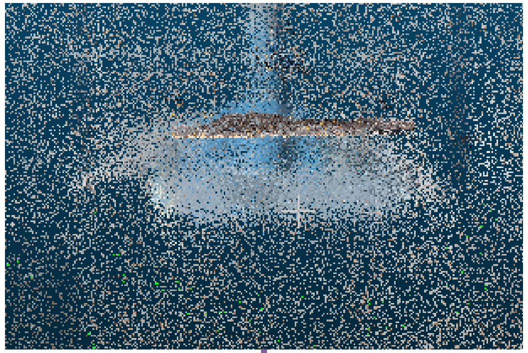


Step 4. Perform Tight Alignment: ICP Result

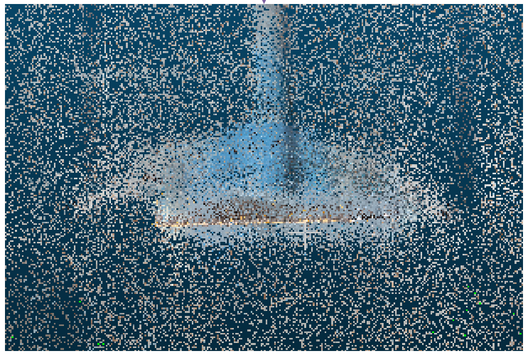
Local Map (*M_2*) registered to Global Map (*M_1*) **using Iterative Closest Point (ICP)** (Tight Alignment)



Global Registration Result



ICP

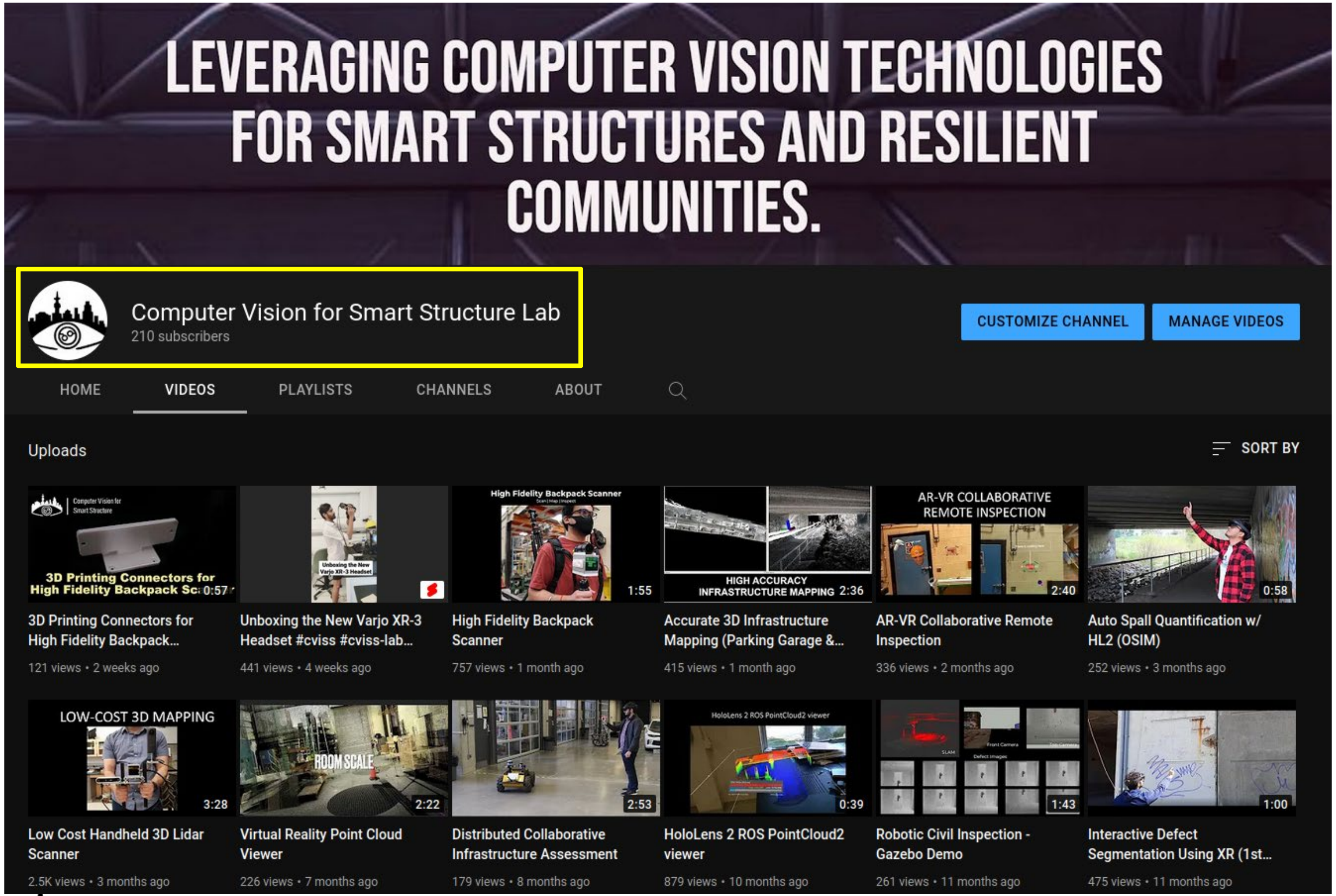


Step 4. Perform Tight Alignment: Refined Result

Local Map (M_2) registered to Global Map (M_1) **using ICP** (Tight Alignment) - **post refinement**

Conclusions

1. We provide an efficient way to
   - Perform quick mapping of larger structures
   - High accuracy mapping for ROI
2. Perform registration to build a Multi-Resolution Map which can enable Multi-Dimensional Structural Assessment



Thank you!
Any Questions?

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