

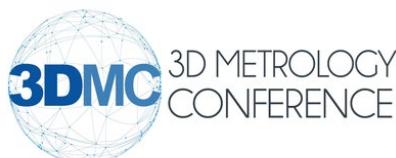
CONSTRUCTION OF POINT CLOUD FROM MONOCULAR CAMERA MOTION: EVALUATION AND MINIMIZATION OF REPROJECTION ERRORS

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Dionata Nunes

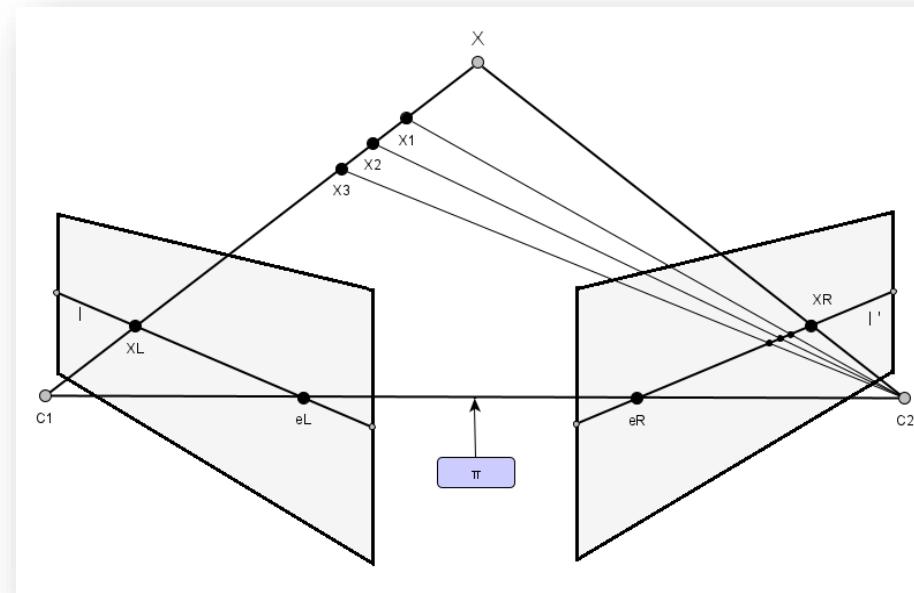
dionata.silva@senairs.org.br



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About Structure from Motion (SfM)



Data Accessibility

SfM can be used with images from conventional cameras, such as smartphone cameras or DSLR cameras



Reduced cost

SfM does not require expensive hardware, making it an economical option for 3D reconstruction



Flexibility

SfM is a very versatile technique that can be applied in different scenarios, from reconstructing small objects to mapping large areas, such as landscapes or buildings



Widely available input data

In many cases, images of a location or object are already available due to the widespread use of cameras on mobile devices



Incremental reconstruction capability

With SfM, you can add new images or video frames over time to enhance or expand the existing 3D reconstruction

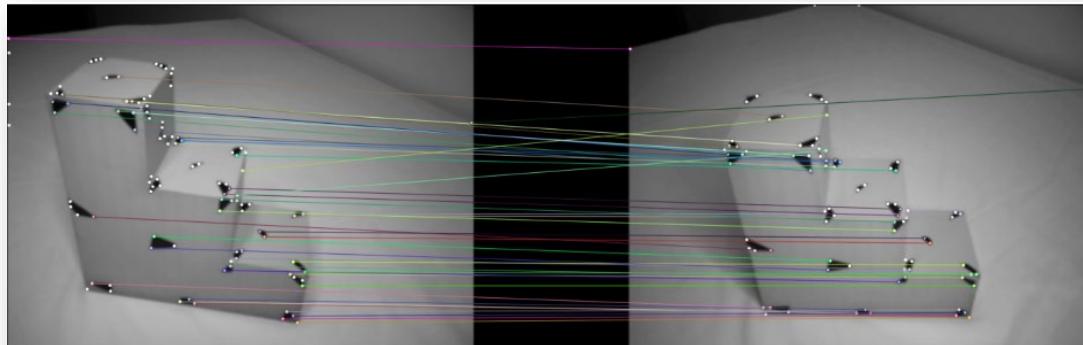


Motion applicability

Suitable for moving scenes. This makes it valuable for applications in autonomous vehicles, drones and mobile robotics



Restrictions of Structure from Motion



Dependence on visual features

SfM relies heavily on the presence of visual correspondence points across multiple images



Need for image overlap

For accurate 3D reconstruction, captured images must have significant overlap



Sensitivity to mismatch

Errors in matching points of interest in input images can result in inaccurate 3D reconstructions. Fixing these errors can be challenging



Scale limitations

SfM itself cannot determine the scale of the reconstructed scene (a reference object is needed)



Limitations in reconstructing transparent or highly reflective objects

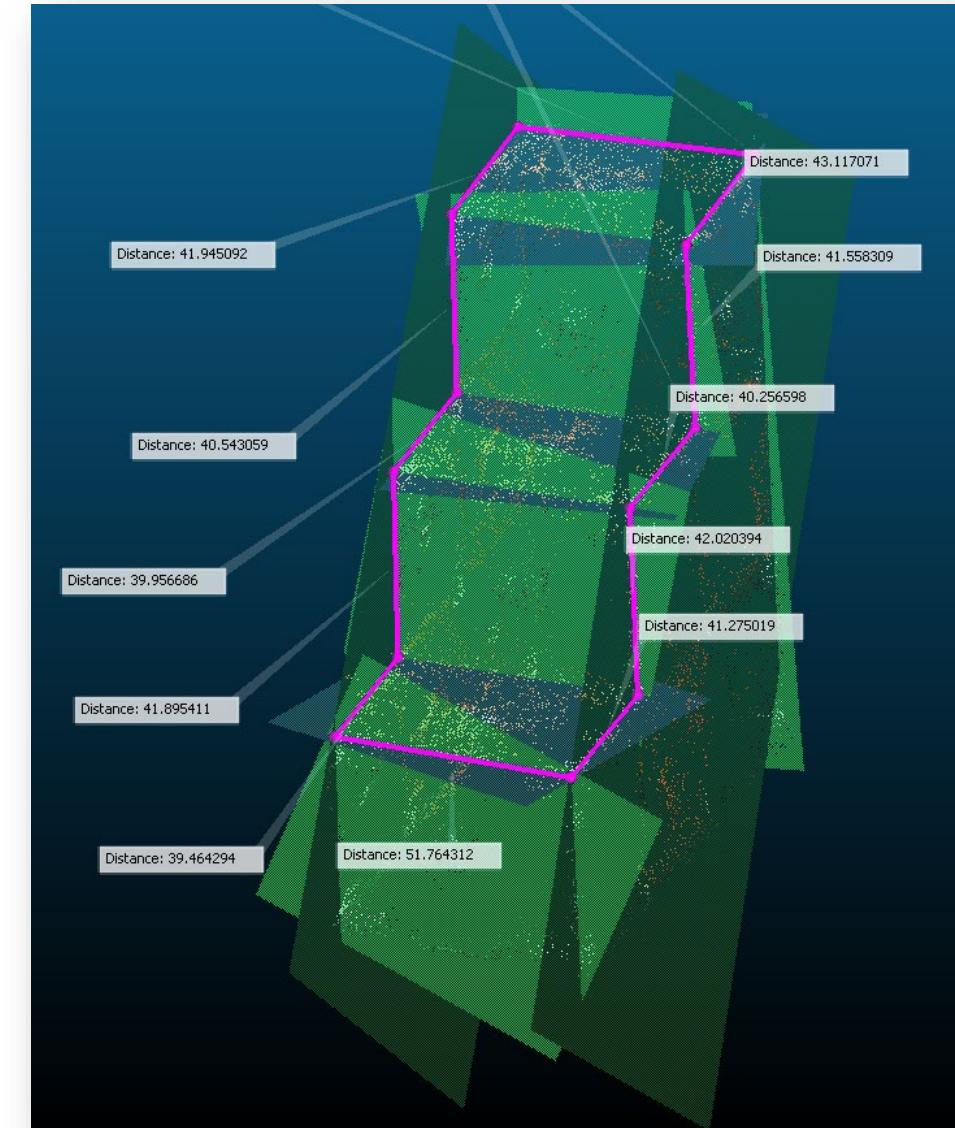
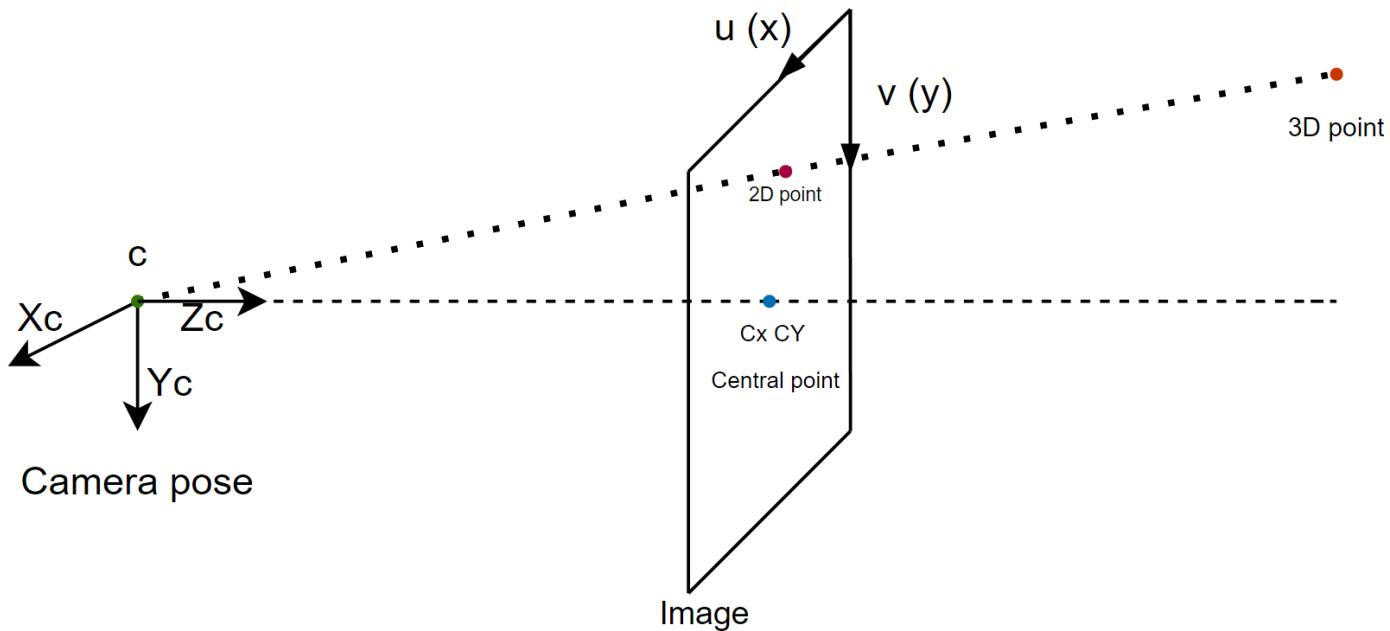
Transparent, mirrored, or highly reflective surfaces can be difficult to reconstruct accurately using SfM, as point correspondences can be difficult to identify in these materials



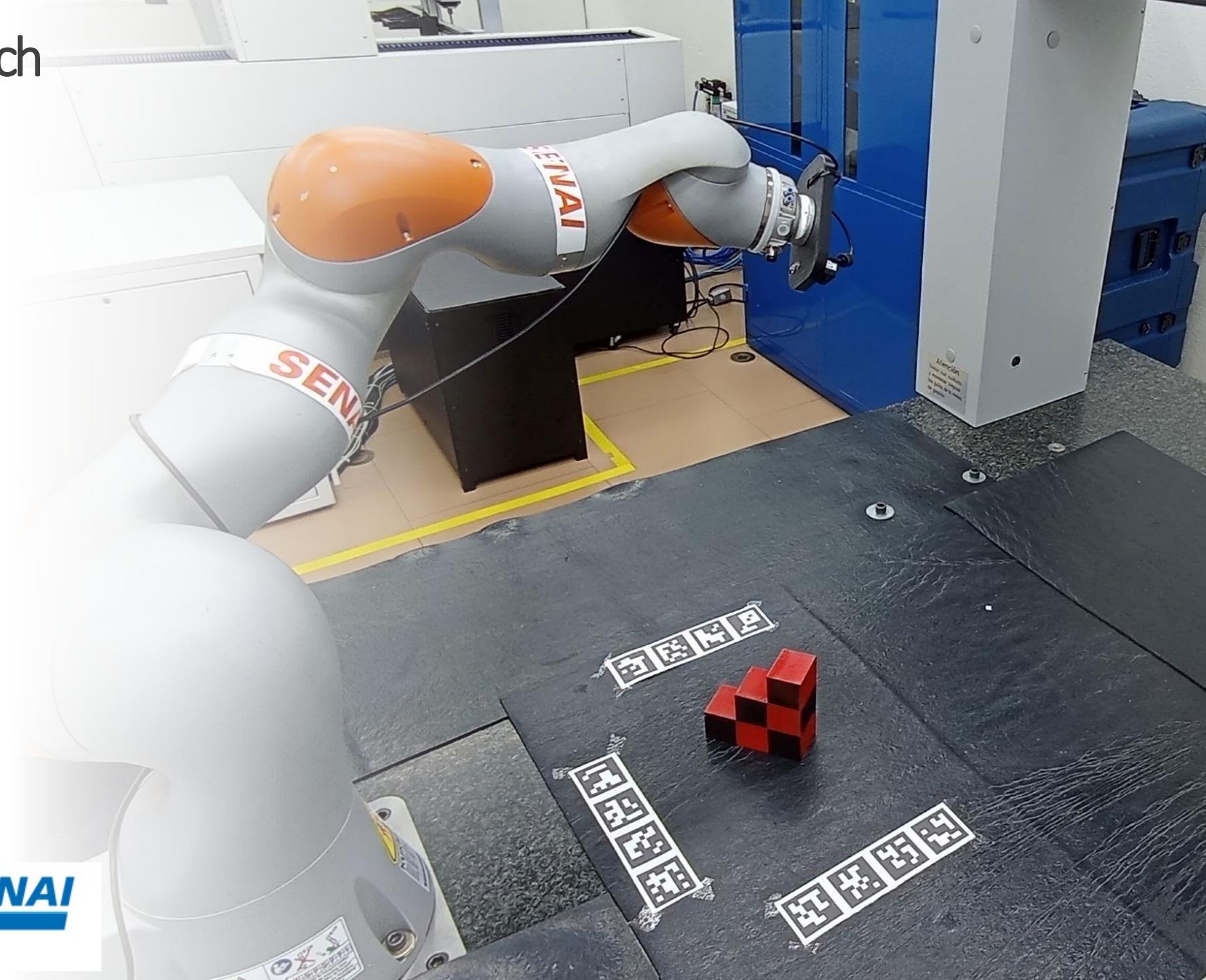
Lack of texture

Flat or uniformly textured surfaces can be difficult to reconstruct using SfM as they do not provide distinct correspondence points for triangulation

How accurate is SfM reconstruction?



Experimental approach



Main equipment used in the experiments

- CAD model of the KUKA robotic arm, used to plan the camera mounting on the flange



- Camera used for mounting: DFK AFU050-L34 Color Camera (resolution: 2592x1944)



- Camera used for image capture: Canon D200 (resolution: 3872x1944)



- Laser Scanner - FARO



- Leica T-SCAN

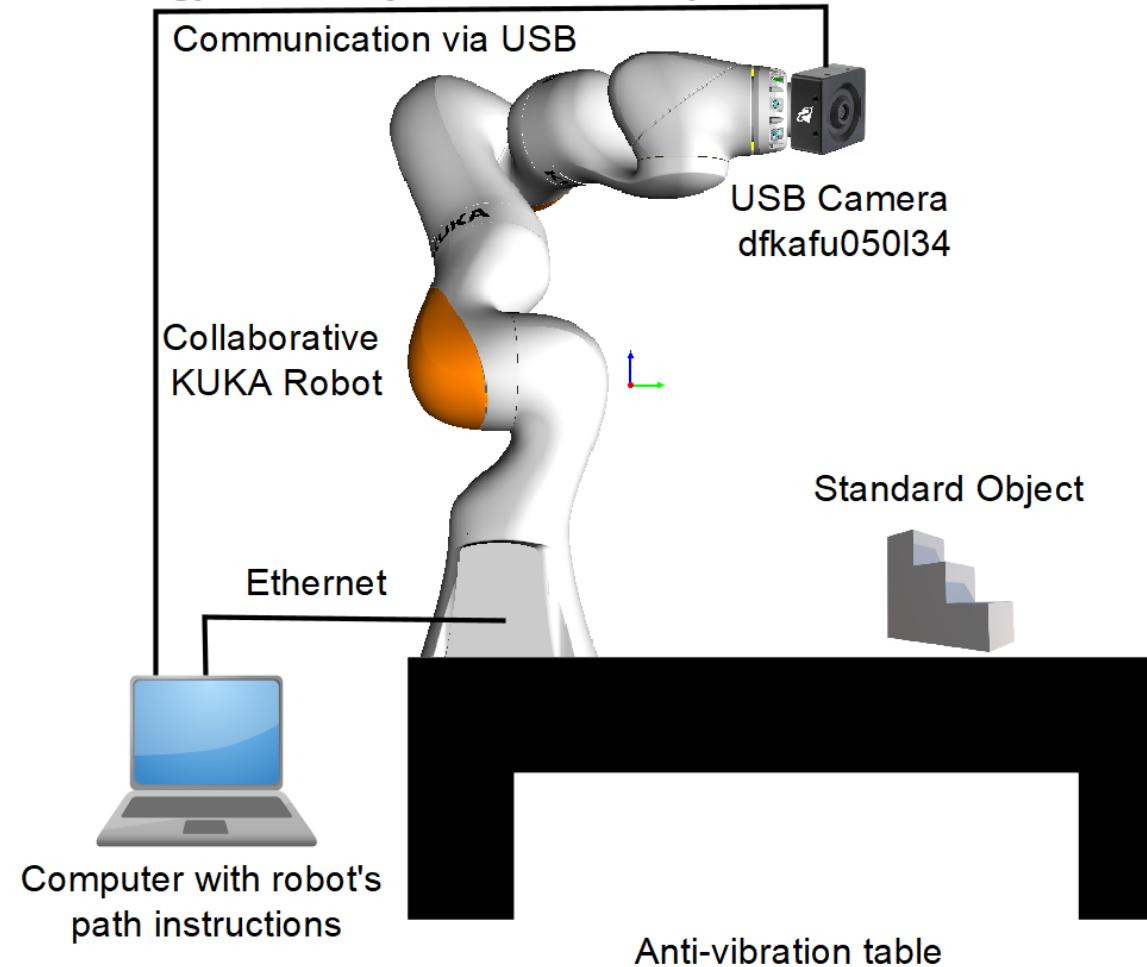


- ZEISS Prisma Ultra coordinate measuring machine

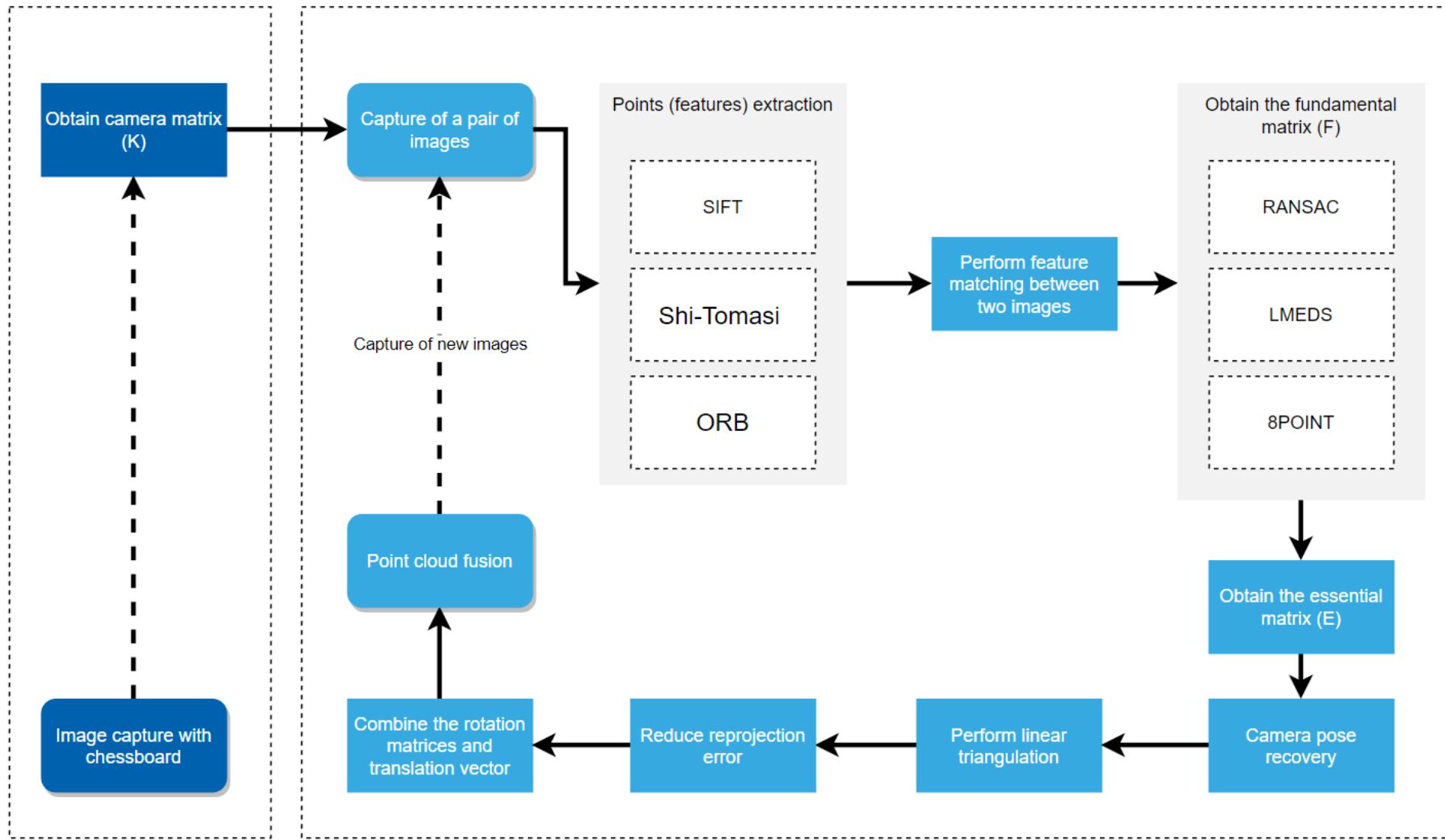


Experiment setup

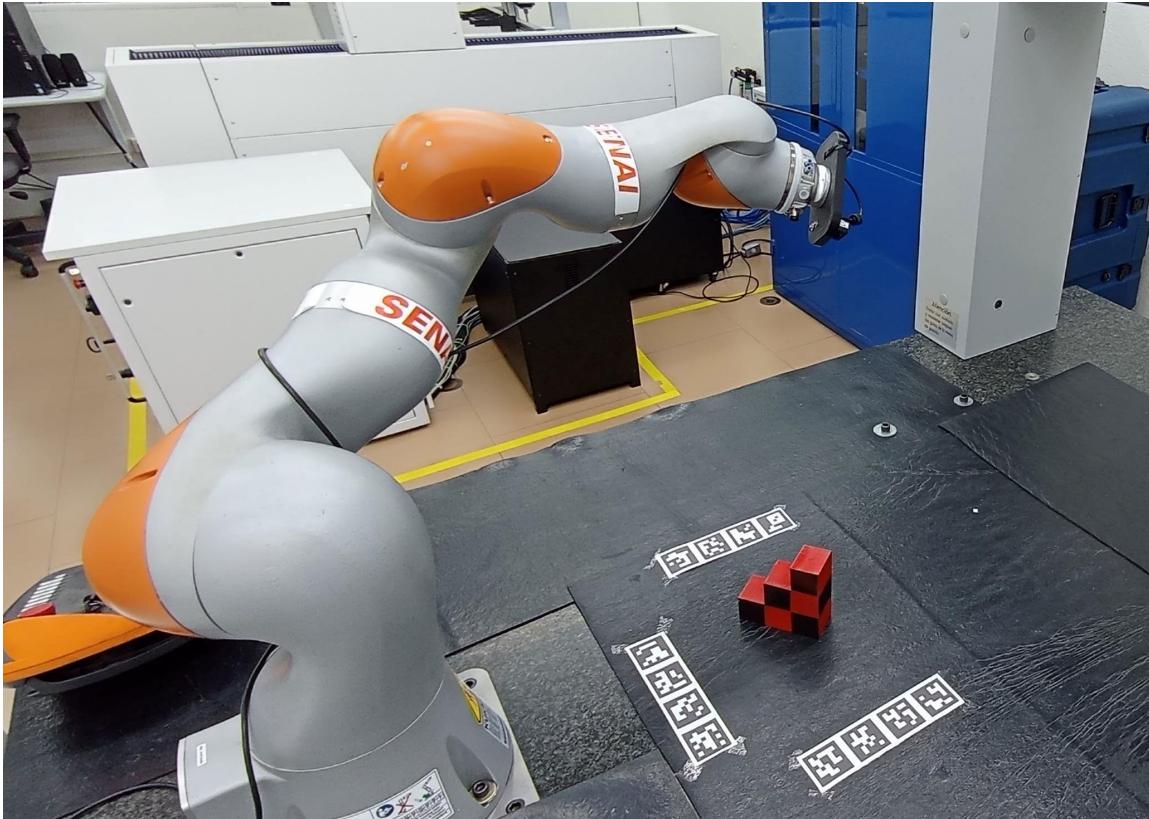
Metrology laboratory: controlled temperature, vibration, and humidity



Implementation: Overall System Diagram



Implementation: Steps of the Structure From Motion (SfM) methodology



1

Image capture

The image captures were performed using a camera attached to a robotic arm.

2

Intrinsic camera parameters

The intrinsic camera parameters were obtained by identifying patterns in the images.

3

Feature extraction from images

The features were extracted from each image using the SIFT algorithm.

4

Correspondences between descriptors

For each feature acquired in the images, descriptors were defined and used for correspondences between the images.

5

Camera pose recovery

The camera pose was recovered using the essential matrix and the parameter K (camera matrix), along with the cv.recoverPose algorithm from OpenCV.

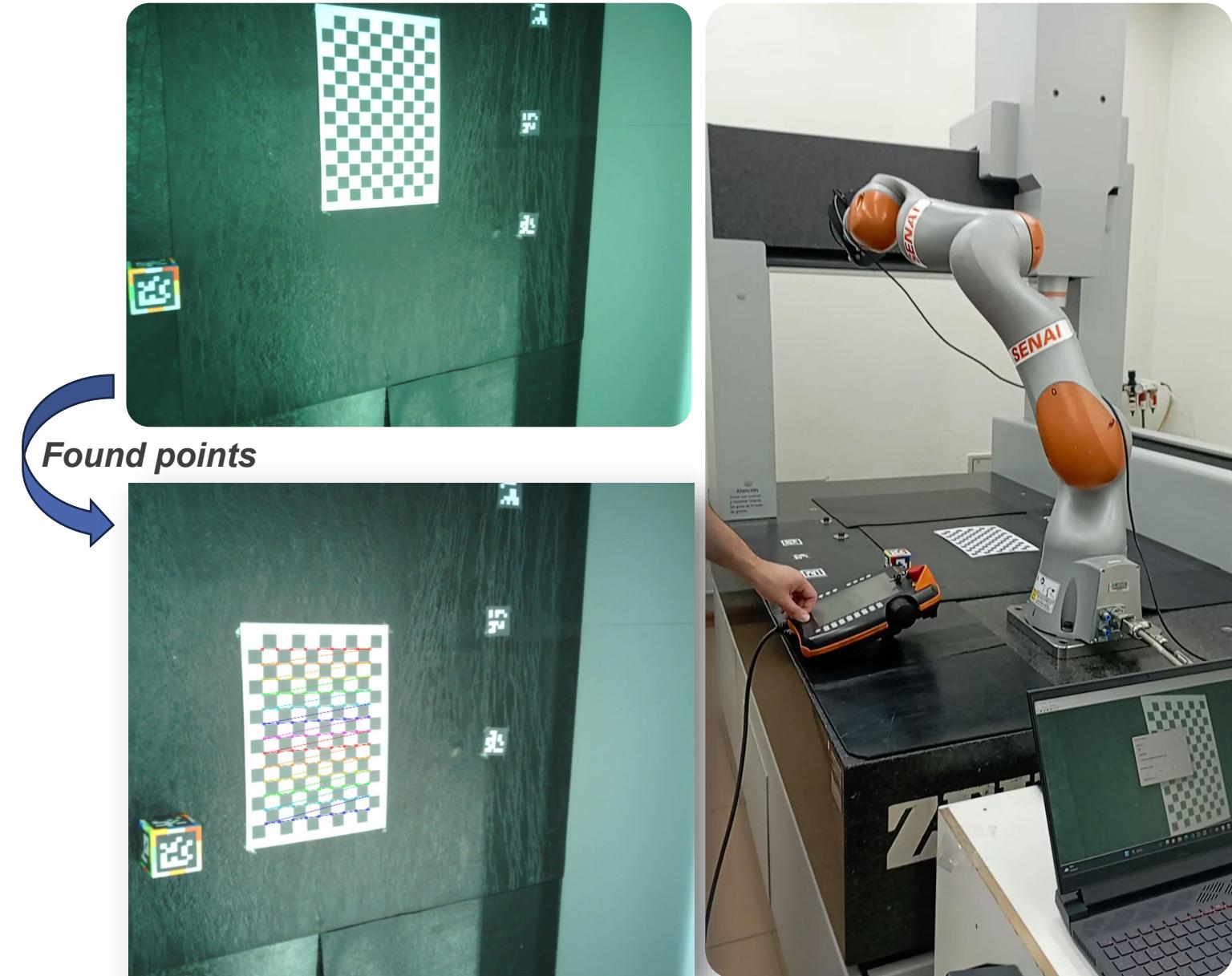
6

Triangulation

To recover the 3D coordinates, the linear triangulation method was used.

Implementation: Intrinsic camera parameters (K)

- Obtain the camera matrix from the camera.
- The camera calibration is performed using this chessboard as a reference, allowing us to find points in the three-dimensional space.



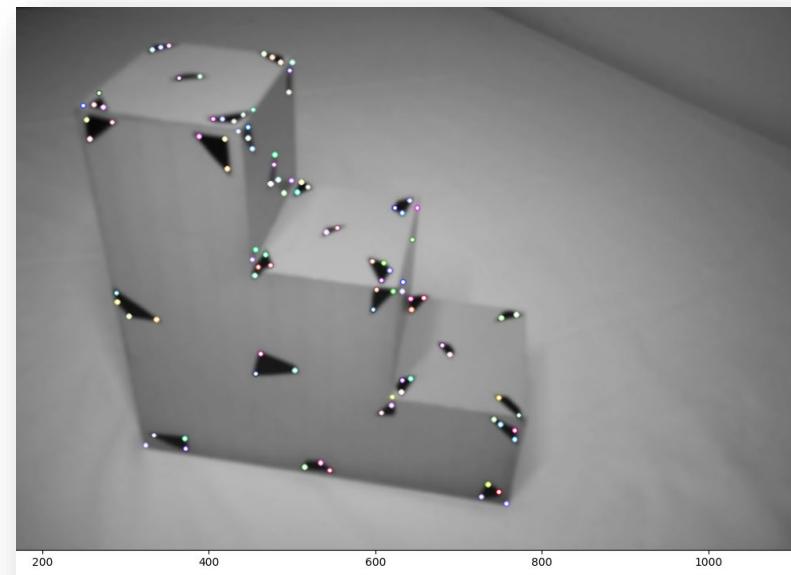
Implementation: Correspondences between descriptors

To find the correspondences between descriptors, the feature extraction algorithm called SIFT (Scale-Invariant Feature Transform) was used. Other algorithms were tested as well, such as SURF, Shi-Tomasi, and ORB.

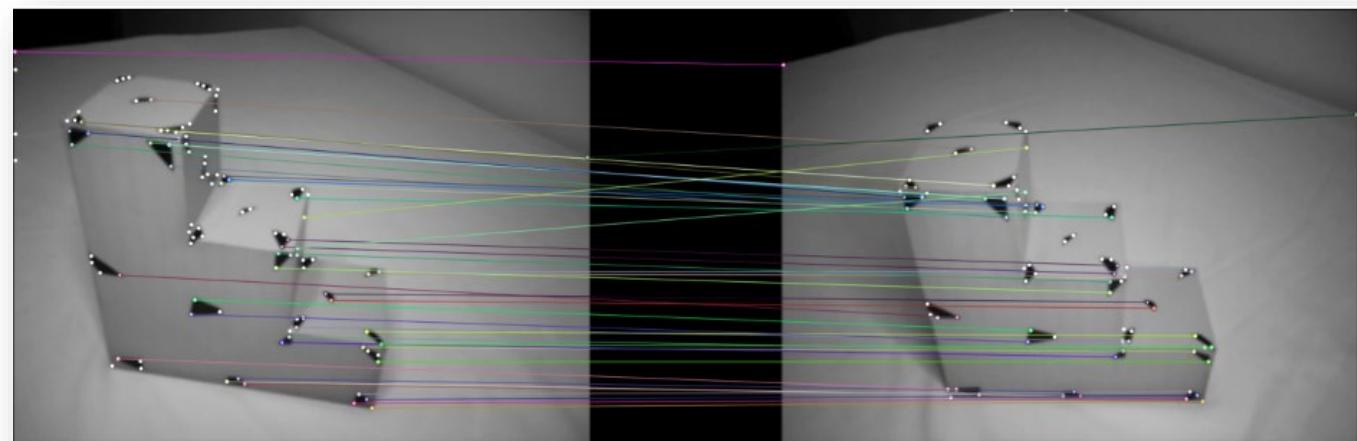
The choice to use the SIFT algorithm is due to its robustness in handling scale and orientation changes in images.

The correspondences between descriptors are a crucial step in determining the fundamental matrix (F), which allows for tracing appropriate epipolar lines between the images.

Correspondences between descriptors



Feature extraction from images



Implementation: Camera pose recovery

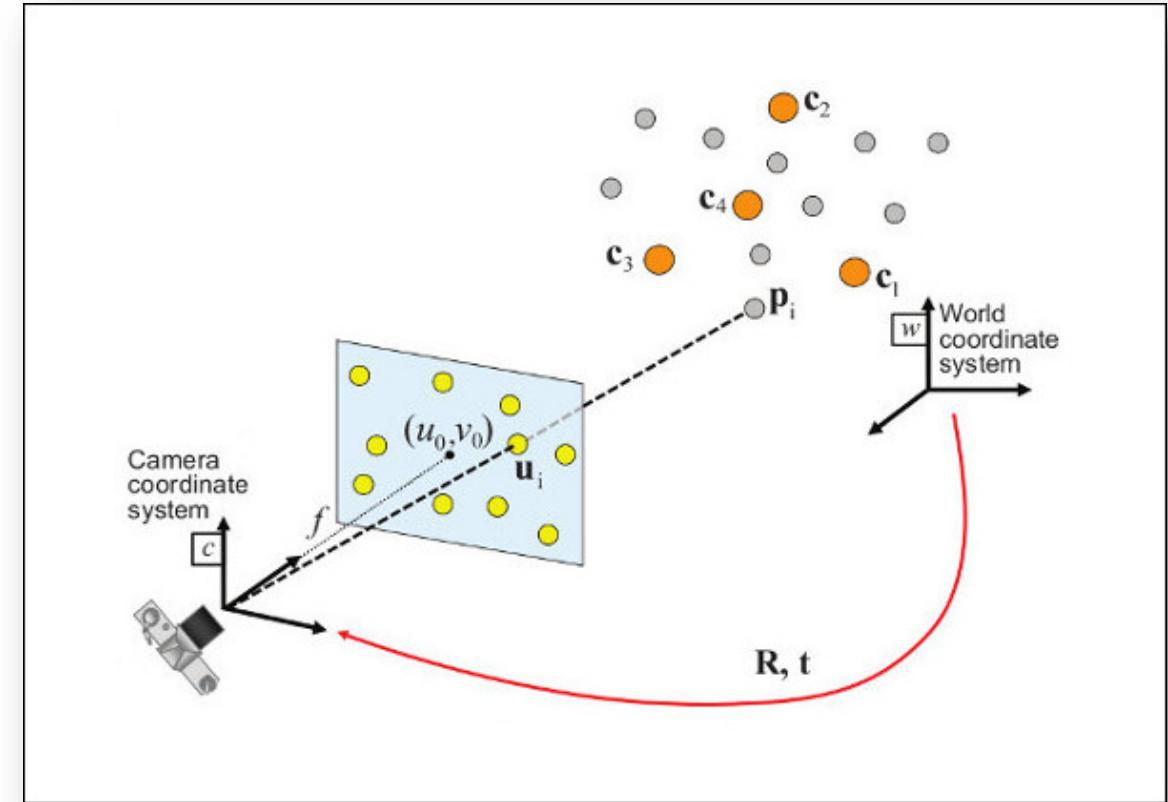


THE CAMERA POSE WAS RECOVERED USING THE ESSENTIAL MATRIX AND THE PARAMETER K (CAMERA MATRIX), ALONG WITH THE CV.RECOVERPOSE ALGORITHM FROM OPENCV.



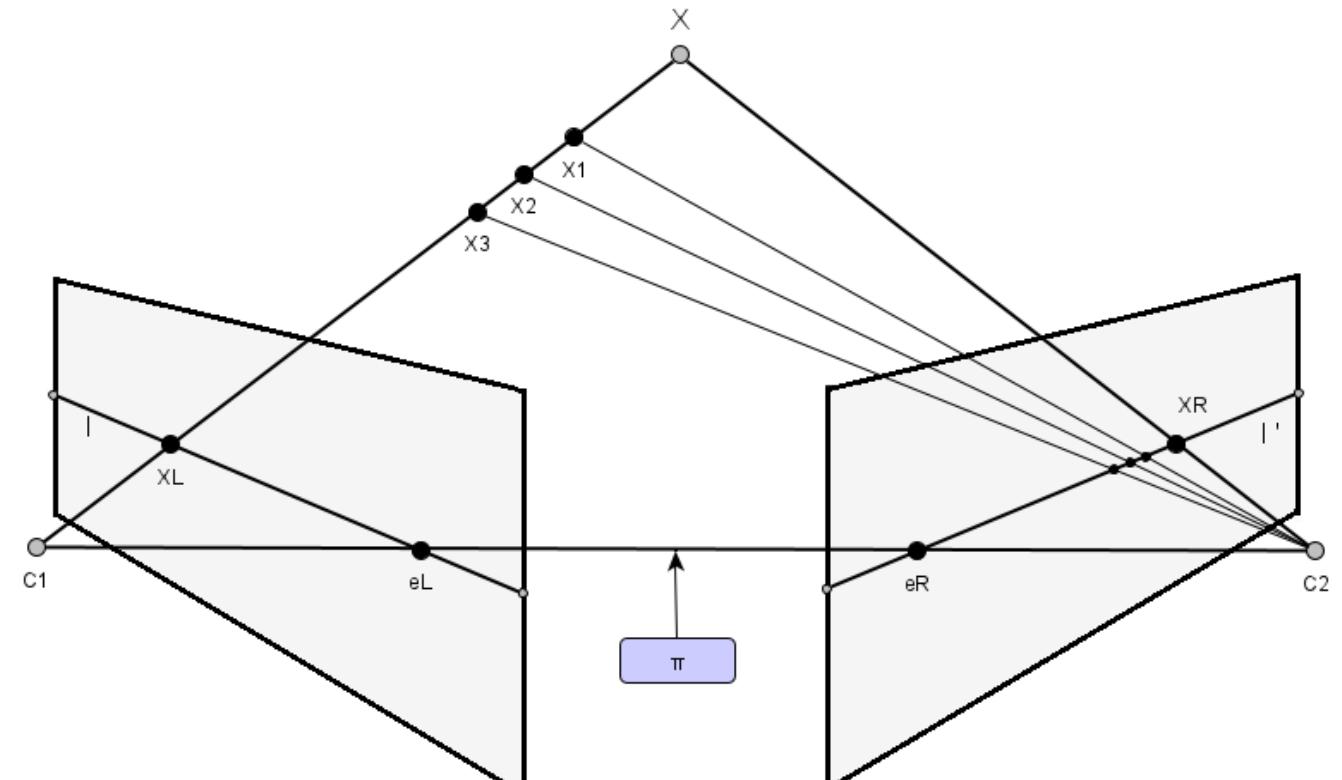
AFTER OBTAINING THE INITIAL CAMERA POSE, IT NEEDS TO BE UPDATED FOR EACH NEW IMAGE. FOR THIS PURPOSE, THE 'SOLVEPNPTRANSAC' FUNCTION IS USED. THIS FUNCTION IS AIMED AT ESTIMATING THE 3D POSE OF AN OBJECT BASED ON ITS PROJECTION IN AN IMAGE. THE TERM "PNP" STANDS FOR "PERSPECTIVE-N-POINT," REFERRING TO THE PROBLEM OF ESTIMATING THE POSE (POSITION AND ORIENTATION) OF A 3D OBJECT BASED ON THE COORDINATES OF SOME CORRESPONDING POINTS IN A 2D IMAGE.

Perspective-n-Point



Implementation: Triangulation

EPIPOLAR LINES



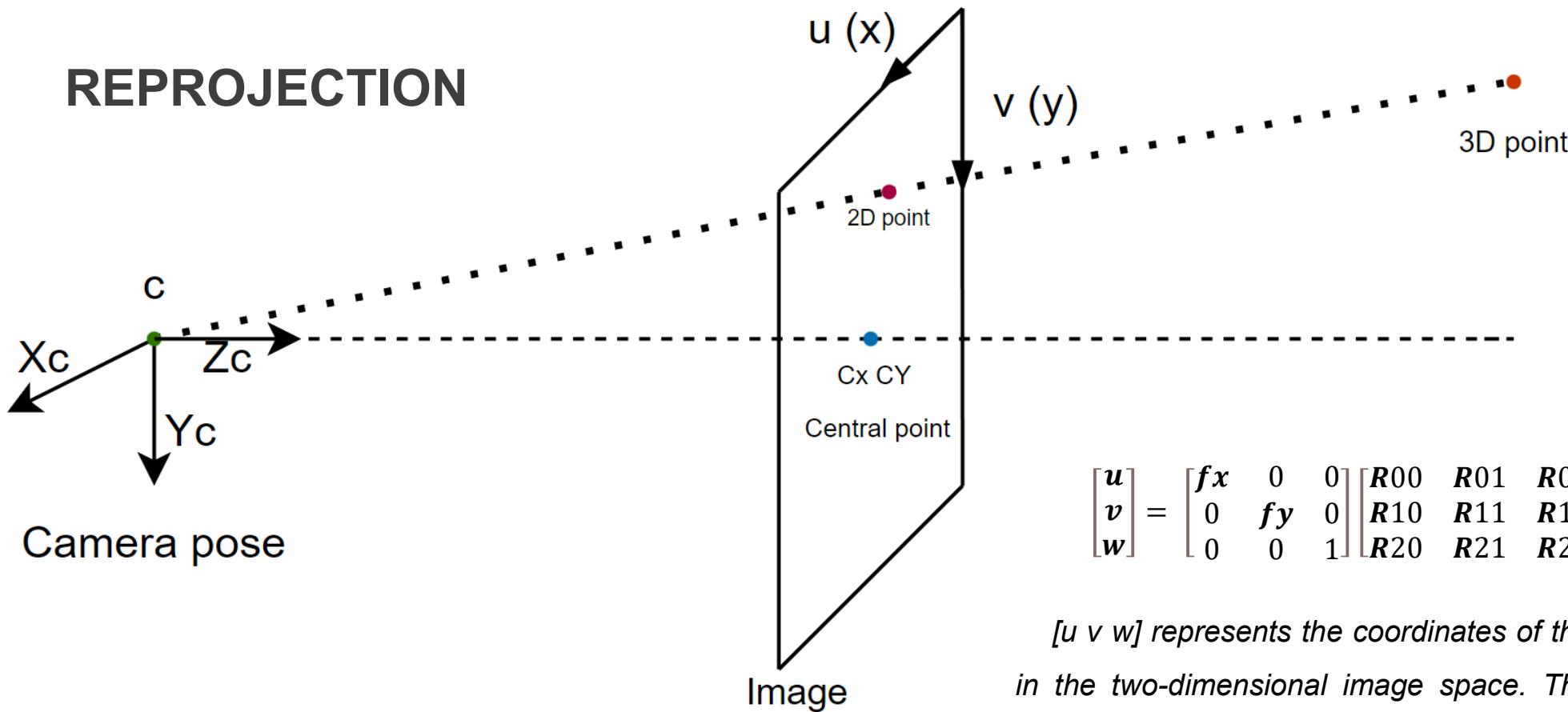
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Implementation: Bundle_adjustment

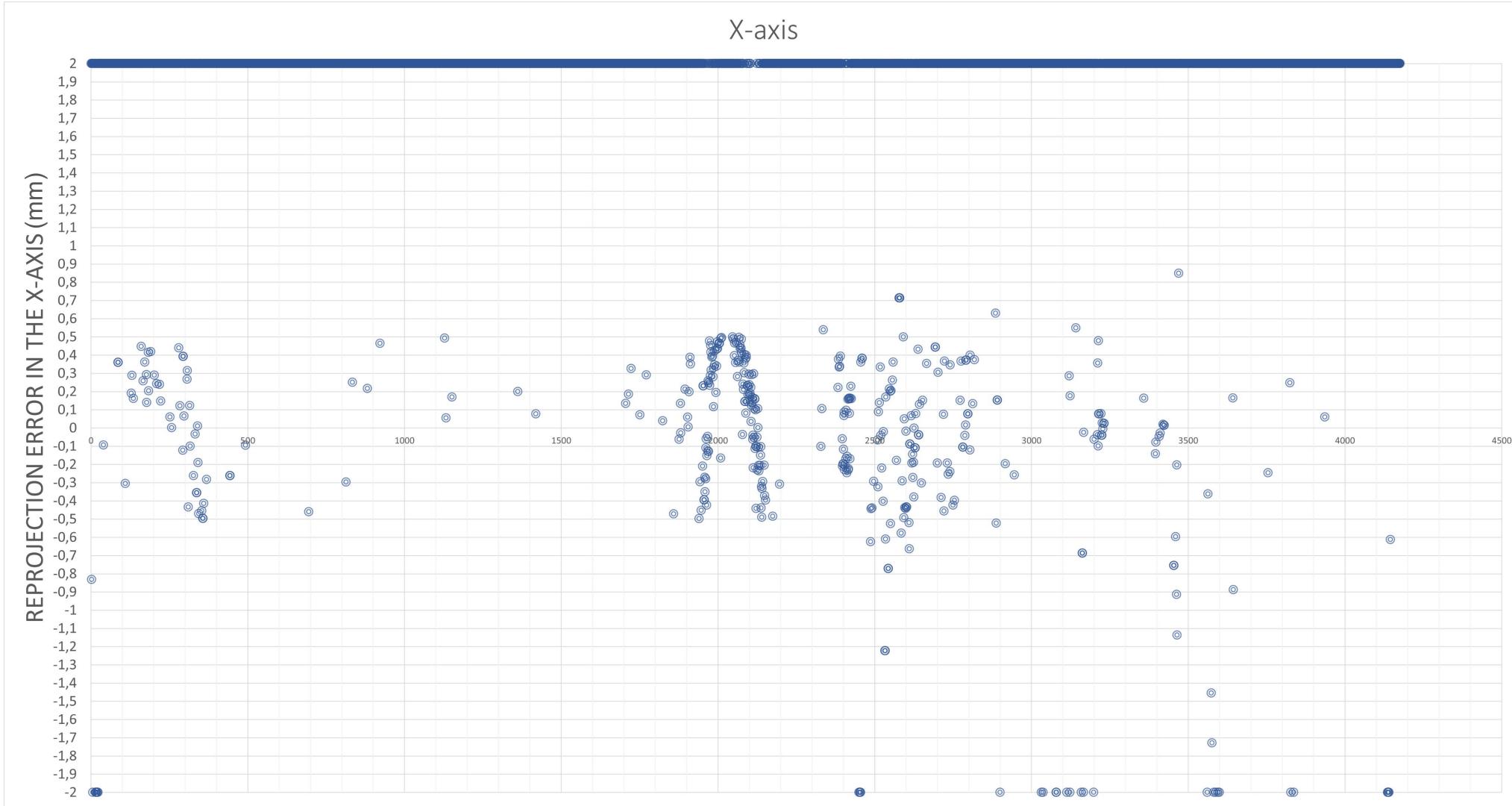
REPROJECTION



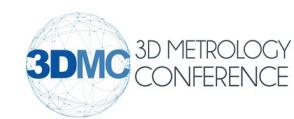
$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} fx & 0 & 0 \\ 0 & fy & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R_{00} & R_{01} & R_{02} \\ R_{10} & R_{11} & R_{12} \\ R_{20} & R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} fxt_0 \\ fyt_1 \\ t_2 \end{bmatrix}$$

$[u \ v \ w]$ represents the coordinates of the projected point in the two-dimensional image space. The parameters fx and fy correspond to the focal lengths along the x and y axes, respectively.

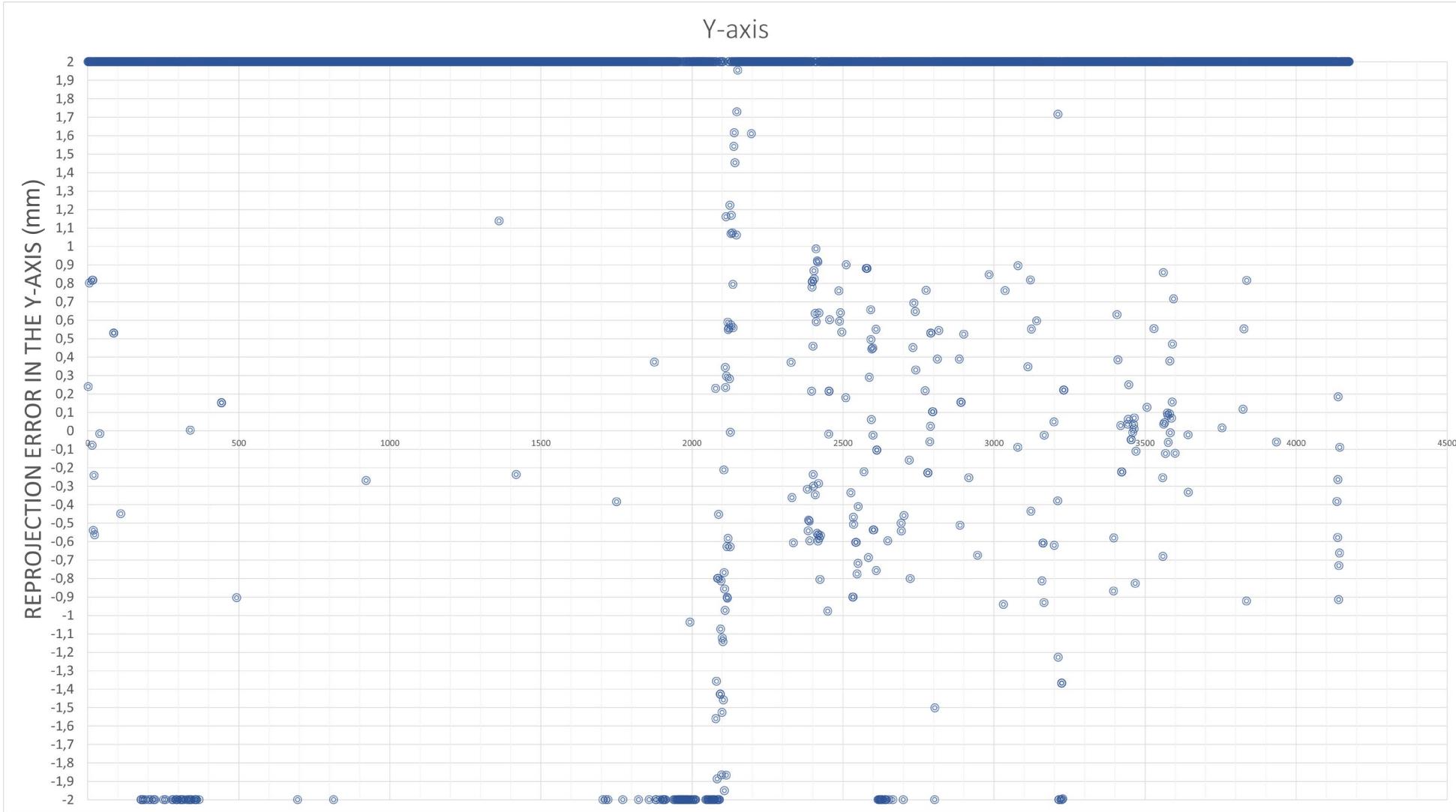
Reprojection Error Distribution



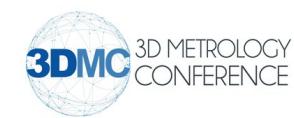
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Reprojection Error Distribution

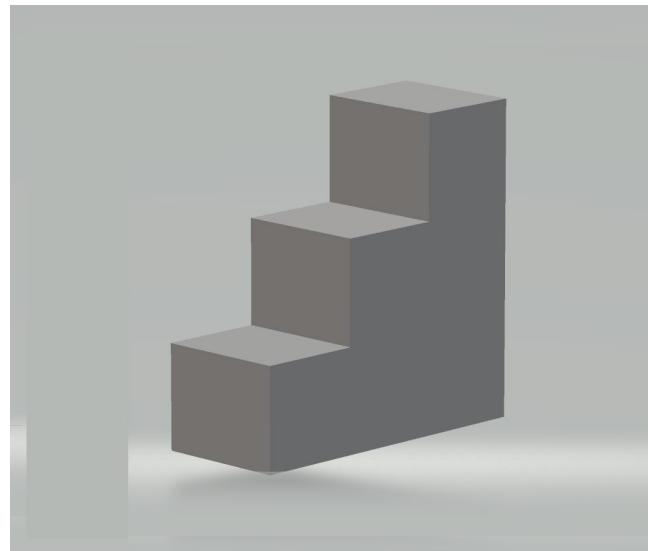


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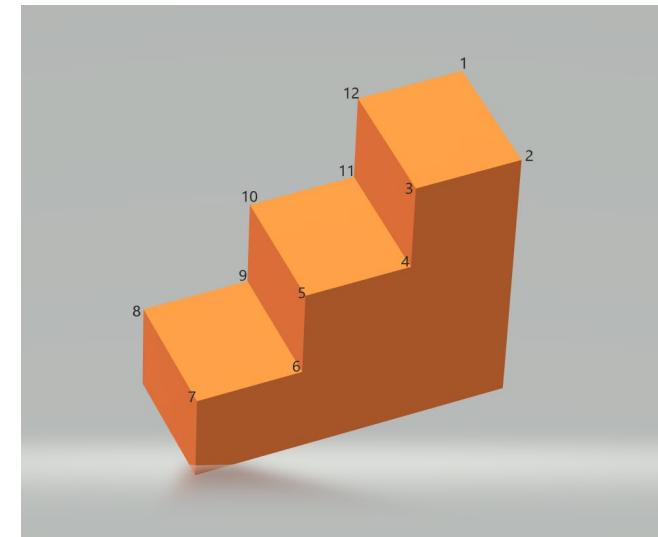


Results: Contextualization

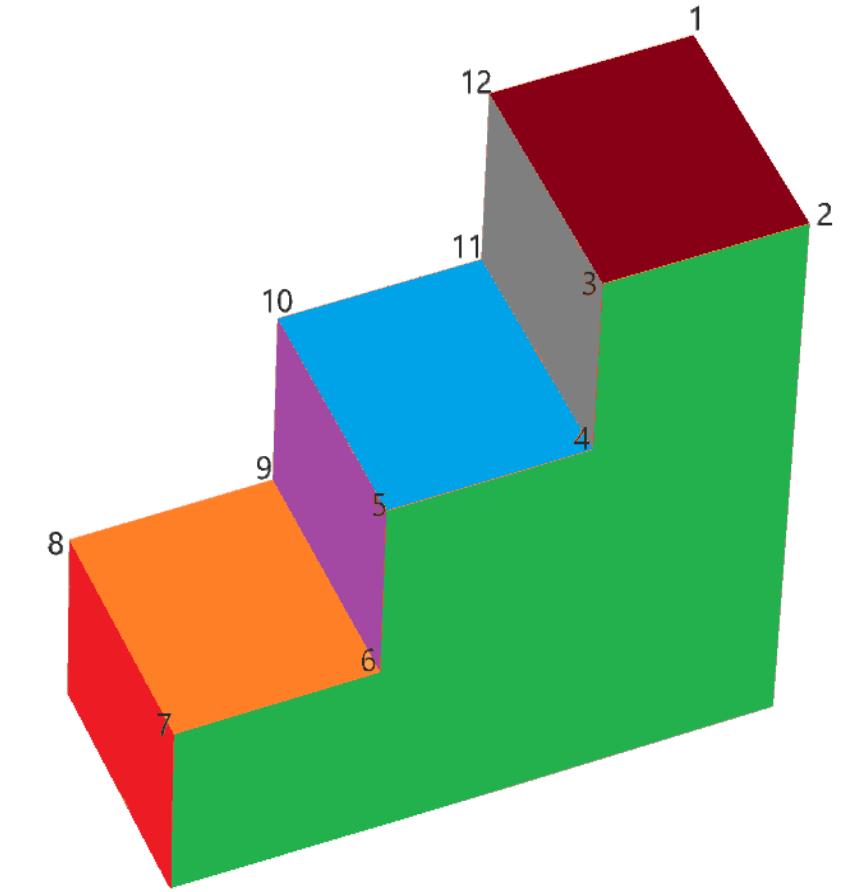
Definition of planes



Reference model



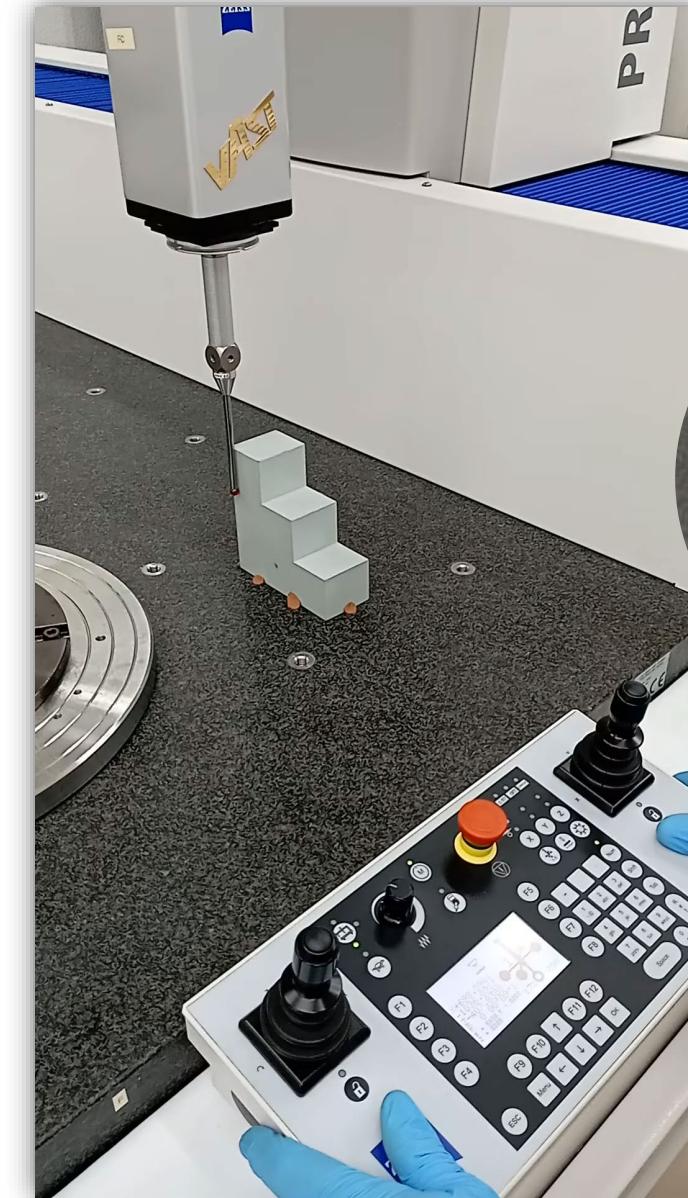
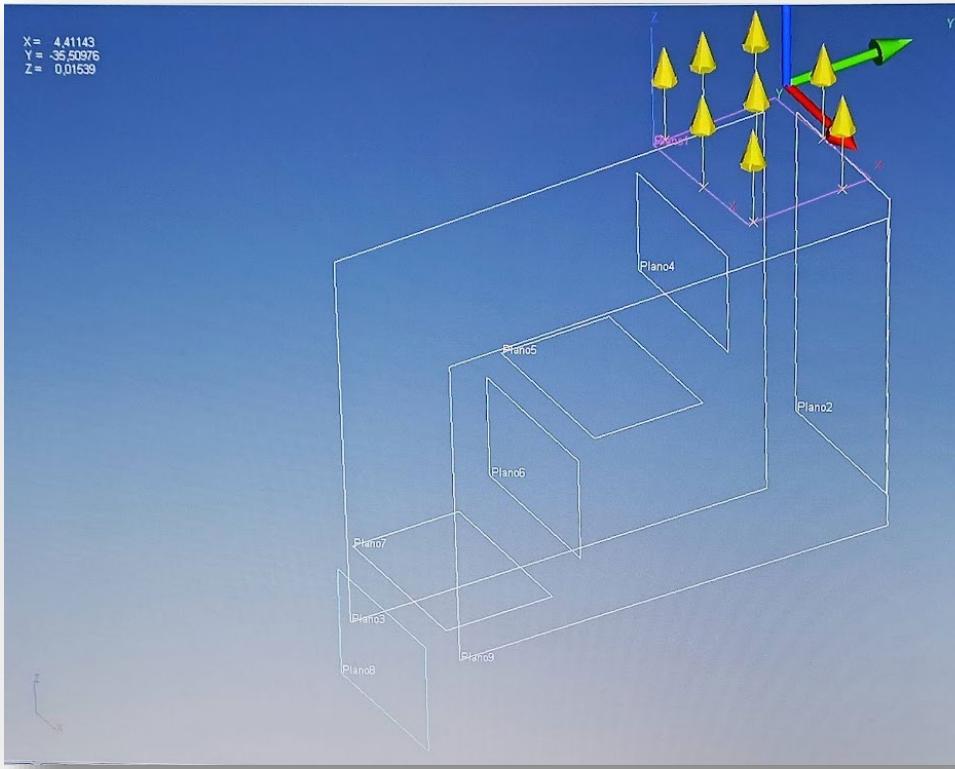
Marking of measurements



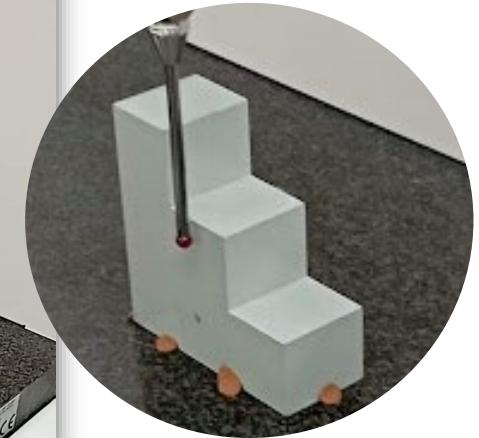
Used planes

Results: Planes defined for measurements by the Zeiss Prisma Ultra machine

Planes defined in Zeiss Prisma Ultra

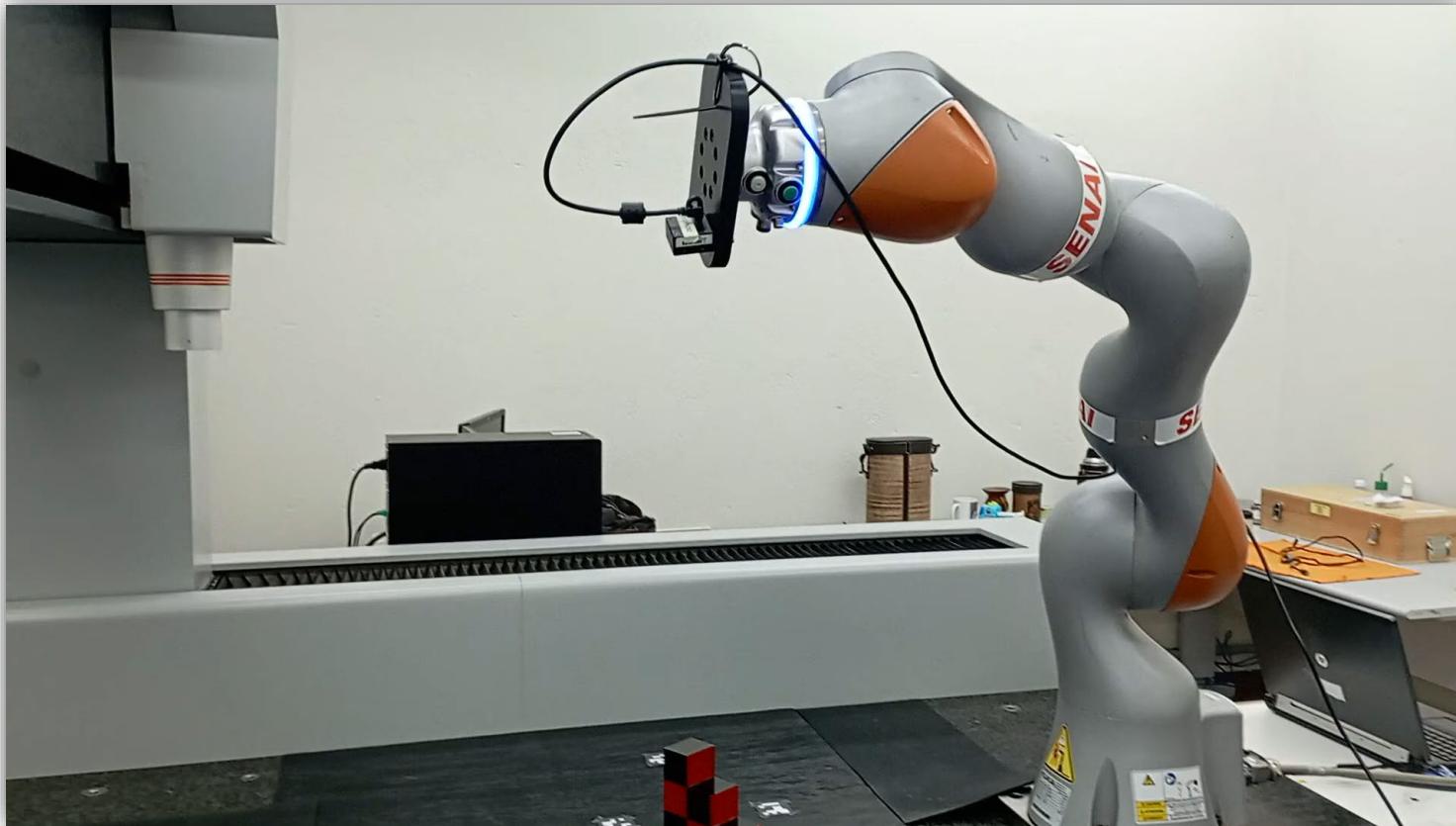


Touch probe



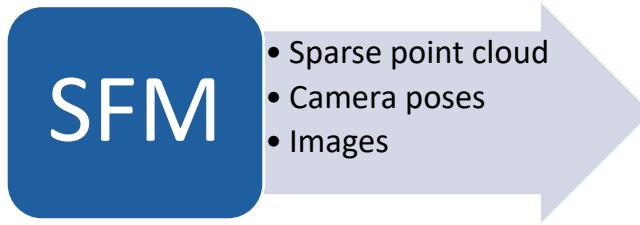
Results: Measurements performed by the SfM system

Captured images

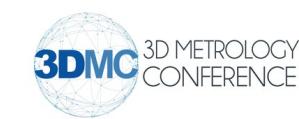


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Results: SfM

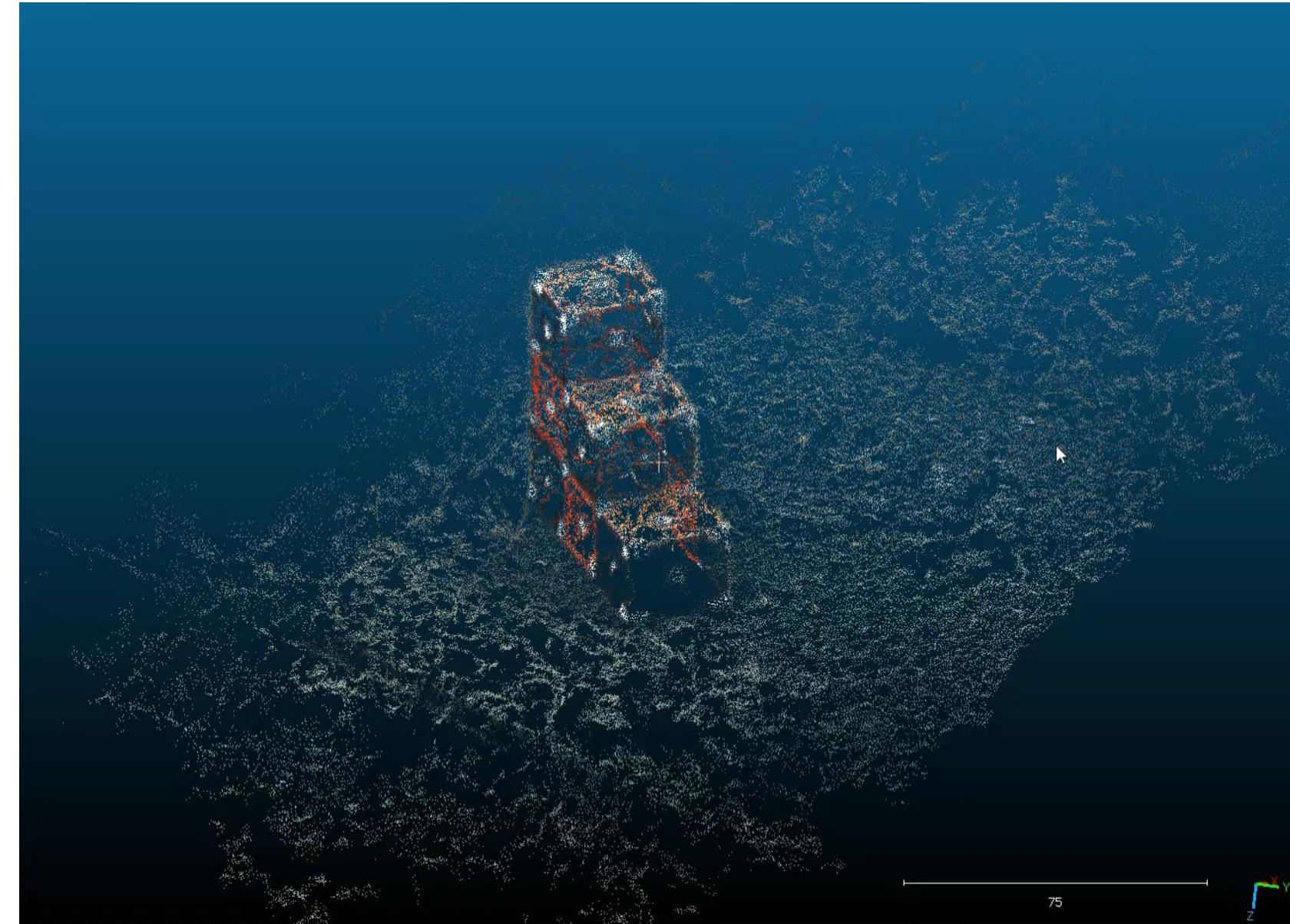
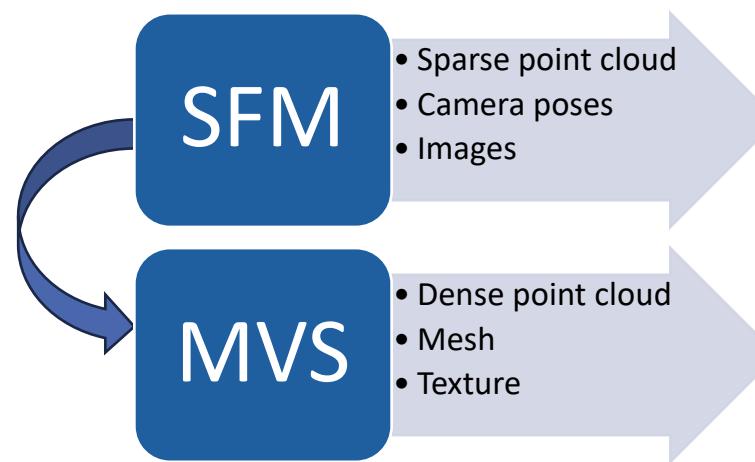


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Results: OpenMVS

(Open Multiple View Stereovision)



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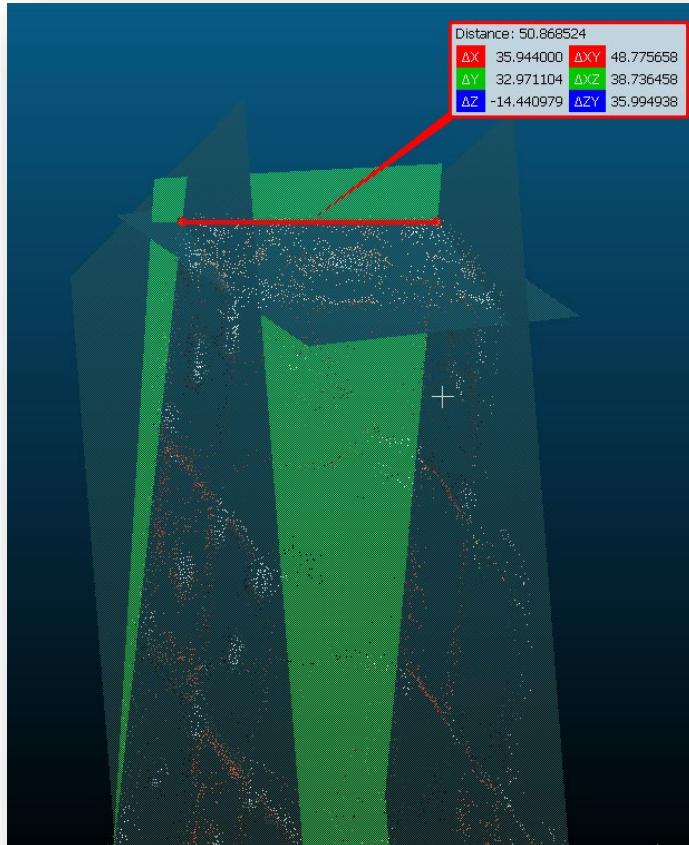
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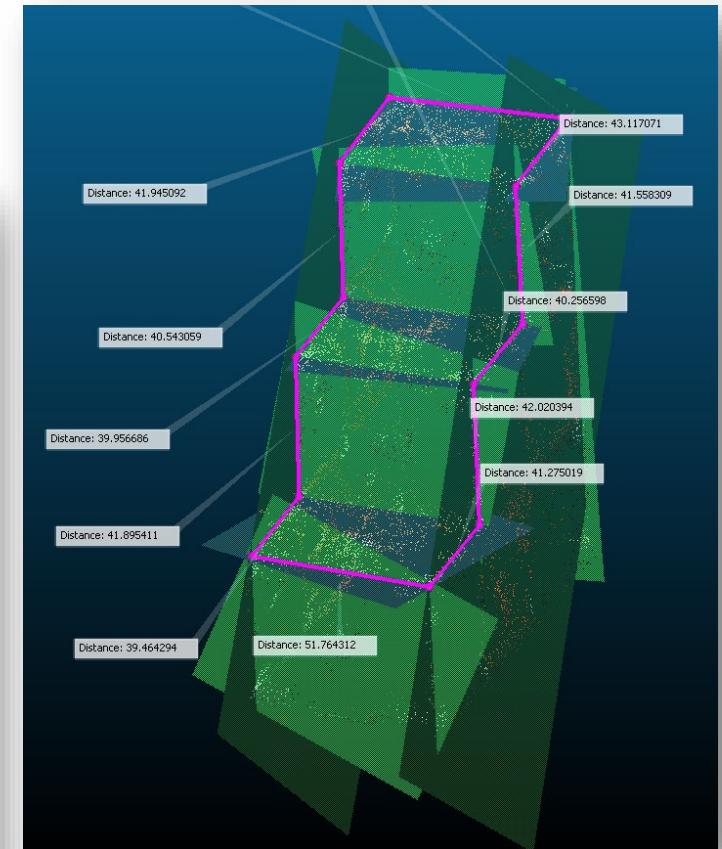
Results: Definition of planes and measurements

- The least squares approach was employed to determine the planes among the points, following which the intersection between the planes was defined as a point. This point was used to measure the distance between the points.
- The same measurement order used in Zeiss Prisma Ultra was applied.

Definition of points between the intersections of the planes



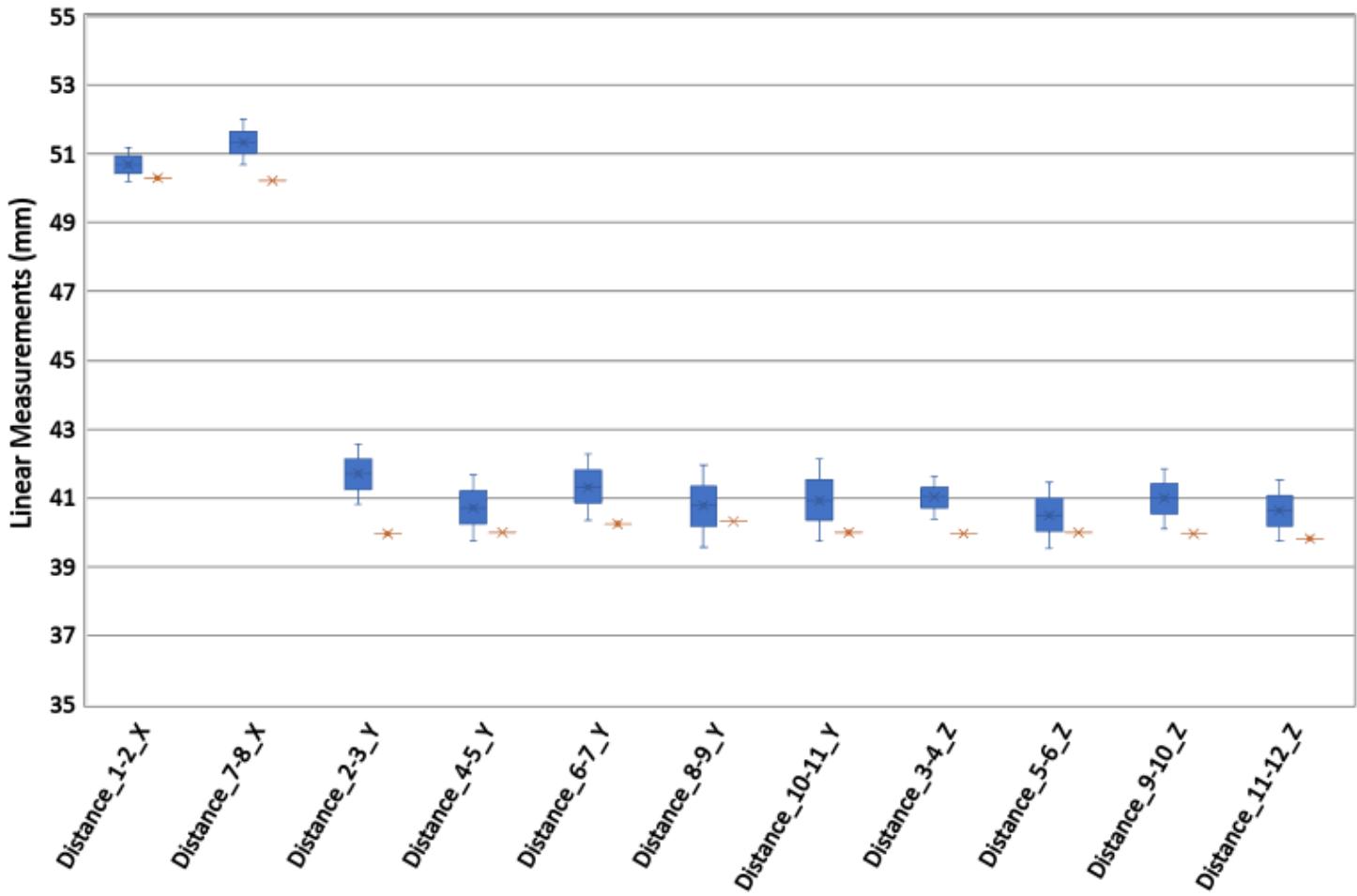
All planes and measurements conducted



Results: Measured values

Measurement Methods in Step Gauge

■ SfM ■ ZEISS PRISMO ULTRA CMM (Reference)

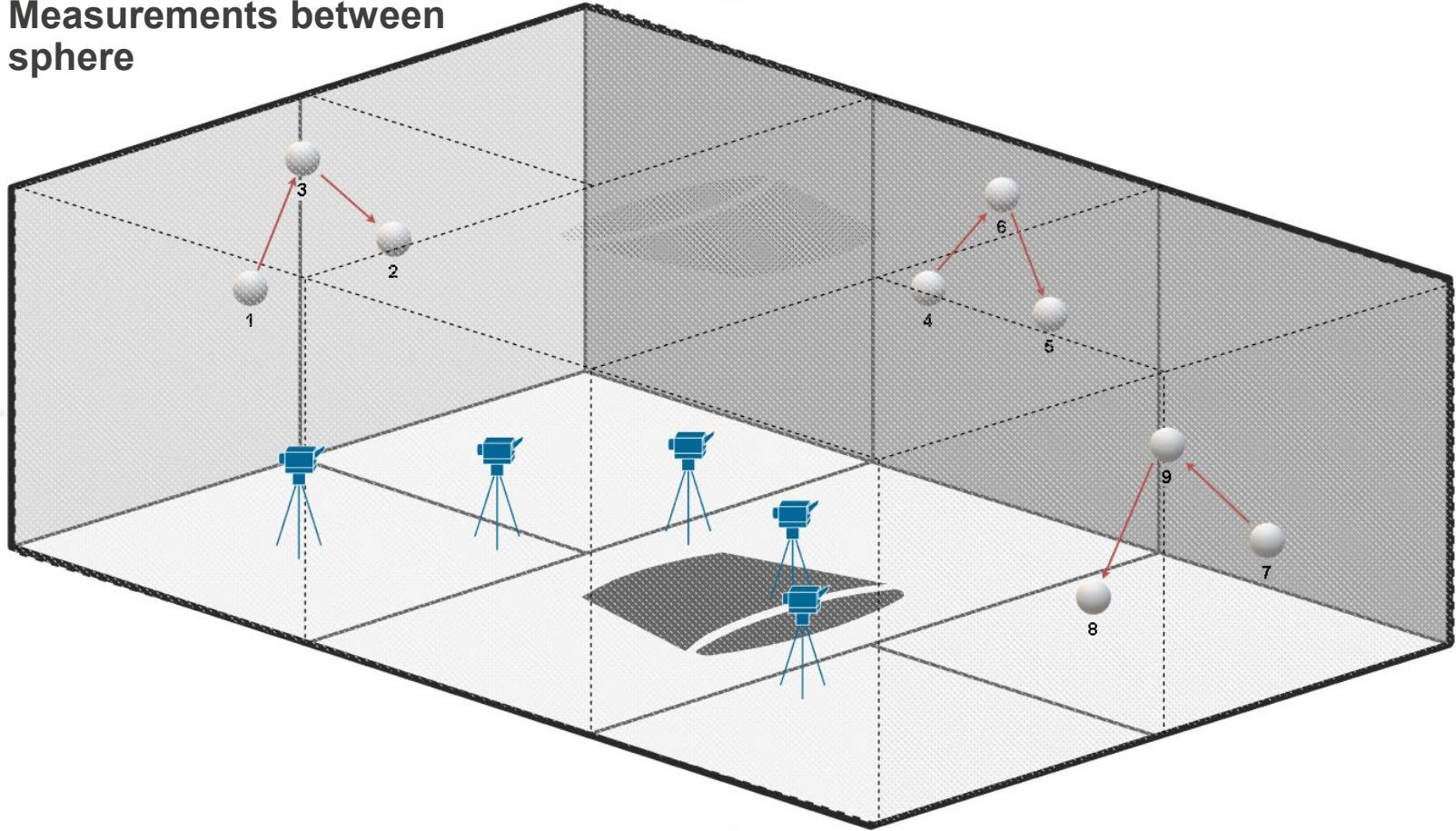


Room measurement uncertainty assessment

Camera used for image capture (Canon D200)



Measurements between sphere

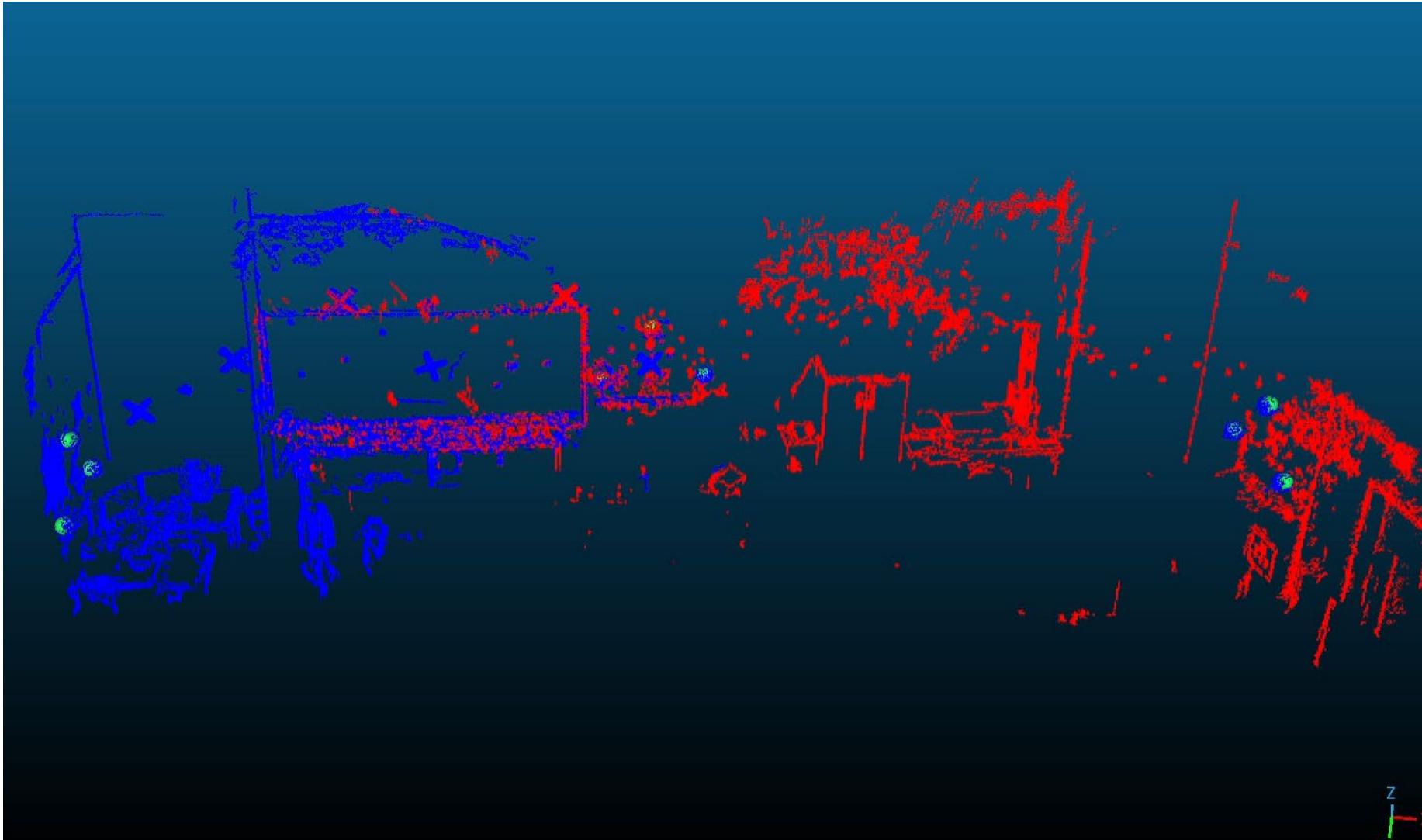


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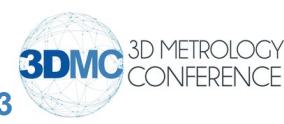
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Room measurement uncertainty assessment



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Room measurement uncertainty assessment

Sphere

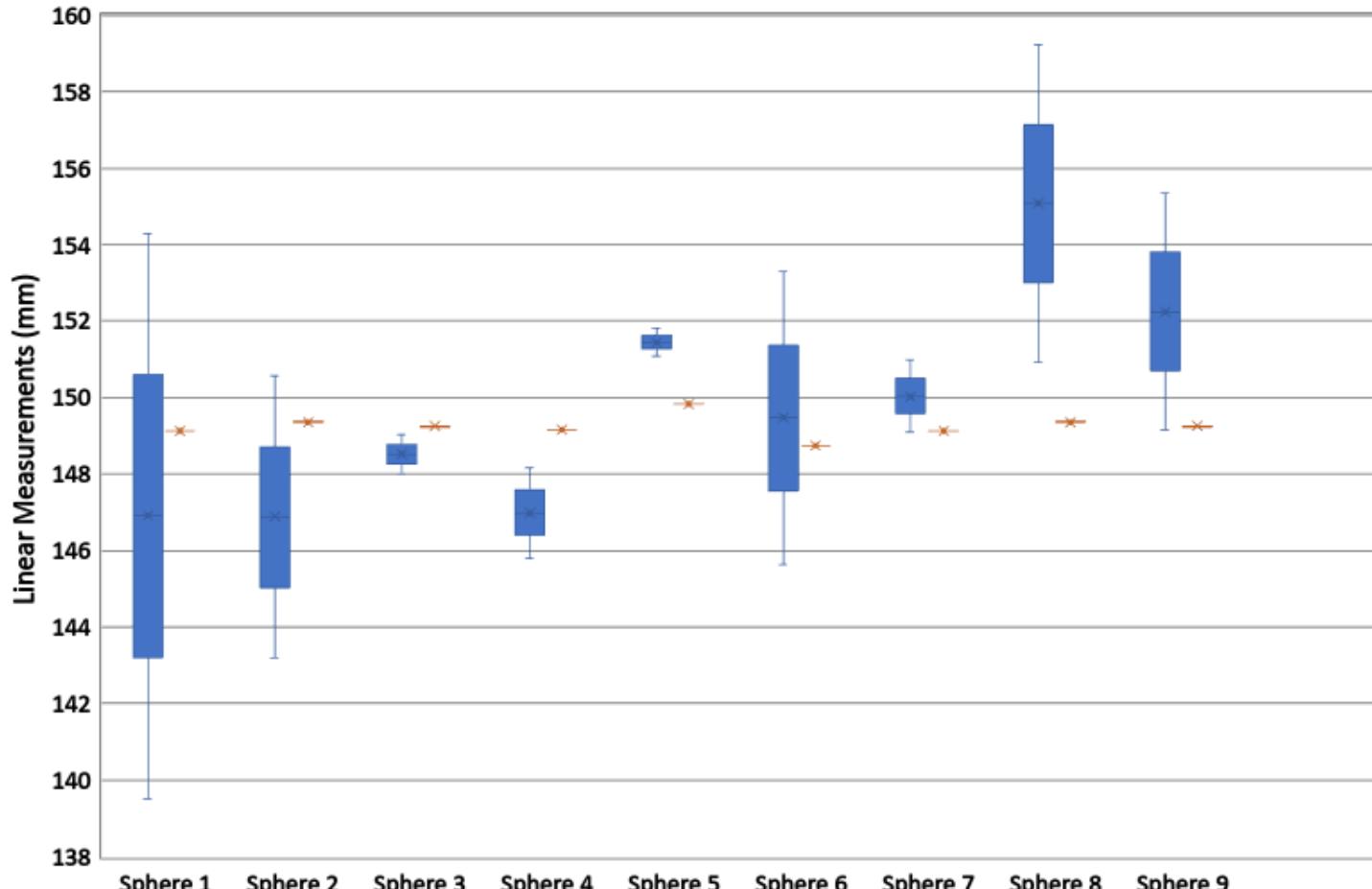


Measurement - Zeiss



Measurement Methods in Spheres

■ SfM ■ ZEISS PRISMO ULTRA CMM (Reference)



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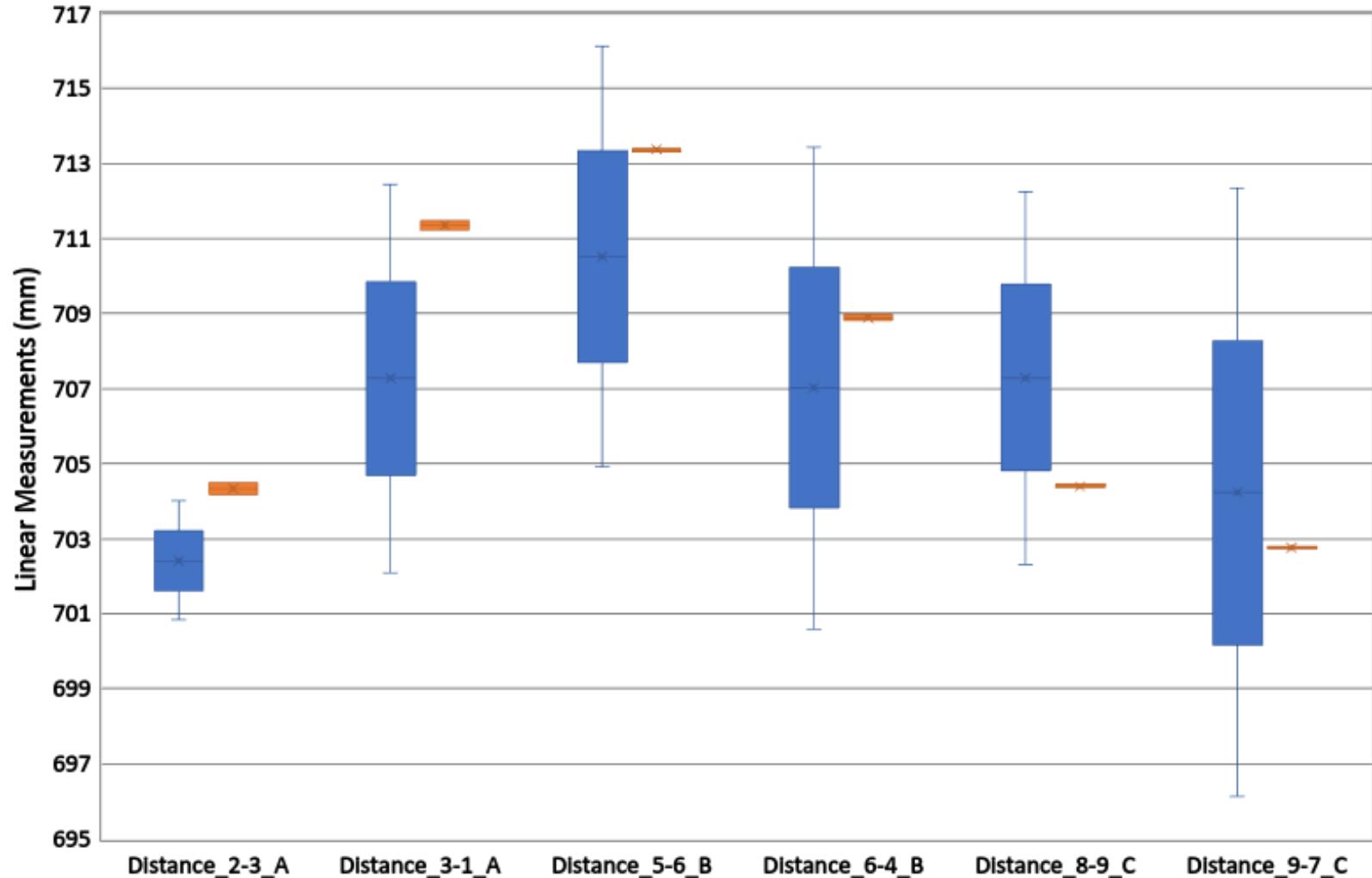
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Room measurement uncertainty assessment

Methods for Measuring Distances Between Sphere Centers in the Same Plane

■ SfM ■ Laser Traker LEICA + T-Scan (Reference)

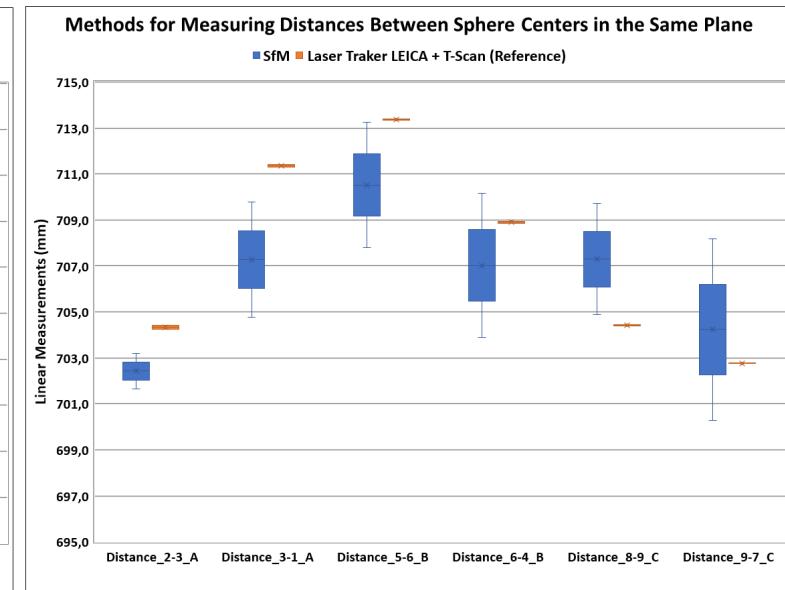
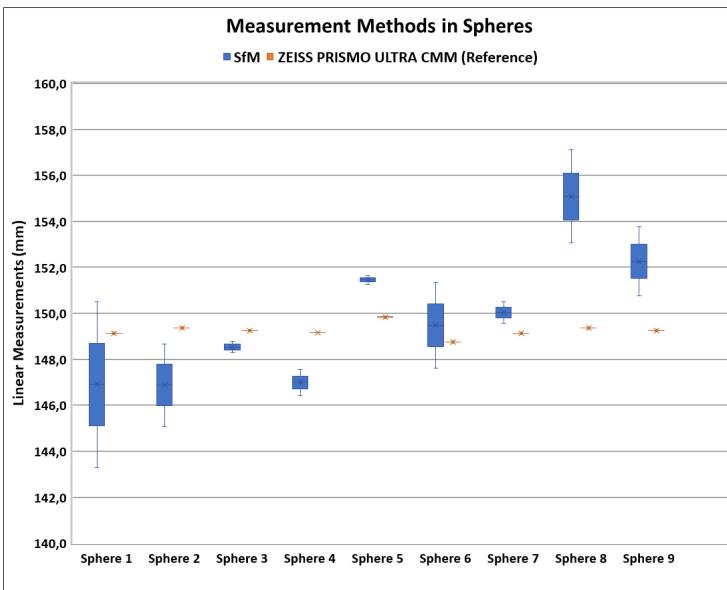
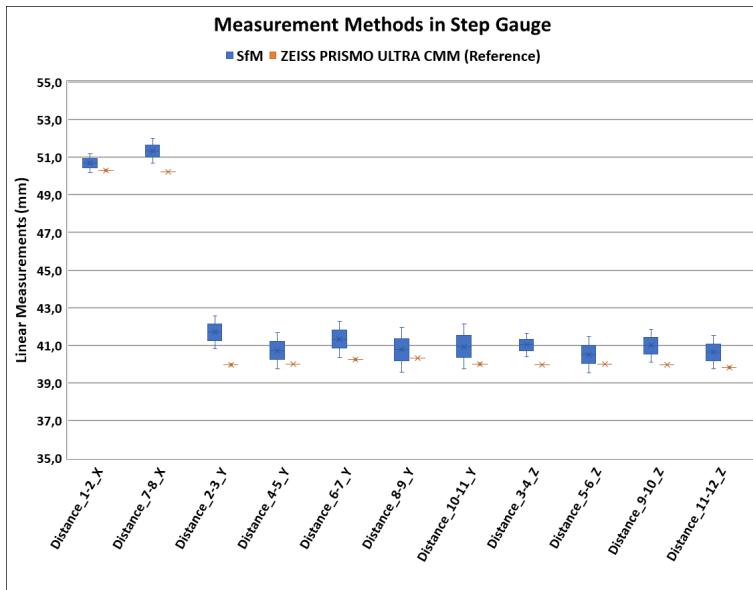


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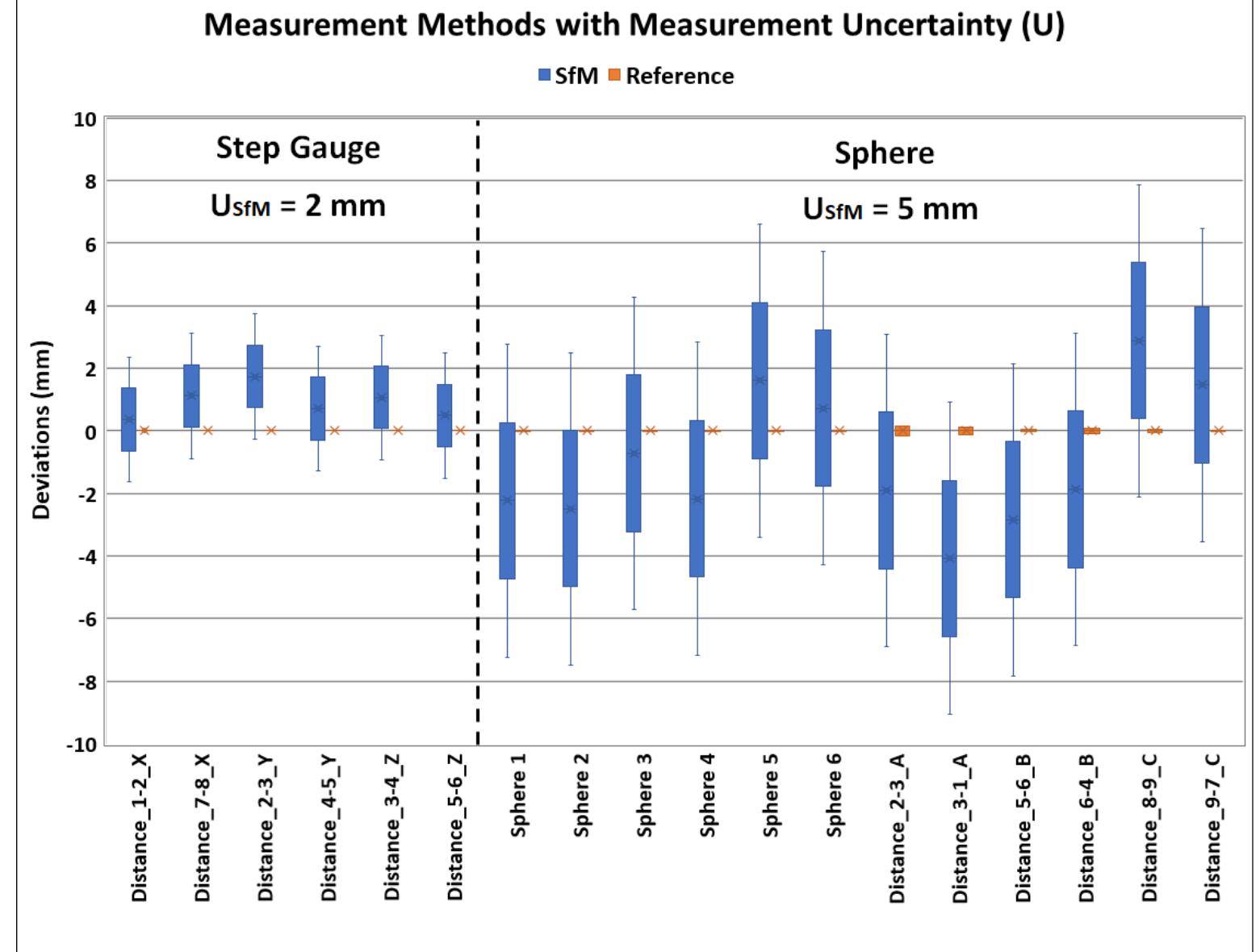
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Room measurement uncertainty assessment



Room measurement uncertainty assessment



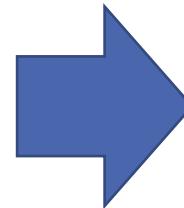
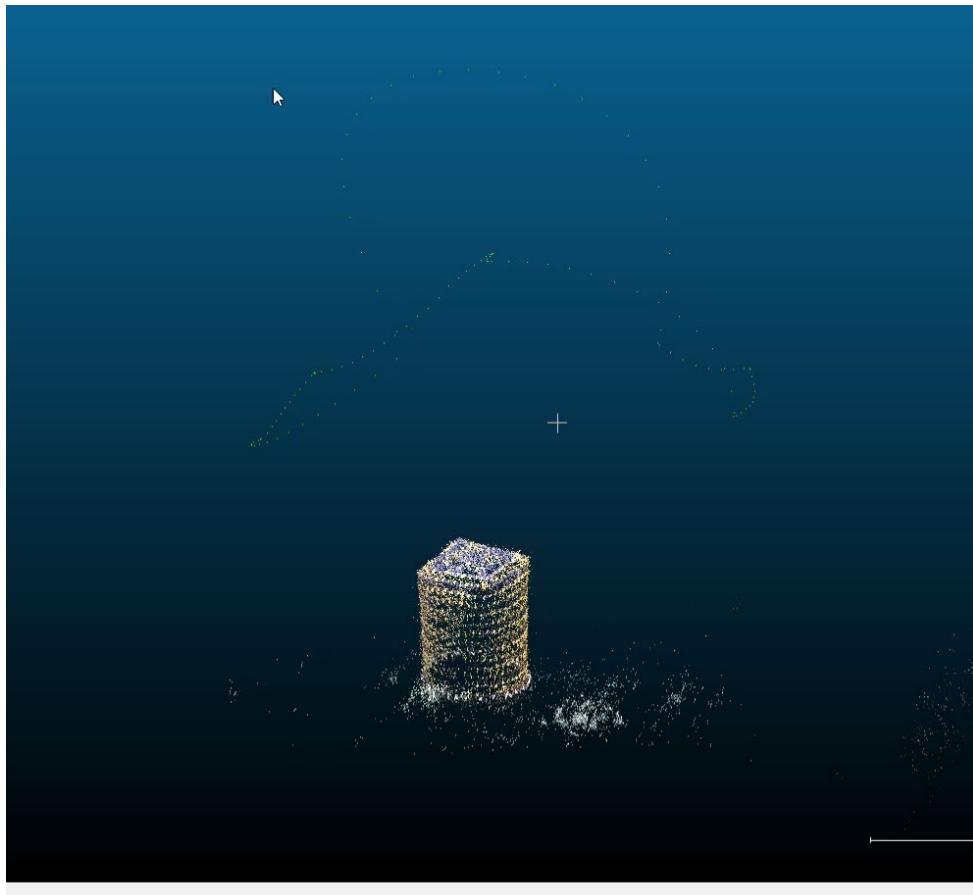
Advantage of objects with many characteristics

- OBJECT

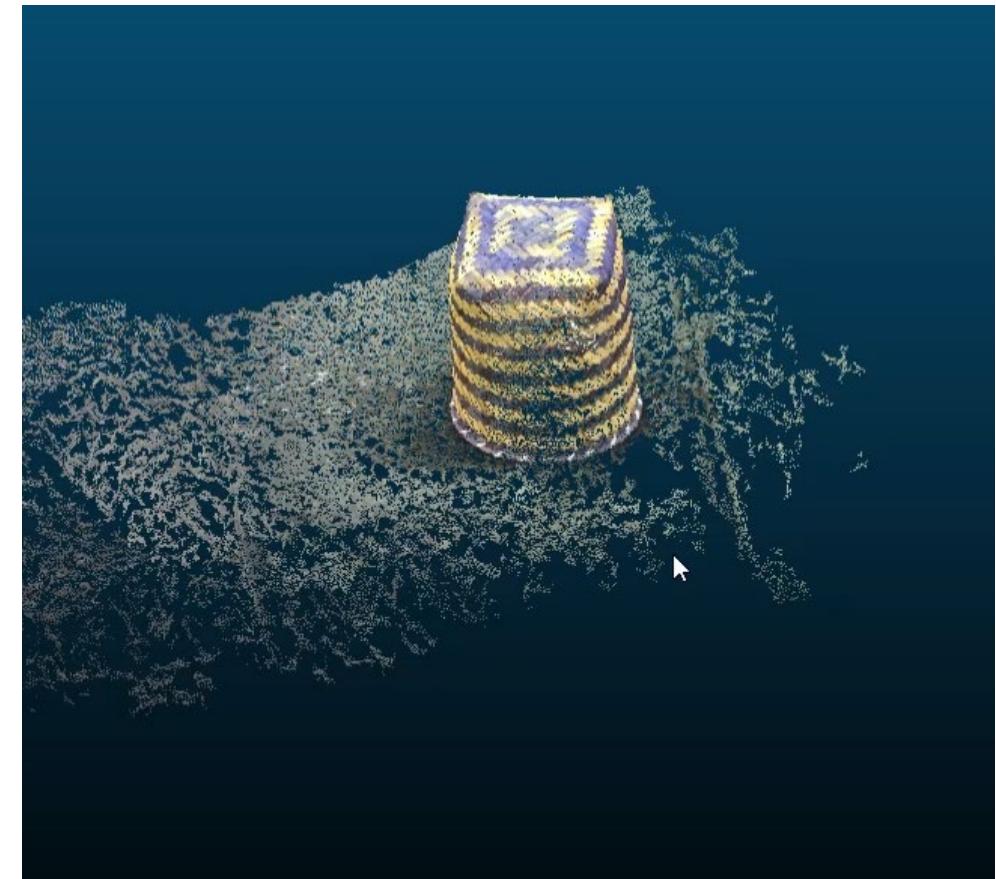


Results: Other tests

SfM



MVS



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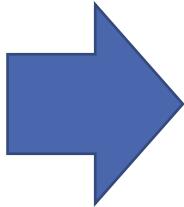
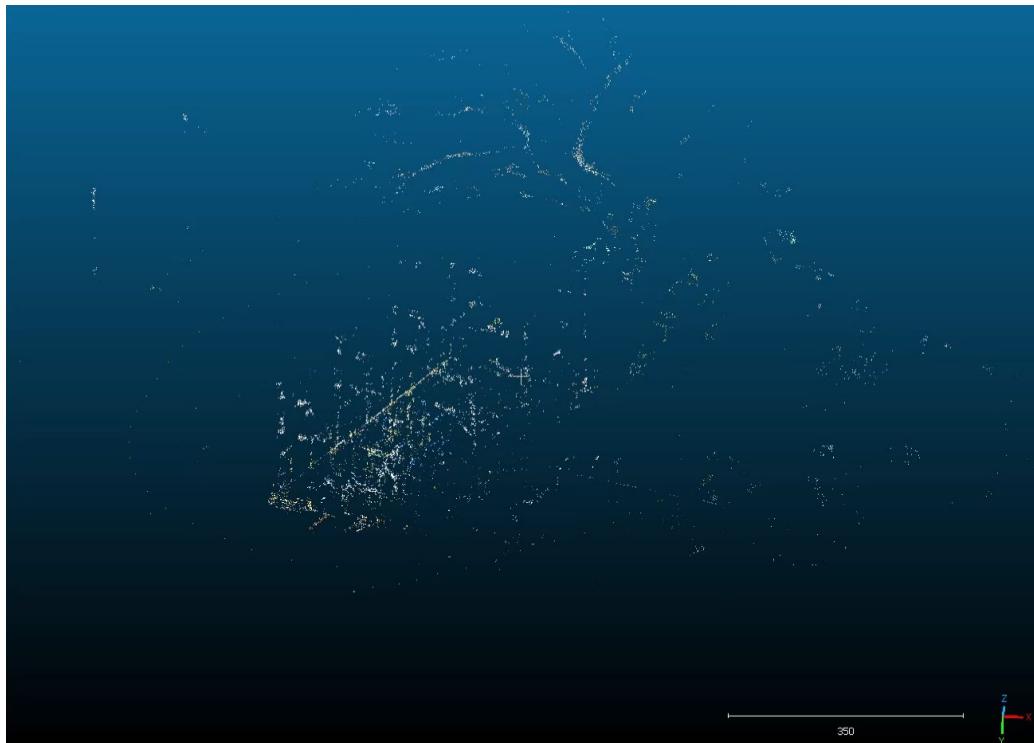
Reconstruction of external scenery

SCENE

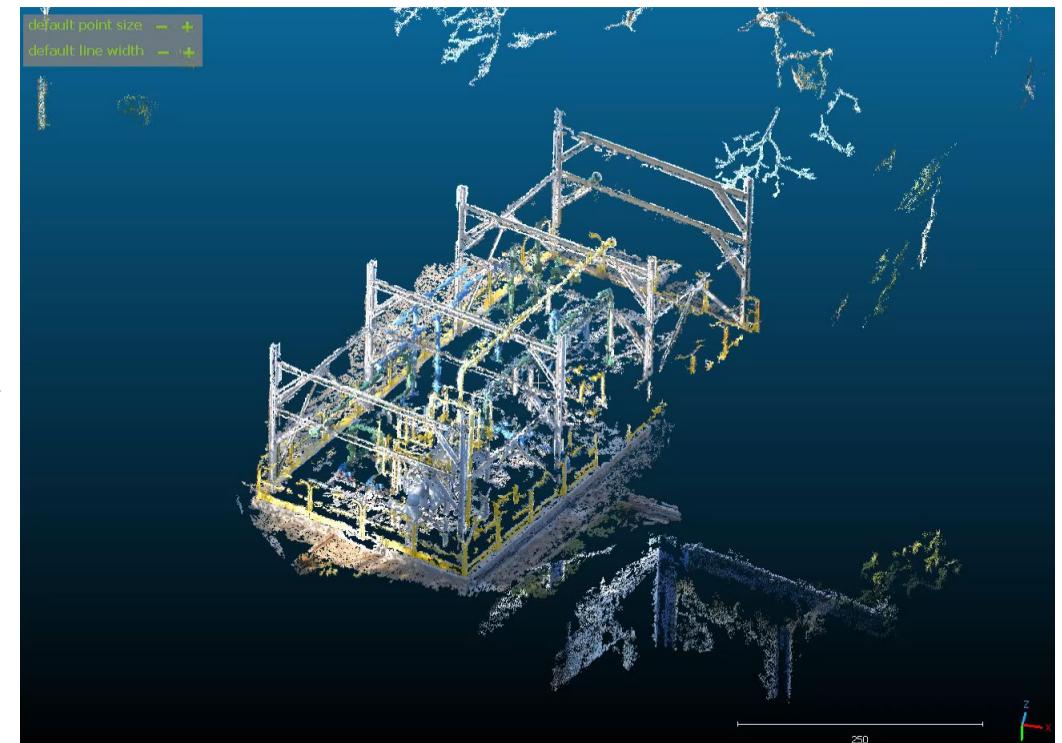


Results: Tests - Structure

SfM



MVS



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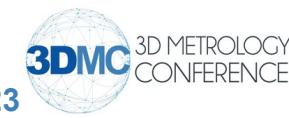
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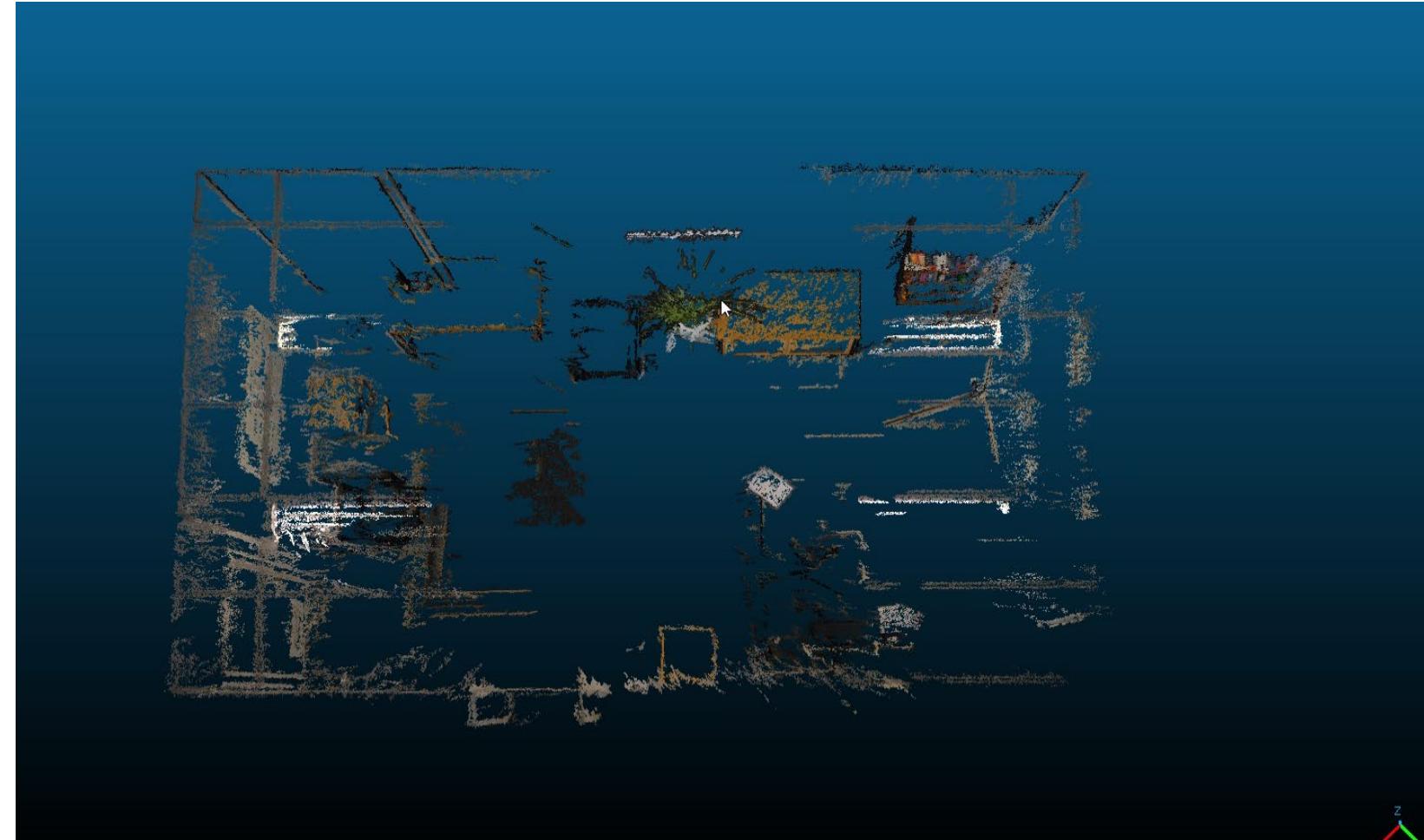
Room wall and door measurements



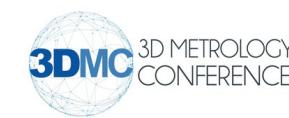
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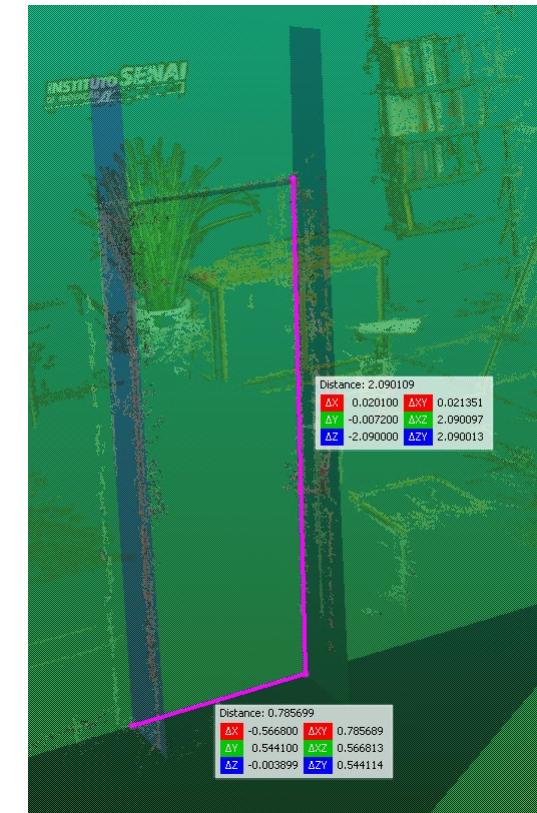
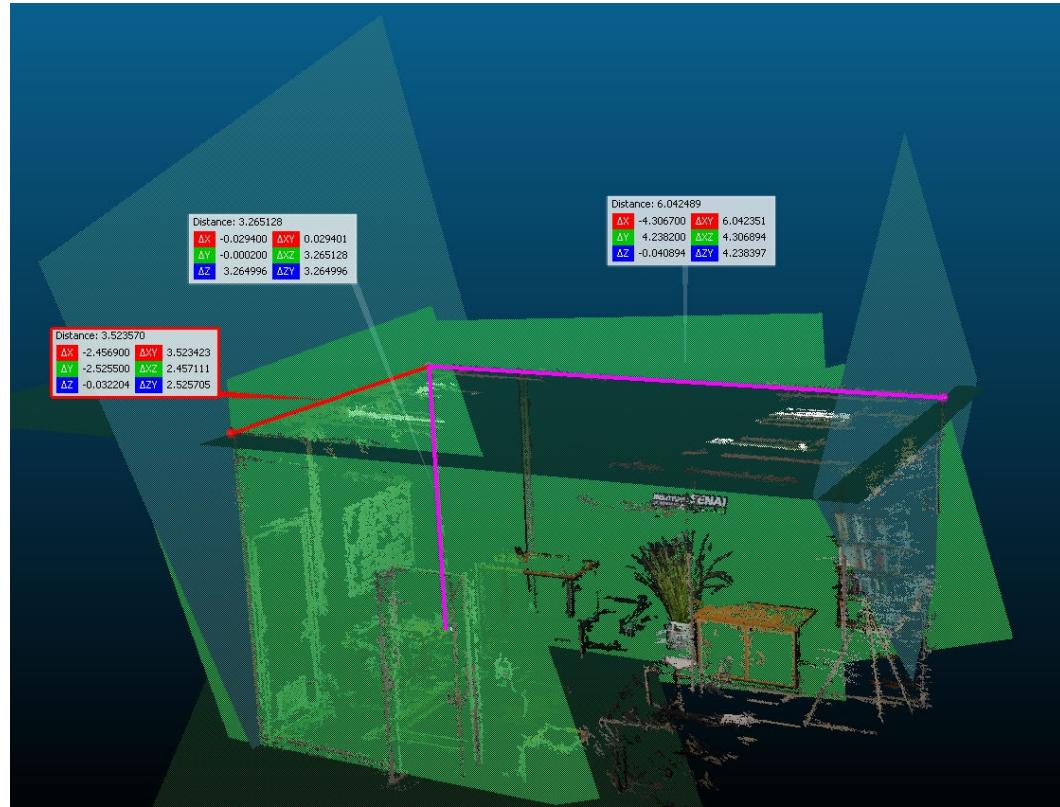
Room wall and door measurements



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Room wall and door measurements

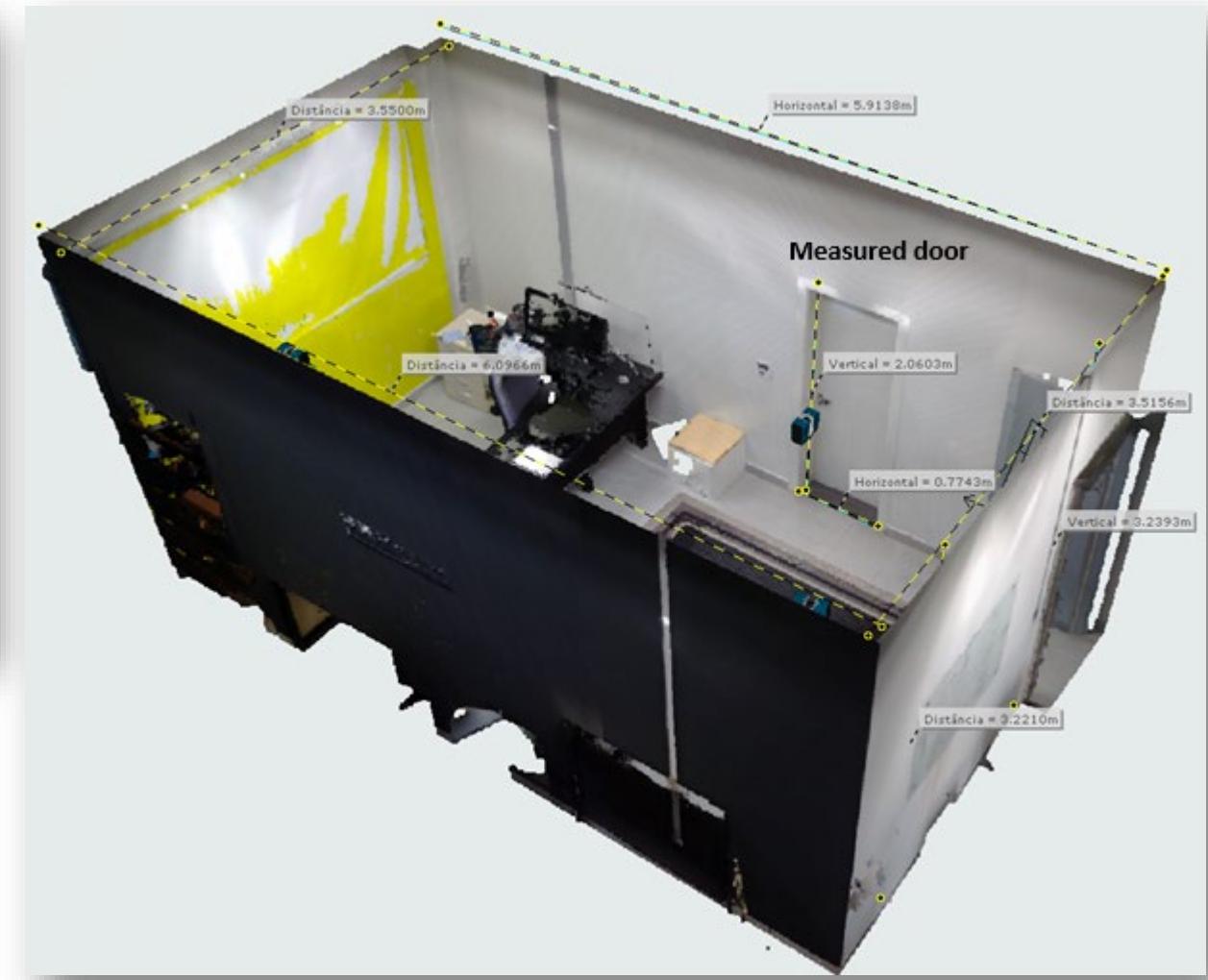
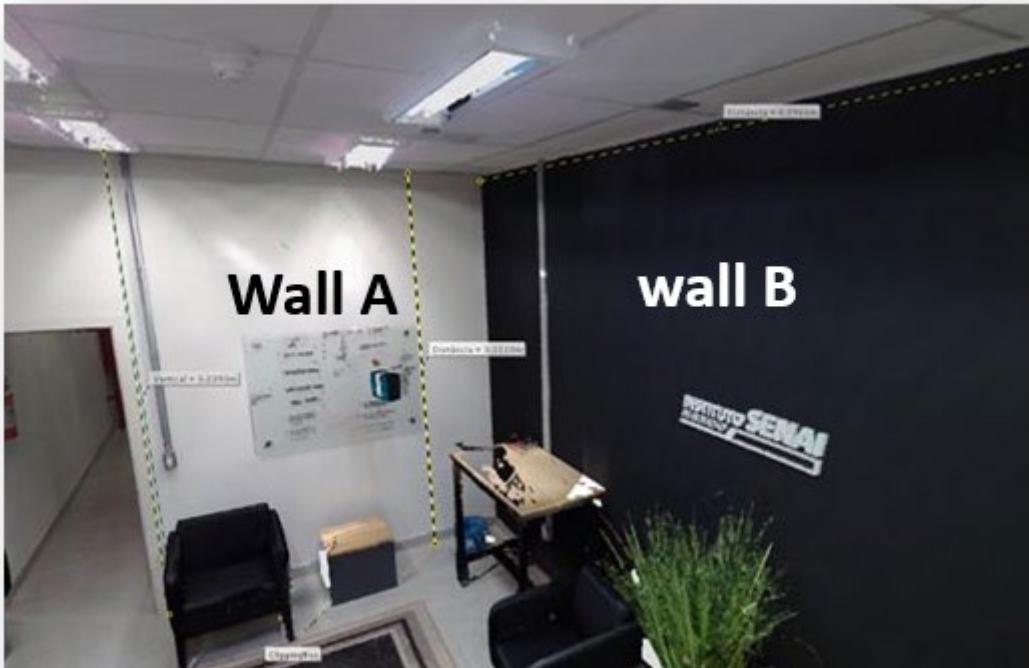


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Location of measurements

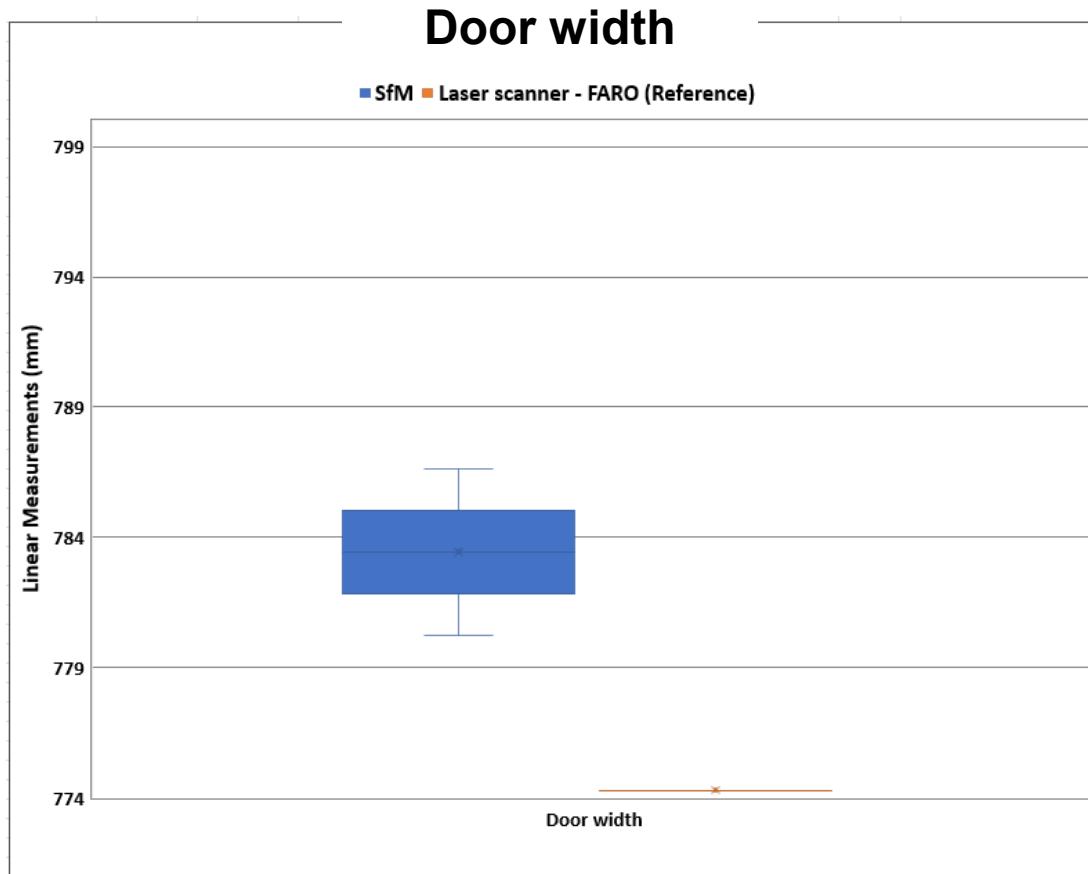


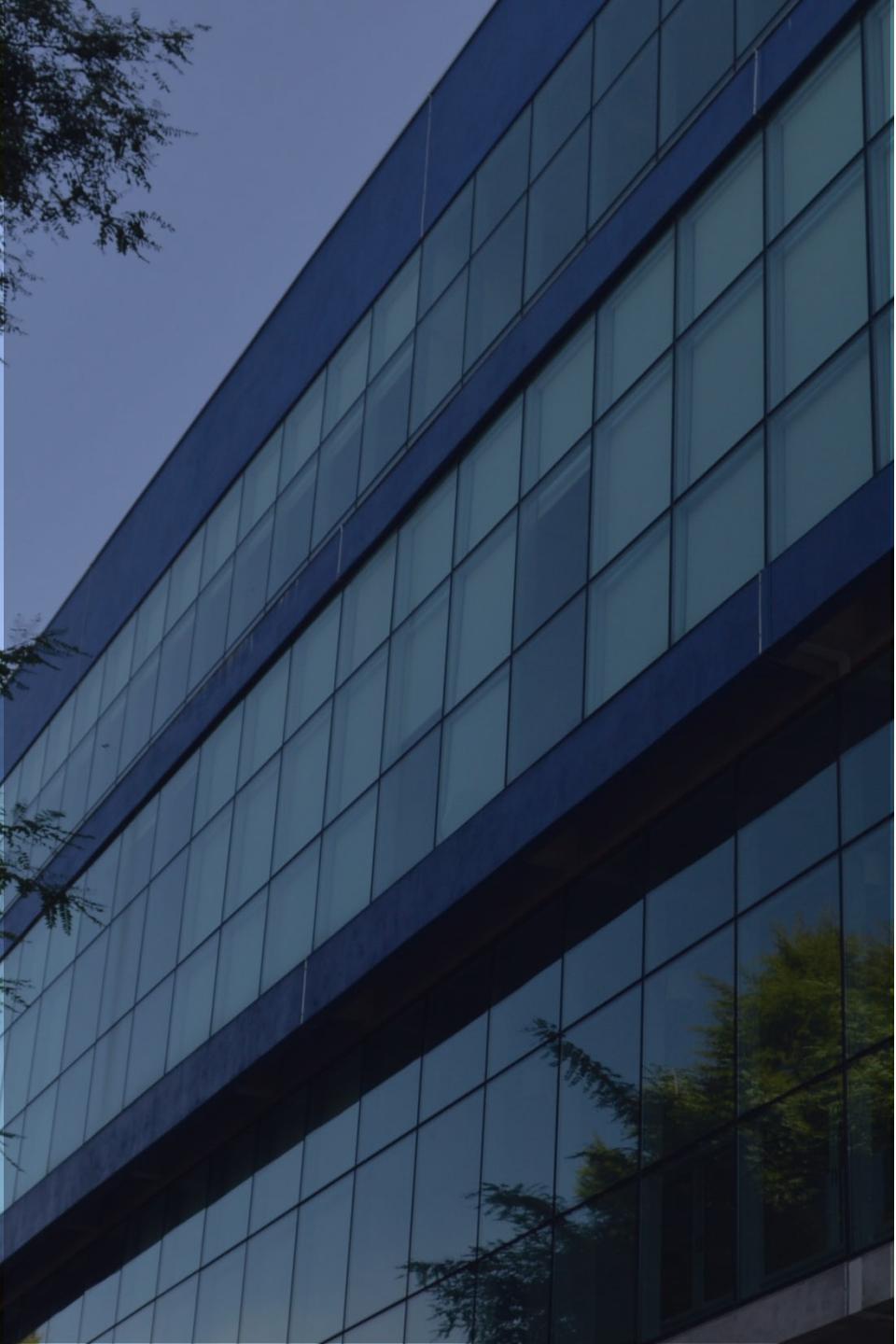
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Door measurements result



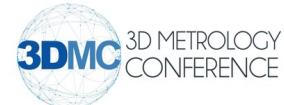


INSTITUTO SENAI DE INOVAÇÃO EM SOLUÇÕES INTEGRADAS EM METALMECÂNICA

Unidade EMBRAPII em Sistemas de Sensoramento

Unidade credenciada no Programa BNDES IoT (Internet of Things)

Dr. Eng. Vitor Nardelli
vitor.nardelli@senairs.org.br



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