Spatial augmented reality for human support in shipyards

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Context

1. Production of ships currently requires the operator to interpret CAD drawings and assembly documentation for knowing how and where to perform operations such as:
    i. Laying out the ship foundations and support structures.
    ii. Perform cutting and welding operations.
    iii. Assemble components, such as pipes, stiffeners, brackets, cable trays, among many others.
2. The interpretation of the drawings and documentation may lead to mistakes and the operator may perform an inaccurate measurement of the place of cutting, welding or assembly.
3. As such, augmented reality systems can help the operator work faster and with higher accuracy by projecting in the environment the spatial information required to perform the cutting, welding and assembly operations.

Examples of ship bulkheads.

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Overview of projection mapping system functionalities for shipbuilding

- Projects on the environment the cutting information that was extracted from CAD model for improving the productivity of the operator.
- Uses 3D perception to estimate the 6 DoF pose of the projector in relation to the target object in the environment.
- Avoids the usage of measuring tapes and printed drawings by the operator resulting in a reduction of operator marking time of around 70%.
- Human operator has both hands free to perform his tasks while he is observing the projected information to know where to cut the ship sections.

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Projection mapping for cut openings in silos

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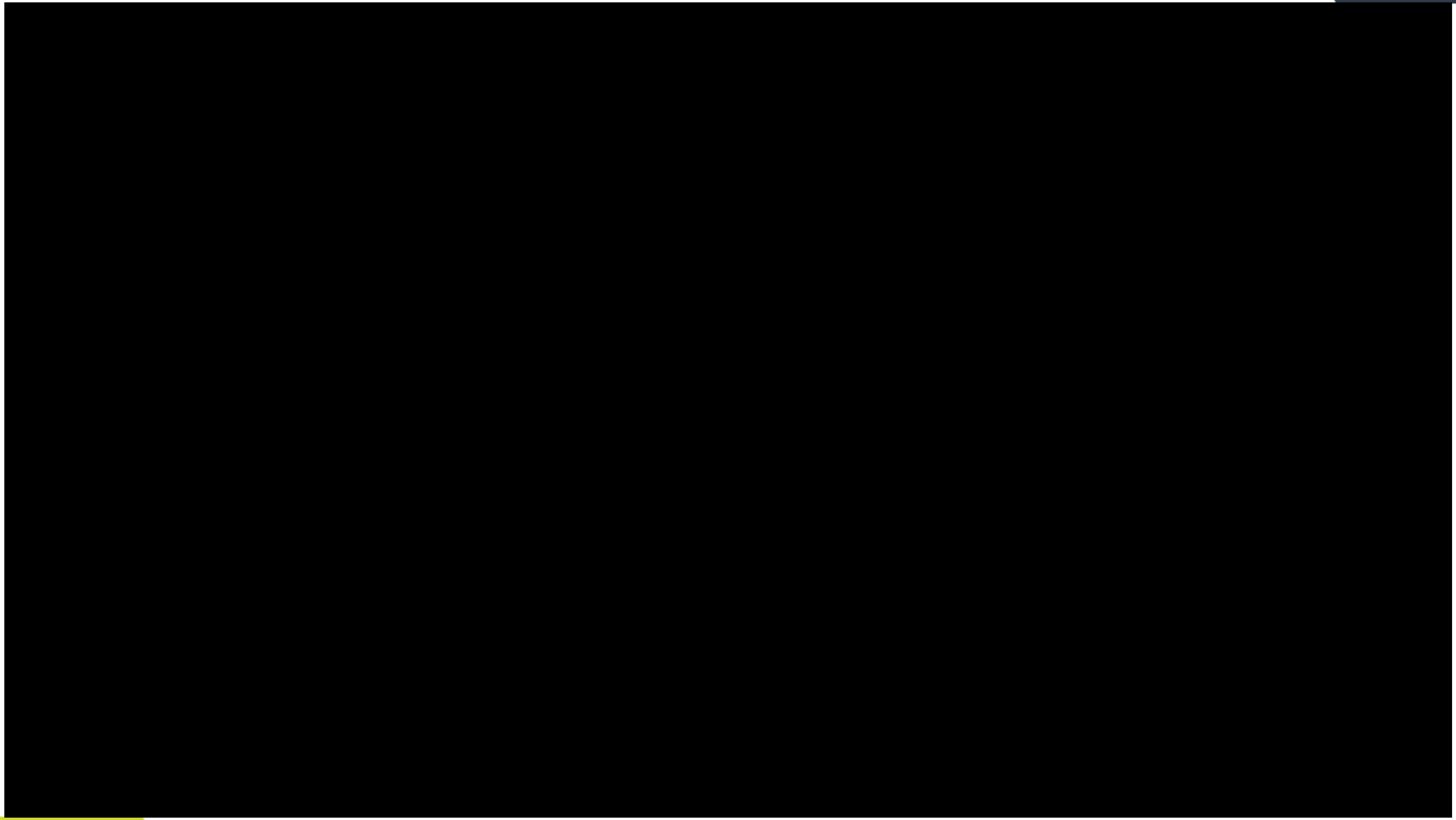
Projection mapping for tack welding of beam structures



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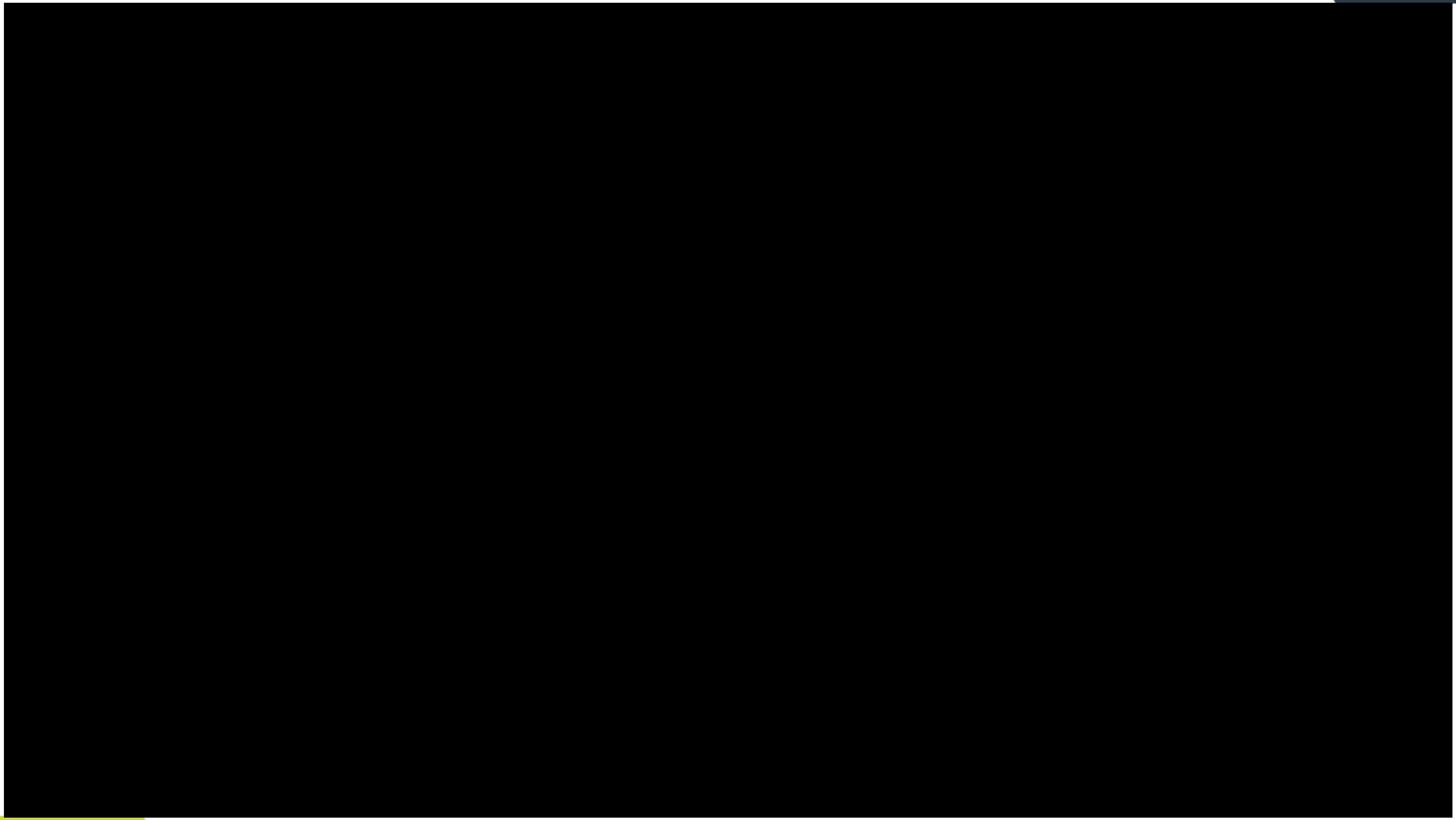
Projection mapping for assembly operations and Human-Machine interface



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Overview of main stages required for performing projection mapping

Calibration

Estimation of the intrinsic and extrinsic parameters of the projector and the 3D sensor.

Required for modeling the projection and sensing hardware and known the spatial relation between them.

3D sensing and perception

Estimation of the relative translation and rotation between the target object and the 3D sensor and projector.

Required for rendering the target object from the correct perspective.

Rendering and projection

Generation of the projection image with the target information retrieved from the CAD model along with other metadata.

Spatial dimensions are critical for cutting and welding tasks.

Intuitive instructions are critical for assembly tasks.

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Calibration of intrinsic and extrinsic parameters of projector and camera

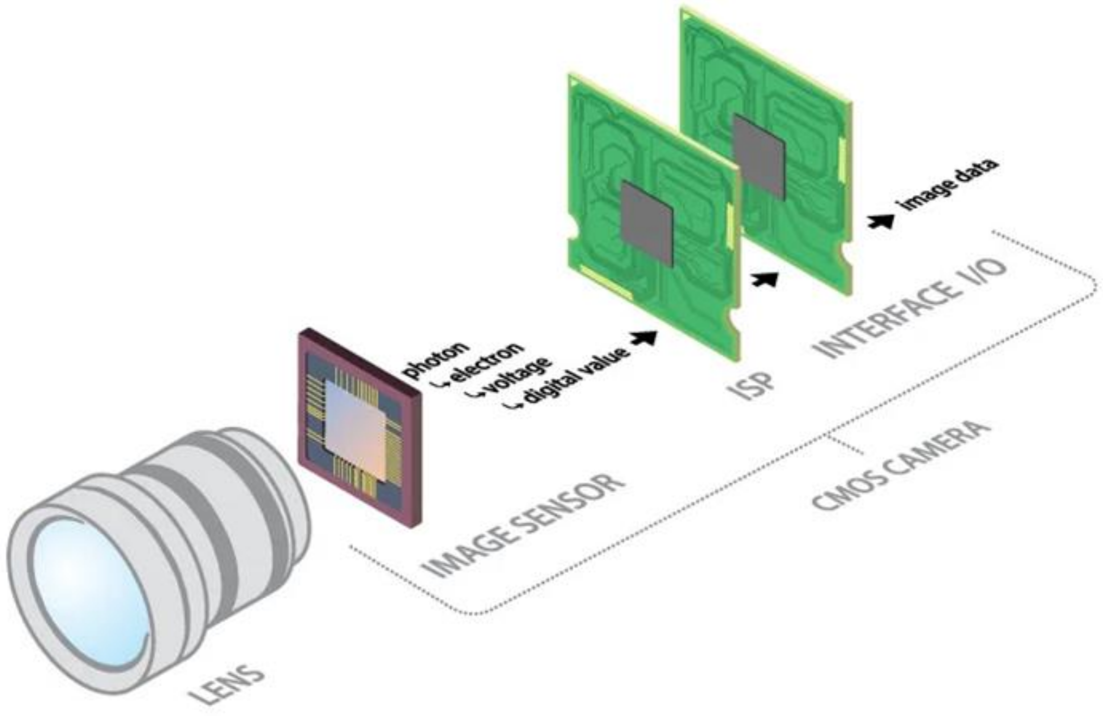

Diagram of a digital camera with the lens, CMOS image sensor and boards to process and transfer the data.

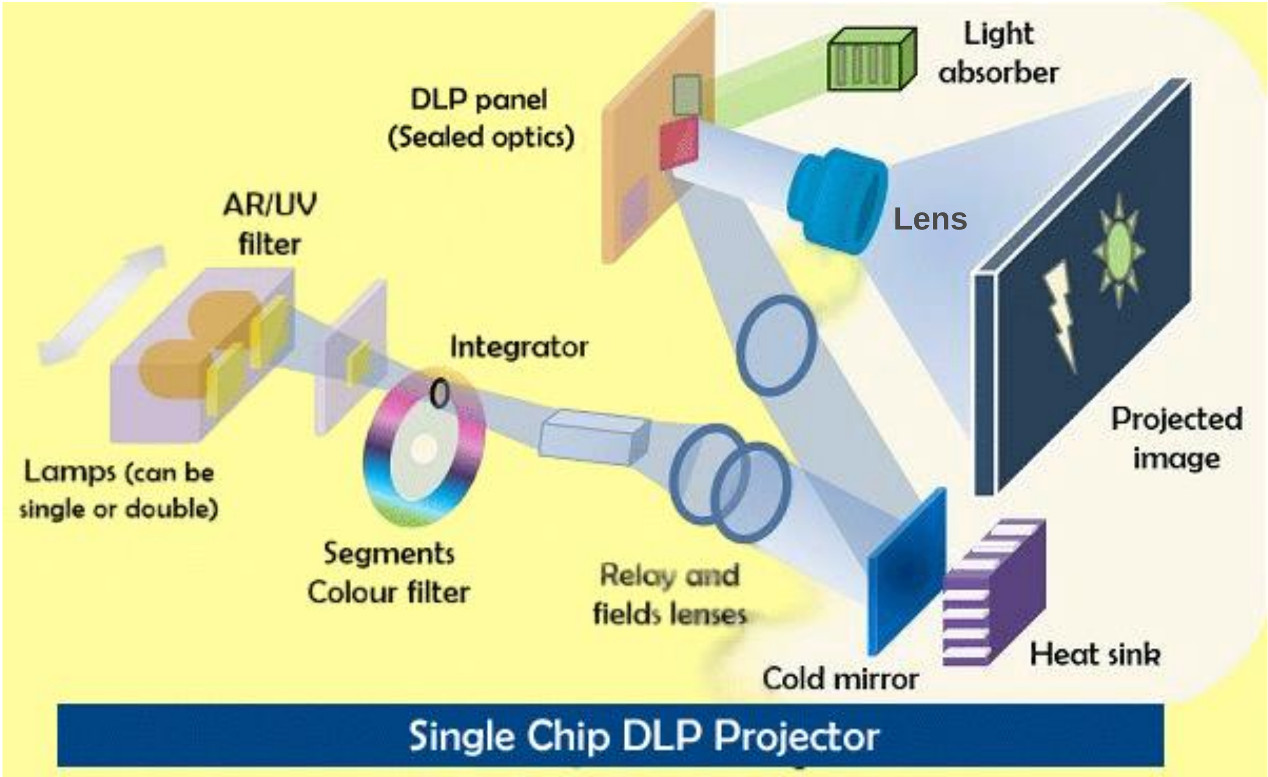

Diagram of a projector with the light source, color wheel, mirror, DMD ship and lens.

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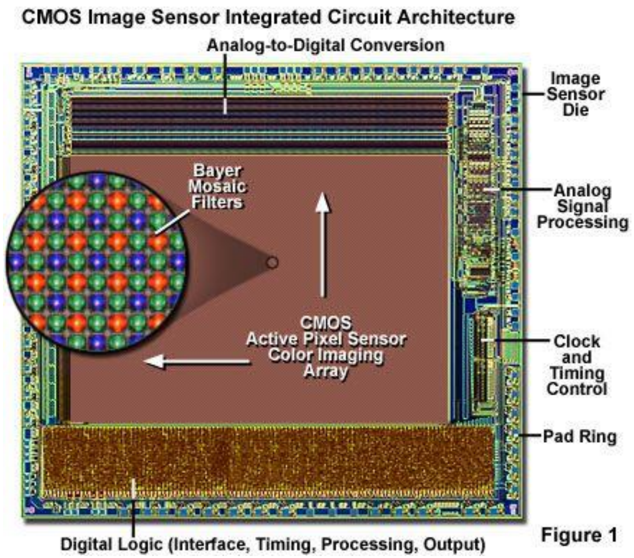
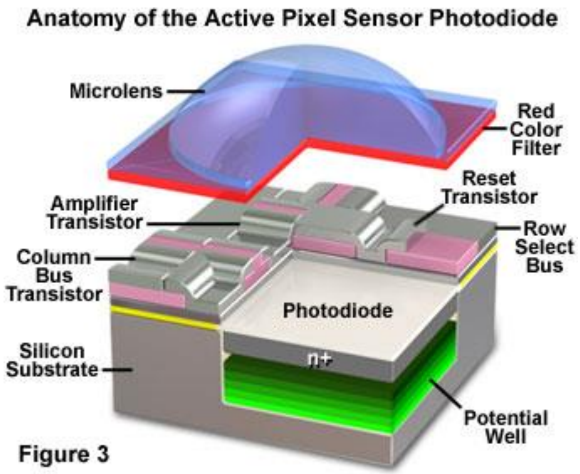
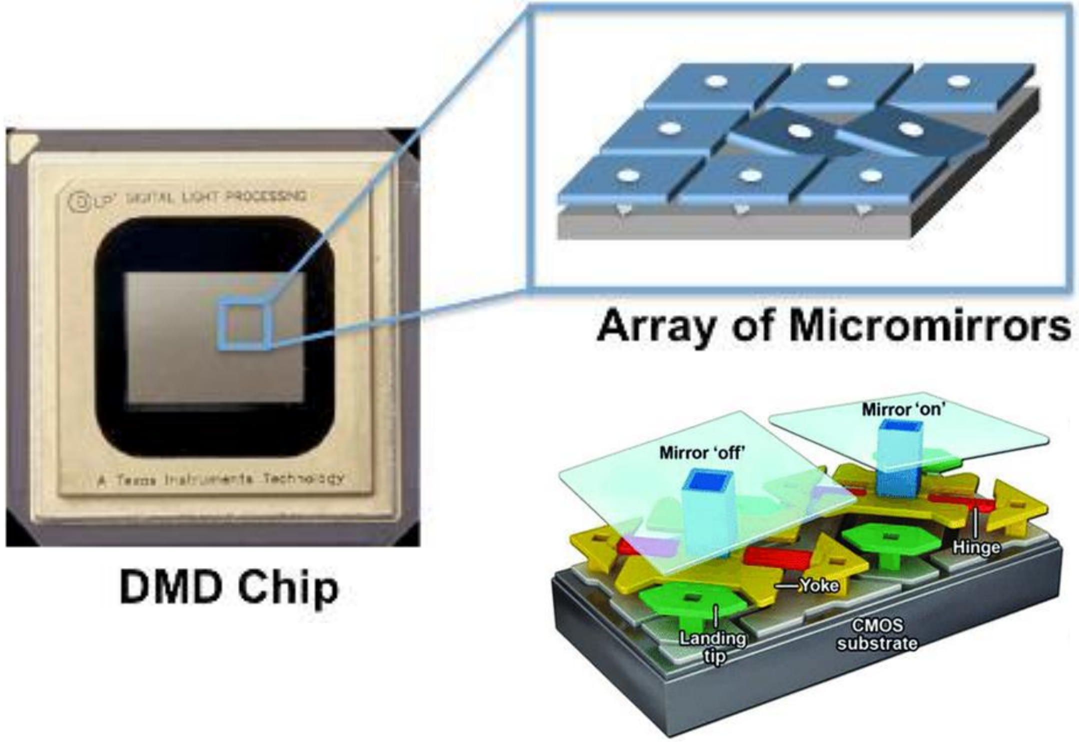
Calibration of intrinsic and extrinsic parameters of projector and camera



Camera CMOS sensor.



CMOS pixel photodiode that **captures** light.



Projector DMD chip and example of the mirror that **reflects** the light associated with each pixel.

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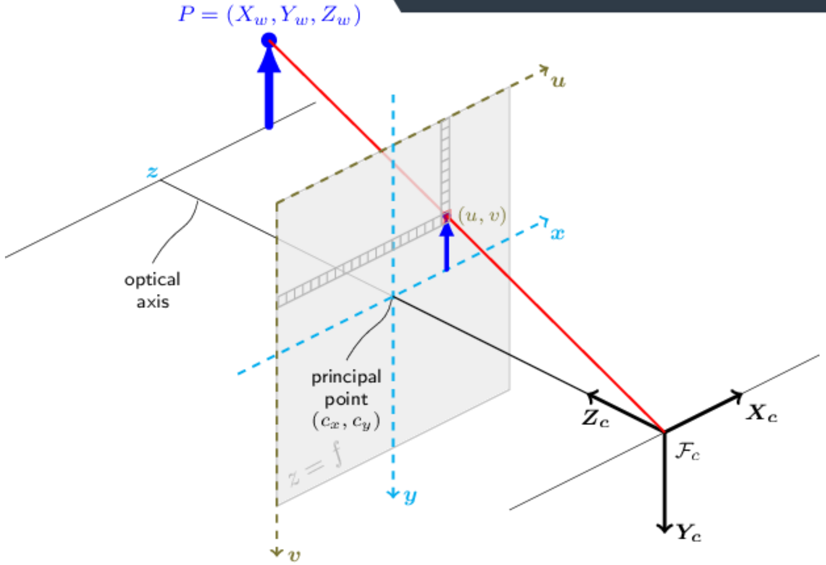
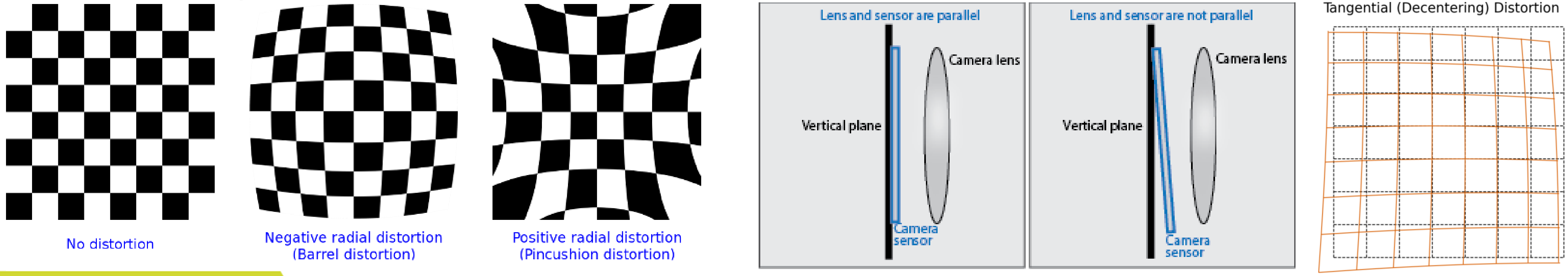
Calibration of intrinsic and extrinsic parameters of projector and camera

1. For accurately projecting information into the environment, it is necessary to model and simulate the projector hardware inside the 3D virtual world that has the CAD models and then render the projection images that will contain the marking information.

2. A projector can be considered as an inverse camera, in which it projects light through a lens instead of capturing it, and as such, for calibrating a projector it can be used the same mathematical models and software (OpenCV) for estimating the intrinsic parameters (focal lengths, principal point and lens distortion correction parameters) and extrinsic parameters (rotation and translation between the projector and the camera).



Pinhole camera model.



Examples of lens distortion.

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Calibration of intrinsic and extrinsic parameters of projector and camera

1. The camera intrinsic parameters (fx, fy, cx, cy) along with the radial (k1, k2, k3, k4, k5, k6) and tangential (p1, p2) lens distortion parameters can be computed using cv::calibrateCamera.
2. The calibration requires the detection of a 2D pattern and the associated 3D points.
3. For the camera, the 3D points are created based on the physical dimensions of the printed asymmetric circles pattern.
4. For the projector, the 3D points are computed using a ray-plane intersection algorithm, in which every projected circle center detected in the camera image is projected into the 3D plane of the physical pattern. For doing this step, the camera must be calibrated before the projector and then the rvecs and tvecs parameters returned by cv::calibrateCamera can be used to create the plane equation for each observed physical pattern.

$$A = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

Intrinsic parameters.

$$\begin{bmatrix} x'' \\ y'' \end{bmatrix} = \begin{bmatrix} x' \frac{1+k_1 r^2+k_2 r^4+k_3 r^6}{1+k_4 r^2+k_5 r^4+k_6 r^6} + 2p_1 x' y' + p_2(r^2 + 2x'^2) \\ y' \frac{1+k_1 r^2+k_2 r^4+k_3 r^6}{1+k_4 r^2+k_5 r^4+k_6 r^6} + p_1(r^2 + 2y'^2) + 2p_2 x' y' \end{bmatrix}$$

Radial and tangential lens distortion parameters.

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}$$

Extrinsic parameters.

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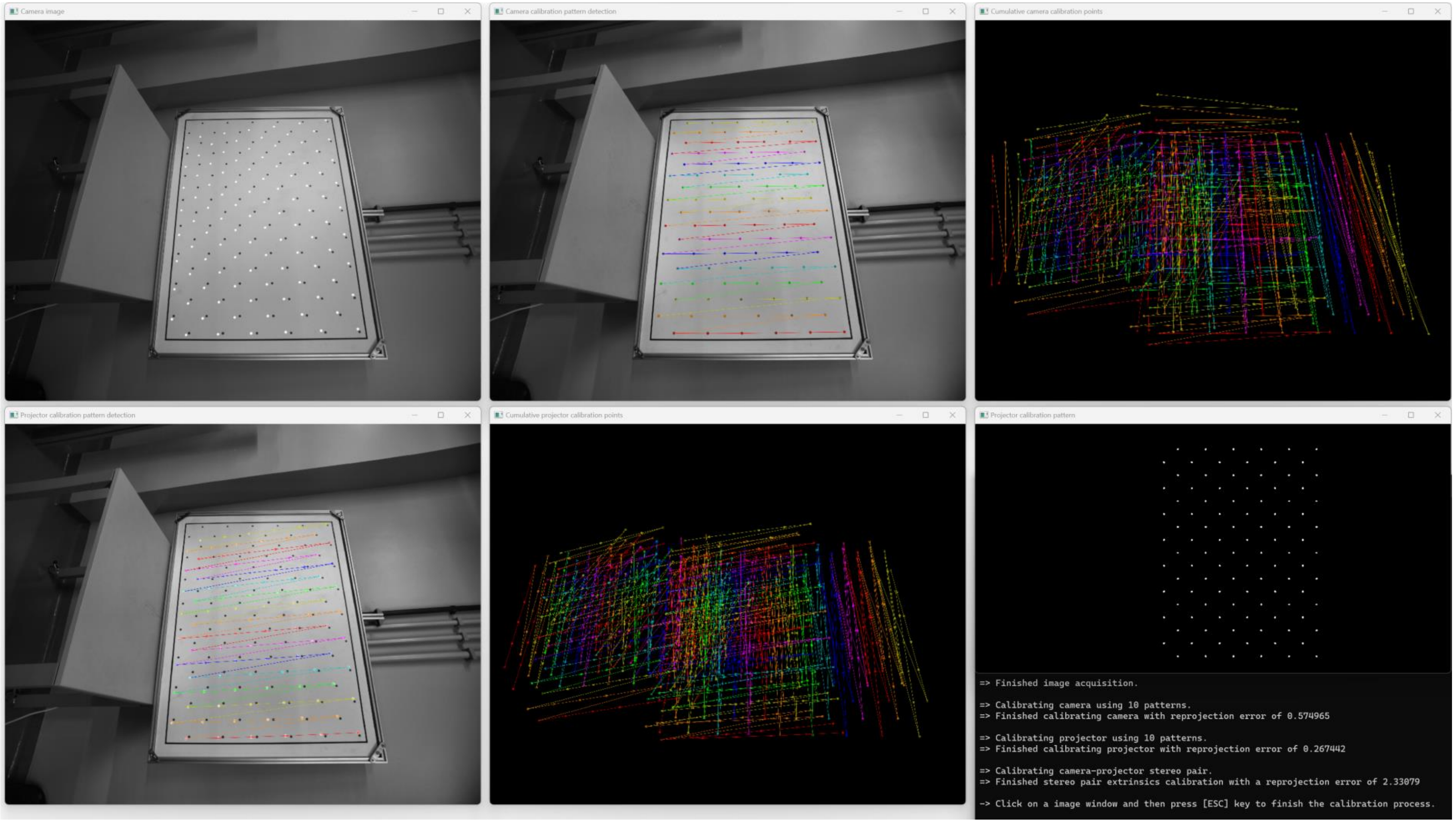
Calibration of intrinsic and extrinsic parameters of projector and camera



User interface with the detection of the printed and projected asymmetric circles patterns for calibrating the projector and the Mako G-507C camera.

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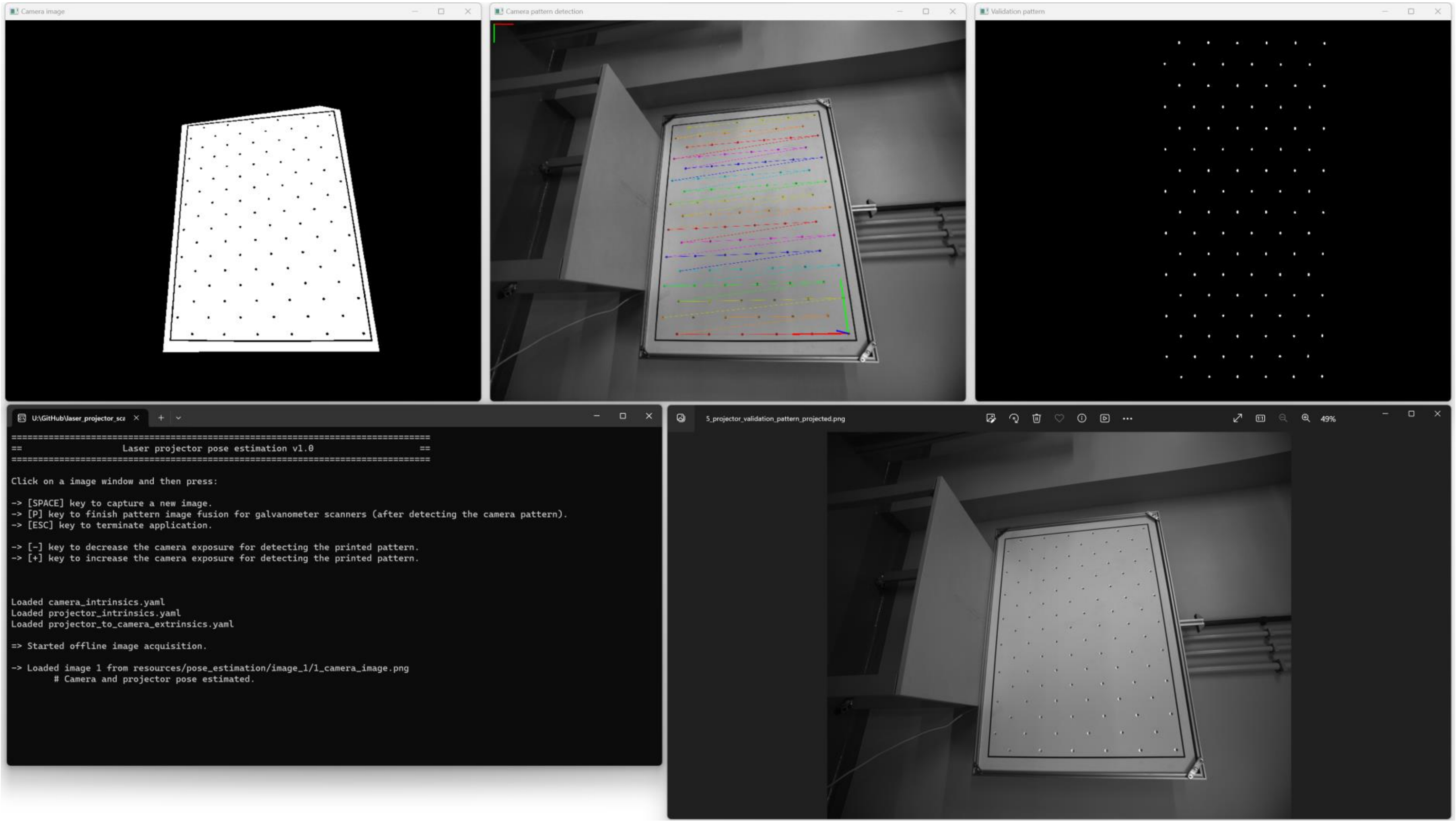
Validation of calibration



User interface for estimating the pose of a pattern and then create a validation image created using the intrinsic and extrinsic parameters for being projected for validating and evaluating the calibration.

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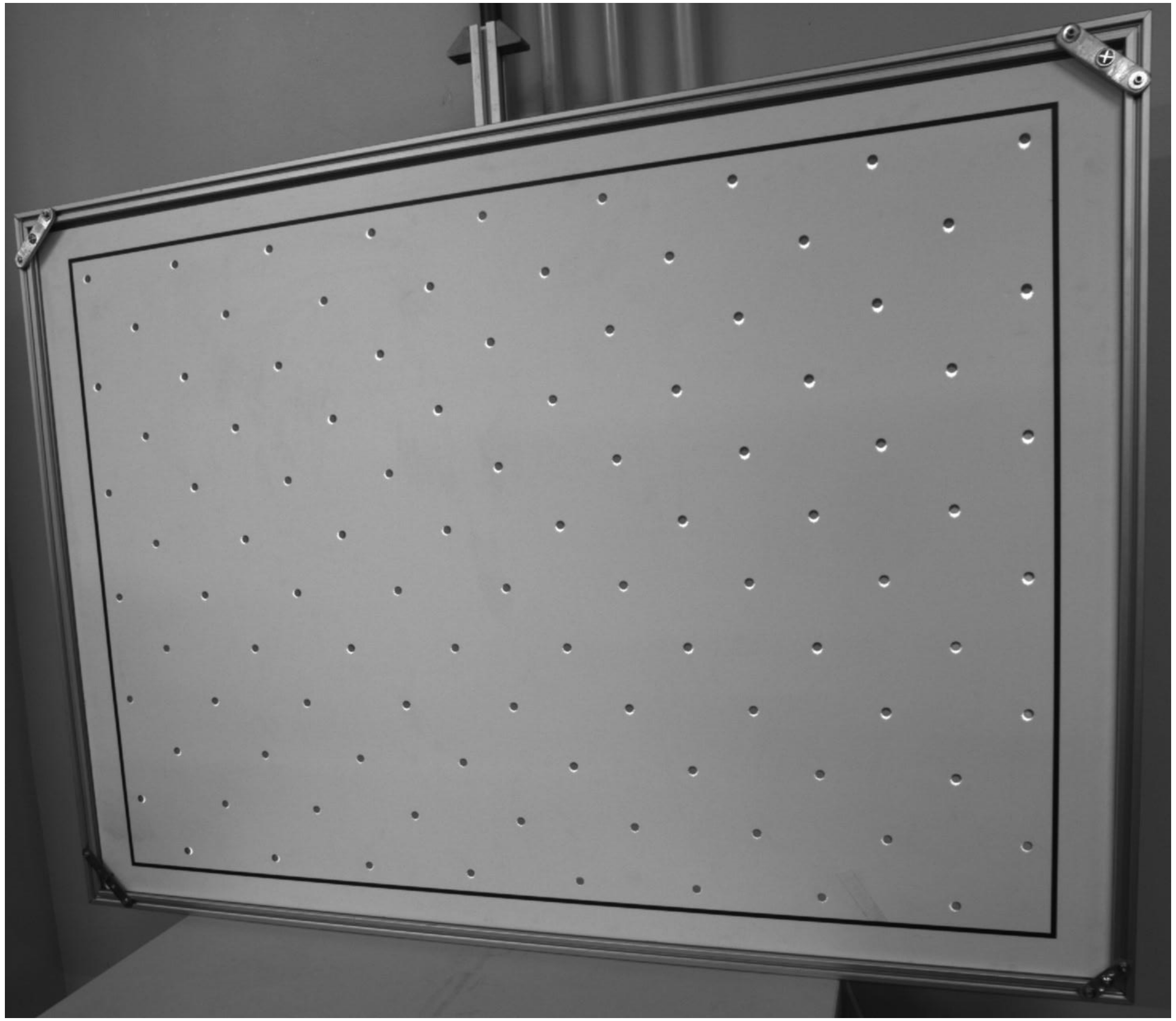
Validation of calibration



Validation image projected into the printed pattern, in which the projected white circles had an error below 4.5 mm in relation to the center of the black printed circles (which have a diameter of 9 mm).

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Calibration of extrinsics parameters between projector and 3D sensor

1. In order to use the 6 DoF pose computed using ICP from the 3D sensor data (for setting the projector pose within the virtual world that has the CAD models), it is necessary to calibrate the 3D rotation and 3D translation between the 3D sensor and the projector.
2. The 3D rotation and 3D translation extrinsic parameters between the 2 cameras can be computed using cv::stereoCalibrate, which receives as input, several pairs of images captured from the Mako G-507C camera (that was used to calibrate the projector) and the 2D camera image from the 3D sensor (RGB sensor in the case of the Asus Xtion Pro Live).
3. The Mako G-507C was used to calibrate the projector instead of the RGB camera from the Asus Xtion Pro Live, because the Mako G-507C has a much higher resolution (2464x2056), which results in better calibration of the projector. After calibration, the Mako G-507C can be removed from the projection platform, which only needs the projector and the 3D sensor to operate.
4. For improving the factory calibration of the Asus Xtion Pro Live, the intrinsic and extrinsic parameters of the RGB and IR cameras were calibrated using the software presented previously.
5. The images were captured with the maximum resolution supported by the sensor, which is 1280x1024.
6. The projection and rectification matrices were computed using cv::stereoRectify.

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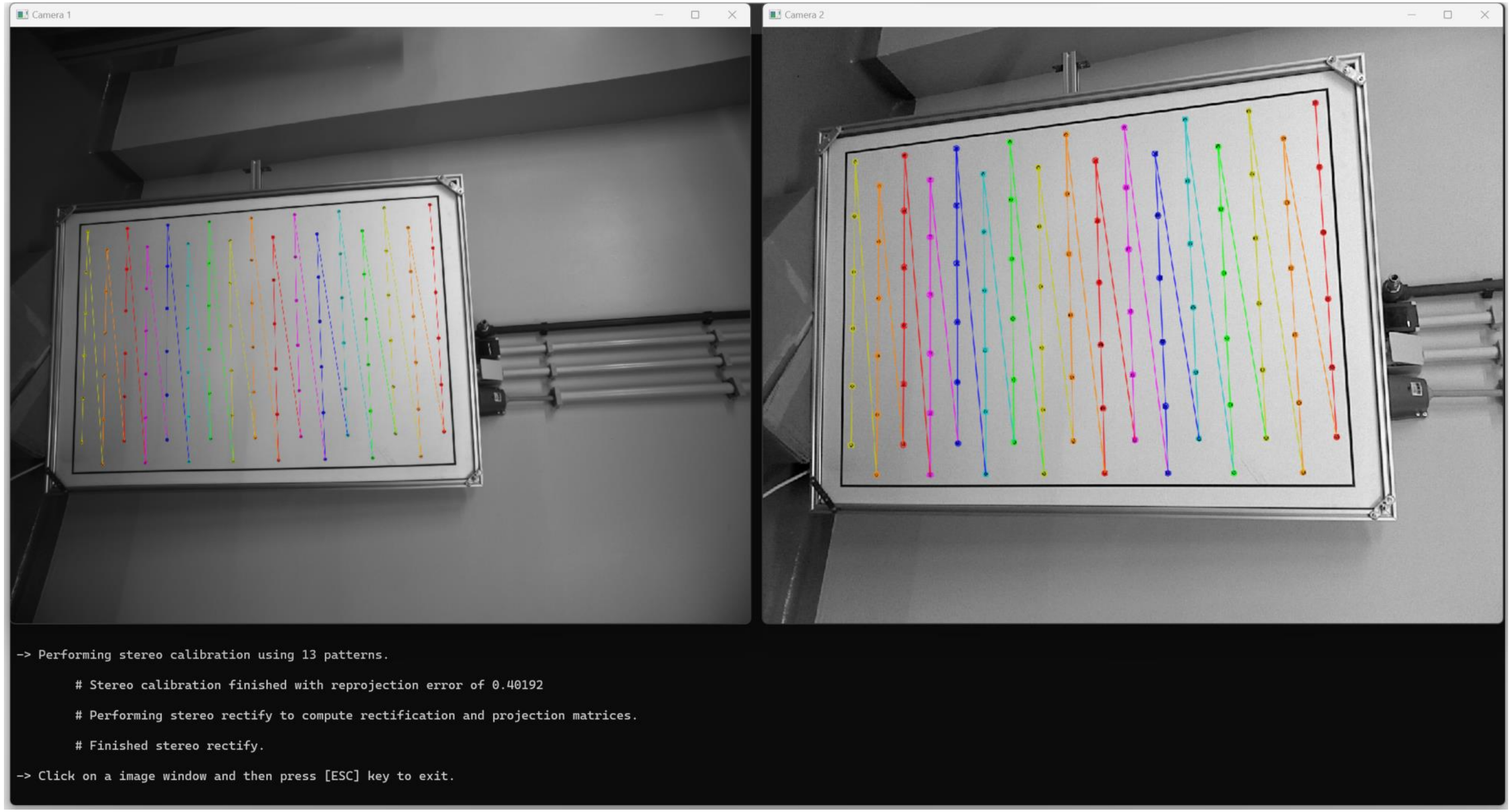
Calibration of extrinsic parameters of projector and 3D sensor



User interface with the detection of the printed asymmetric circles patterns for calibrating the extrinsics between the Mako G-507C camera and the Asus Xtion Pro Live RGB camera.

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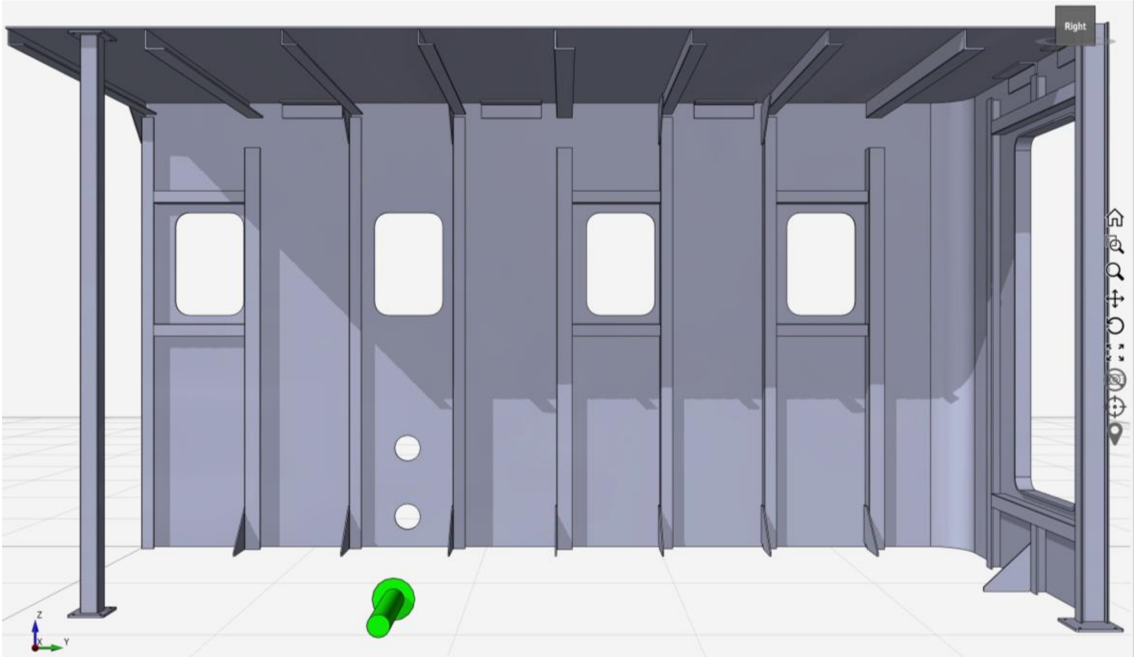
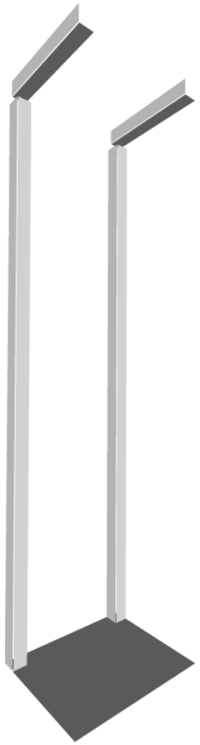
6 DoF pose estimation – Reference point cloud

1. For projecting accurate marking information into the ship walls, it is necessary to compute the 3D rotation and 3D translation between the projector and the ship structure coordinate system.
2. For optimizing the perception speed and reliability, currently the surfaces to use as a reference point cloud are carefully selected by an expert that performs an analysis of the CAD model and chooses the surfaces that are likely to allow a good convergence for the point cloud matching algorithm while also avoiding surfaces that are redundant and slowdown the alignment process.
3. From the CAD on the left, the surfaces on the center image were extracted and then the point cloud on the right image was generated in meshlab using the surface midpoint subdivision algorithm with 2 mm of edge threshold and the clustered vertex sampling algorithm with a cell size of 10 mm to ensure uniform point density, which is important for the point cloud matching algorithms.





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6 DoF pose estimation – Segmentation and point cloud alignment

1. The 3D perception system starts by loading the reference point cloud from a .ply file and capturing a new point cloud of the ship surfaces using the 3D sensor.
2. A voxel grid of 10 mm is used to downsample the sensor data to speed up the processing in the following stages.
3. A RANSAC algorithm is used to segment the largest plane (the ship wall), and then it is selected the points that are above that plane and facing the camera.
4. The initial pose that the operator provided in the GUI is used to perform an initial alignment of the sensor point cloud in relation to the reference point cloud.
5. The Iterative Closest Point (ICP) algorithm from the Point Cloud Library (PCL) is used to perform the point cloud registration and compute the 6 DoF pose of the 3D sensor in relation to the coordinate system of the reference point cloud that was extracted from the CAD model.
6. For validating the alignment, it is computed the percentage of points from the sensor point cloud that have a correspondence with short distance in relation to the reference point cloud and also the percentage of points in the reference point cloud that have a correspondence with short distance in relation to the sensor point cloud. If these overlap percentages are above the predefined thresholds, then the alignment is considered valid. Otherwise, an error is shown to the user in the GUI to readjust the initial pose.

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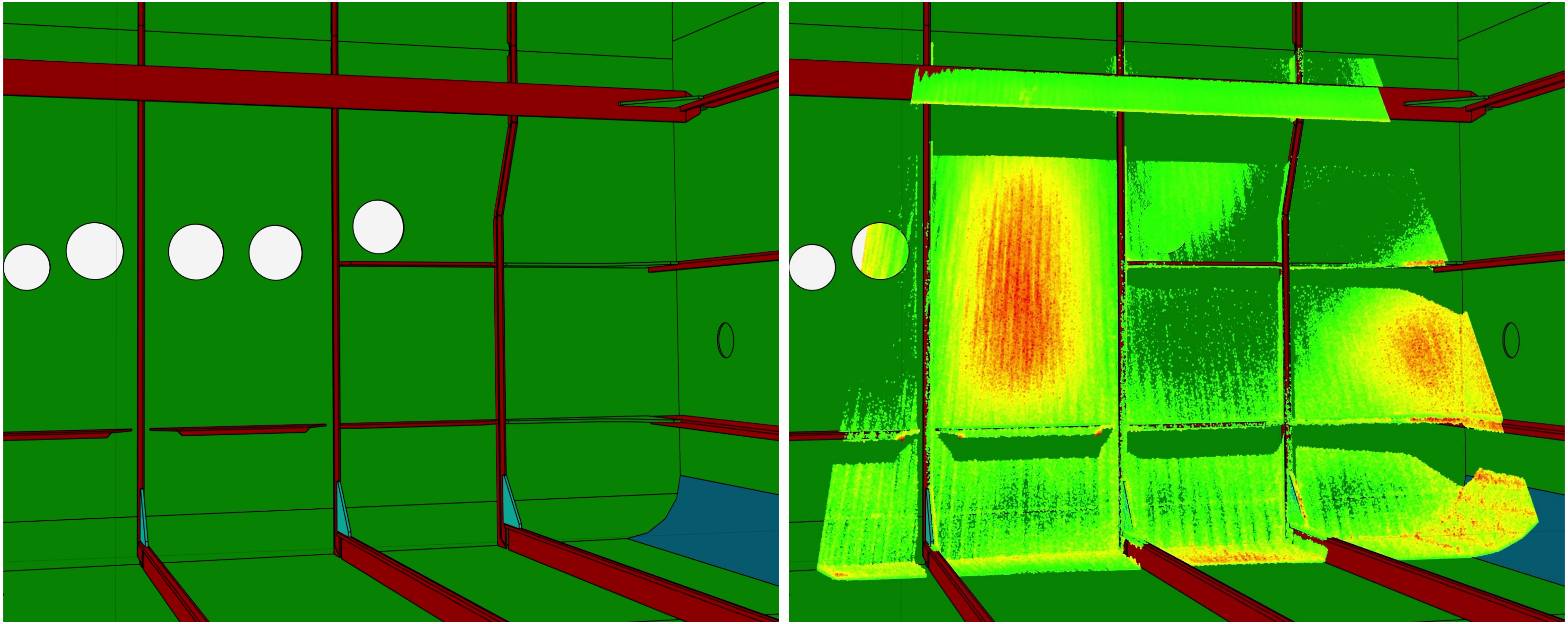
6 DoF pose estimation – Zivid 2+ L110



Example of alignment of the CAD model with the sensor data (shown with red to green color-coded gradient to represent the points distance to the CAD model) for the ceiling of the ship wall using the Zivid 2+ L110 3D sensor.

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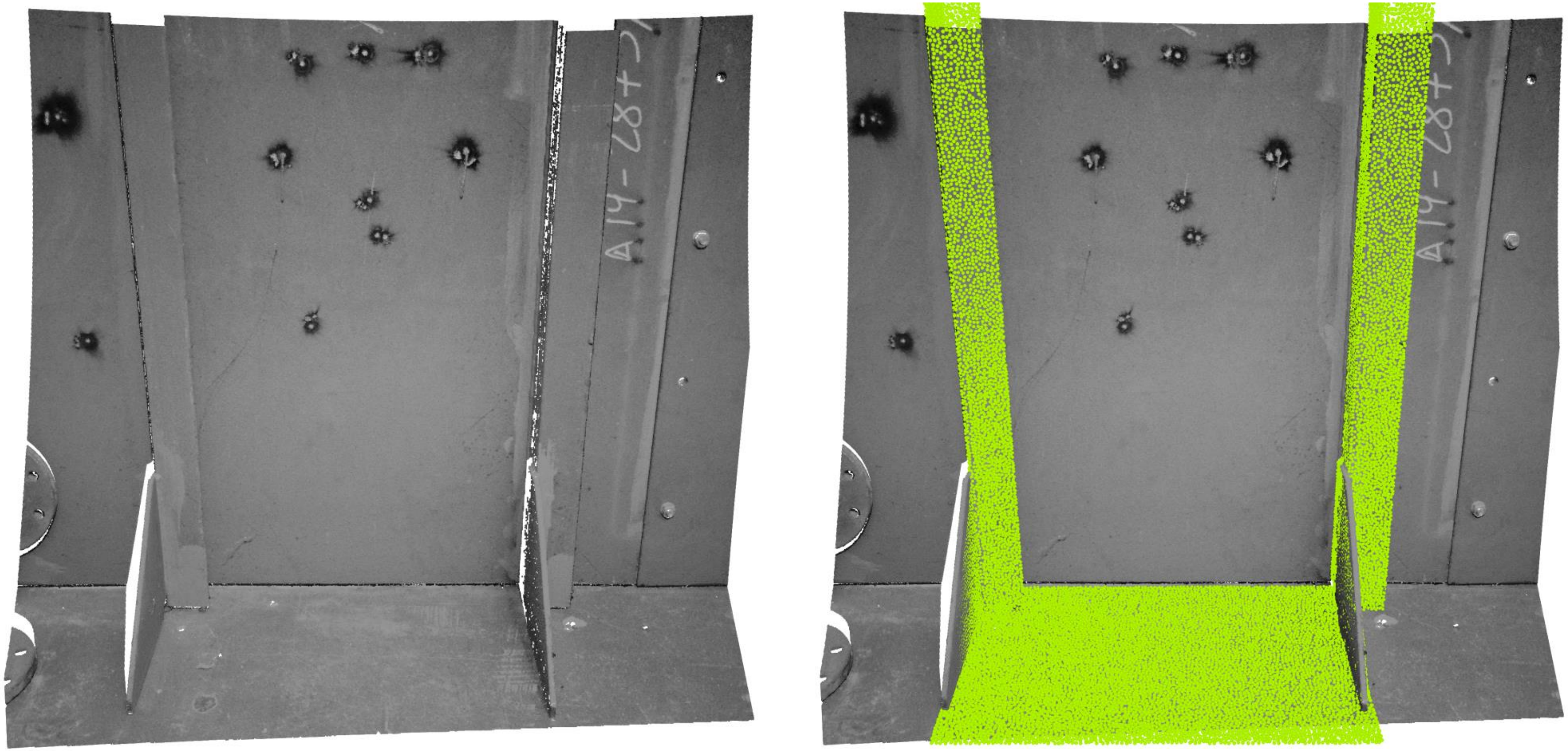
6 DoF pose estimation – Photoneo PhoXi XL



Example of alignment of the reference point cloud (shown as green circles) for the bottom section of the ship wall using the Photoneo PhoXi XL 3D sensor.

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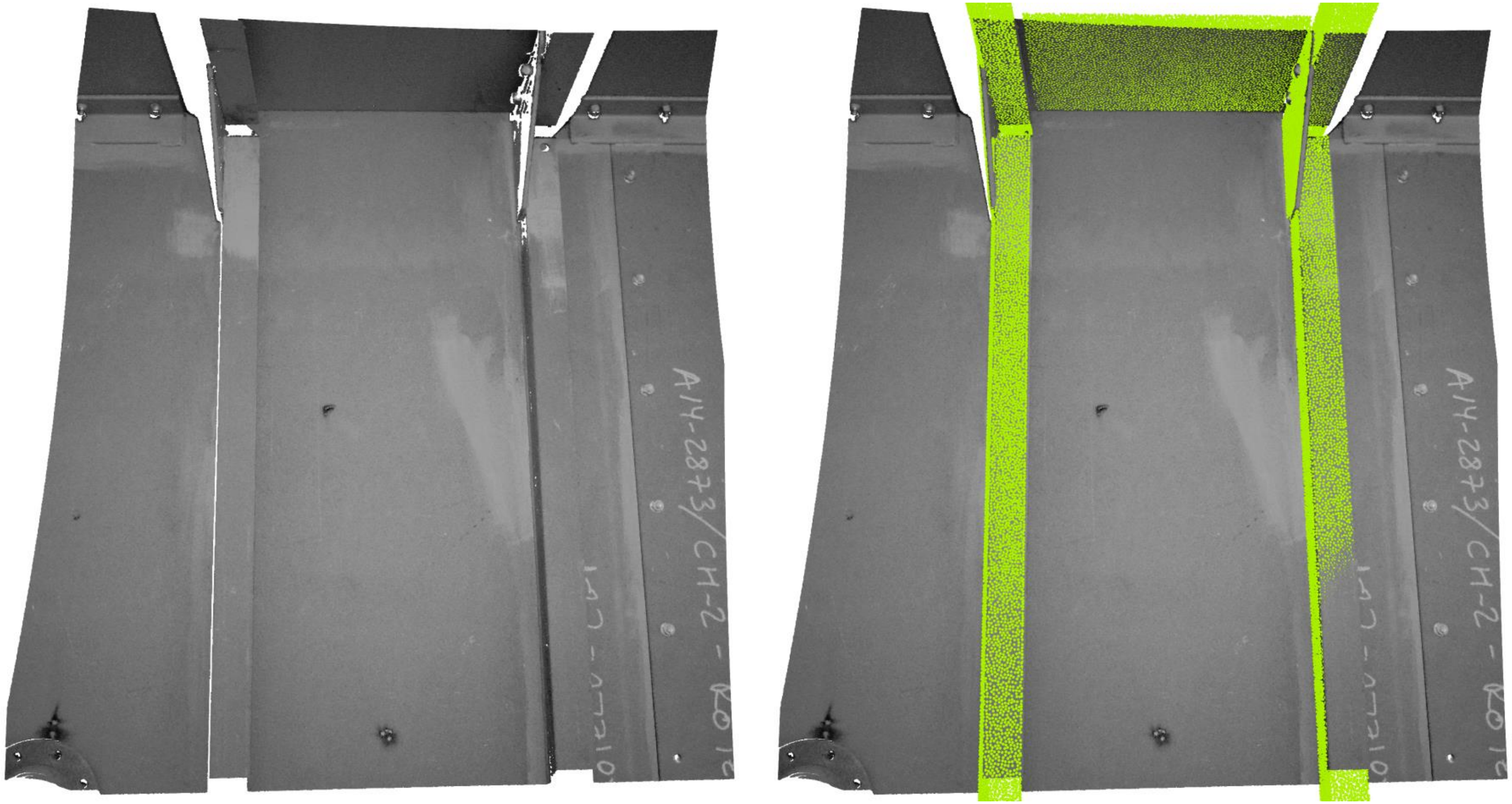
6 DoF pose estimation – Photoneo PhoXi XL



Example of alignment of the reference point cloud (shown as green circles) for the top section of the ship wall using the Photoneo PhoXi XL 3D sensor.

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6 DoF pose estimation – Asus Xtion Pro Live

Example of alignment of the reference point cloud (shown as green circles) for the bottom section of the ship wall using the Asus Xtion Pro Live 3D sensor.

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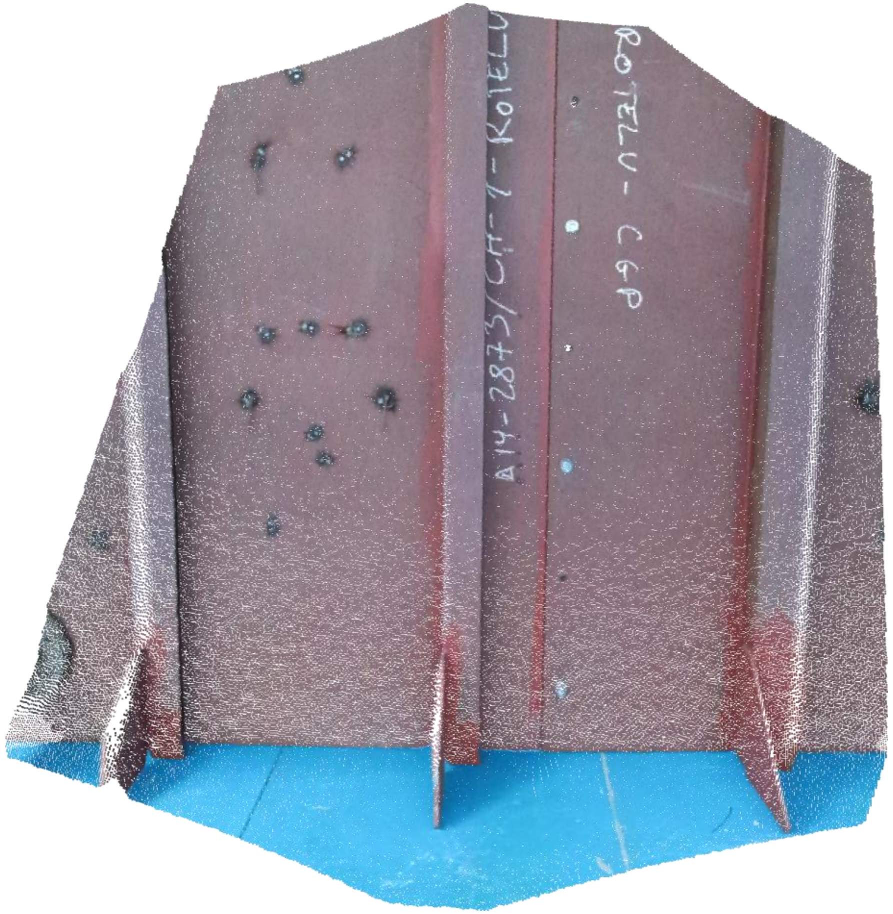
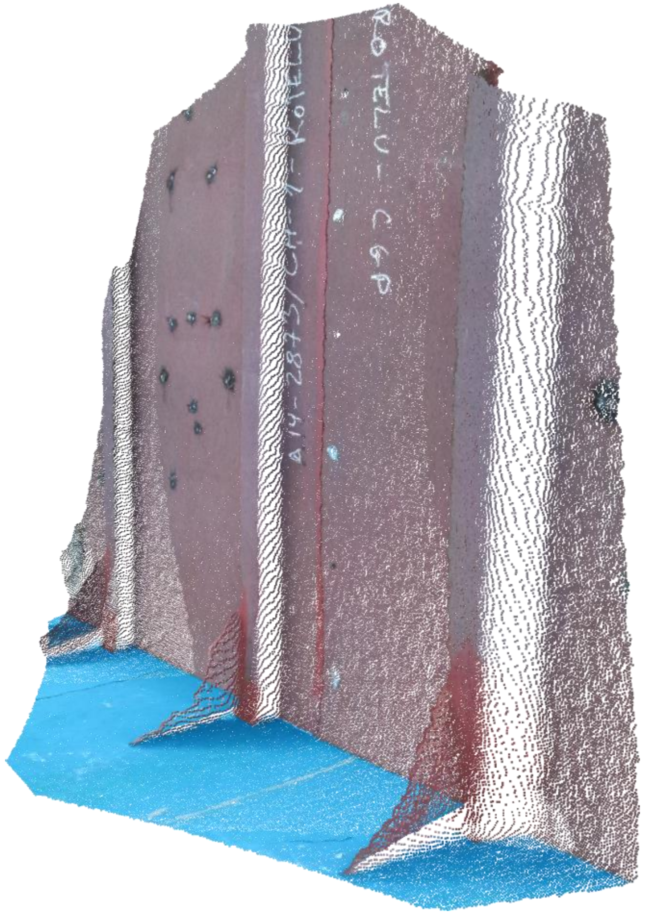
Test of other 3D sensors – Kinect Azure (ToF)





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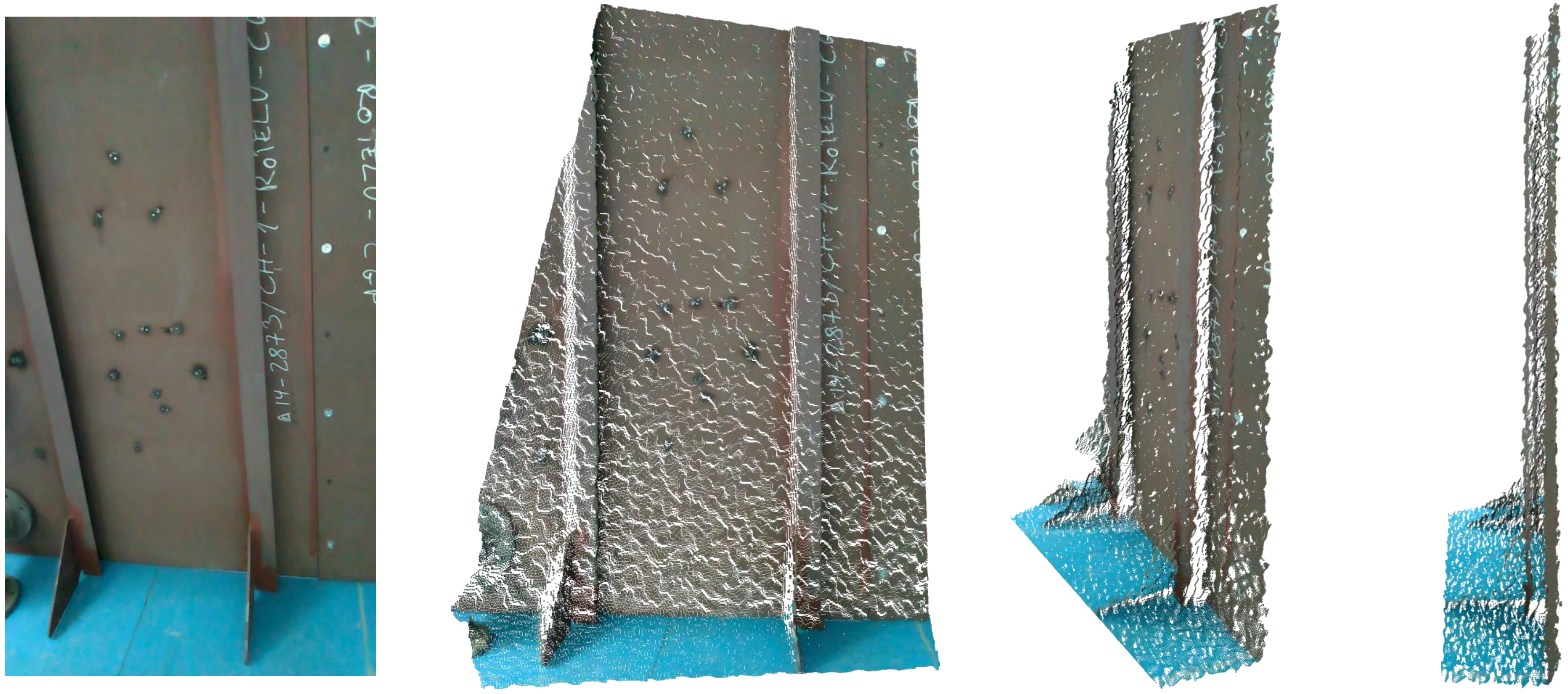
Test of other 3D sensors – Intel RealSense L515 (Lidar)



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Test of other 3D sensors – Intel RealSense D455 (stereo structured light - default preset)

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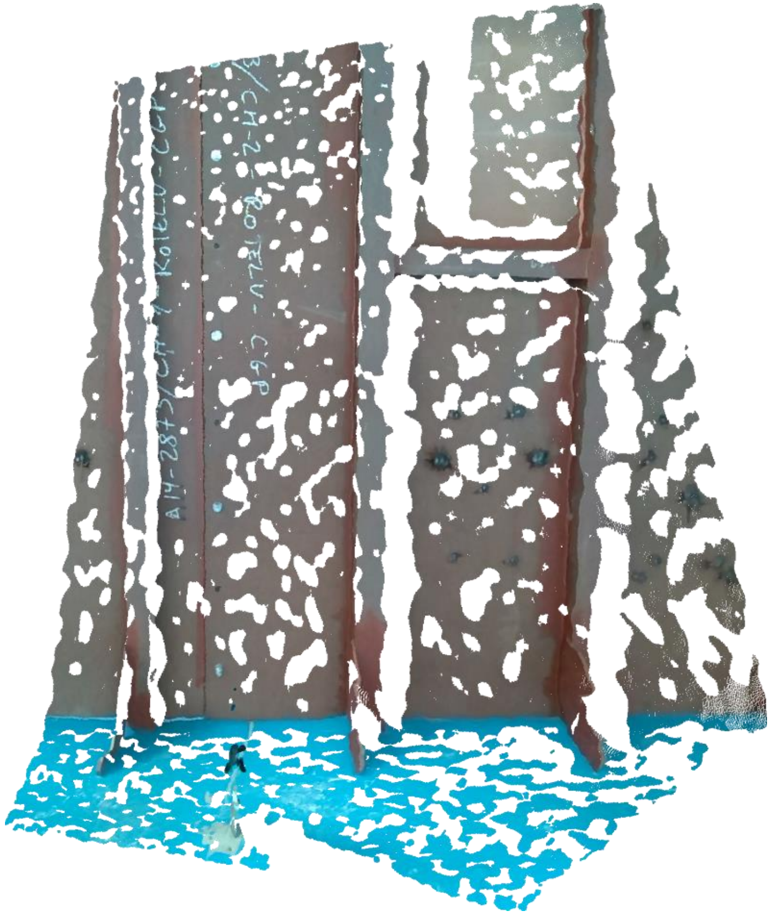
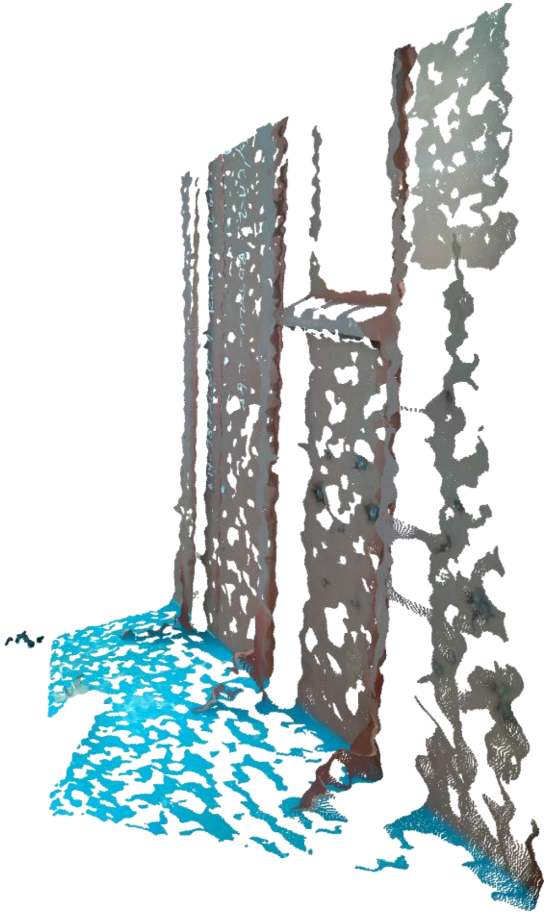
Test of other 3D sensors – Intel RealSense D455 (stereo structured light - accuracy preset)





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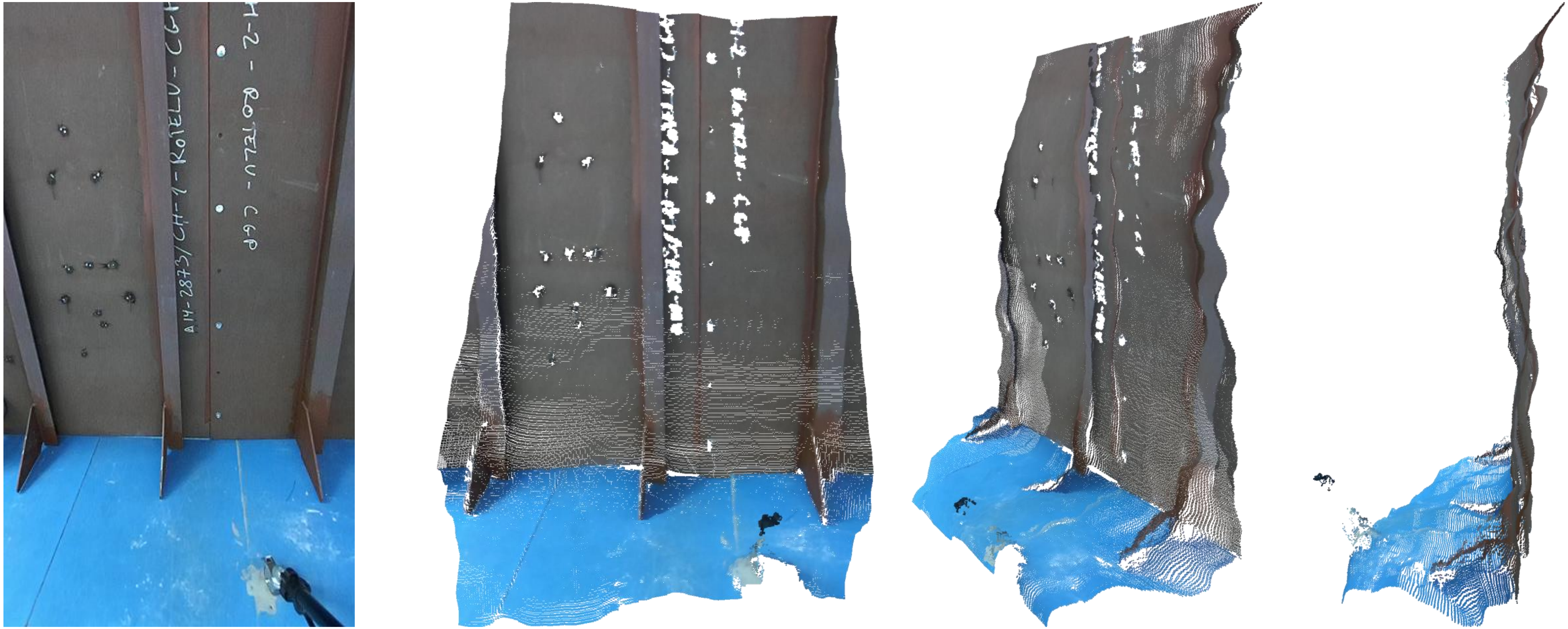
Test of other 3D sensors – Zed Mini (stereo)



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Rendering and projection

The last stage of a projection mapping system is the rendering of the CAD model using a virtual camera modelled with the calibrated intrinsic and extrinsic parameters, followed by the projection of the raster image into the environment.

The rendering is done using a graphics engine (Direct3D or OpenGL), for having hardware acceleration using a GPU to generate the raster images quickly.

In the Mari4yard project we used the devdept Eyeshot SDK. In other projects we also used the gazebo simulator.

Example of rendered images (top row)
and the respective projection (bottom row)

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Thank you for your attention!

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