ElectroCap Final Pitch

Indoor 3D-Sensor Based Navigation

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TÉCNICO LISBOA

Disclaimer:

This document contains videos that are not able to be seen in a PDF format. Click here to download the Power-Point version of the file.

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Abreviations

AMCL - Adaptive Monte Carlo Localization

DWA - Dynamic Window Approach

LiDAR - Light Detection and Ranging

MRL - Mobile Robotics Laboratory

PDDL - Planning Domain Definition Language

RGB-D - Red Green Blue-Depth

ROS - Robot Operating System

SLAM - Simultaneous Localization and Mapping

Key Concepts (I)

Cost map - Representation of the robot environment that assigns a cost value to each cell based on the occupancy, obstacle distance, inflation radius, and other factors.

Gazebo - Open source 3D robotics simulator.

Launch file - File of code that allows the user to start up and configure a number of executables simultaneously.

LiDAR - Determine ranges by targeting an object or a surface with a laser and measuring the time for the reflected light to return to the receiver.

Navigation - Firstly, the robot needs to create a map of the room it is in (Mapping). Then it needs to know where it is (Localization). Finally, it needs to know how to move from point A to point B autonomously without colliding with obstacles (Path Planning/Guidance).

Key Concepts (II)

Odometry (Odom) - Use of data from motion sensors to estimate change in position over time. It is used by legged or wheeled robots to estimate their position relative to a starting location.

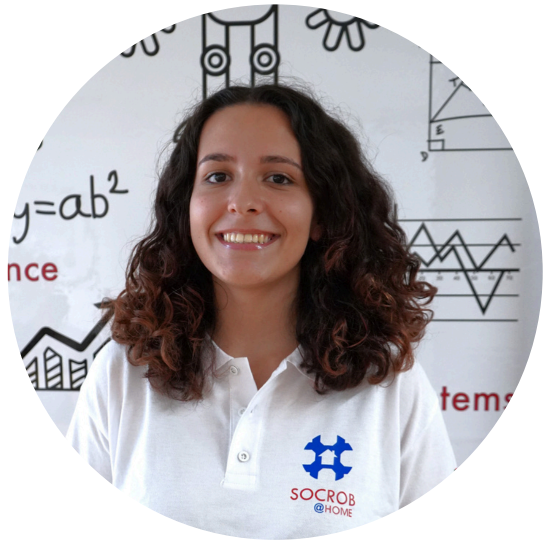
Point Cloud - Set of points usually defined by the coordinates X,Y or X,Y,Z. They are used to represent the external surface of an object or environment.

ROS - Set of tools and libraries that enable the creation of robotic applications.

RViz - 3D visualization tool for ROS.

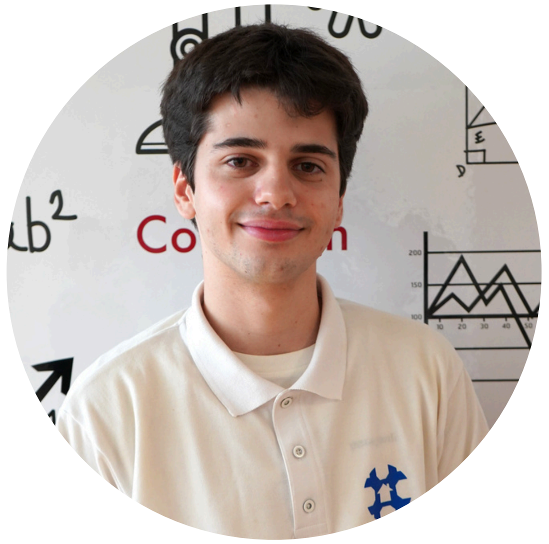
Yaw Angle - A yaw rotation is a movement around the z axis of a rigid body that changes the direction it is pointing, to the left or right of its direction of motion

1. Team

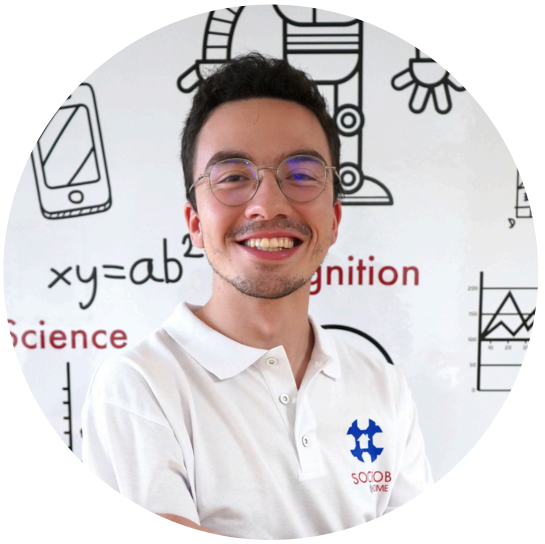


Catarina Caramalho
LEEC

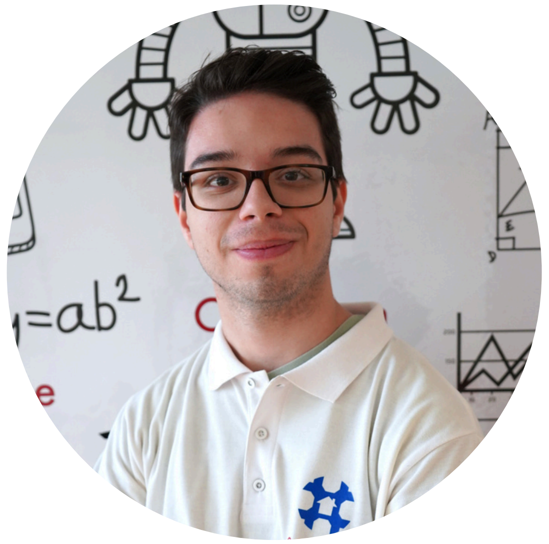
António Carvalho
LEEC



Tiago Teixeira
LEEC



João Pinheiro
LEEC



João Carranca
LEEC

Patrícia Torres
LEFT

2. Advisors and Mentor

- **Scientific Advisor:** Prof. Luís M. Correia.
- **Scientific Co-advisors:** Prof. Pedro Lima and Rui Bettencourt.
- **Coordinator:** Prof. Luís M. Correia.
- **Co-coordinator:** Prof. João Felício.
- **Mentor:** Rodrigo Serra.

3. Introduction (I)

- Previously the TIAGo robot from the SocRob@Home team performed 2D navigation that used data provided by a 2D LiDAR. This data was used to build a 2D map for localization and navigation. The navigation could result in collisions if the environment includes challenging furniture not fully seen by the 2D LiDAR, such as a single-leg or a legless table.

- The furniture mentioned above must be accurately detected and mapped, as the top of a table is undetected (in the 2D map), and TIAGo can collide.

3. Introduction (II)

Single-leg table

"Complete Indoor Table with Walnut Color Elm Wood Top," Bistro Tables & Bases. Accessed: Dec. 22, 2023. Available: https://bistrotablesandbases.com/product/complete-indoor-elmwood-table/

Legless table

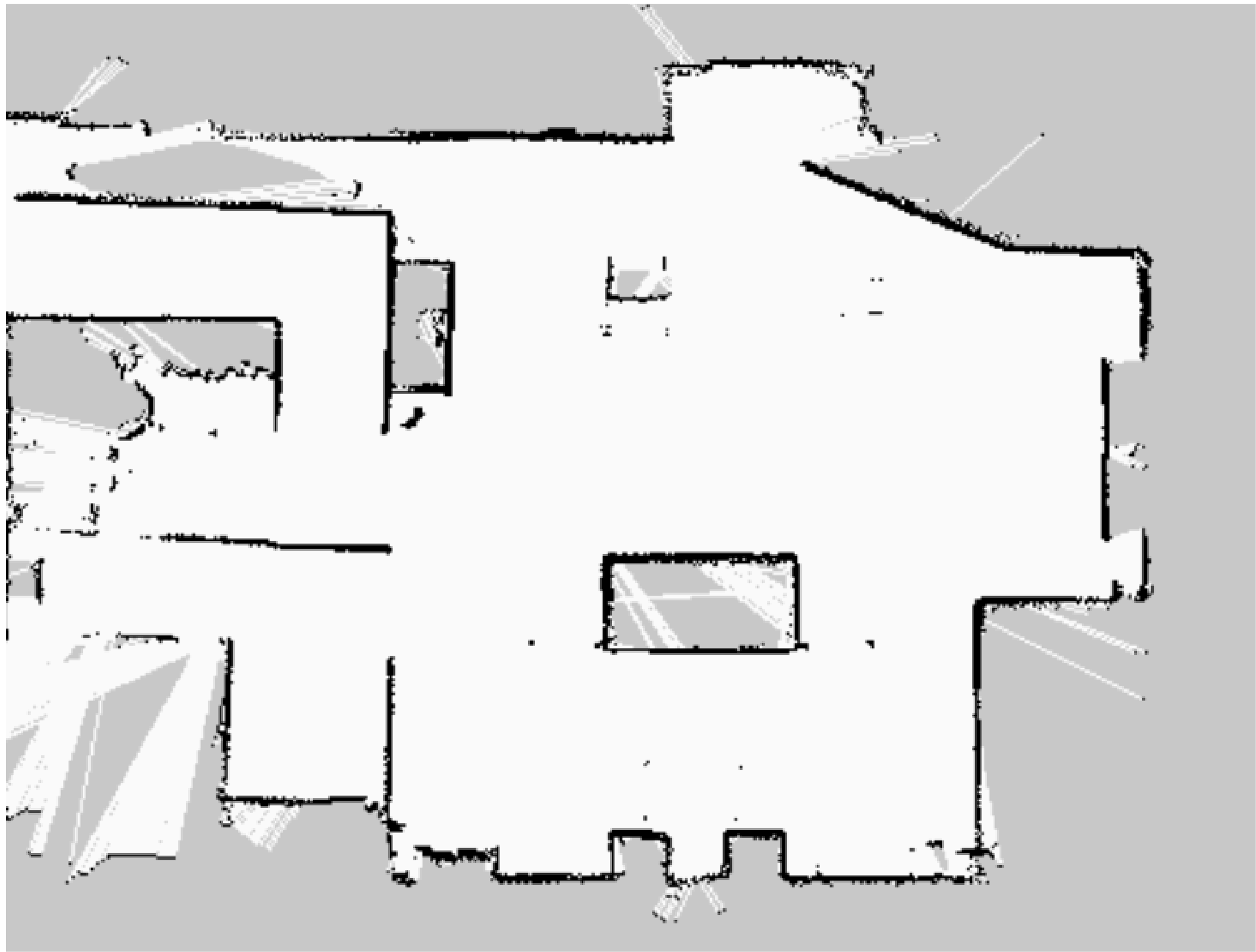
"BJURSTA Wall Mounted Folding Table - IKEA." Accessed: Dec. 22, 2023. Available: https://www.polantis.com/ikea/bjursta-wall-mounted-folding-table

3. Introduction (III)

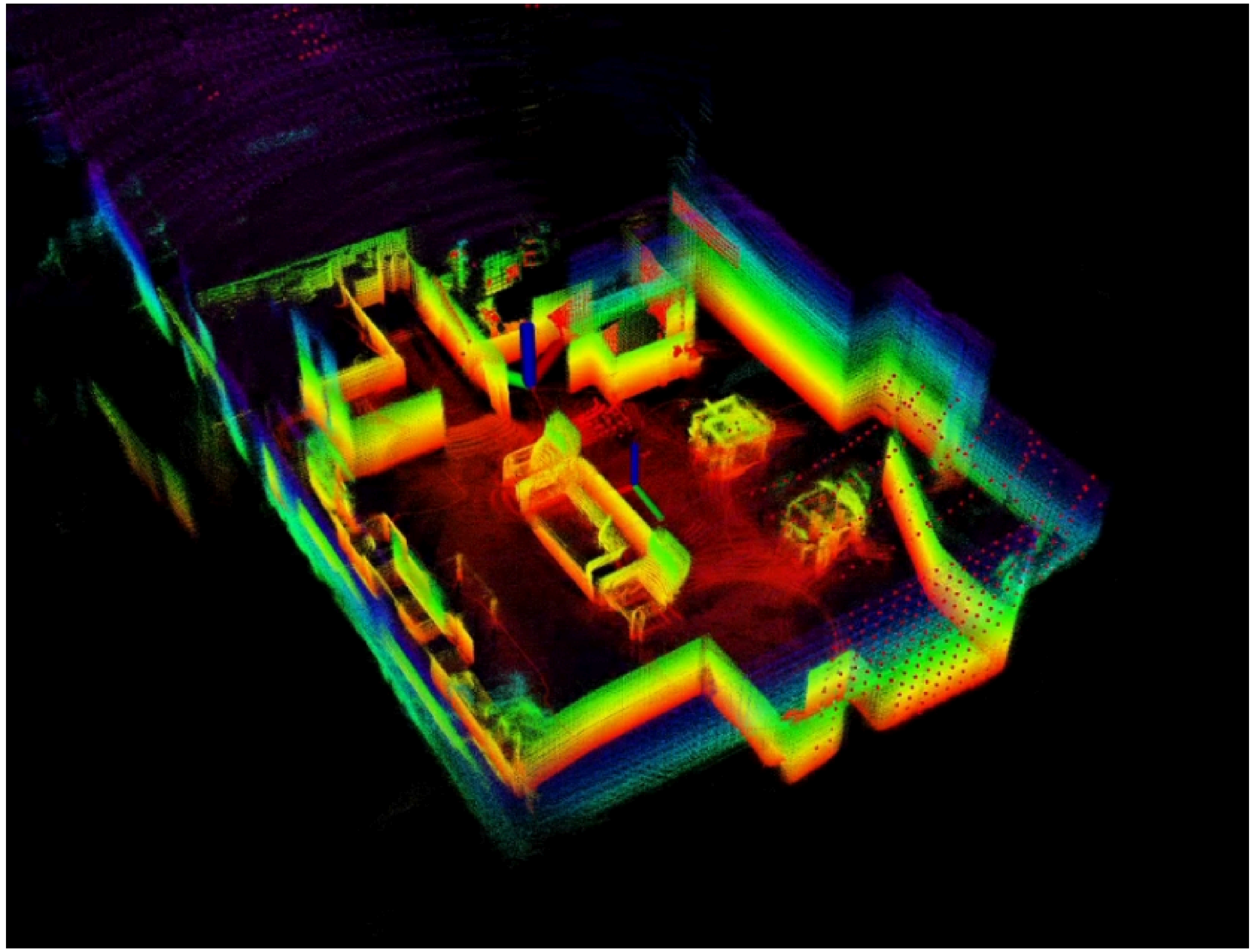
- The students proposed the integration of a 3D LiDAR, using its 3D data for environment representation through a 3D map. This map contains much more information, including the challenging furniture not seen by a 2D LiDAR.

- Localization was based on 2D LiDAR data. By replacing this sensor, the localization method was upgraded to use 3D information. This represents an advantage as the robot will have more information to localize itself. For example, with a 3D LiDAR, the robot can localize itself based on the crown molding between the walls and the roof, which can not be done with a 2D LiDAR.

3. Introduction (IV)



2D Map
(Testbed at the MRL)



3D Map
(Testbed at the MRL)

4. Problem definition

Install a 3D LiDAR to detect objects in 3 Dimensions to improve 2D Navigation of an autonomous domestic mobile robot.

TIAGo Robot
toward, "TOWARD - Torque controller walking development," Toward. Accessed: Jan. 26, 2024. [Online]. Available: https://toward.fr/en/

5. Solution - Robot Pipeline (I)

The robot pipeline is ilustrated in slide 14. Students primarly focused on the **Navigation** and **Laser Scanner** modules:

- **Navigation:** Enables the robot to navigate effectively and safely, while accommodating diverse navigation scenarios and challenges. Key features include the Localization, Mapping, Path Planning and Guidance Systems and Multi-Sensor Integration.

- **Laser Scanner:** Responsible for detecting static obstacles in the robot's environment. It uses a LiDAR sensor to detect static and dynamic obstacles.

5. Solution - Robot Pipeline (II)

Other modules that are connected to the ones previously mentioned are the following:

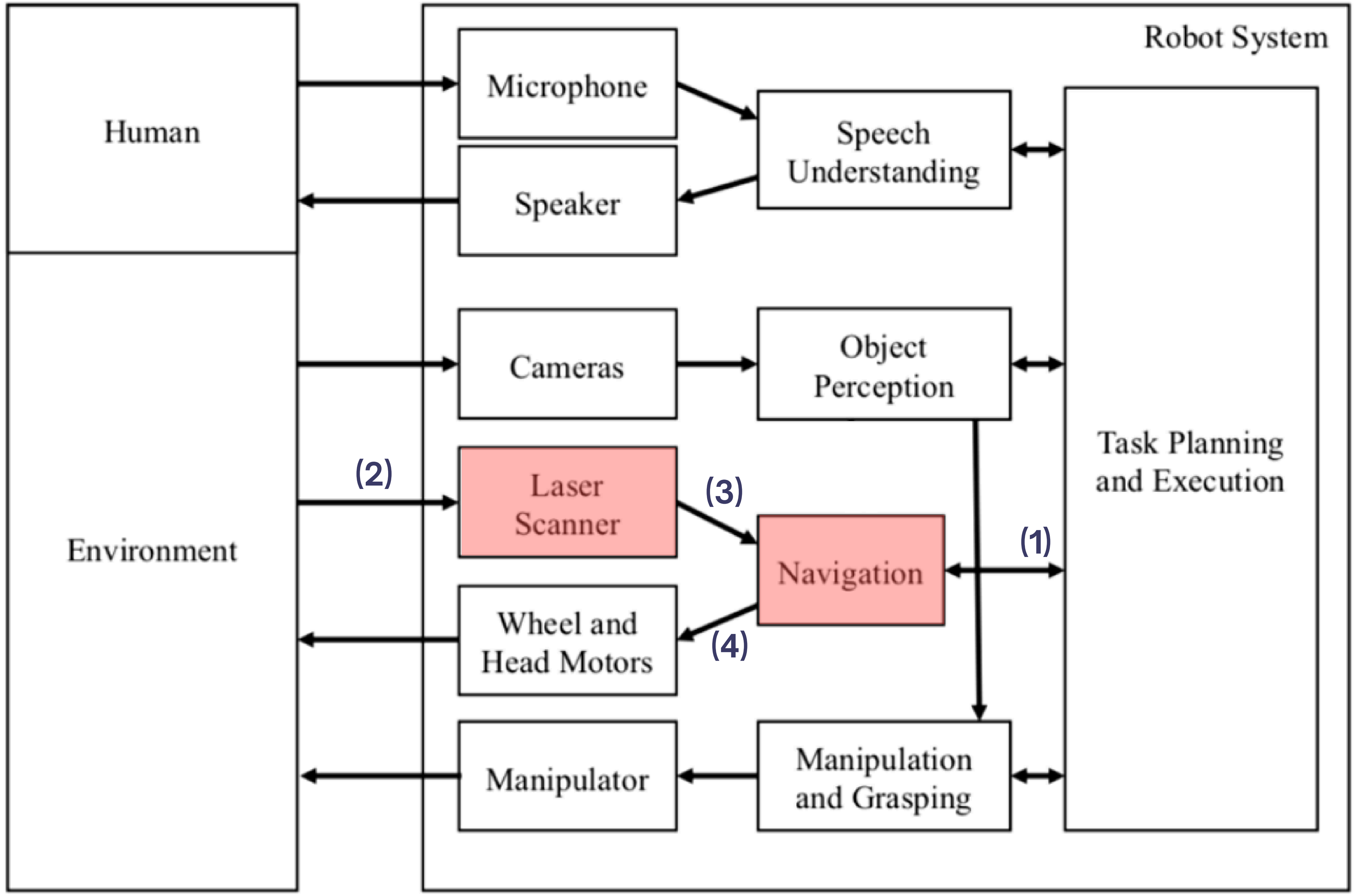
- **Environment:** It represents the data from the environment such as obstacles and objects.
- **Wheel and Head Motors:** The differential wheels are used for movement and the pan-tilt head used to control the orientation of the RGB-D camera.

5. Solution - Robot Pipeline (III)

Other modules that are connected to the ones previously mentioned are the following:

- **Task Planning and Execution:** Includes components such as the automated PDDL problem generator, planner interface, plan validation, knowledge base, scheduler, and planning coordinator. These enable the robot to generate task plans based on the current knowledge base and execute them in real time.

5. Solution - Robot Pipeline (IV)



Adapted from P. U. Lima et al., “SocRob@Home”, KI - Künstliche Intelligenz, vol. 33, no. 4, pp. 343–356, Dec. 2019, doi: 10.1007/s13218-019-00618-w. Adapted with permission.

Red boxes correspond to what the students worked on

(#=1,…,4) Interactions between modules to be explained in the next slides

5. Solution - Robot Pipeline (V)

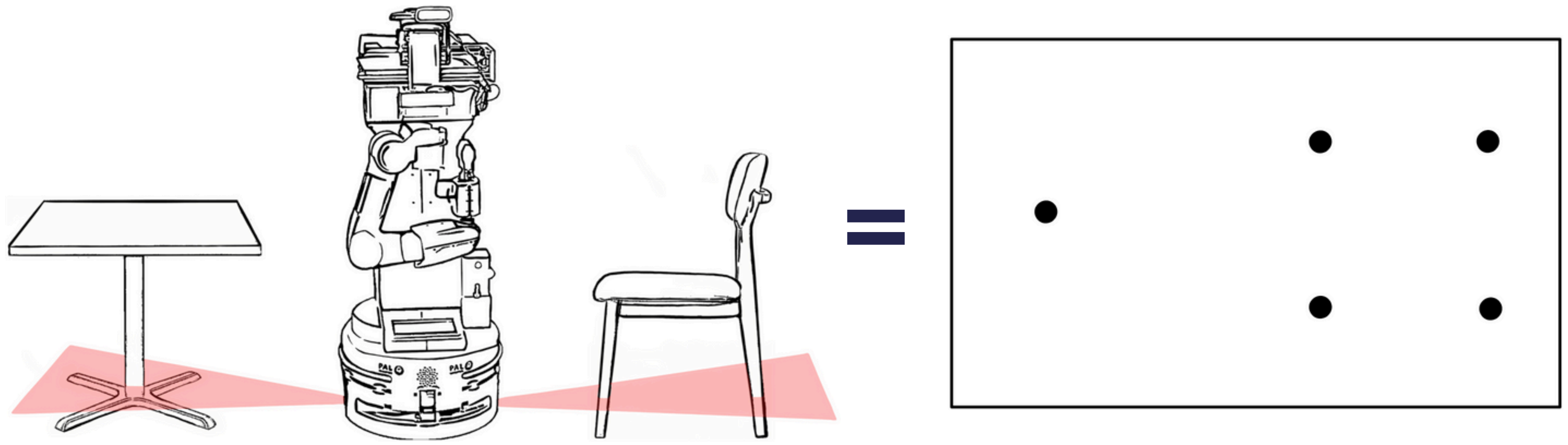
(1)

- The task planning and execution module inputs a problem for the navigation module to solve, usually the need of moving the robot from point A to point B. Later, the navigation module outputs feedback about the success of the task.

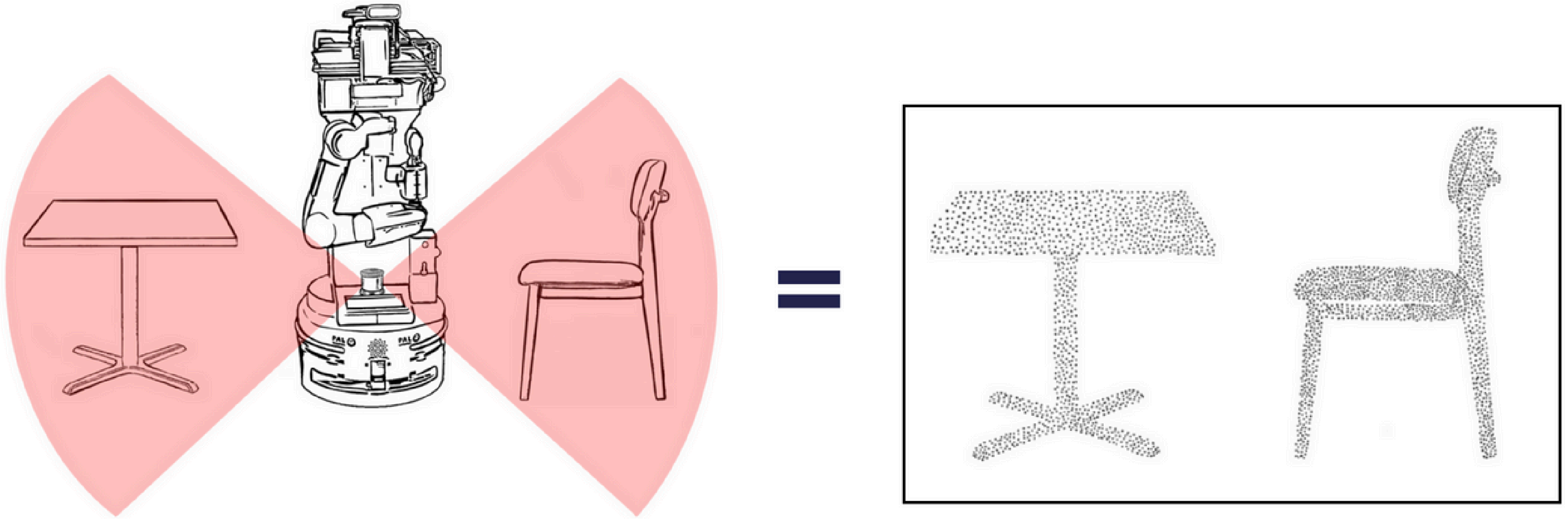
5. Solution - Robot Pipeline (VI)

(2)

- Environment was perceived by the data collected from the laser scanners.



Environment perceived with a 2D laser scanner



Environment perceived with a 3D laser scanner

5. Solution - Robot Pipeline (VII)

(3)

- The information provided by the laser scanners was also used to form a static and a dynamic map. These maps were then used in path planning and guidance techniques, in order to avoid obstacles.

5. Solution - Robot Pipeline (VIII)

(4)

- Actuation on the robot's wheels is determined by a DWA-based guidance technique which aims to guide the robot base through the path determined in a Dijkstra algorithm-based motion planning technique while avoiding unexpected obstacles.

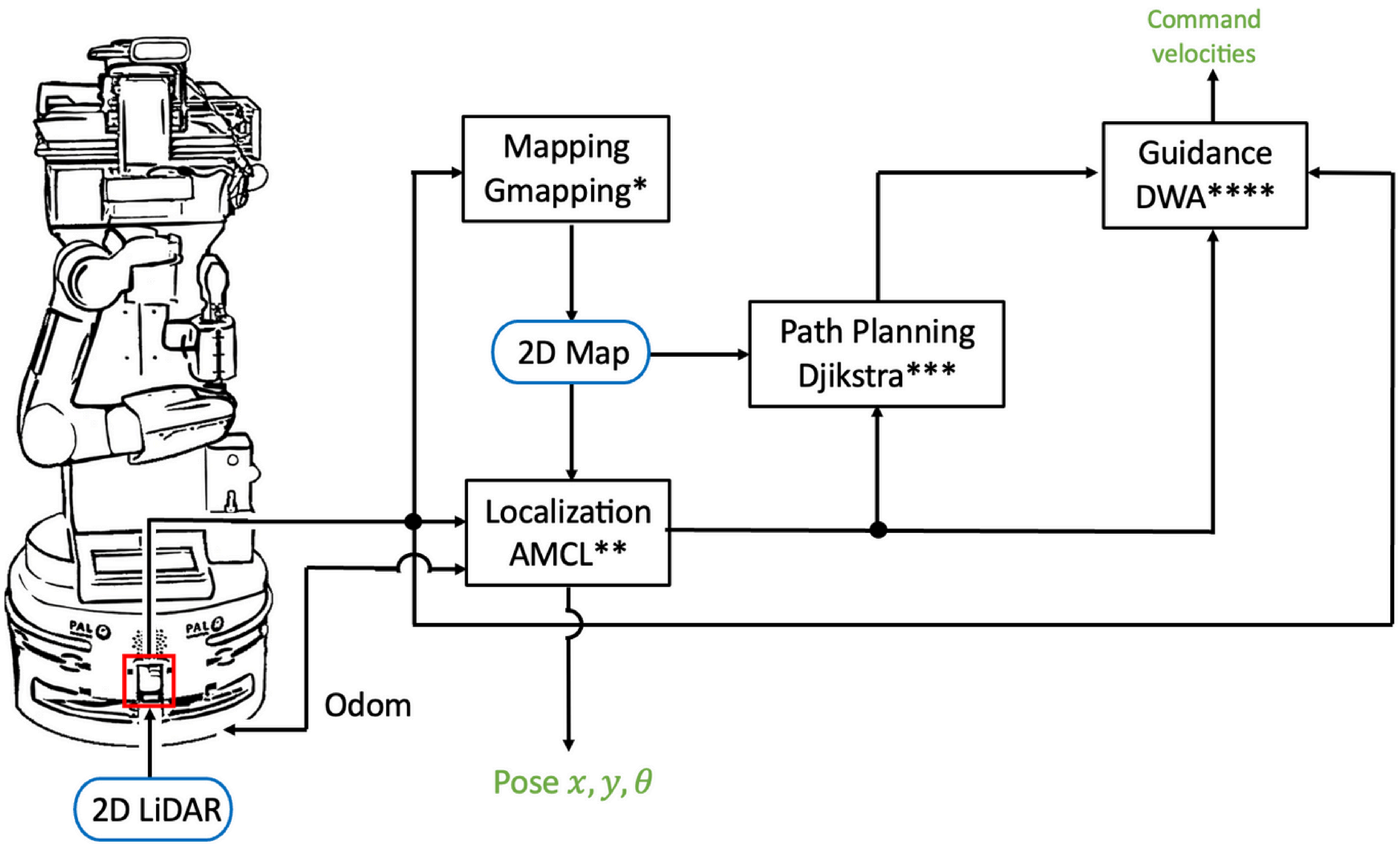
5. Solution - What was done (I)

- Based on the data provided by a **2D LiDAR**, a **2D Map** of the environment was built using a SLAM algorithm (**Mapping** module).

- The **Localization** used the AMCL algorithm and a 2D point cloud provided by the **2D LiDAR**.

- **Path planning** and **Guidance** modules used data from a **2D LiDAR**. This system also assumed that the robot had its arm always retracted during navigation meaning that guidance techniques accounted for a smaller and constant footprint.

5. Solution - What was done (II)



* Gmapping Algorithm – SLAM algorithm used to build the 2D map when the environment is unknown

** AMCL – Probabilistic algorithm used to find robot´s localization

*** Dijkstra Algorithm – Used to find the best path between 2 points in the room

**** DWA – Technique that ensures that the path is correctly followed by the robot

5. Solution - What we did (I)

- With the integration of a **3D LiDAR**, the **Mapping** module receives data from this sensor and builds a **3D Map.** This involves using a 3D SLAM algorithm.

- Regarding **Localization,** a 3D algorithm is used for the robot to be able to localize itself on a **3D Map**.

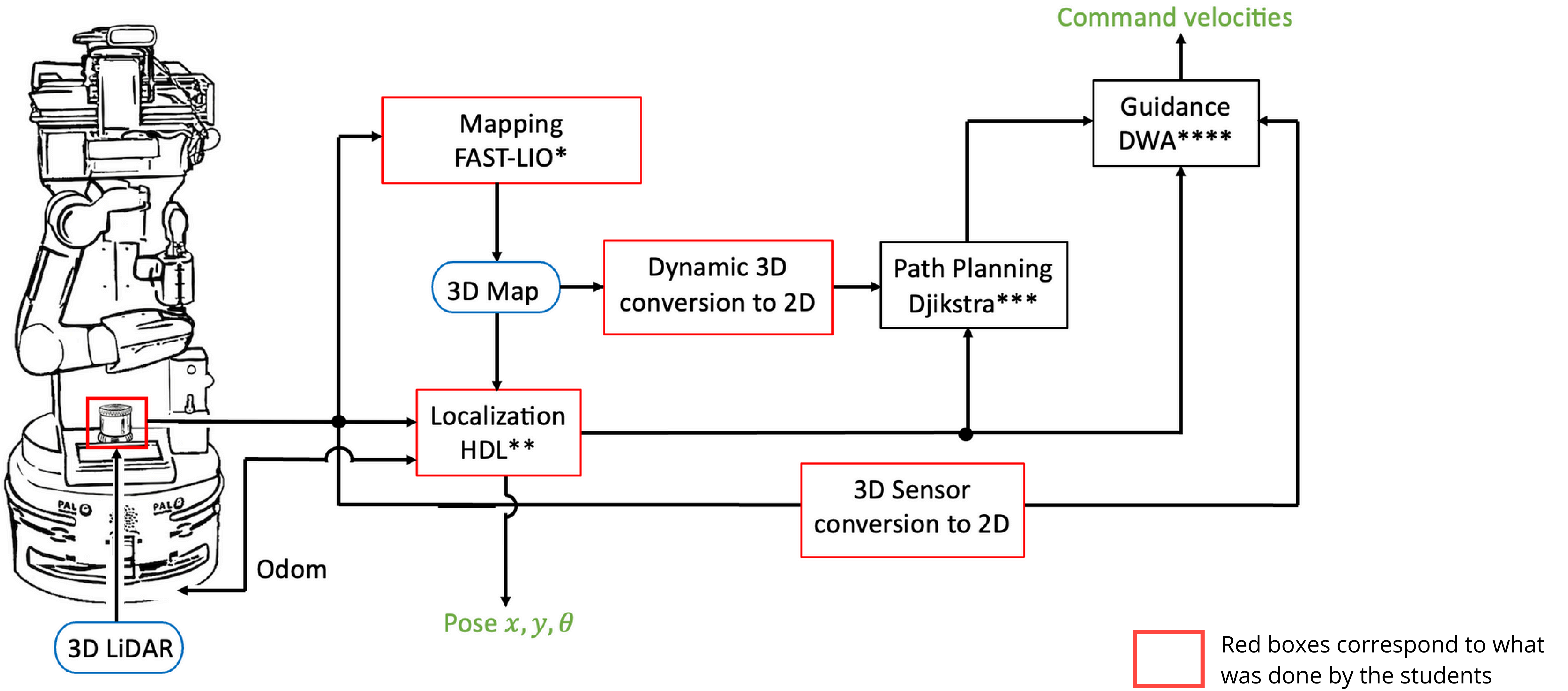
- With the replacement of the **2D LiDAR** for a 3D one, a need for the **conversion of the information provided by the 3D LiDAR to a 2D plane** appears. Since a 3D view can be perceived as multiple stacked 2D planes, obstacles above and below the sensor will now be correctly accounted for in a 2D cost map.

5. Solution - What we did (II)

- Regarding the conversion mentioned in the last slide there was a method that did not consider that the robot could change its torso height. So a module that handles **Dynamic 3D conversion to 2D** to ignore obstacles that are above the robot was developed.

- An essential aspect was the development of a system that considers the precise current footprint based on the robot's arm position during navigation. This becomes crucial as it has the potential to alter the way paths are planned.

5. Solution - What we did (III)



* **FAST-LIO Algorithm** – Uses data from a 3D point cloud and/or IMU data
** **HDL Algorithm** – Receives data from a 3D point cloud instead of a 2D point cloud
*** **Dijkstra Algorithm** – Used to find the best path between 2 points in the room
**** **DWA** – Technique that ensures that the path is correctly followed by the robot

6. Costs and benefits

Costs

- The 3D LiDAR used is much more expensive than the 2D LiDAR.
- The 3D-Sensor based Navigation requires more computational power than the 2D-Sensor based Navigation.

Benefits

- With 3D sensor data the robot can avoid obstacles that are not avoided with 2D sensor data (single leg and legless tables, etc.).
- The robot avoids much frequently smaller obstacles that will be shown in later slides.

7. Target audience (I)

The so called direct beneficiaries might benefit from our project:

- **Robot fabricants** that may want to use this solution/technology. That is, **other robots** that might face similar challenges as the ones described in the "Introduction" section.

7. Target audience (II)

The project mainly focuses on a domestic environment. So one can think of such indirect beneficiaries (final users):

- **Elderly people.**
- **Individuals with disabilities or illnesses.**

8. Competitors (I)

- **Products with an Indoor Navigation System based on 3D data** (e.g., assistant robots, indoor mail robots, among others).

- The **work that was already developed by SocRob@Home** includes a 2D navigation system with 2D sensors.

8. Competitors (II)

These are the potential competitors:

- Marvel Mind
- Clearpath Robotics
- Zebra
- Locus Robotics
- Robotnik
- Relay Robotics
- Slamcore
- Pal Robotics

9. Solution requirements (I)

For the solution to be well implemented, it is necessary that:

- The robot conveys confidence in its movements, ensuring the safety of people and objects.
- It can accurately and efficiently detect the 3D world with a resolution of at least 5 cm (ideally 2.5 cm) - with the current 2D navigation method the map had a resolution of 5 cm, hence the interest of maintaining this feature.
- There is a positive tradeoff for the advantages of the application of using a 3D sensor versus its cost.

9. Solution requirements (II)

The robot's decision time to react to a dynamic obstacle and avoid a collision is approximated by:

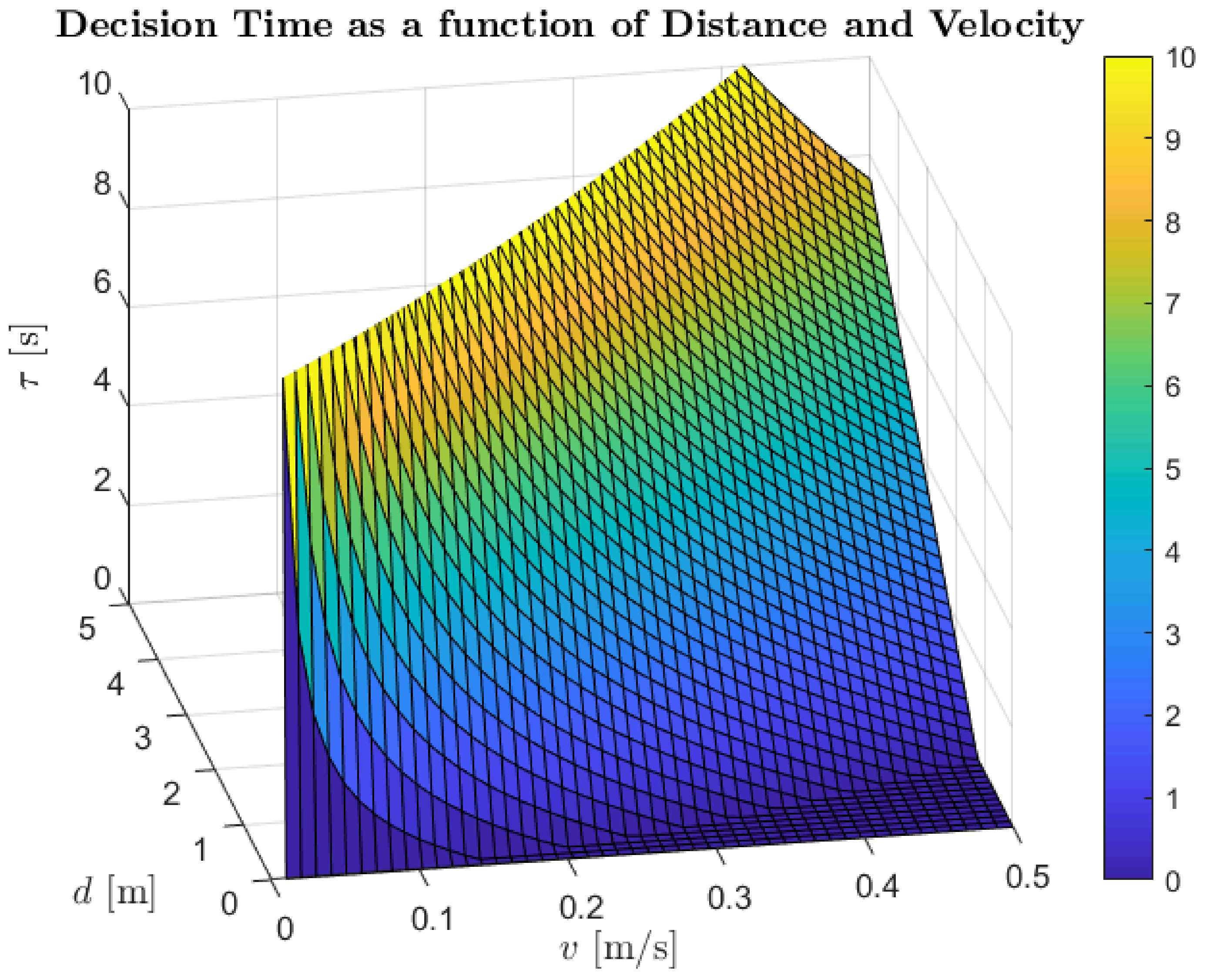
$$\tau = \frac{d}{v} - \frac{v}{a}$$

where:

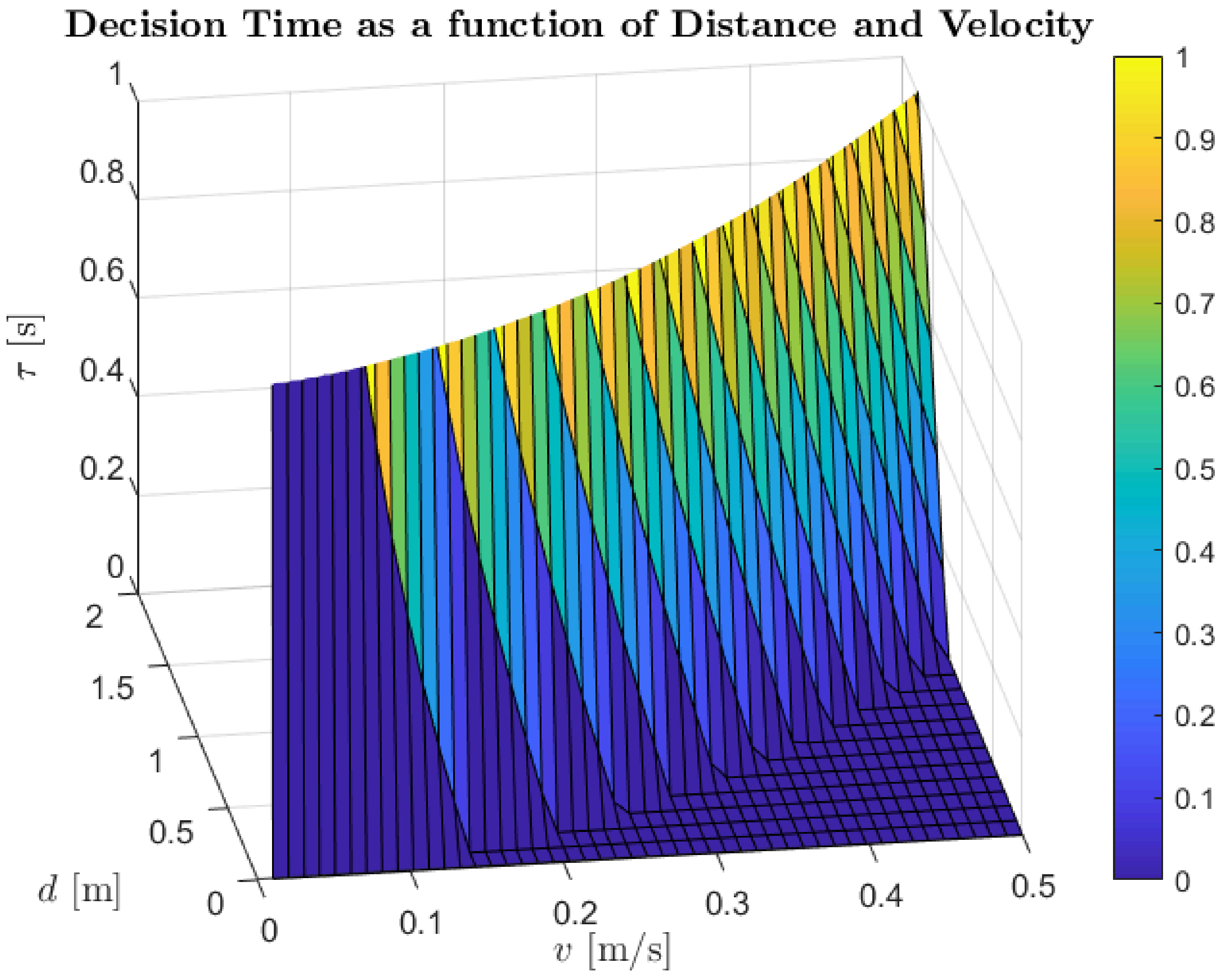
- τ - Robot's decision time in seconds
- d - Distance between TIAGo and an obstacle in meters
- v - Robot's velocity in meters per second (limited to 0.5 m/s)
- a - Robot's max decelaration in meters per second squared (equal to -0.2 m/s^2)

9. Solution requirements (III)

Based on the previous slide, we can see how the decision time varies in function of distance and velocity.



a)



b)

9. Solution requirements (IV)

Graph b) is an enlargement of a) in the zone of values of greater interest - shorter distances. When the decision time is equal to zero it means that the robot will collide with an obstacle.

Hence, for a velocity of 0.3 m/s and an arbitrary distance of 1 m we have the following solution requirement:

- **Decision time:** 1.8 seconds

10. Technical challenges (I)

- Positioning the 3D sensor on the robot: Determining the ideal placement of the sensor to capture the most accurate data.

- Connecting the various tasks/parts.

- Avoiding dynamic obstacles considering the robot´s height (moving objects, people).

10. Technical challenges (II)

- Navigating in 2D using 3D information about the environment: The 3D data from the mapping and localization needs to be converted to 2D, so as to be used in the path planning component.

- Dynamically changing the shape of the robot´s footprint (its 2D projection) which would be something like a circle when it´s arm is not extended but different when it is.

11. Partners (I)

Project Integration:

- Integration within SocRob@Home Team, part of ISR at Instituto Superior Técnico.

11. Partners (II)

- The TIAGo robot that belongs to the SocRob@Home team will be used to perform tests.

TIAGo Robot

"TIAGo," robots.ros.org. Accessed: Nov. 27, 2023. Available: https://robots.ros.org/tiago/

12. Testing and validation metrics (I)

The final system was tested in a simulation and in a real environment, on a TIAGo robot.

TIAGo in a realistic environement in Gazebo - simulation

TIAGo in testbed at ISR - real environment

12. Testing and validation metrics (II)

The tests that were conducted:

- Navigation in the testbed to a random waypoint without dynamic obstacles.
- Navigation in the testbed to a random waypoint with a dynamic obstacle (e.g., a person walking).
- Navigation in the testbed to a random waypoint with a small obstacle that 2D navigation does not avoid (e.g., sponge).

12. Testing and validation metrics (III)

- Navigation in the testbed to a random waypoint, ensuring the robot avoids complex 2D navigation furniture (e.g., tables with center legs, chairs without back legs, suspended board).

The students repeated each experiment 10 times, recorded collisions and successes, and performed a statistical analysis for the method developed by the PIC1 team.

12. Testing and validation metrics (IV)

The methods currently in use involve the following frequency levels:

- Localization - 10 Hz
- Path Planning - 2 Hz
- Guidance - 10 Hz

Students compared the frequency levels obtained with the new methods with those that are mentioned above.

12. Testing and validation metrics (V)

The localization accuracy will be evaluated with a Motion Capture System, based on 12 OptiTrack PRIME13 cameras that have a sub-millimeter accuracy. The error obtained will be compared with the error of the current method used.

OptiTrack PRIME13

A. David, "The ISRoboNet@Home Testbed," Institute For Systems and Robotics. Accessed: Jan. 26, 2024. Available: https://welcome.isr.tecnico.ulisboa.pt/isrobonet/

12. Testing and validation metrics (VI)

In the "Solution requirements" section regarding the robot's decision time, it was discussed the following:

- **Velocity:** 0.3 m/s
- **Distance:** 1 m
- **Decision time:** 1.8 s

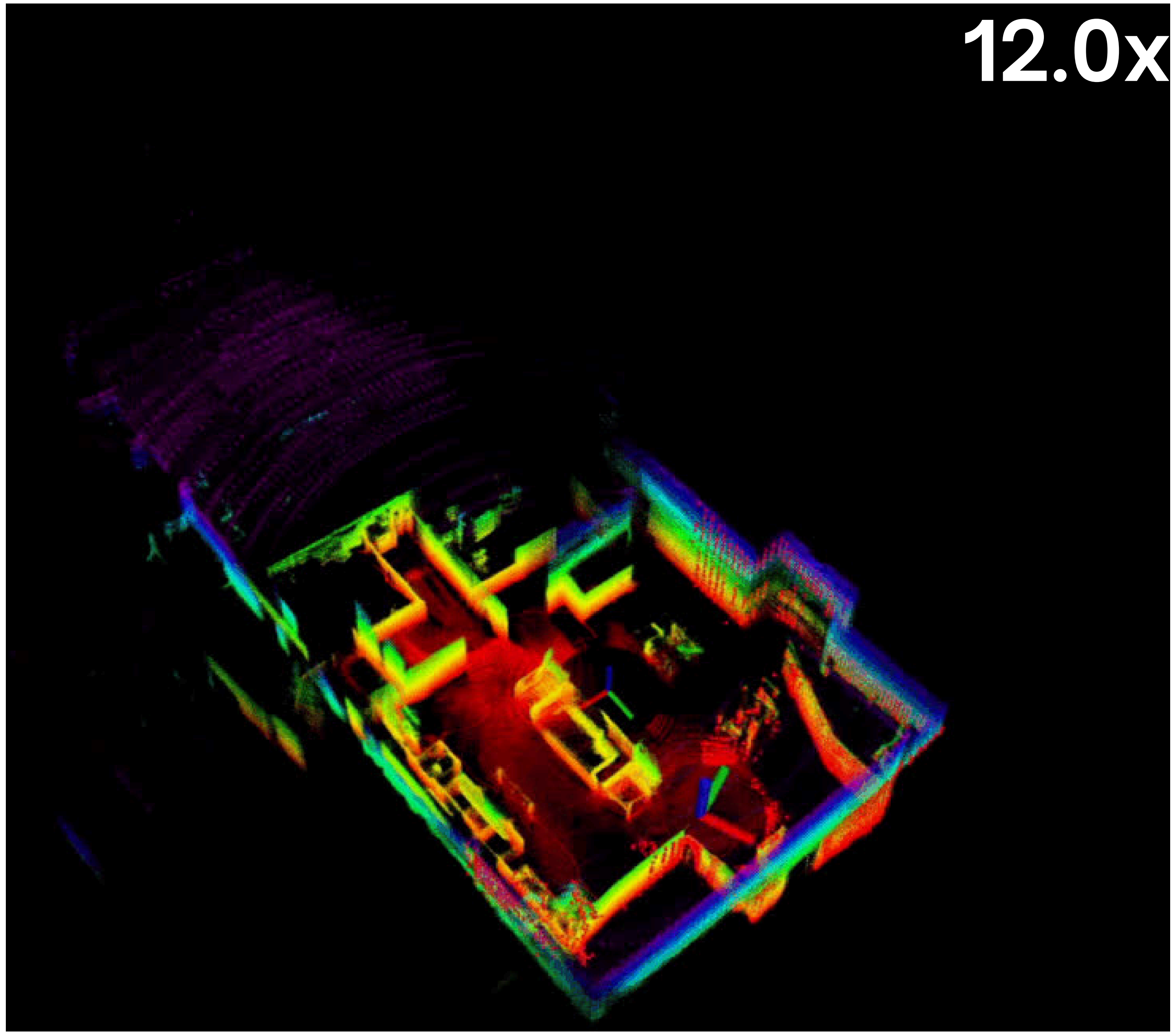
It was tested if the above mentioned decision time is obtained for the correpondent velocity and distance values.

13. 3D Mapping - Achieved results

Contribution: António Morais.

A map of the MRL was built with a resolution of 5 cm.

- On the right is shown the building process (with a video playback speed of 12.0x) of the map using the FAST-LIO[1] algorithm.



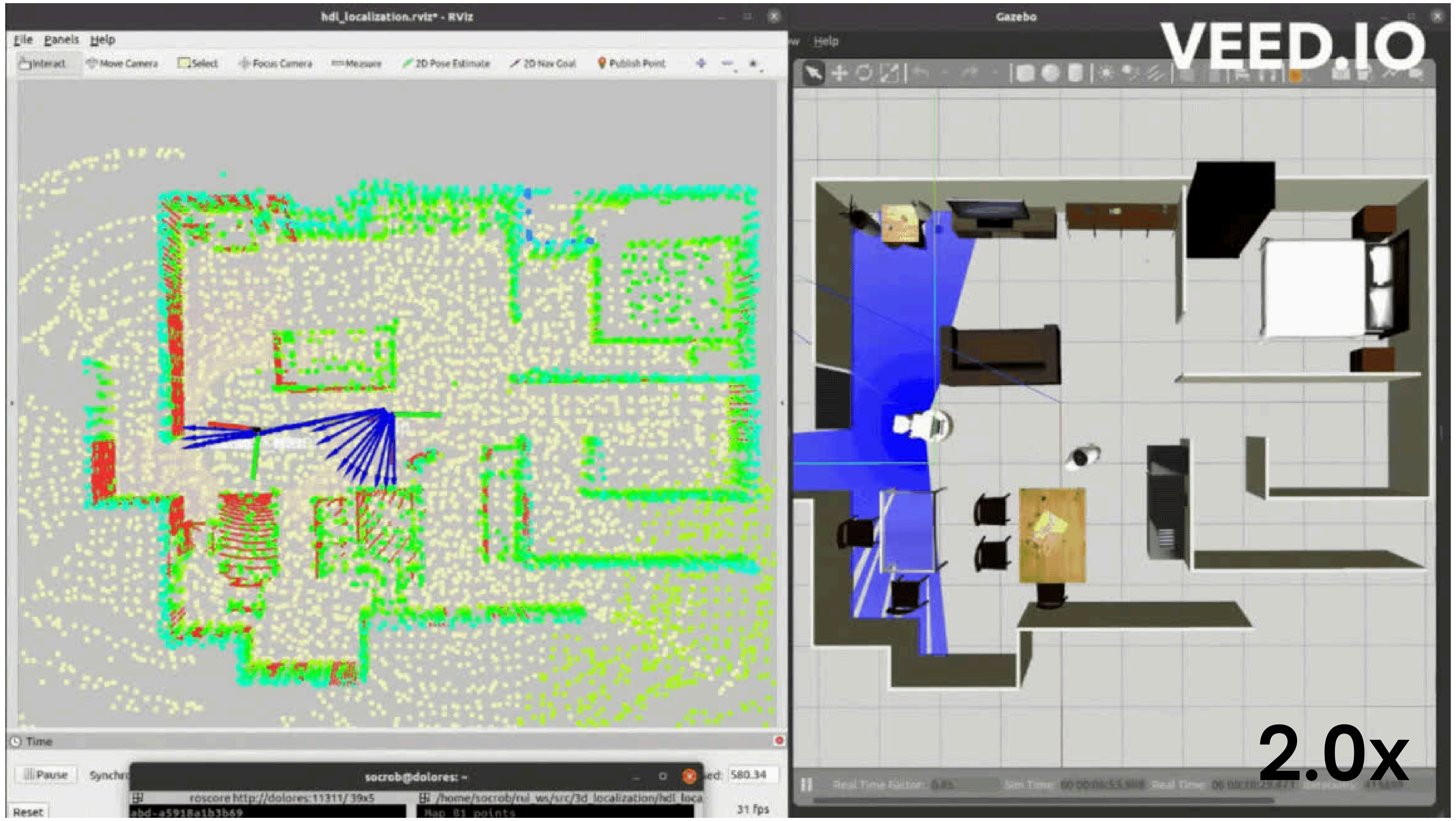
Real dataset visualization in Rviz of the MRL (resolution of 5 cm)

[1] https://github.com/hku-mars/FAST_LIO

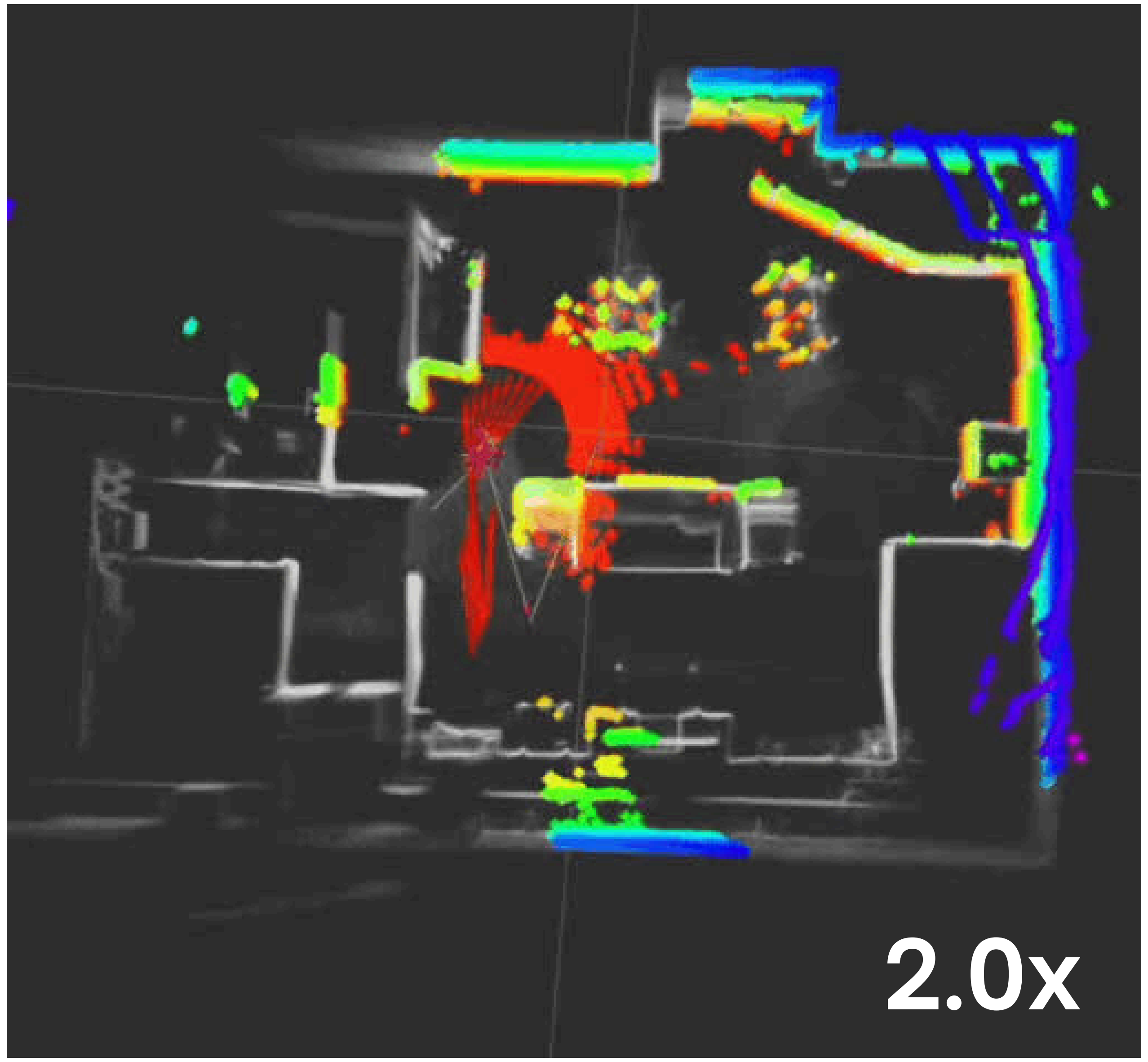
14. 3D Localization - Achieved results (II)

Contribution: Catarina Caramalho and João Pinheiro.

HDL Algorithm[1] - To detect a good localization performance, the points detected by the sensor need to overlap with the map:



Simulation dataset visualization in Rviz (left) and Gazebo (right) of the MRL

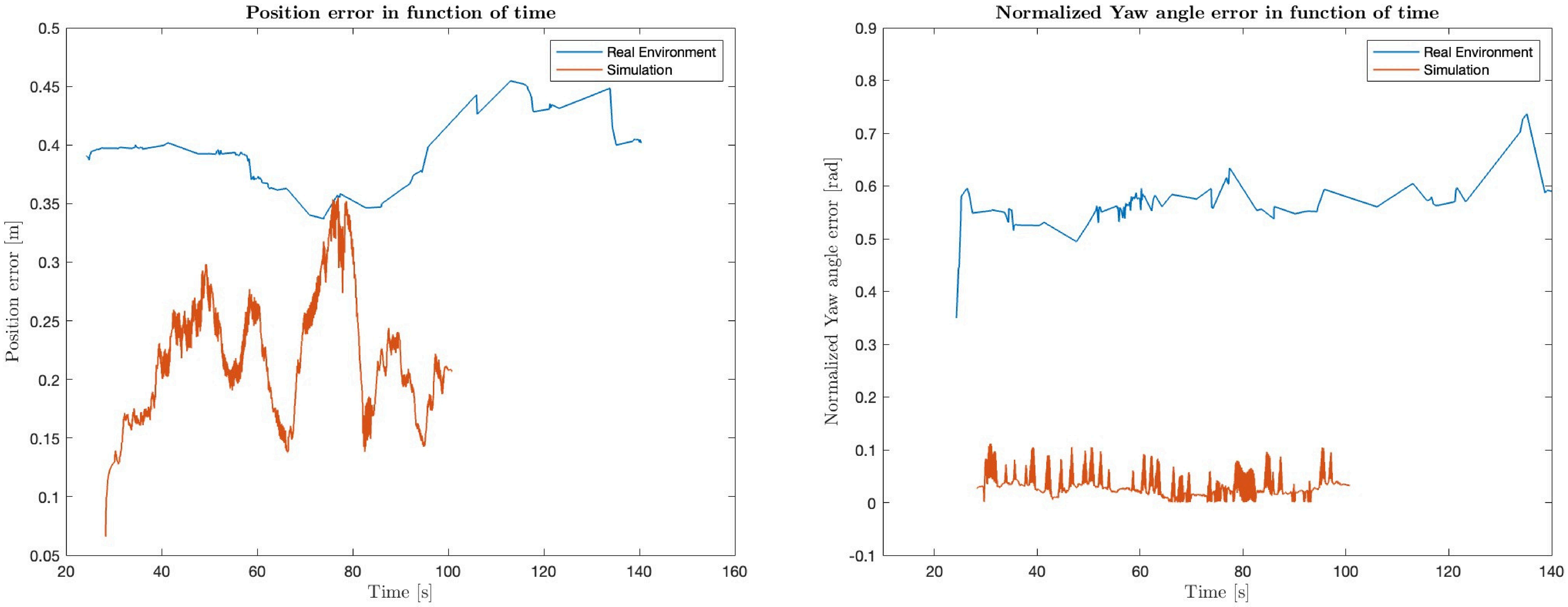


Real dataset visualization in Rviz of the MRL

[1] https://github.com/koide3/hdl_localization

14. 3D Localization - Achieved results (V)

Contribution: Catarina Caramalho and João Pinheiro.



HDL Algorithm **position** (left) and **orientation** (right) errors with odometry as ground truth for simulation, and Motion Capture System (slide 41) as ground truth for real data

15. 2D Path Planning/Guidance - Achieved results (I)

Contribution: Tiago Teixeira and João Carranca.

1. Convert the Ouster 3D point cloud information into 2D obstacles.
2. Make this conversion dynamic considering the current robot's height.

15. 2D Path Planning/Guidance - Achieved results (II)

Contribution: Tiago Teixeira and João Carranca.

For the Dynamic 3D to 2D Conversion task, the students were required to:

- Adjust a launch file to enable the method *pointcloud_to_laserscan*[1] to accept the point cloud from the Ouster sensor and translate it into obstacles on a 2D map.

- Edit the source code of the method mentioned earlier to dynamically calculate the robot's height every second instead of assuming a fixed value.

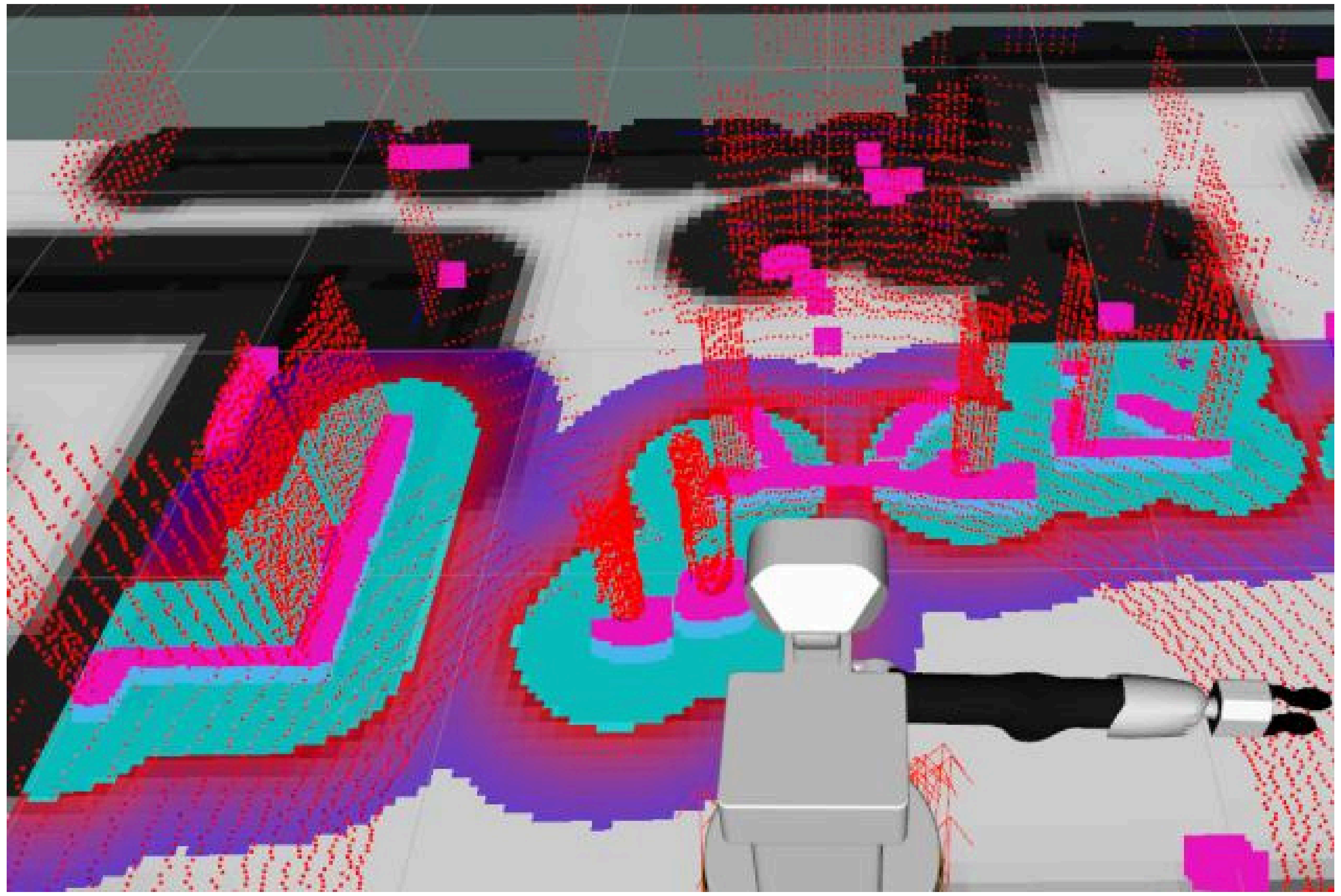
1 https://github.com/ros-perception/pointcloud_to_laserscan

15. 2D Path Planning/Guidance - Achieved results (III)

Contribution: Tiago Teixeira and João Carranca.

1. 3D to 2D conversion

Testbed

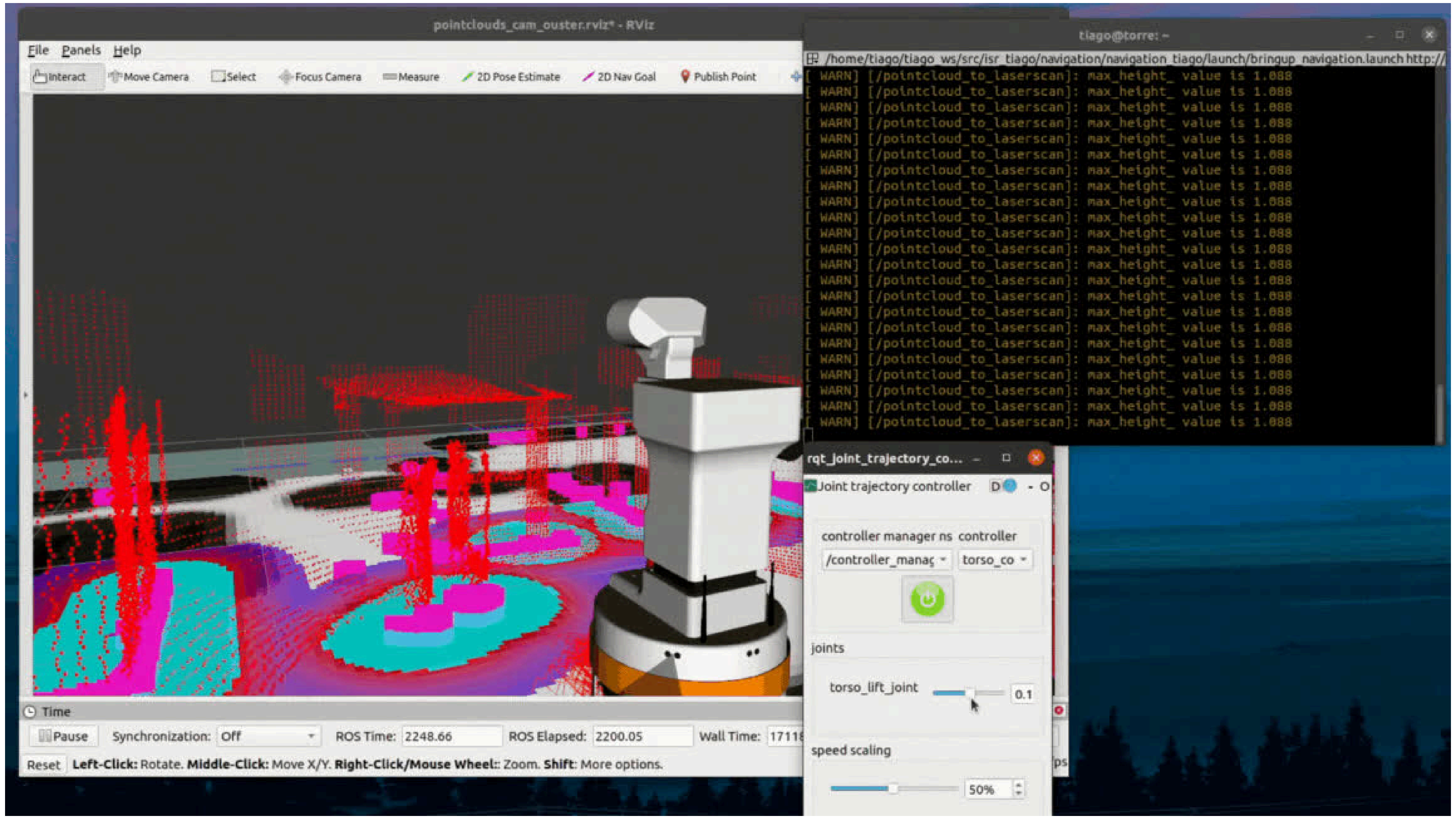


Testbed perceived by the robot

15. 2D Path Planning/Guidance - Achieved results (IV)

Contribution: Tiago Teixeira and João Carranca.

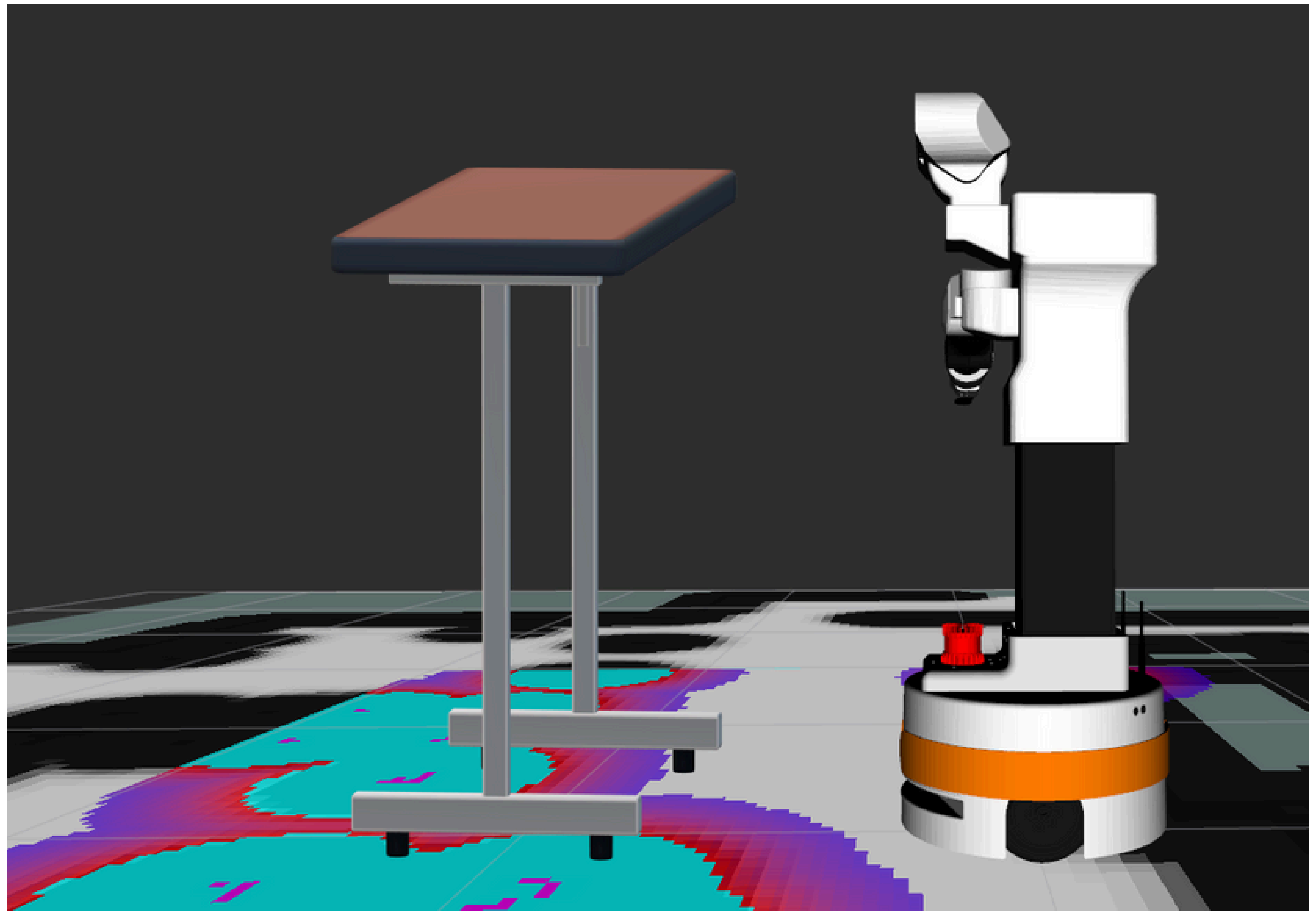
2. Dynamic conversion

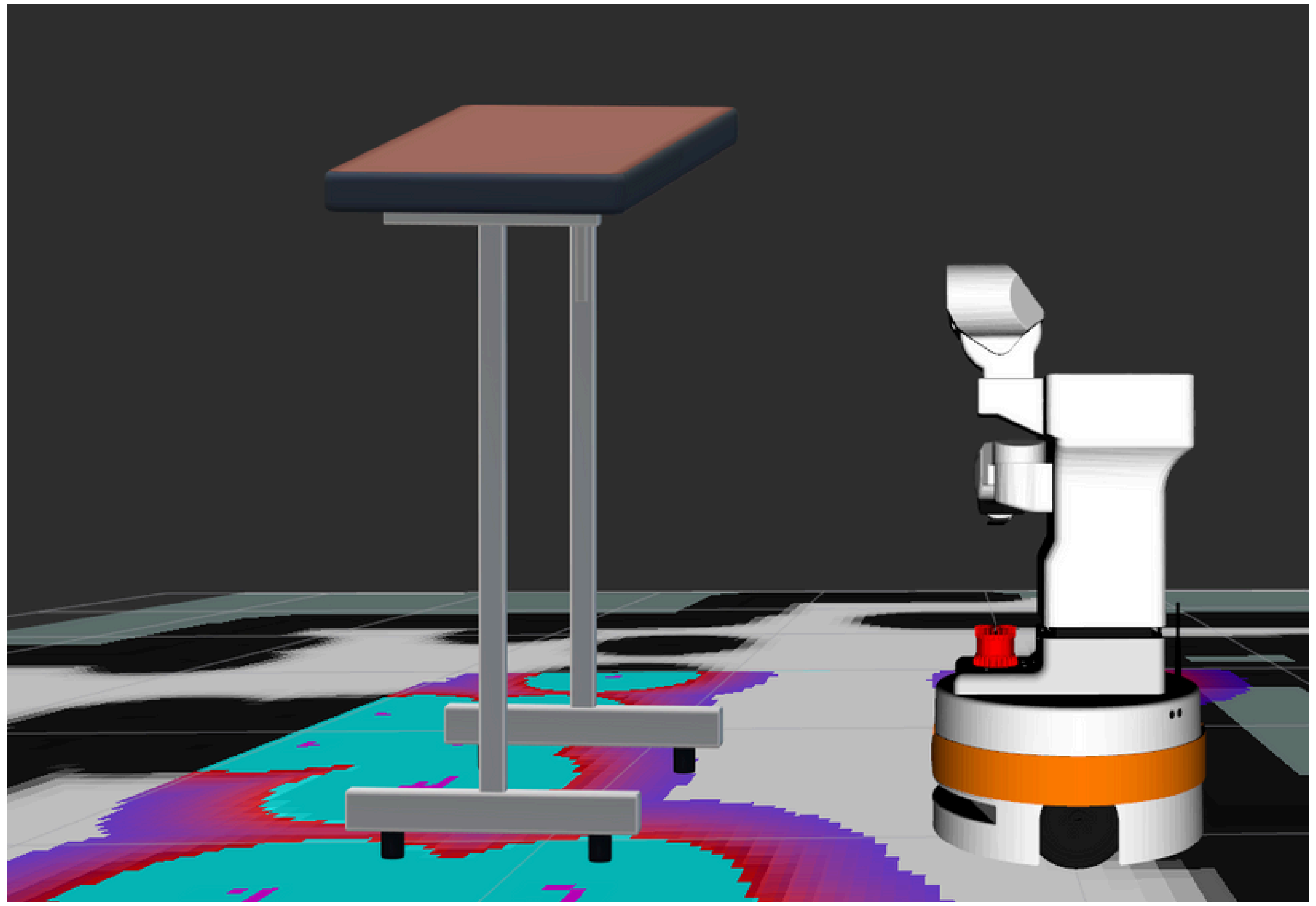


15. 2D Path Planning/Guidance - Achieved results (V)

Contribution: Tiago Teixeira and João Carranca.

To understand the importance of this task we could think of the following example:





15. 2D Path Planning/Guidance - Achieved results (VI)

Contribution: Tiago Teixeira and João Carranca.

- With the original implementation of the *pointcloud_to_laserscan* method, any change in the robot's height, such as retracting its torso, would go unnoticed.

- Consequently, the lack of detection would impede the system from recognizing the possibility for the robot to navigate underneath obstacles like tables, which could limit its navigation capabilities.

16. Final Project - Achieved results (I)

Contribution: All.

Regarding metrics mentioned in the “Testing and validation metrics” section:

- The team’s solution components have the same frequency levels as the 2D-Sensor based Navigation.
- The team could not precisely determine the decision time for a velocity of 0.3 m/s and a distance of 1 m. However, during tests it was approximately ensured that the robot checked the requirement. It also avoided obstacles even at smaller distances expected to cause collisions.

16. Final Project - Achieved results (II)

Contribution: All.

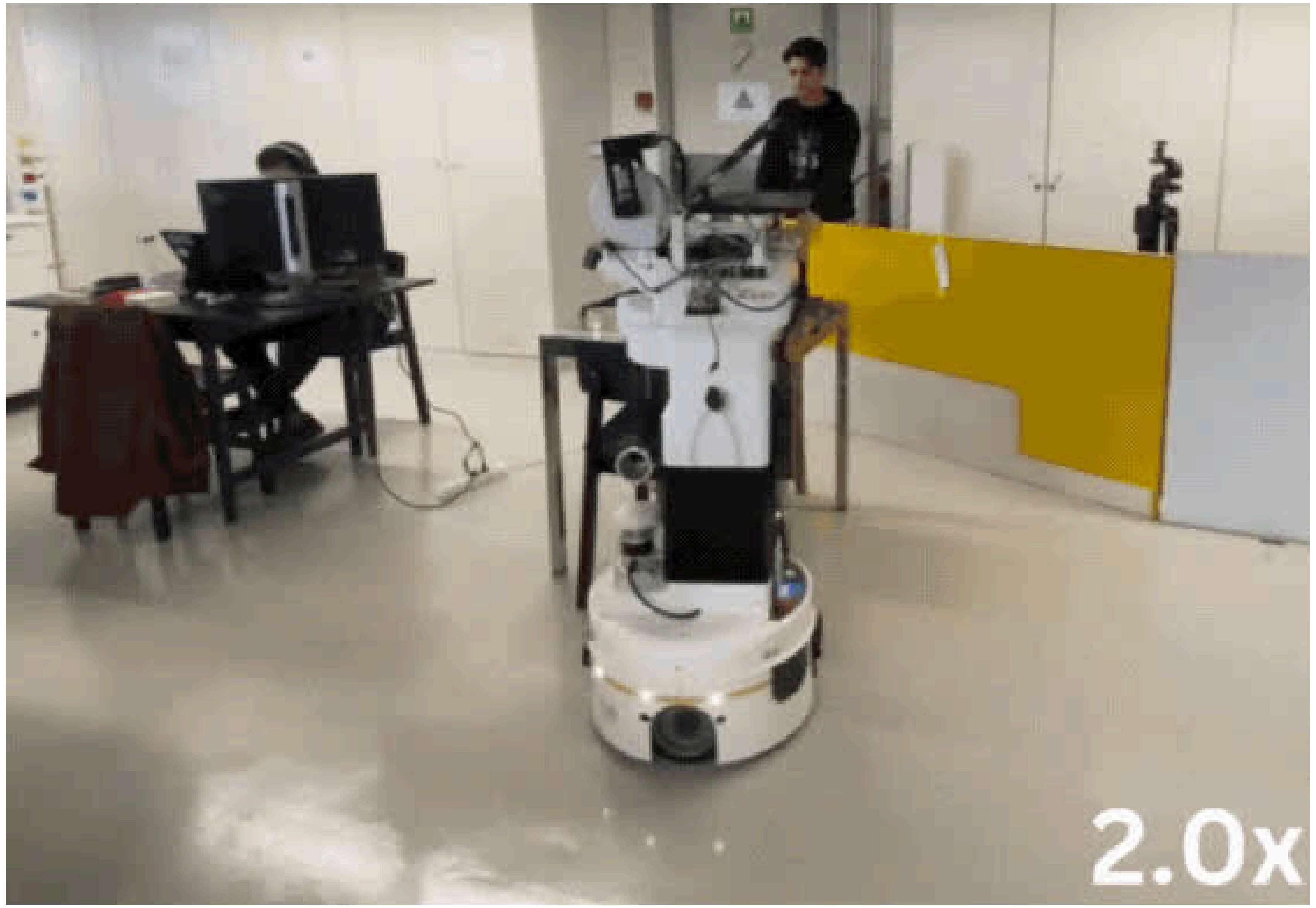
Successful tests were conducted:

- Using static obstacles (chairs).
- Using static obstacles (chairs) and a suspended obstacle (board).
- Using static obstacles (chairs), a suspended obstacle (board), and a dynamic obstacle (a person).
- With gradually smaller static obstacles (bin, cereal box, iron cylinder, cardboard box and a cup) up to a height of 9 cm.

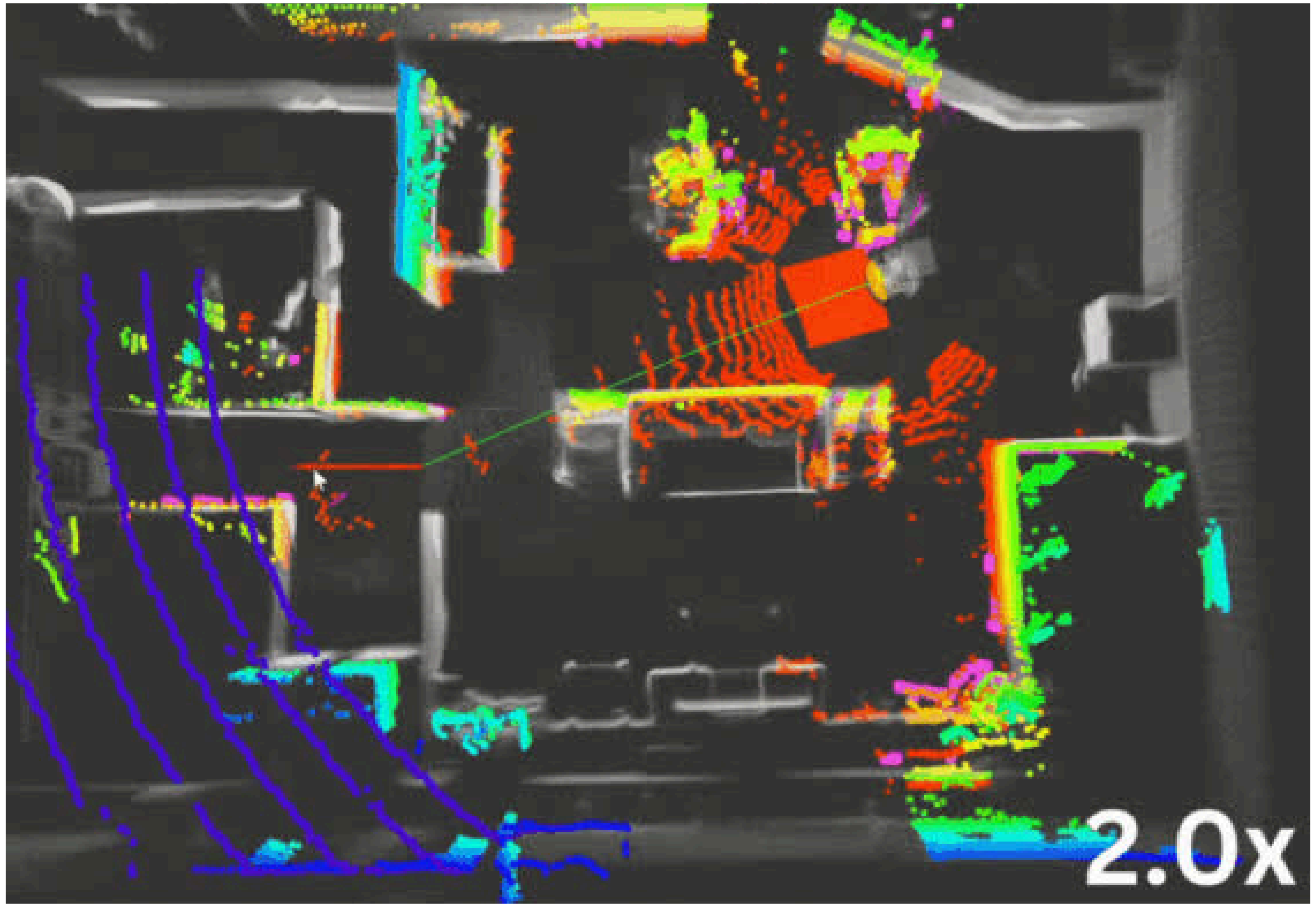
16. Final Project - Achieved results (III)

Contribution: All.

No obstacles



Robot in the real environment



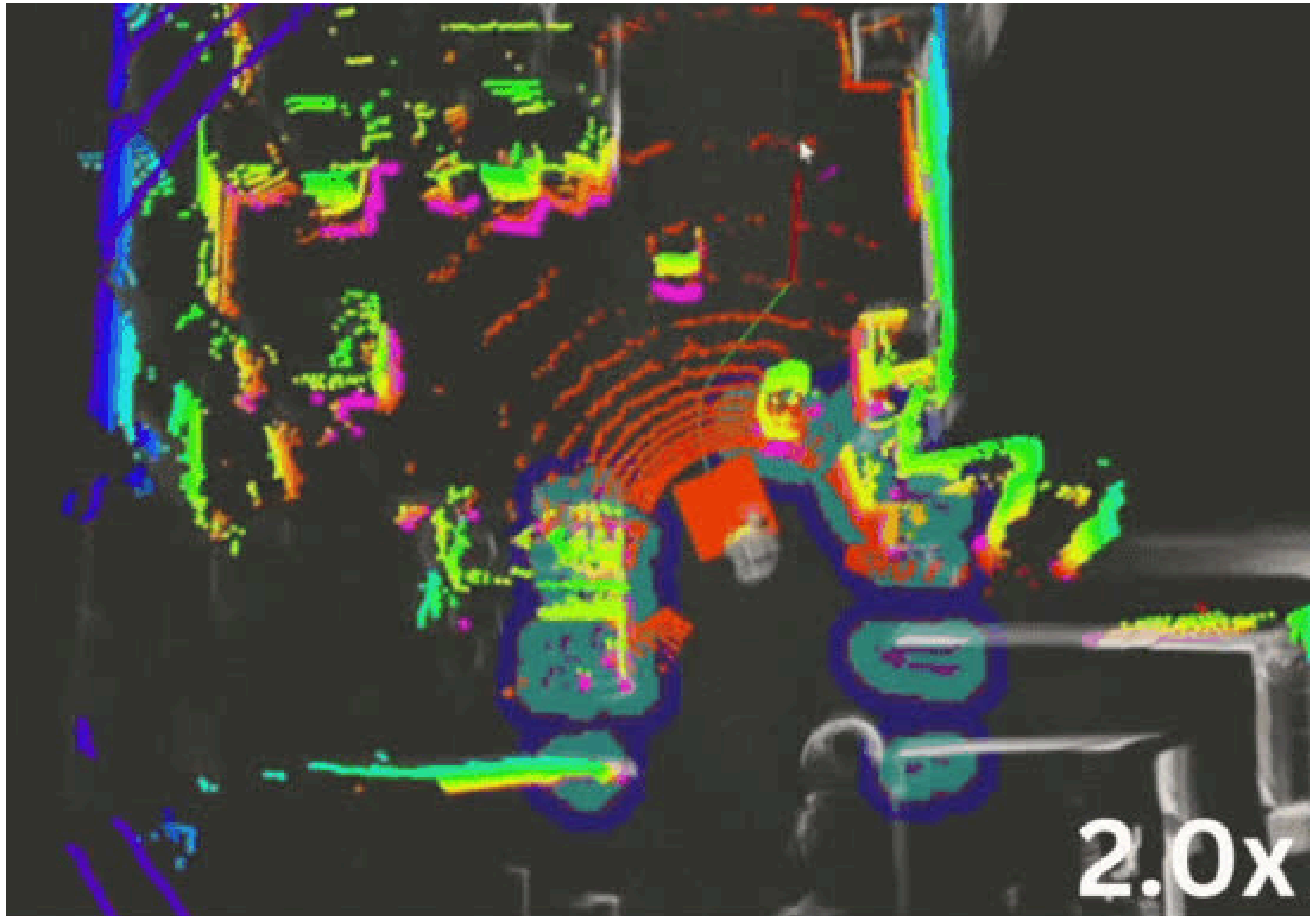
The real environment perceived by the robot

16. Final Project - Achieved results (IV)

Contribution: All.

Static obstacles

Robot in the real environment



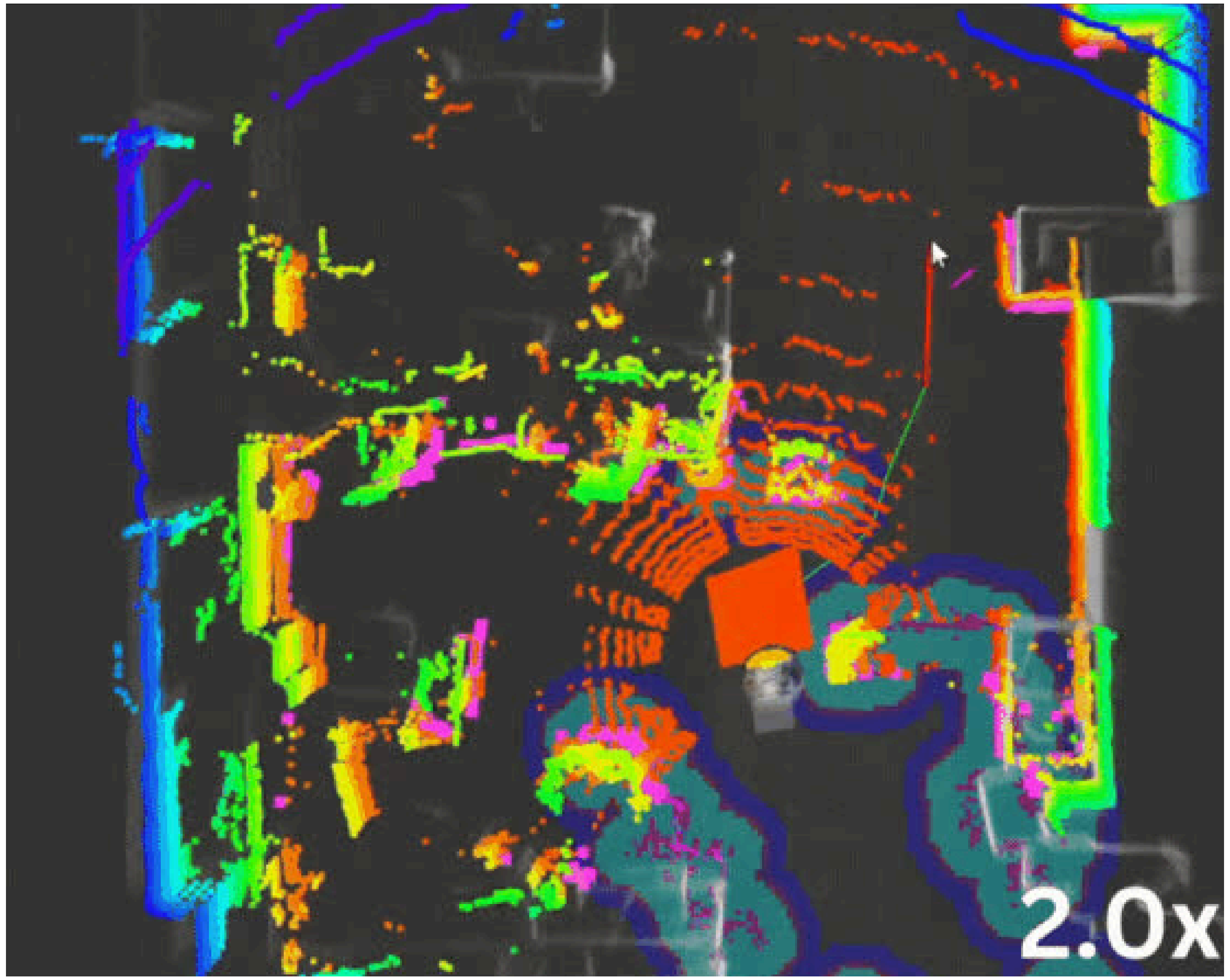
The real environment perceived by the robot

16. Final Project - Achieved results (V)

Contribution: All.

Static obstacles and static obstacle that 2D-Sensor based navigation doesn't avoid

Robot in the real environment



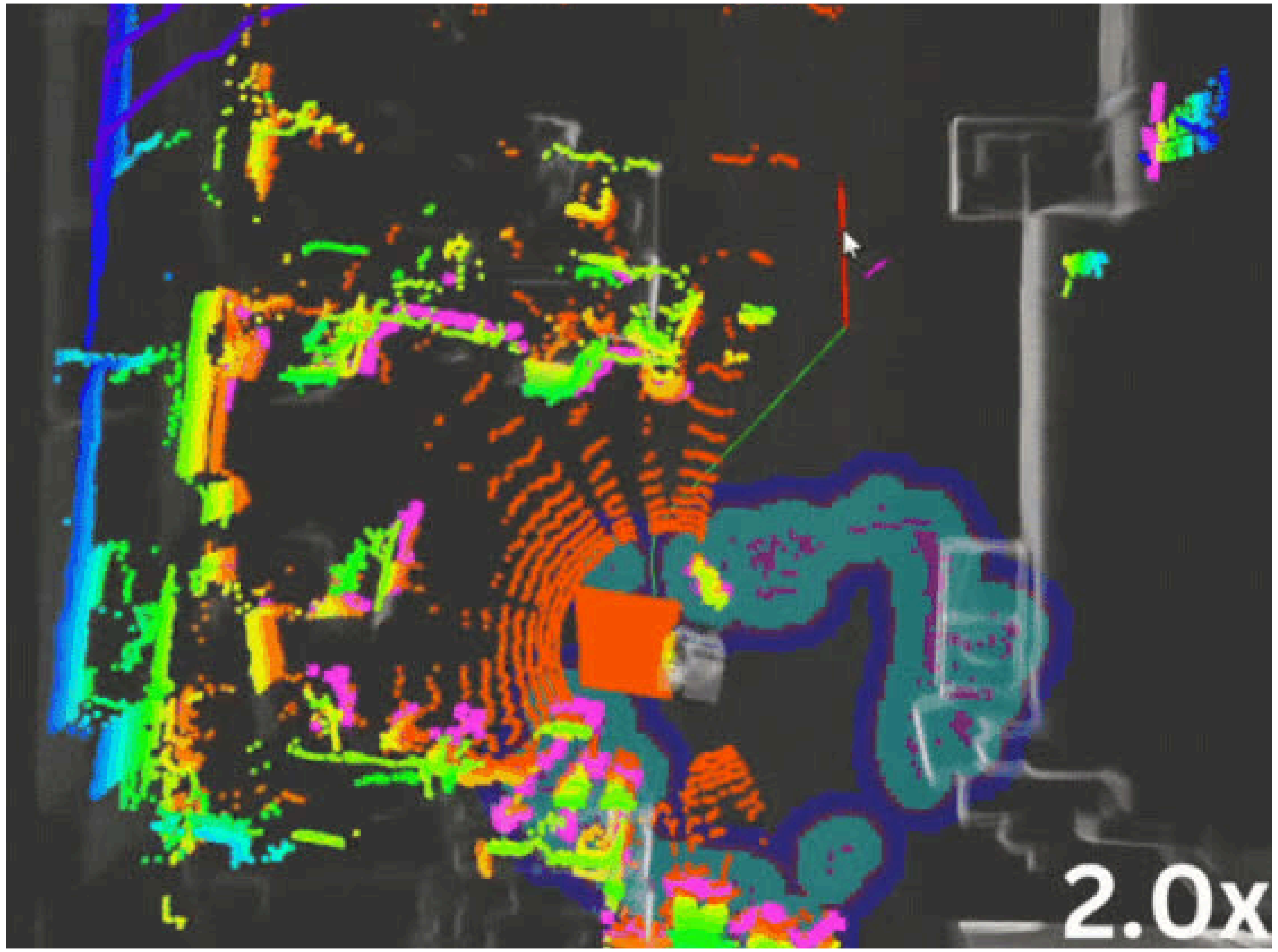
The real environment perceived by the robot

16. Final Project - Achieved results (VI)

Contribution: All.

Static obstacles, static obstacle that 2D-Sensor based navigation doesn't avoid and dynamic obstacle

Robot in the real environment



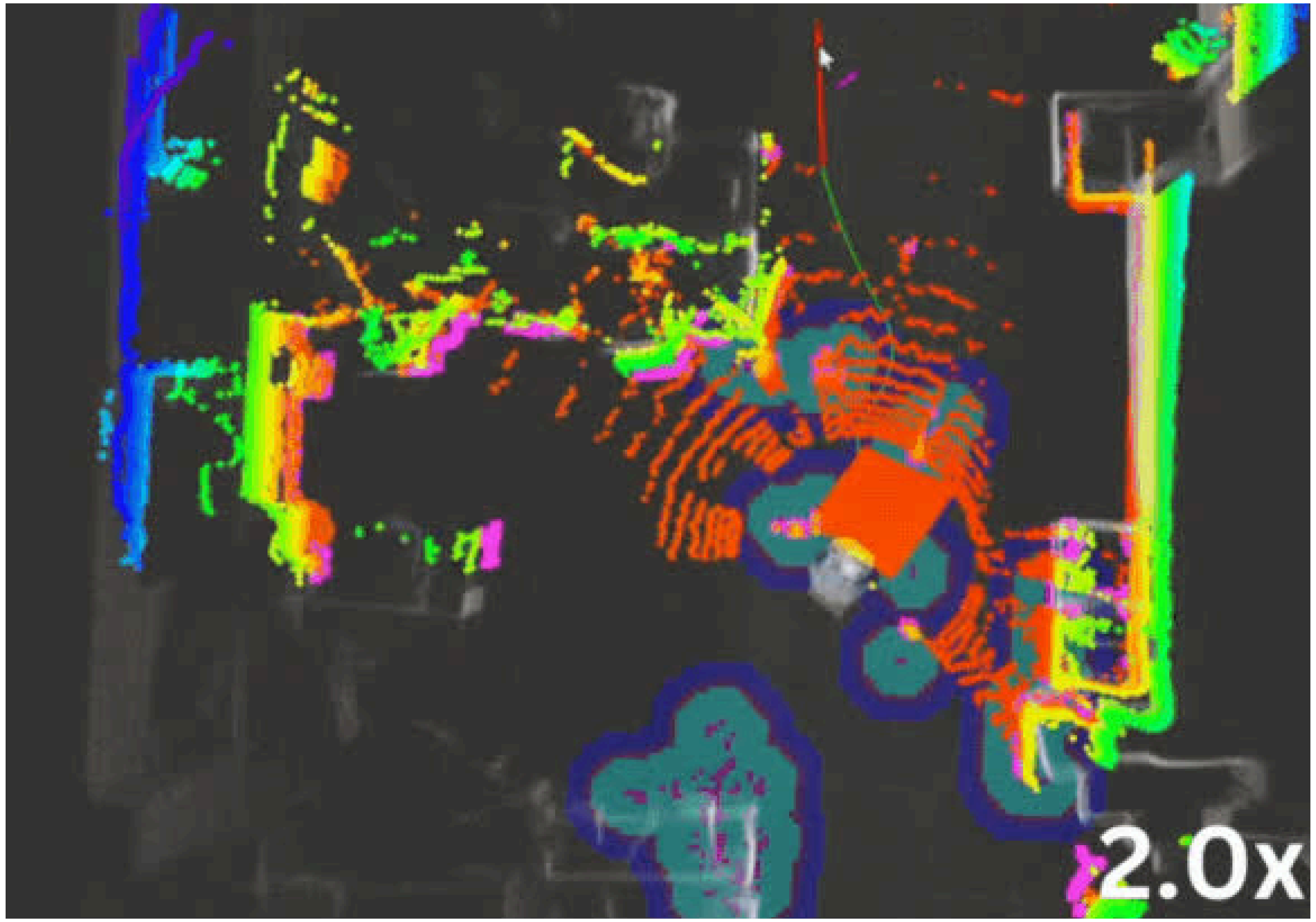
The real environment perceived by the robot

16. Final Project - Achieved results (VII)

Contribution: All.

Gradually smaller static obstacles

Robot in the real environment



The real environment perceived by the robot

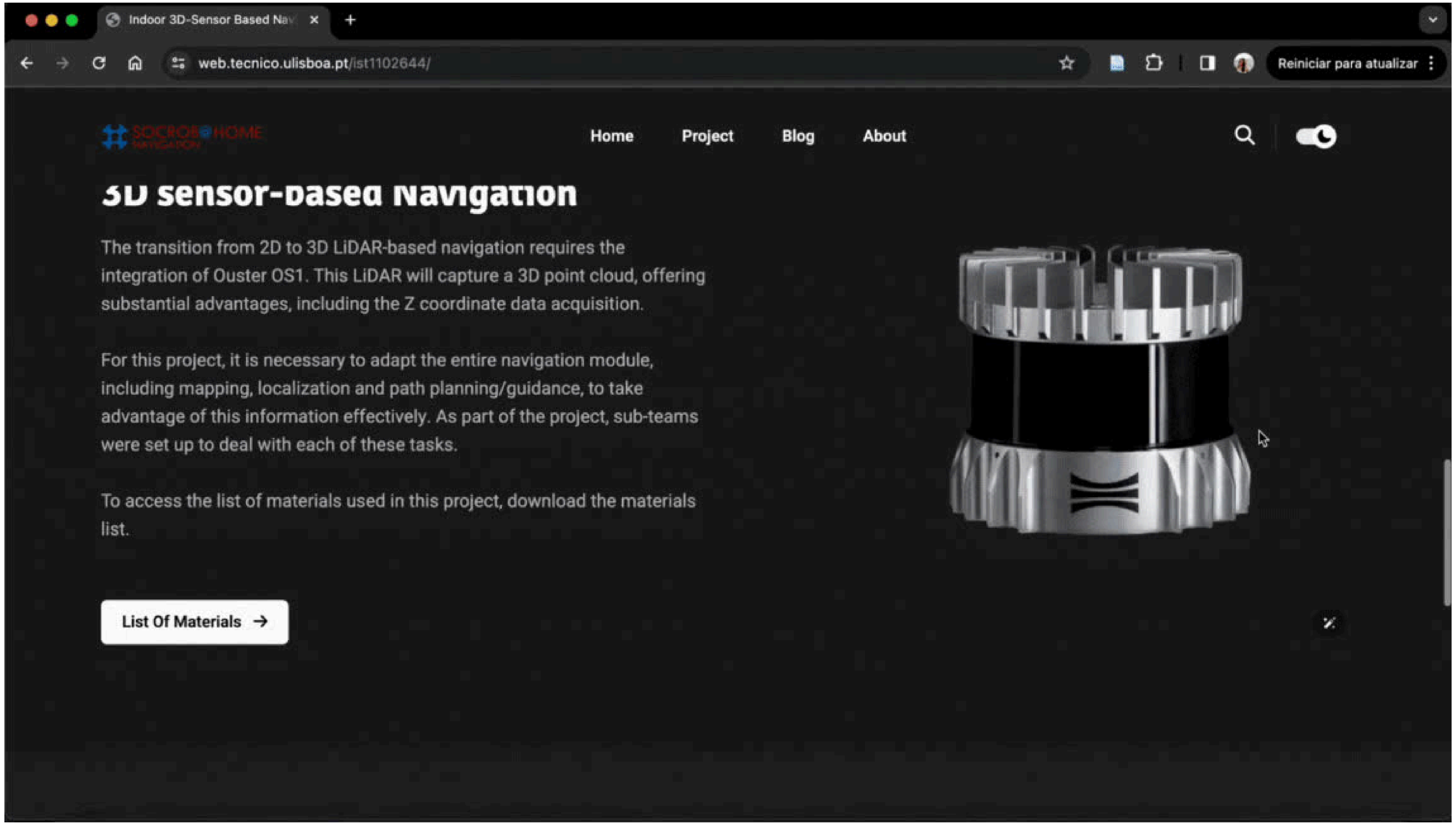
16. Final Project - Achieved results (VIII)

Contribution: All.

Type of test performed	Number of successful trials (out of 10)
No obstacles	10
Static obstacles	10
Static obstacles + Obstacle that 2D-sensor based navigation doesn't avoid	10
Static obstacles + Obstacle that 2D-sensor based navigation doesn't avoid + Dynamic obstacle	10
Gradually smaller static obstacles	9

17. Subject assessment - Website

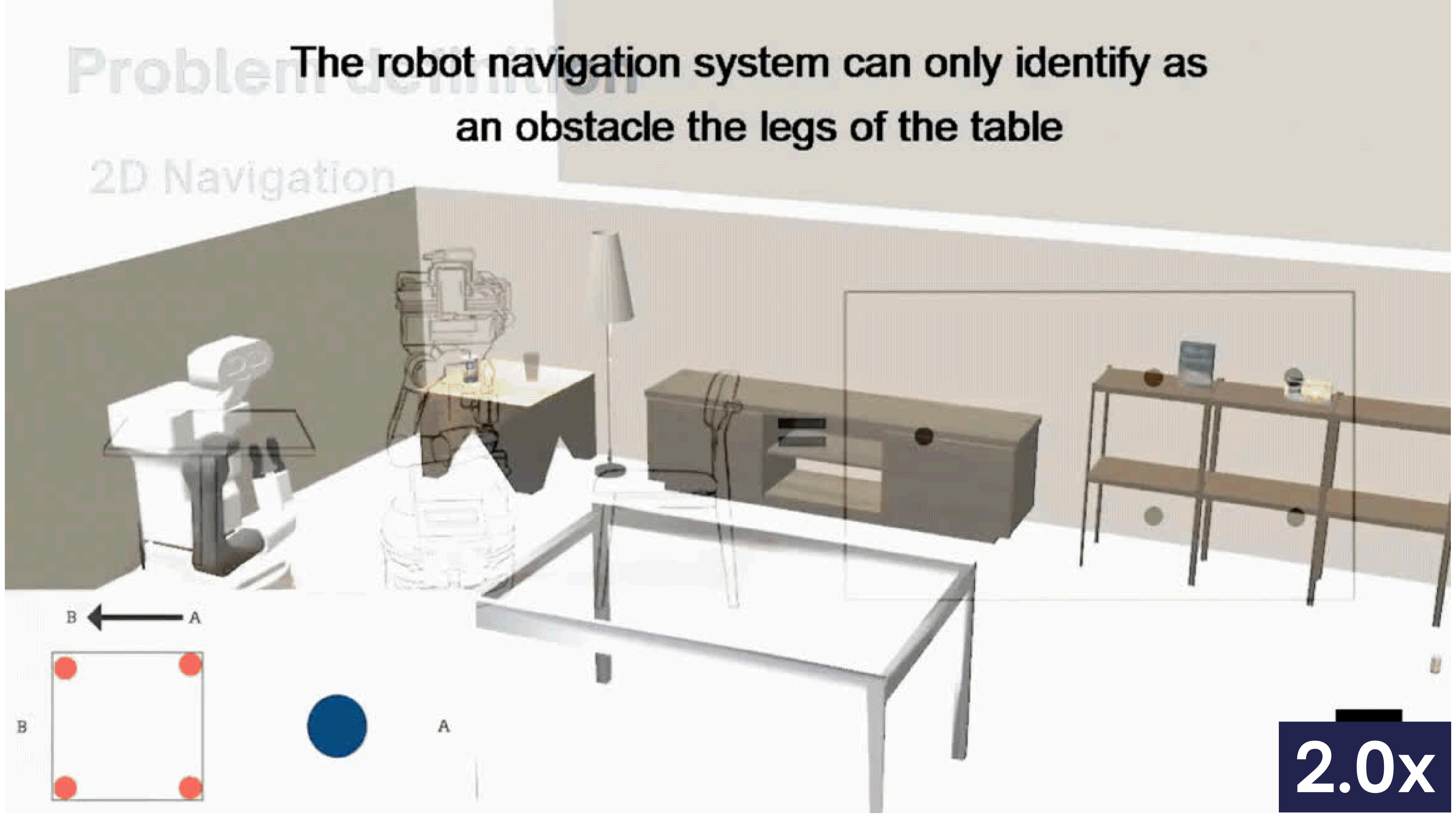
Contribution: All.



Website Link: https://web.tecnico.ulisboa.pt/ist1102644/

17. Subject assessment - Video

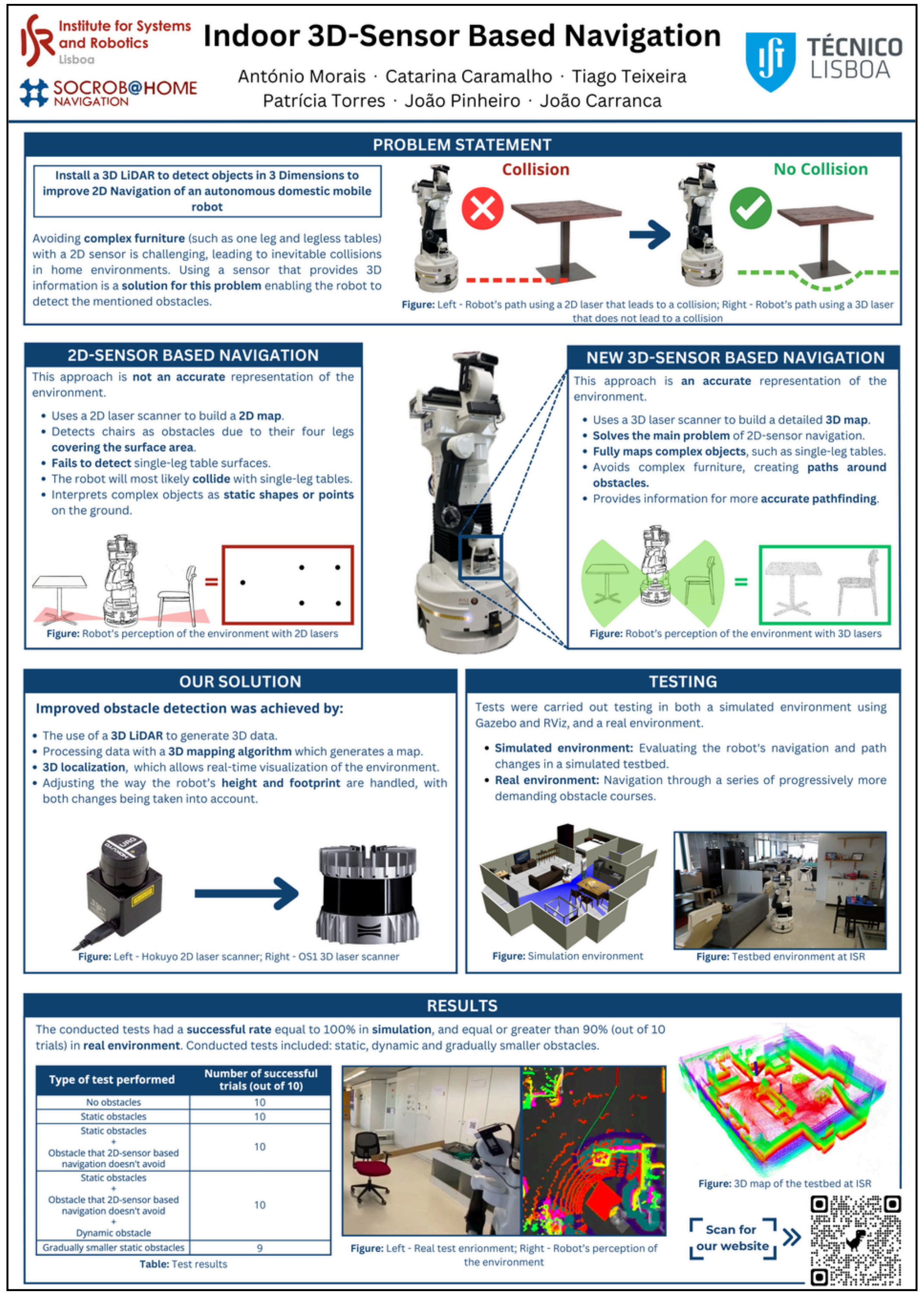
Contribution: João Pinheiro and Tiago Teixeira.



Click here to watch the complete video

17. Subject assessment - Poster

Contribution: António Morais, João Carranca e Catarina Caramalho.



17. Subject assessment - Final Pitch Deck

Contribution: António Morais and Catarina Caramalho.

Subtasks defined include:

- Slides
- Content selection support
- Presentation
  - **Contribution:** All.

Thank you!

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