The COBRA Heterogenous Multiple-robot Localization and Mapping Dataset

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***Abstract*—This paper presents a heterogenous, two-dimensional and three-dimensional, single-robot and multiple-robot localization and mapping dataset. The dataset is collected with educational and research purposes: to save time in dealing with hardware and to compare the results with a benchmark dataset. The data is collected in standard Robot Operating System (ROS) format. The environments, robots, and sensors configurations are explained in detail. Highly accurate blueprints of the environments or Vicon positioning are available as ground truth. The dataset is available for download[1].**

***Index Terms*—Multiple-robot, Quadrotor, Unmanned Ground Vehicle, Simultaneous Localization and Mapping (SLAM).**

I. Introduction

THIS paper presents a heterogenous, two-dimensional and three-dimensional, single-robot and multiple-robot localization and mapping dataset collected at the University of New Brunswick, by the COllaboration Based Robotics and Automation (COBRA) group. The dataset can be used for multiple and single robot simultaneous localization and mapping (SLAM) [1]. Multiple-robot SLAM by a team of homogenous or heterogenous robots is motivated by the fact that mapping and exploration is done faster [2], [3], [4], [5], [6]. The data is collected to assist algorithm developments and help researchers to compare results. Robotic datasets are specifically important when it is related to a flying robot such as a quadrotor, which are rarely available.

The dataset is provided with two skid-steering ground robots and one quadrotor. It is collected in four different configurations. Each configuration includes different sensors such as scanning laser ranger, Inertial Measurement Unit (IMU), Sound Navigation and Ranging (SONAR), and wheel encoders. In two configurations, only one robot is involved (ground robot or quadrotor). For the remaining two configurations, two ground robots in one case and in the other case, one ground robot and one quadrotor are used. Each reading in the dataset is timestamped with a synchronized clock. The dataset with ground truth blueprints or Vicon positiong are available for download at [7].

The Robotics Data Set Repository (RADISH) by A. Howard and N. Roy [8] hosts 41 well-known single-robot and multiple-robot datasets with different sensors; however, there is no dataset in RADISH which includes flying and ground robots together. In [9], a dataset by only one quadrotor is produced, but there is no laser ranger in this dataset. The dataset by the University of Freiburg[2] includes laser measurement from a quadrotor but lacks measurements from ground robots. K. Leung et al. [10] present a 2D multiple-robot dataset which also lacks laser data. The dataset in [11] includes only imagery and GPS information for a fixed-wing aircraft. This work presents all combination of heterogenous robotic datasets by two ground robots and one quadrotor. The proposed dataset in this paper has been used in authors' other paper [12].

The rest of the paper is organized as follows: Section II presents data collection details including the environments, robots, and sensors. Section III explains the collected data with a few developed sample maps, and Section IV makes some general conclusions.

II. Data Collection

The dataset is collected in three indoor environments: classroom environment, hallway environment, and Vicon lab. The classroom environment is relatively small. Its area is approximately 170 m^2 and includes two rooms. The hallway environment is relatively large and includes four long hallways, with the total area of approximately 684 m^2 . The effective positioning area of the Vicon lab is approximately 24 m^2. The maximum error of the VICON measurements is 0.5 millimeters. All datasets are produced at the University of New brunswick. Each robot collects its own data, while robots have synchronized clocks. The robots are guided by remote controllers.

A. Robots and Sensors

In this work, two different types of robots are used. A custom-built quadrotor called *COBRA* quadrotor and two *CoroBot* robots. In this section, each robot is explained in detail.

1) COBRA Quadrotor: The COBRA quadrotor is a custom-built four-rotor quadrotor designed and developed at COBRA lab at the University of New Brunswick. It is equipped with an IMU, a SONAR sensor, and a scanning laser ranger. For more information about the quadrotor, please see [13], [14], [15]. The scanning laser ranger is mounted upside down for more stability during flight. Fig. 1 shows the quadrotor. Detailed information about the sensors is presented later.

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[1] http://www.ece.unb.ca/COBRA/open_source.htm

[2] http://ais.informatik.uni-freiburg.de/projects/datasets/quadrotor079/

Figure 1. COBRA quadrotor equipped with an IMU, a SONAR, and a scanning laser ranger.

2) CoroBot Robot: The CoroBot robot is a four-wheeled skid-steering mobile platform developed by CoroWare Inc. It has an on-board mini computer and two High Speed Phidget Encoders. Fig. 2 shows two robots of this type, each equipped with a Hokuyo UTM-30LX scanning laser rangefinder. For data collection, two configurations of these robots are used. In the first configuration, each robot is equipped with one scanning laser ranger (Fig. 2). In the second configuration, only one robot is used, and it is equipped with two perpendicular scanning laser rangers (Fig. 3).

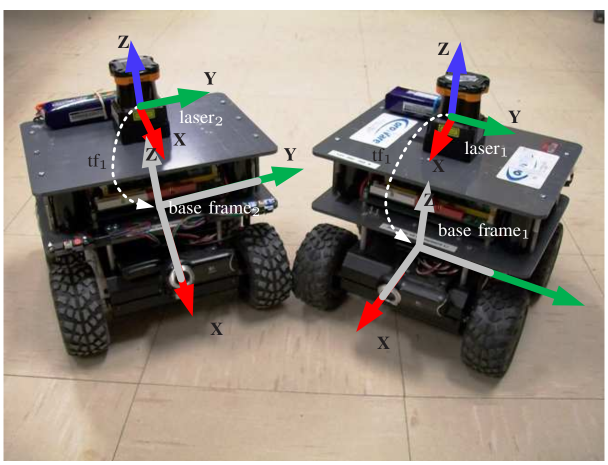

Figure 2. First Configuration of ground robots and sensors. Each robot is equipped with one laser ranger and two wheel encoders. The laser ranger is located at the center of the robot.

3) Scanning Laser Ranger: For the scanning laser ranger, the Hokuyo UTM-30LX scanning laser rangefinder[3] is used. It operates at 40 Hz and can detect up to 60 m, but only a maximum range of 30 m is guaranteed. Its accuracy is maximum ±50 mm. Its angular resolution is 0.25^o with a coverage of 270^o. It weighs about 370 g, which is relatively a heavy load for a typical quadrotor. A reflective mirror is also mounted on the laser ranger to reflect a few beams to the ground and measure the altitude of the quadrotor (see

[3]http://www.hokuyo-aut.jp/02sensor/07scanner/utm_30lx.html

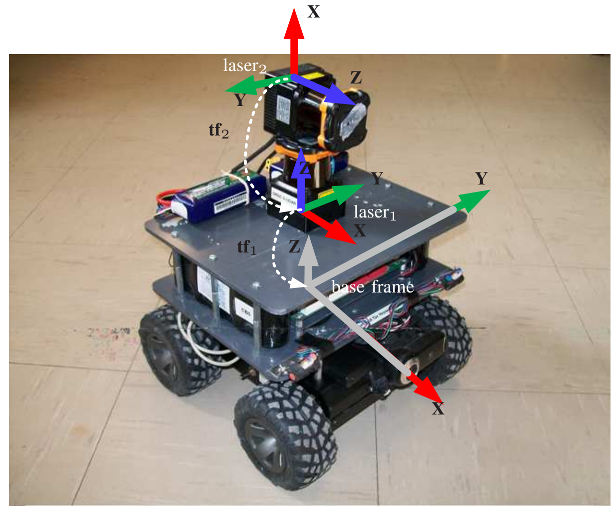

Figure 3. Second Configuration of one ground robot with two laser rangers. In this configuration, the data collection is performed by one CoroBot robot equipped with two perpendicular scanning laser rangers. The horizontal laser ranger is located at the center of the robot, while the other one is perpendicular to it. The mirror of the vertical laser is located 4 cm in front of the horizontal laser. The transformations between the frames are given in Table II.

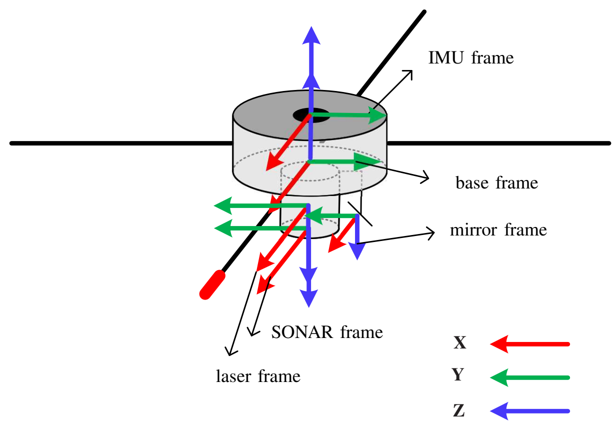

Figure 4. Frames of the quadrotor. The transformations between the frames are given in Table III

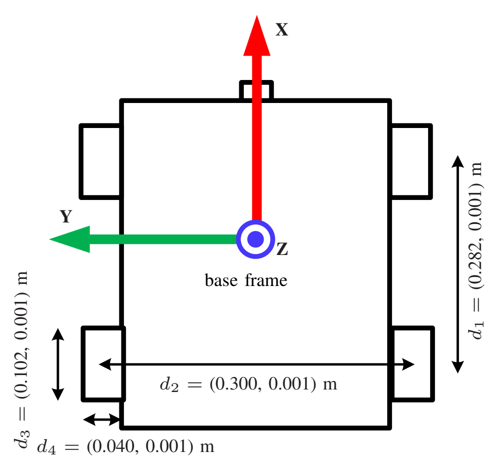

Figure 5. Frames of the CoroBot robot. The mean and standard deviation of each measurement is also given in Table I.

Fig. 4). 10 beams are reflected to the ground, and the results are averaged to produce an average distance. If the average distance of the beams is d, the altitude of the 3D pose, z, with respect to the mirror, is calculated as follows:

$$z = d \cos\phi \cos\theta, \tag{1}$$

where ϕ and θ are roll and pitch angles. The roll and pitch angles, which are directly used from the EKF implementation of the IMU, have less than one degree error.

4) Inertial Measurement Unit: The CH Robotics UM6 IMU is a light weight orientation sensor which measures the orientation in 3D. It operates at 500 Hz and includes rate gyros, accelerometers, and magnetic sensors.

5) Sound Navigation and Ranging: The SensComps MINI-A PB Ultrasonic Transducer is used. This sensor is a 50 KHz electrostatic transducer and can measure from 1 foot to 12 feet[4]. The sensor was calibrated over its range using six measurements for each foot. In the experiments, the altitude is measured through either the reflective mirror or the SONAR sensor.

6) Wheel Encoder: There are two wheel encoders on each ground robot, CoroBot, one on each side of the robot. Wheel encoders are High Speed Phidget Encoders[5]. Displacement using wheel encoders can be calculated, given the number of ticks per revolution and other specifications of the robot according to Table I. The code provided may be used for this purpose[6]. The physical dimensions of the robot are also presented in the table. For each given dimension, 10 measurements were acquired and the mean and standard deviation are given.

Table I
SPECIFICATION OF ENCODERS AND THE ROBOT.

parameter	value (meas, standard deviation)
Diameter of wheel	(0.105 m, 0.001 m)
Width of wheel	(0.040 m, 0.001 m)
Width of the robot	(0.300 m, 0.001 m)
Distance between wheels	(0.282 m, 0.001 m)
Ticks per revolution	624

7) Transformation Frames: The transformations between the sensors of the robots are given in this section. The naming and the transformations are based on the ROS standard[7]. According to the standard, a static transformation between a parent frame and a child frame is given based on the following convention:

$$[parent\,frame \quad child\,frame \quad x \quad y \quad z \quad yaw \quad pitch \quad roll], \tag{2}$$

where x, y, and z are the offset values along $\mathbf{X}$, $\mathbf{Y}$, and $\mathbf{Z}$ axis in meters, and yaw, pitch, roll are the rotation angles in radians. Also, $\mathbf{X}$, $\mathbf{Y}$, and $\mathbf{Z}$ axis are colored in red, blue, and green, respectively. Assume ϕ, θ, and ψ are Euler angles in the body frame which represent roll (rotation around $\mathbf{X}$), pitch (rotation around $\mathbf{Y}$), and yaw (rotation around $\mathbf{Z}$) angles respectively. To transform a vector from the body frame to the inertial frame, the following transformation is used [15]

$$R = \begin{bmatrix} c\psi\, c\theta & c\psi\, s\phi\, s\theta - c\phi\, s\psi & s\phi\, s\psi + c\phi\, c\psi\, s\theta \\ c\theta\, s\psi & c\phi\, c\psi + s\phi\, s\psi\, s\theta & c\phi\, s\psi\, s\theta - c\psi\, s\phi \\ -s\theta & c\theta\, s\phi & c\phi\, c\theta \end{bmatrix}, \tag{3}$$

where the order of rotation used is yaw, followed by pitch, followed by roll. $c\phi$ and $s\phi$ denote $cos(\phi)$ and $sin(\phi)$ respectively, similarly for ϕ and θ. The inertial frame ($\mathbf{X}$ is forward, $\mathbf{Y}$ is left, and $\mathbf{Z}$ is up) in the Vicon lab is located at the center of the lab, and the positions of the markers on the robots are given with respect to this frame. The inertial frame in the other environments, in which the blueprints are used as ground truth, can be arbitrary chosen at any point

a) Frames of CoroBot Robot: The frames which sensors and the base of the CoroBot robots are attached to are shown in Figures 2, 3 and 5. The transformations are given in Table II. The components of the transformations have been acquired by averaging at least 10 measurements for each component. The standard deviation for distance measurements is 0.001 m and for angle measurements is 0.017 radians.

Table II
FRAMES OF THE COROBOT ROBOT.

no	transformation
1	[base laser_1 0 0 12.2 0 0 0]
2	[laser_1 laser_2 -0.07 0 0.032 3.14 1.57 0]

b) Frames of COBRA Quadrotor: The frames which sensors and the base of the quadrotor are attached to are shown in Figures 1 and 4. The transformations are given in Table III. Similar to the ground robot, the components of the transformations have been calculated by averaging at least 10 measurements for each component. The standard deviation for distance measurements is 0.001 m and for angle measurements is 0.017 radians.

Table III
FRAMES OF THE QUADROTOR.

no	transformation
1	[base IMU 0.0 0.0 0.05 0.0 0.0 0.0]
2	[base laser 0.0 0.0 -0.11 3.14 3.14 0.0]
3	[laser SONAR 0.0 0.0 0.023 0.0 0.0 0.0]
4	[laser mirror 0.0 -0.03 0.0 0.0 0.0 0.0]

B. Data Structure

In this section, time synchronization, data formats, and data access are explained.

1) Time Synchronization: To synchronize time on different machines, Chrony[8] is used. Chrony supports online and offline

[4] http://www.senscomp.com/
[5] http://www.phidgets.com/products.php?product_id=1057_2
[6] http://ros.org/wiki/corobot_state_tf?distro=fuerte
[7] http://wiki.ros.org/tf
[8] http://chrony.tuxfamily.org/

time adjustment by two different applications. In the online case, a Network Time Protocol (NTP) daemon runs in the background and synchronizes the time with time servers. For an isolated machine, one might enter the time periodically. For this work, time is updated automatically using NTP daemon. The synchronized time appears as a label in the header of each acquired data. The maximum error of the time synchronization is 1 millisecond.

2) Data Format: The collected datasets are organized using ROS data formats.

Each sensor data is available under a ROS *topic* name. Each reading in the topic starts with a header which indicates the time of the data acquisition followed by a set of parameters if available. At the end, the sensed data is printed.

Each laser scan is structured according to Table IV[9]. The string of data starts with a header. The header includes the time when the first laser beam is acquired. Note that if the acquired ranges are outside of the range_min and range_max interval, they should be discarded. Beams 0 to 10 are used for the reflective mirror.

Table IV
LASERSCAN MESSAGE.

data type	name	description
std_msgs	header	timestamp
float32	angle_min	start angle of the scan (rad)
float32	angle_max	end angle of the scan (rad)
float32	angle_increment	angular distance between measurements (rad)
float32	time_increment	time between measurements (sec)
float32	scan_time	time between scans (sec)
float32	range_min	minimum range value (m)
float32	range_max	maximum range value (m)
float32[]	ranges	range data (m)
float32[]	intensities	intensity data (vendor specific)

Each IMU reading is formatted according to Table V[10]. The string of data starts with a header which includes the time stamp.

Each SONAR reading is formatted according to Table VI, which includes the header followed by a float showing the range. The range of the SONAR sensor is calibrated.

Finally, measurements of encoders on the ground robot are formatted according to Table VII. Each reading includes the number of ticks counted from the last reading for both encoders[11].

[9]http://ros.org/doc/api/sensor_msgs/html/msg/LaserScan.html
[10]http://www.ros.org/doc/api/sensor_msgs/html/msg/Imu.html
[11]http://ros.org/wiki/corobot_msgs

Table V
IMU MESSAGE.

data type	name
std_msgs	header(timestamp)
geometry_msgs/ Quaternion	orientation
float64	orientation_covariance
geometry_msgs/ Vector3	angular_velocity
float64	angular_velocity_covariance
geometry_msgs/ Vector3	linear_acceleration
float64	linear_acceleration_covariance

Table VI
SONAR MESSAGE.

data type	name	description
std_msgs/Header	header	timestamp
float64	sonar	calibrated range value

Table VII
ENCODER MESSAGE.

data type	name	description
std_msgs/Header	header	timestamp
int32	px	right encoder
int32	py	left encoder

3) Data Access: To record and replay the data, *rosbag* package[12] is used. Rosbag is designed to have high performance. It also avoids deserialization and reserialization of messages. This package reords data from sensors into a file. The file is called *rosbags*. One can easily reord/replay a dataset using command-line tools. It is also possible to work with the bagfile using APIs.

Each sensor reading is recorded under a name, called topic name. For example if a rosbag file includes encoder and laser ranger data from one robot, then there are two topics in the rosbag file. One indicates encoder data, and the other indicates laser data. The topic name for the encoder usually starts with *position_data*, and the topic name for the laser usually starts with *scan*. The topic names might be followed by more information to identify the type of the robot or the type of the sensor.

III. DATASET

Four different datasets are presented in this section. The first one is performed by one COBRA quadrotor in the classroom environment. The second dataset is collected by one CoroBot robot in the hallway environment. This case is done by two laser rangers depicted in Fig. 3. Sample maps and trajectories

[12]http://www.ros.org/wiki/rosbag

are presented for these two cases. The third case represents a dataset collected by one quadrotor and one CoroBot robot in the Vicon lab. In this case, the Corobot robot has one laser ranger, installed as shown in Fig. 2. Finally, the last dataset is produced by two CoroBot robots as shown in Fig. 3. This dataset is also collected in the Vicon lab. Table VIII summarizes these four datasets.

Table VIII
DATASETS.

no	robots	environment	description
1	one quadrotor	classroom	single-robot
2	one ground robot	hallway	single-robot
3	one quadrotor and one ground robot	Vicon lab	multiple-robot
4	two ground robots	Vicon lab	multiple-robot

A. Case 1: A Single Quadrotor

This dataset is collected by one COBRA quadrotor. The data is collected in the classroom environment. In this dataset, measurements from an inverted scanning laser rangers, a SONAR, and an IMU are collected. A sample 2D map produced from this dataset is shown in Fig. 6. The blue print of the environment and the dataset are available for download at [7].

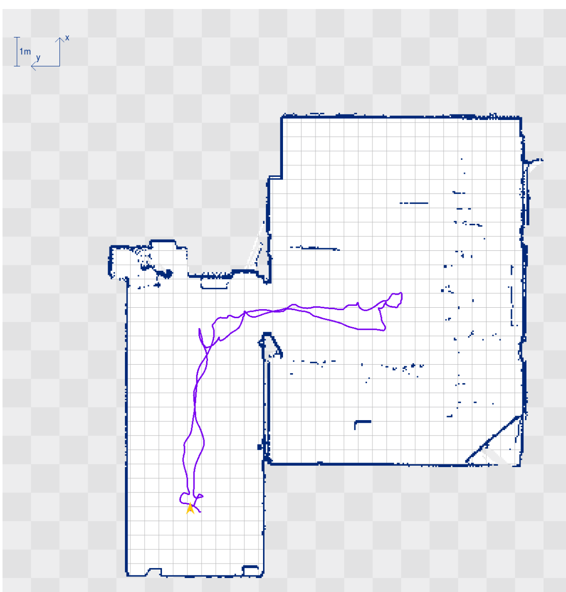

Figure 6. Case 1 (sample map): mapping with one COBRA quadrotor. In this dataset, one quadrotor traveled 35 m and collected data by one inverted laser ranger shown in Fig. 1.

B. Case 2: A single Ground Robot

This dataset is collected by one CoroBot robot with the configuration shown in Fig. 3. The data is collected in four connected hallways. This is a dataset for loop closure problems. In this datset, measurements from two scanning laser rangers and two encoders are available. A sample 2D map produced from this dataset is shown in Fig. 7. The blue print of the environment and the dataset are available for download at [7].

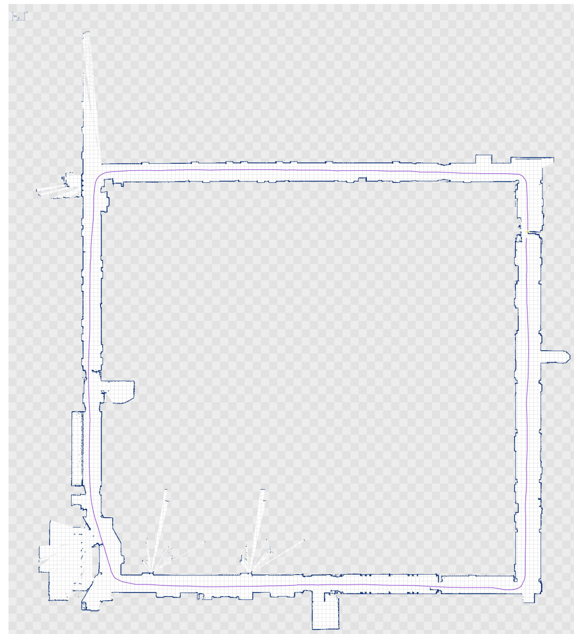

Figure 7. Case 2 (sample map): mapping with one CoroBot robot. In this dataset, one CoroBot robot traveled 232 m and collected data by two lasers based on the second configuration of ground robots, shown in Fig. 3.

C. Case 3: A Quadrotor and a Ground Robot

This dataset is collected by one CoroBot robot with the configuration shown in Fig. 2 and one COBRA quadrotor. The data is collected in the Vicon lab (see Fig. 8). The measurements from the ground robot includes two encoders and one laser ranger, while for the quadrotor, it includes one IMU and one laser ranger. Instead of the SONAR sensor, data from the reflective mirror was recorded. The initial relative transformation between the base frames of the two robots, following the ROS standard, is $[1.82, 1.22, 0.05, 0, 0, 0]^T$, representing the translation and rotation components in meters and radians respectively, while the quadrotor is on the ground, and the parent frame is the CoroBots's base frame.

D. Case 4: Two Ground Robots

This dataset is collected by two CoroBot robots with the configuration shown in Fig. 2. Similar to the case of a quadrotor and a ground robot, the data is collected in the Vicon lab (Fig. 8). In this dataset, for each robot, measurements from the scanning laser ranger and two encoders are recorded. The relative transformation between the base frames of the two robots is $[1.82, 1.22, 0, 0, 0, 1.57]^T$, representing the translation and rotation components in meters and radians respectively, where the parent frame is the base frame of CoroBot #1.

Figure 8. The Vicon lab. In this lab, two datasets are collected: a quadrotor and a ground robot, two ground robots

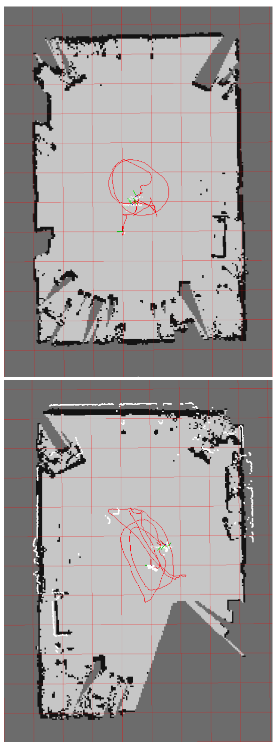

Figure 9. Case 3 (sample maps): map of the Vicon lab developed by the ground robot (top), and the quadrotor (bottom). Note that in this dataset, obstacles shown in Fig. 8 were removed to provide more space for the quadrotor.

IV. Conclusion

In this work, four different datasets by two ground robots and a quadrotor are presented. The datasets include sensor readings from the scanning laser ranger, SONAR, IMU, and wheel encoder. The sensors data, ground truth data, sample maps, and an instruction manual (explaining how to play the bagfiles) are available for download at [7].

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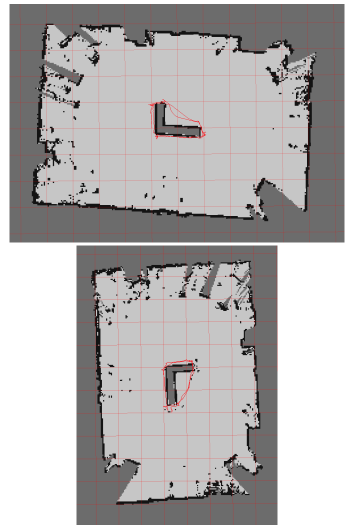

Figure 10. Case 4 (sample maps): map of the Vicon lab developed by the CoroBot #1 (top) and CoroBot #2 (bottom).

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