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The UTIAS multi-robot cooperative localization and mapping dataset

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Abstract

This paper presents a two-dimensional multi-robot cooperative localization and mapping dataset collection for research and educational purposes. The dataset consists of nine sub-datasets, which can be used for studying problems such as robot-only cooperative localization*, cooperative localization with a known map, and cooperative* simultaneous localization and mapping (SLAM)*. The data collection process is discussed in detail, including the equipment we used, how measurements were made and logged, and how we obtained groundtruth data for all robots and landmarks. The format of each file in each sub-dataset is also provided. The dataset is available for download at http://asrl.utias.utoronto.ca/datasets/mrclam/.*

Keywords

Localization, mapping, SLAM, distributed robotics, networked robots

1. Introduction

This paper presents a two-dimensional multi-robot cooperative localization and mapping (MR.CLAM) dataset produced at the *University of Toronto Institute for Aerospace Studies (UTIAS)*. The intended users of this dataset are researchers who are interested in state estimation for multi-robot systems. More specifically, the dataset can be used in studying *cooperative localization* (where robots use only relative measurements between one another for state estimation), cooperative localization with a known map (where robots use relative measurements between each other, landmark measurements, as well as information on landmark locations for state estimation), and cooperative *simultaneous localization and mapping (SLAM)*.

The dataset consists of nine sub-datasets, each ranging between 15 to 70 minutes in duration. The dataset is produced using a fleet of five mobile robots in an indoor workspace with 15 static landmarks (which are repositioned for each sub-dataset). Each sub-dataset contains timestamped odometry (velocities) and range-bearing measurements that are logged by each robot. In addition, by using a 10-camera Vicon motion capture system, we are able to obtain precise groundtruth data for all robot poses (position and orientation), as well as groundtruth landmark positions (which is rarely available in SLAM problems). Figure 1 is a photograph taken during the production of a sub-dataset. Users can access the dataset via the website: http://asrl.utias.utoronto.ca/datasets/mrclam/.

Fig. 1. The data collection process for the UTIAS multi-robot cooperative localization and mapping dataset uses a fleet of five robots. Groundtruth data for all landmark positions and robot poses is provided by a 10-camera Vicon motion capture system.

The remainder of this paper is structured as follows. In Section 2 we will provide the details on the data collection workspace, equipment, and process. Section 3 contains information on the formatting of the dataset, as well as specific notes regarding each sub-dataset. In Section 4 we will

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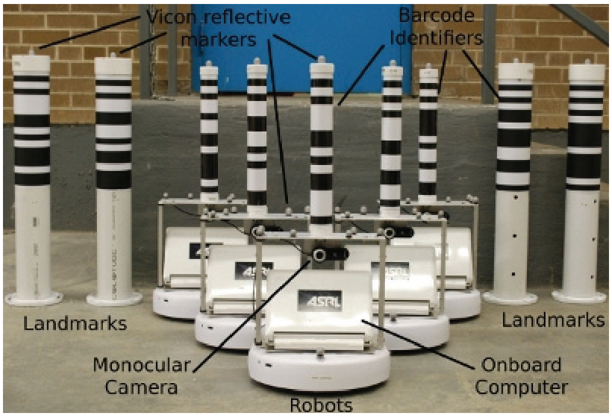

Fig. 2. The fleet of five robots and a few of the landmarks used in the making of the dataset. The barcode patterns are used in producing range–bearing measurements from the camera mounted on each robot.

show how the dataset can be used for the aforementioned problems of cooperative localization, cooperative localization with a known map, and cooperative SLAM. Finally, in Section 5, we will mention some software tools that are available for parsing the data.

2. Data collection

The multi-robot cooperative localization and mapping dataset collection is produced in a rectangular indoor space with an area of approximately $15\,\mathrm{m} \times 8\,\mathrm{m}$. The floor in this space is visually flat. For each sub-dataset, 15 landmarks and five robots are placed in the workspace. For the duration of each sub-dataset, each robot logs its own odometry data while driving to randomly generated waypoints in the workspace and avoiding obstacles (landmarks and other robots). When another robot or landmark is in a robot's field of view, a range and bearing measurement is made and logged. Throughout the entire data collection process a 10-camera Vicon motion capture system monitors and logs the pose of each robot, as well as the position of all landmarks, for groundtruth data.

2.1. Robots

The fleet of five robots used in producing the dataset are identical in construction (see Figure 2), and are built from the iRobot Create (two-wheel differential drive) platform. Each robot is equipped with a netbook, which interfaces with a monocular camera that serves as the primary sensing instrument. Conveniently, the camera is mounted at a location where the measurement coordinate frame coincides with the robot's body frame in two dimesnions, as shown in Figure 3. A cylindrical barcode tube is installed on each robot and centered above the robot's body frame. Each barcode pattern is 30 cm in height and allows for the identification of a robot. Furthermore, range and bearing measurements can be made when the barcode is detected by another robot.

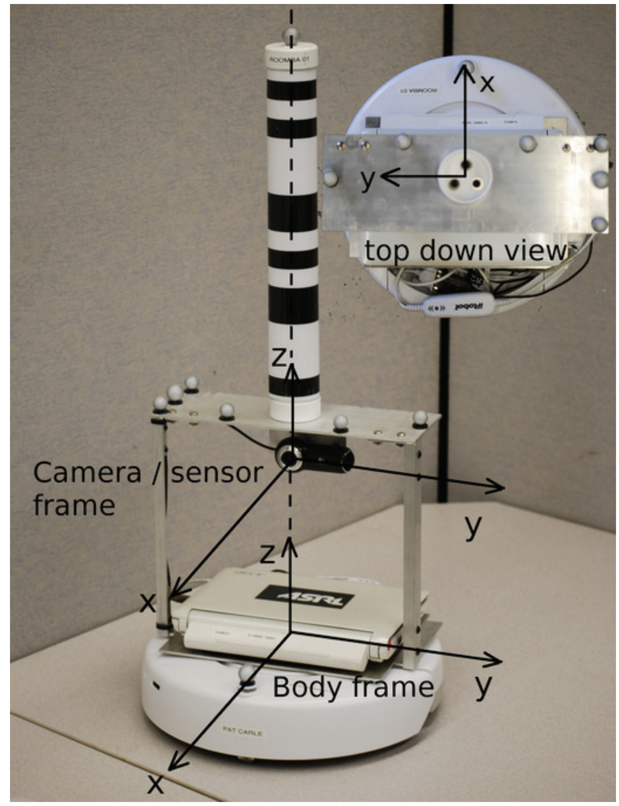

Fig. 3. Reference frames for the robot body and the sensor (camera). The frames are aligned such that the transformation between them only consists of a translation in the z direction.

In terms of software, each robot runs the *Player* server (Gerkey et al., 2003). This software is responsible for performing motion control, obstacle avoidance, and image processing (for measurements), as well as data logging through a collection of custom-coded and default Player drivers.

2.2. Landmarks

Cylindrical tubes similar to the ones installed on each robot (but larger in diameter) serve as landmarks. Each landmark has a unique barcode pattern that is 30 cm in height for identification and measurement purposes.

2.3. Odometry

Forward velocity (along the x-axis of the robot body frame) commands, v, and angular velocity commands (rotation about the z-axis of the robot body frame using the right-hand rule), ω, are logged at an average of 67 Hz as odometry data. The maximum forward velocity of a robot is 0.16 m/s, and the maximum angular velocity is 0.35 rad/s.

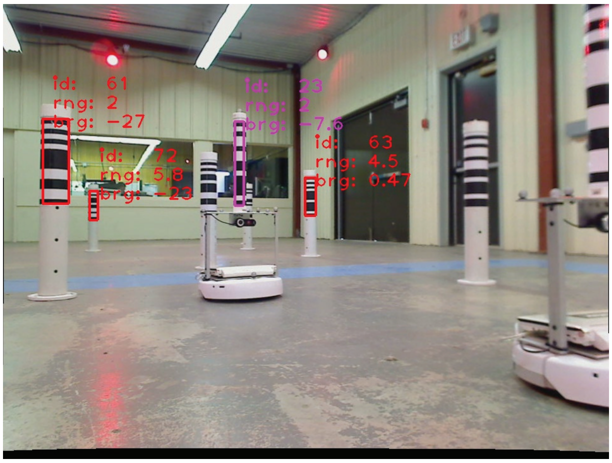

Fig. 4. An example of barcode detection from an undistorted image. A detected barcode provides a range–bearing measurement, as well as a unique identification signature. The signatures can be ignored when we perform SLAM with unknown correspondence (data association).

2.4. Measurements

During dataset production, images captured by the monocular camera on each robot (at a frame rate of 10 Hz and a resolution of 960×720) are processed by a custom Player driver. The cameras have a field of view of approximately 60 degrees, and the camera on each robot is individually calibrated using a planar checkerboard (Zhang, 1999) to obtain the parameters necessary to undistort images. A process that primarily relies on edge detection is used on the undistorted images for detecting barcodes. Figure 4 shows the typical output of the barcode detection process. Range measurements are obtainable since the vertical focal length and the barcode height are known. Bearing measurements correspond to the horizontal position of a barcode in an image. Lighting conditions, slight tilting of the robot on the presumed-level floor, and motion blurs are sources of measurement error.

Each barcode pattern begins (from top to bottom) with a black–white–black start code followed by a series of alternating black and white bars that encodes two digits in accordance with the *Universal Product Code* (*UPC*) standard. To reduce the chance of misreading a barcode the two digits that identify a robot must add up to a checksum of five, while the digits for a landmark must sum to seven or nine. In rare instances, mislabeled barcodes have been found when barcodes partly occlude one another. These instances are easy to detect using the groundtruth data but users of the dataset should keep this in mind when performing data association. The set of identification numbers encoded as a barcode for the robots are $\{05, 14, 23, 32, 41\}$, and the set of numbers encoded for the landmarks are $\{07, 09, 16, 18, 25, 27, 36, 45, 54, 61, 63, 70, 72, 81, 90\}$.

Fig. 5. In sub-dataset 9, data collection was performed with barriers in the workspace to increase occlusions for measurements.

2.5. Occlusions

For sub-dataset 9, barriers were placed in the workspace between landmarks to occlude the robots' views, as shown in Figure 5. This resulted in a decrease in the number of measurements made by the robots, and also a decrease in the maximum measurement range. For sub-datasets 1-8, users may also limit measurement range artificially in their own software.

2.6. Groundtruth

A Vicon motion capture system consisting of 10 (MX-40+) cameras provides groundtruth data for the dataset. The groundtruth coordinate frame also serves as the inertial reference frame in which the positions of a landmarks (x,y) and robot poses (x,y,θ) are reported. A unique constellation of reflective markers on each robot allows the system to identify and track the local body frame (position and orientation) of each robot in three dimensions at 100 Hz. Reflective markers are centered on the top of each landmark cylinder so that landmark positions are also recorded. Vicon claims that the accuracy of their tracking system is of the order of 1×10^{-4} m, and a study (on an older system – Windolf et al. (2008)) appears to support this claim. However, for the workspace used in producing the dataset, we believe that positional accuracy is of the order of 1×10^{-3} m. Occasionally the Vicon system fails to identify a robot from its constellation of markers. The log entries of these occasions (identifiable by observing zero values for all position and rotation components) have been conveniently removed from the dataset for the users. On rare occasions the Vicon system will also make an error fitting the proper model to the constellation of markers representing a robot. These instances (detectable by physically impossible changes in position and orientation) have also been removed from the groundtruth data. Since our dataset is in two dimensions position information in the global z direction, as well as body pitch and roll angles, are not provided in the dataset.

2.7. Time synchronization

A *Network Time Protocol* (*NTP*) daemon is used to synchronize the clocks between the computers and each robot, as well as the groundtruth data logging computer. The performance of the NTP daemon is checked prior to the collection of each sub-dataset. For each sub-dataset, the average error reported by the NTP daemon on each computer is of the order of 1×10^{-3} s, while the maximum error is of the order of 1×10^{-2} s. Based on this we consider the clocks on all computers to be synchronized. Timestamps are applied to all odometry data, range and bearing measurements, groundtruth data, and camera images. Delays in logging measurements due to image processing time have also been accounted for.

3. Data description

The initial positions of the robots as well as landmark placement is different for each sub-dataset. Table 1 contains a brief description of each sub-dataset, as well as comments that may be of interest to users.

3.1. Format

Each sub-dataset will always contain 17 tab-delimited text files, which include:

- one barcode identification file;
- one groundtruth file for the landmarks;
- five groundtruth files for the robots;
- five odometry files for the robots;
- five measurement files for the robots.

In each sub-dataset a *subject* refers to a robot or a landmark. Robots are always assigned a subject number from 1–5, while the stationary landmarks are always assigned a subject number from 6–20. The barcode identification file indicates the barcode digits that correspond to a particular subject and contains two fields:

subject #	barcode #

The landmark groundtruth data file contains the averaged Vicon position measurements of all landmarks (x,y) in meters, as well as the standard deviations of the Vicon measurements. There are five fields in this file:

subject #	x [m]	y [m]	x std-dev [m]	y std-dev [m]

For the remaining files (associated with the robots), the number in the filename corresponds to the subject number. Each of the robot groundtruth data files contains timestamped robot pose (x,y,θ) information in the following format:

time [s]	x [m]	y [m]	θ [rad]

The odometry data file for each robot contains timestamped velocity commands (v,ω) as follows:

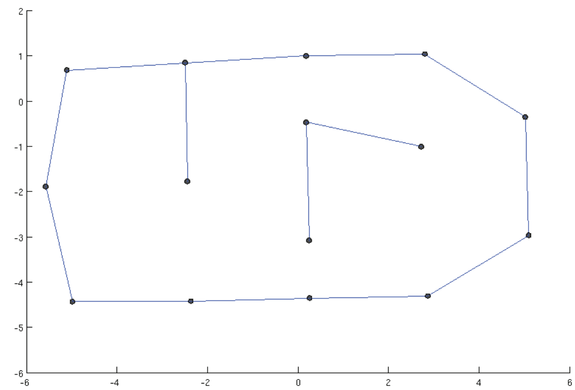

Fig. 6. A map of the barriers in sub-dataset 9.

time [s]	v [m/s]	ω [rad/s]

Lastly, the measurement data file for each robot contains the timestamped range and bearing (r,ϕ) measurements to particular subjects. The format is:

time [s]	subject #	r [m]	ϕ [rad]

3.2. Images

For sub-dataset 7, the undistorted camera images (20 GB in size) from all five robots are available in JPEG format should users wish to perform their own image processing. The filename of each image contains the timestamp of the image. Image quality is comparable to the one shown in Figure 4.

4. Data usage

The dataset can be customized for various multi-robot problems.

4.1. Cooperative localization

In cooperative localization, robots use relative measurements between one another to estimate the state of the robot team (Leung et al., 2009, 2010a). To use a sub-dataset for this problem the users will need to ignore all landmark measurements (by examining the barcode number identified in each measurement). The groundtruth landmark positions should also be ignored, while groundtruth robot poses should be used to evaluate localization performance.

4.2. Cooperative localization with a known map

For localization with a known map, the groundtruth landmark position data can be used to construct the map, and groundtruth robot poses should be used to evaluate localization performance.

4.3. Cooperative SLAM

For SLAM, the groundtruth data for both robot poses and landmark positions should be used to evaluate state estimation performance. An example of using the dataset collection for SLAM can be found in the work by Leung et al. (2010b).

4.4. Other possibilities

In each of the above problems, we can impose a limitation on the number of robots or landmarks by ignoring all the information relevant to specific robots and landmarks. We can also impose a measurement range limit by ignoring measurements that exceed a user-defined range. For work that involves studying the exchange of information between robots for state estimation, we can use the groundtruth data of robot poses to determine the distances between robots and impose a communication range limit.

5. Data access methods

Users can access and download the multi-robot localization and mapping dataset from the website http://asrl.utias.utoronto.ca/datasets/mrclam/. Each sub-data set can be downloaded individually. For the convenience of the dataset users we have also made several useful Matlab scripts available on the website (but the use of the dataset is not limited to Matlab). One of the Matlab scripts will parse the dataset files into Matlab arrays. Another script will allow the users to sample the data at a fixed frequency. There is also an animation script for visualizing the groundtruth and measurement data.

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Conflict of interest

The authors declare that they have no conflicts of interest.

Tables

Table 1. Sub-dataset descriptions.

Sub-dataset	Duration [s]	Description and comments
1	1500	Individual landmarks are scattered randomly throughout the workspace. Robots are also initially placed randomly in the workspace.
2	1900	Individual landmarks are placed in a ‘S’-shaped pattern in the workspace. Robots are initially placed at random locations in the workspace. At 1160 s robots 4 and 5 touched each other and moved while in contact with each other until 1240 s. Increased dead reckoning error can be expected in this time period.
3	1800	Individual landmarks are scattered randomly throughout the workspace. Robots are initially placed at random locations in the workspace. At 600 s robot 4 stops moving and making measurements for the remainder of the sub-dataset.
4	1400	Individual landmarks are scattered randomly throughout the workspace. Robots are initially placed at random locations in the workspace. At 260 s robots 3 and 4 touched each other. At 980 s robot 1 stops moving for the remainder of the sub-dataset, but it continues to make measurements while remaining stationary.
5	2300	Landmarks are placed together to form clusters at one end of the workspace. Robots are initially placed in close proximity to the landmark clusters.
6	900	Landmarks are placed together to form clusters at opposite ends of the workspace. Robots are initially placed randomly in the workspace.
7	900	Landmarks are placed together to form clusters at opposite ends of the workspace. Robots are initially placed in close proximity to the landmark clusters at one end of the workspace.
8	4400	This sub-dataset uses only 14 landmarks. Landmarks are placed together to form clusters at opposite ends of the workspace. Robots are initially placed in close proximity to the landmark clusters at one end of the workspace. At 2360 s robots 1 and 2 touched each other.

Sub-dataset	Duration [s]	Description and comments
9	2100	Barriers are placed between landmarks as shown in Figure 6. Robots are initially placed in close proximity at one end of the workspace. There are temporary decreases in accuracy for the groundtruth data between: 524–561 s for robot 5, 758–836 s and 991–1046 s for robots 3 and 4, and 1258–1273 s for robots 1 and 2.

References

Gerkey B, Vaughan R and Howard A (2003) The player/stage project: Tools for multi-robot and distributed sensor systems. In: *International Conference on Advanced Robotics* 317–323 (2003), Coimbra, Portugal.

Leung KYK, Barfoot TD and Liu HHT (2009) Decentralized localization for dynamic and sparse robot networks. In: *Proc of the IEEE International Conference on Robotics and Automation* (ICRA 09), Kobe, Japan.

Leung KYK, Barfoot TD and Liu HHT (2010a) Decentralized localization of sparsely-communicating robot networks: A centralized-equivalent approach. *IEEE Transactions on Robotics* 26: 62–77.

Leung KYK, Barfoot TD and Liu HHT (2010b) Decentralized simultaneous localization and mapping for dynamic and sparse robot networks. In: *Proc of the IEEE/RSJ International Conference on Intelligent Robots and Systems* (2010), Taipei, Taiwan.

Windolf M, Götzen N and Morlock M (2008) Systematic accuracy and precision analysis of video motion capturing systems - exemplified on the Vicon-460 system. *Journal of Biomechanics* 41: 2776–2780.

Zhang Z (1999) Flexible camera calibration by viewing a plane from unknown orientations. In: *Proc of the International Conference on Computer Vision* 666–673 (2008), Corfu, Greece.