

RAWSEEDS

Robotics Advancement through Web-publishing
of Sensorial and Elaborated Extensive Data Sets

*Raw seeds can be consumed as they are...
or be the start for the growth of new results.*



RAWSEEDS

WorkPackage 2

Deliverable D2.2

Raw Data (outdoor)

Accompanying Document

date due: September 30, 2008 to January 31, 2009^(*)

authors: Giulio Fontana (WP-2 Leader), Davide Rizzi

contributors: Matteo Matteucci, Domenico G Sorrenti

date of preparation of this document: March 13, 2009

^(*) D2.2 could be delayed up to month 27, if some experiments had to be repeated to meet validation standards.



Table of Contents

PREFACE.....	3
1. INTRODUCTION.....	4
2. ACCESS TO THE DATASETS.....	6
2.1 HOW TO REACH THE DATASETS.....	6
2.2 DIRECTORY STRUCTURE OF THE DATASETS.....	7
2.3 CONTENTS OF EACH DATASET.....	10
2.4 DATA FORMATS.....	11
3. THE DATASETS.....	14
3.1 SENSORS USED TO GENERATE THE DATA.....	14
3.1.1 <i>Description of the sensor systems</i>	14
3.1.2 <i>Relative pose of onboard sensors</i>	17
3.2 CALIBRATION PROCEDURES.....	23
3.2.1 <i>Calibration of the stereo rig</i>	24
3.2.2 <i>Calibration of the frontal camera</i>	27
3.3 DESCRIPTION OF THE DATASETS.....	31
3.3.1 <i>Outdoor datasets</i>	34
3.3.1.1 Bovisa_2008-10-04_Static	34
3.3.1.2 Bovisa_2008-10-07_Dynamic.....	36
3.3.1.3 Bovisa_2008-10-11b_Static.....	38
3.3.2 <i>Mixed datasets</i>	40
3.3.2.1 Bovisa_2008-09-01_Static.....	40
3.3.2.2 Bovisa_2008-10-06_Dynamic.....	42
3.3.2.3 Bovisa_2008-10-11a_Static.....	44
4. ACTIONS TAKEN TO COMPLY WITH THE RECOMMENDATIONS OF WORKPACKAGE 3.....	46
4.1 ACTIONS TAKEN IN ACCORDANCE WITH DELIVERABLE D3.1.....	46



4.2 ACTIONS TAKEN IN ACCORDANCE WITH DELIVERABLE D3.2.....47



Preface

This document is the final version of Deliverable D2.2. It builds on the version submitted on September 30, 2008 - already completely finalized - by incorporating some additional information. Such information has been integrated into the document to maximize its usefulness for the users of RAWSEEDS' datasets, following the recommendations of WorkPackage 3 (*Data validation*) and specifically those listed into Deliverable D3.2 (*Final data certification*). D3.2, in fact, was not yet available at the time of the first submission of this document. Please note that Annex I to the Contract allowed Deliverable D2.2 to be delayed up to month 27 of the project, exactly because the parallel processes of data collection (i.e., WorkPackage 2) and data validation (i.e., WorkPackage 3) were arranged in such a way that the second acted as a feedback to the first, to maximize data quality. Therefore, an explicit mechanism to let the Deliverables coming from WorkPackage 2 be integrated with all the information coming from WorkPackage 3 was introduced, ensuring that such Deliverables could include *all* the useful results generated by the project until the end of WorkPackages 2 and 3. The main reason that required the introduction of such a mechanism was the possibility for WorkPackage 3 to request the repetition of specific data acquisition sessions or campaigns to WorkPackage 2, in case of unrecoverable faults in the datasets. This was a foreseen event that actually happened during the course of WorkPackage 2, without consequences on the schedule, the results, and the budget of the project.

The changes made to the first version of Deliverable D2.2 to transform it in the present version did not alter it substantially, but added to its completeness. Such changes are the following:

- an update of the information about the server hosting the datasets and accessory documentation (this information is now definitive, as the datasets have been moved to the server dedicated to the distribution of RAWSEEDS' Benchmarking Toolkit, where they will be stored from now on);
- the introduction of a new Section (4.2) summarizing the recommendations of Deliverable D3.2 for the outdoor and mixed datasets, and the way they were incorporated into this document;
- an extension of the directory structure of the datasets, to incorporate the executive drawings of the explored locations;
- an expanded description of the calibration methodologies used for the omnidirectional camera;
- a more detailed description of the peculiarities and (minor) defects of the datasets, with the explicit indication of the timestamps for all of them.



1. Introduction

According to Annex I to the Contract, Deliverable D2.2 of the RAWSEEDS project is defined as follows:

Raw data (outdoor). Complete data of the outdoor test locations, i.e., sensor data sets plus robot logs and ground truth of all the outdoor test locations, in final form. Additional documentation (description of the hardware and chosen operating modes, notes, photographic images of the test areas) in final form.

Therefore, the main content of Deliverable D2.2 is the set of datasets collected by performing explorations of suitable outdoor environments with the mobile robot set up by WorkPackage 1. The gathering of the data and their successive processing, formatting and verification have been performed in accordance with the indications of Deliverable D1.2 (*Roadmap - outdoor*) and with the recommendations of WorkPackage 3.

WorkPackage 3 performed a thorough analysis of the datasets and of their associated data and documentation, and generated a set of recommendations to improve and maximize their quality. The results of the work of WorkPackage 3 are collected into two Deliverables: D3.1 (*Preliminary data validation*) and D3.2 (*Final data certification*). D3.1 was the result of a validation work performed on preliminary datasets, specifically generated to make such work possible: by the time when the final datasets were collected, all the issues raised by Deliverable D3.1 had been addressed and solved, as documented by D3.2. Deliverable D3.2 states, indeed, that RAWSEEDS' final datasets reach the required quality standards; it also introduces some suggestions to improve the usability of such datasets and to correct minor imperfections. These suggestions have been implemented as well, both in the datasets and in Deliverables D2.1 and D2.2. Therefore, at the time of delivery of this document, RAWSEEDS' datasets and all associated information are fully compliant with the recommendations of WorkPackage 3. The actions taken to reach such compliance are described in Section 4.

As said above, the outdoor datasets form the core and the bulk of D2.2. However, to be fully usable they must be accompanied by additional material. This material comes in the form of associated data (such as calibration data for the cameras) and in the form of descriptions and explanations. For this reason, the complete Deliverable D2.2 is actually constituted by three elements:

1. the outdoor datasets;
2. the associated data;
3. the additional descriptions and explanations.

Parts 1 and 2 (according to the list above) of D2.2 have been published electronically on a server set up by RAWSEEDS. Publication within a single document was not an option, as massive amounts of data are involved (around 1.5 TeraBytes overall, after



compression). Part 3 is given by this document, which includes all the information needed to access and use parts 1 and 2. This is the reason why the title of the present document is not simply "Deliverable D2.2" but "Deliverable D2.2 - Accompanying Document".



2. Access to the datasets

The datasets included in Deliverable D2.2 are hosted on a server set up expressly by RAWSEEDS for the validation to be performed. Such server is connected to the internet, and therefore is reachable by any computer having internet access: anyway, access to the datasets is currently restricted to the Partners and to the EU Officers. In fact - as specified by the Annex I to RAWSEEDS' Contract - the datasets of Deliverable D2.2 are not, at this stage of the project, to be distributed to the public. For the time being, their use is limited to the Partners, who are validating them and building upon them the Benchmark Problems.

The datasets will be released publicly and freely at the time when the associated Benchmark Problems will be. Such public release will be done through electronic publication on the official website of the project, i.e.,

<http://www.rawseeds.org>

This section will describe the content of the server hosting the datasets and the procedure to be used to gain access to it. Once the datasets will be published on the internet, the following procedure will be voided, and the associated data and account will be removed¹.

2.1 How to reach the datasets

[...]

NOTE: IN THE VERSION OF DELIVERABLE D2.2 PUBLISHED ON RAWSEEDS' WEBSITE, THIS SECTION HAS BEEN EDITED OUT FOR SECURITY REASONS.

2.2 Directory structure of the datasets

The content of the RAWSEEDS-Datasets directory is subdivided into several subdirectories: their hierarchy and content are described by the following scheme. Directory names are in bold; indentation is used to represent the fact that a given directory is internal to another, higher-level one.

RAWSEEDS-Datasets (General container for the datasets and all the associated information.)

Calibration (Data and results of the calibration activities performed on the sensors.)

¹ Please note that, for security reasons, the versions of Deliverable D2.1 and Deliverable D2.2 published on the project's website lack the information about server access. Public diffusion of access information to servers is, in fact, not advisable.



Calibration_NN, where *NN* is a two-digit integer (Complete set of data and results for one of the calibration procedures applied to the robot. The two-digit number *NN* identifies the specific procedure considered. As the characteristics of the sensors can change from one dataset to the other, more than one of these directories can be present.)

Images (Images used for the calibration, plus the complete streams from which they were extracted. In this way a user - if so she desires - can perform her own calibration of the cameras, possibly using images different from those who were chosen by RAWSEEDS' staff.)

All_images (Complete calibration video streams, one for each camera. The images actually used for camera calibration by the RAWSEEDS staff have been extracted from these streams.)

Used_for_calibration (Subsets of images, one for each camera, chosen by the RAWSEEDS staff for the calibration of the cameras.)

Results (Results of the calibration procedure, i.e., the Matlab files produced by the calibration procedures. Such procedures will be described in section 3.2.)

FRONTAL (Calibration results for the frontal monocular camera.)

OMNI (Calibration results for the omnidirectional camera.)

SVS (Calibration results for the SVS trinocular system.)

Datasets (Sensor data gathered by the robot.)

Indoor (Datasets gathered in indoor environments. These datasets are described in Deliverable D2.1.)

LOCATION_DATE_TYPE, where *LOCATION* is the name of a location for data-gathering experiments chosen between those described by Deliverable D1.2, *DATE* identifies the day on which the dataset was gathered - in the format YYYY-MM-DD - and *TYPE* can be "Static" or "Dynamic"; if two or more datasets of the same type have been generated on the same day and in the same location, a further lowercase letter ("a", "b", and so on) is attached to the *DATE* to differentiate between them (Within this directory there is one file for each of the sensor streams recorded during a single exploration session by the robot. The name, number and type of such files will be described in section 2.3 of this document.)

Calibration_NN, where *NN* is a two-digit integer (Symbolic link to the directory containing the calibration data for the dataset. The content of such a directory has already been described above.)

Drawings_NN, where *NN* is a two-digit integer (Symbolic link to



the directory containing the executive drawings associated to the dataset. The content of such a directory will be described below.)

FileFormats_NN, where *NN* is a two-digit integer (Symbolic link to the directory containing the file formats used for the dataset. The content of such a directory will be described below.)

SensorPositions_NN, where *NN* is a two-digit integer (Symbolic link to the directory containing the sensor positions used for the dataset. The content of such a directory will be described below.)

Mixed (Datasets gathered in mixed - i.e., partly indoor and partly outdoor - environments.)

LOCATION_DATE_TYPE, where *LOCATION* is the name of a location for data-gathering experiments chosen between those described by Deliverable D1.2, *DATE* identifies the day on which the dataset was gathered - in the format YYYY-MM-DD - and *TYPE* can be "Static" or "Dynamic"; if two or more datasets of the same type have been generated on the same day and in the same location, a further lowercase letter ("a", "b", and so on) is attached to the *DATE* to differentiate between them (Within this directory there is one file for each of the sensor streams recorded during a single exploration session by the robot. The name, number and type of such files will be described in section 2.3 of this document.)

Calibration_NN, where *NN* is a two-digit integer (Symbolic link to the directory containing the calibration data for the dataset. The content of such a directory has already been described above.)

Drawings_NN, where *NN* is a two-digit integer (Symbolic link to the directory containing the executive drawings associated to the dataset. The content of such a directory will be described below.)

FileFormats_NN, where *NN* is a two-digit integer (Symbolic link to the directory containing the file formats used for the dataset. The content of such a directory will be described below.)

SensorPositions_NN, where *NN* is a two-digit integer (Symbolic link to the directory containing the sensor positions used for the dataset. The content of such a directory will be described below.)

Outdoor (Datasets gathered in outdoor environments.)

LOCATION_DATE_TYPE, where *LOCATION* is the name of a location for data-gathering experiments chosen between those described by Deliverable D1.2, *DATE* identifies the day on which the dataset was gathered - in the format YYYY-MM-DD - and *TYPE* can be "Static" or "Dynamic"; if two or more datasets of the same type have been generated on the same day and in the same location, a further lowercase letter ("a", "b", and so on) is attached to the *DATE* to



differentiate between them (Within this directory there is one file for each of the sensor streams recorded during a single exploration session by the robot. The name, number and type of such files will be described in section 2.3 of this document.)

Calibration_NN, where *NN is a two-digit integer* (Symbolic link to the directory containing the calibration data for the dataset. The content of such a directory has already been described above.)

FileFormats_NN, where *NN is a two-digit integer* (Symbolic link to the directory containing the file formats used for the dataset. The content of such a directory will be described below.)

Drawings_NN, where *NN is a two-digit integer* (Symbolic link to the directory containing the executive drawings associated to the dataset. The content of such a directory will be described below.)

SensorPositions_NN, where *NN is a two-digit integer* (Symbolic link to the directory containing the sensor positions used for the dataset. The content of such a directory will be described below.)

Docs (Accessory documentation necessary or useful to use the datasets, including this document.)

Drawings (Executive drawings of the locations covered by the datasets.)

Drawings_NN, where *NN is a two-digit integer* (Directory that includes one or more CAD files describing the locations explored by the robot. It can also include accessory files (e.g., lists of features extracted from the CAD files). The two-digit number NN identifies the specific set of CAD files considered.)

FileFormats (File formats used for the sensor data.)

FileFormats_NN, where *NN is a two-digit integer* (Description of one of the sets of file formats used for the datasets. The two-digit number NN identifies the specific set considered. As the characteristics of the sensors - e.g., their operating mode - can change from one dataset to the other, more than one of these directories can be present.)

SensorPositions (Position of the sensors onboard the robot during the data-acquisition sessions.)

SensorPositions_NN, where *NN is a two-digit integer* (Description of one of the sets of sensor positions used for the datasets. The two-digit number NN identifies the specific set considered. As such positions can change from one dataset to the other, more than one of these directories can be present.)

Utils (Utilities that can prove useful to perform operations on the datasets, such as formatting.)



The RAWSEEDS-Datasets directory includes a text file, called README, with a brief summary of the above information.

2.3 Contents of each dataset

In Section 2.2 we showed that each dataset is associated to a directory within the file system of the server. The contents of such a directory are a set of symbolic links and a set of files.

The links are the following:

- a link to the directory containing the calibration data pertaining to the dataset considered;
- a link to the directory containing the executive drawings pertaining to the dataset considered;
- a link to the directory containing the file formats pertaining to the dataset considered;
- a link to the directory containing the sensor positions pertaining to the dataset considered.

The files contain the sensor data of the dataset and the associated ground truth data, one stream per file. A description of the sensors mounted on the robot will be given in Section 3: such sensors are - with one minor modification - those already described in Deliverable D1.2 (Outdoor Roadmap). Specifically, each dataset is composed of the following files:

- **FRONTAL**: data stream from the front-mounted Unibrain Fire-I monocular camera.
- **GPS**: data stream from the Trimble 5700 GPS receiver.
*NOTE: THE GPS STREAM IS TO BE REGARDED AS CONCEPTUALLY DIFFERENT FROM ALL THE OTHERS, AS IT CORRESPONDS TO THE **GROUND TRUTH DATA**. THESE DATA INCLUDE THE ABSOLUTE POSITIONS OF THE ROBOT OVER TIME, AS GIVEN BY A RTK-GPS TWO-UNIT GPS SYSTEM (PLEASE SEE DELIVERABLE AD2.3 FOR THE DETAILS). FOR EACH POSITION IN THE GPS DATA STREAM, AN MEASURE OF THE UNCERTAINTY ASSOCIATED TO THAT POSITION IS GIVEN. IN PARTICULAR, IN THE TIME INTERVALS WHEN FULL RTK PRECISION IS AVAILABLE (DEPENDING FROM SATELLITE RECEPTION, WHICH IN TURN IS HEAVILY INFLUENCED BY THE PRESENCE OF BUILDINGS OR TALL OBSTACLES IN THE VICINITY OF THE ROBOT) THE ABSOLUTE POSITION OF THE ROBOT IS TYPICALLY KNOWN WITHIN A FEW CENTIMETERS.*
- **HOKUYO_FRONT, HOKUYO_REAR**: data streams from the front- and rear-mounted Hokuyo URG-04LX laser range finders.
[Note: these sensors are designed for indoor applications, and have been verified to be "useless for SLAM in outdoor datasets taken in daylight" by WorkPackage 3 (please see Deliverable D3.1). Nonetheless, their data streams



have been included into the datasets so that the user can have a sample of the kind of data that such sensors produce in outdoor environments. In addition to that, the Hokuyo sensors are perfectly usable in the indoor parts of mixed datasets.]

- **IMU_STRETCHED**: data stream from the Xsense MTi inertial measurement unit, with timestamps stretched as suggested by Deliverable D3.1.
- **ODOMETRY_XYT**: data stream from the odometer of the robot, both raw and geometrically processed in order to express the pose of the robot in a global x,y,z reference system. This system is the *odometry reference system* of the robot which will be described in section 3.1.2, considered in the initial pose of the robot.
- **OMNI**: data stream from the omnidirectional camera (Prosilica GC1020C color camera, configured with a Region Of Interest of 640x640 pixel).
- **SICK_FRONT, SICK_REAR**: data streams from the Sick LMS291 (front) and LMS200 (rear) laser range finders.
- **SVS_R, SVS_L, SVS_T**: data streams from the binocular Videre Design STH-DCSG-VAR system (R and L, standing for Right and Left) and from the third DCSG camera that, in conjunction with it, forms a trinocular system (T, standing for Top).

All the files of each dataset have been compressed with the Bzip2 lossless compression algorithm (<http://en.wikipedia.org/wiki/Bz2>) to reduce their storage occupation and download time. The only exception are image files, which are already compressed: they could not benefit from being compressed again, so they were not. When many files of the same content had to be compressed, they have been reunited in a single .tar file ([http://en.wikipedia.org/wiki/Tar_\(file_format\)](http://en.wikipedia.org/wiki/Tar_(file_format))) before compression. Therefore, RAWSEEDS' data files must be uncompressed, and in some case extracted from a .tar archive, before they can be used. These operations are standard ones, and they can be performed by any of the many existing bzip2- and tar-compatible programs, available for all software platforms.

The format of the data contained in the data files will be described in the following section of this document.

2.4 Data formats

The format of the data included into the stream files comprised into a dataset is as follows:

- **FRONTAL**: the filename of each image is the timestamp ([seconds.microseconds], from the 00:00 of January 1st, 1970); each file follows the PNG format, 320x240 3*8bpp (color); nominal frame frequency = 30Hz;
- **GPS**: after decompressing the file you get a .csv file, the fields are:



- Timestamp [seconds.microseconds]
- (alternating) GGA or GST string according to the NMEA-0183 standard (a detailed description of such standard is available in each of the FileFormats_NN directories)
- nominal frequency = 5Hz;;
- **HOKUYO_FRONT, HOKUYO_REAR:** after decompressing the file you get a .csv file, the fields are:
 - Timestamp [seconds.microseconds]
 - R1...R681 range data [m] (in steps of $360^\circ/1024$)
 - nominal scan frequency = 10Hz;
- **IMU_STRETCHED:** data stream from the Xsense MTi inertial measurement unit, with timestamps stretched as suggested by Deliverable D3.1. After uncompressing the file you get a .csv file, the fields are:
 - Timestamp [seconds.microseconds]
 - # of range data [unitless]
 - Sample counter (modulus $2^{16} - 1$) [unitless]
 - Acceleration along X [m/s^2]
 - Acceleration along Y [m/s^2]
 - Acceleration along Z [m/s^2]
 - Angular velocity around X [rad/s]
 - Angular velocity around Y [rad/s]
 - Angular velocity around Z [rad/s]
 - Earth's magnetic field along X [a.u. (arbitrary units normalized to Earth's field strength)]
 - Earth's magnetic field along Y [a.u.]
 - Earth's magnetic field along Z [a.u.]
 - R1..R9 Orientation matrix, row after row [unitless]
 - nominal scan frequency = 128Hz;
- **ODOMETRY_XYT:** data stream from the odometer of the robot, sampled at a 50Hz nominal frequency. The raw "tick count" stream from the odometer has also been processed in order to express the pose of the robot on an x,y,θ reference system (with reference to the pose of the robot at the start of the odometry stream). The x and y axes are positioned as in the robot reference system, which will be described in section 3. After decompressing the file you get a .csv file, the fields are:
 - Timestamp [seconds.microseconds]
 - Rolling counter [signed 16bit integer]
 - TicksLeftWheel (raw data) [ticks]
 - TicksRightWheel (raw data) [ticks]
 - X [m]
 - Y [m]
 - Theta [rad]
- **OMNI:** the filename of each image is the time-stamp ([seconds.microseconds], from the 00:00 of January 1st, 1970); each file follows the PNG format, 640x640 3*8bpp (color); nominal frame frequency = 15Hz;
- **SICK_FRONT, SICK_REAR:** after decompressing the file you get a .csv file,



the fields are:

- Timestamp [seconds.microseconds]
 - # of range data [unitless]
 - Angular offset [1/4 degree]
 - R1...R181 range data [m]
 - nominal scan frequency = 75Hz;
- **SVS_R, SVS_L, SVS_T:** the filename of each image is the time-stamp ([seconds.microseconds], from the 00:00 of January 1st, 1970); each file follows the PNG format, 640x480 8bpp (grayscale); nominal frame frequency = 15Hz.



3. The datasets

This section of the document presents RAWSEEDS' outdoor datasets and gives a description of each of them, along with a comprehensive overview of the sensor systems used to gather the data. The aim of this section is that of providing the user of the datasets with a general knowledge of their properties, and to let her select the datasets which are more fitting for a specific application.

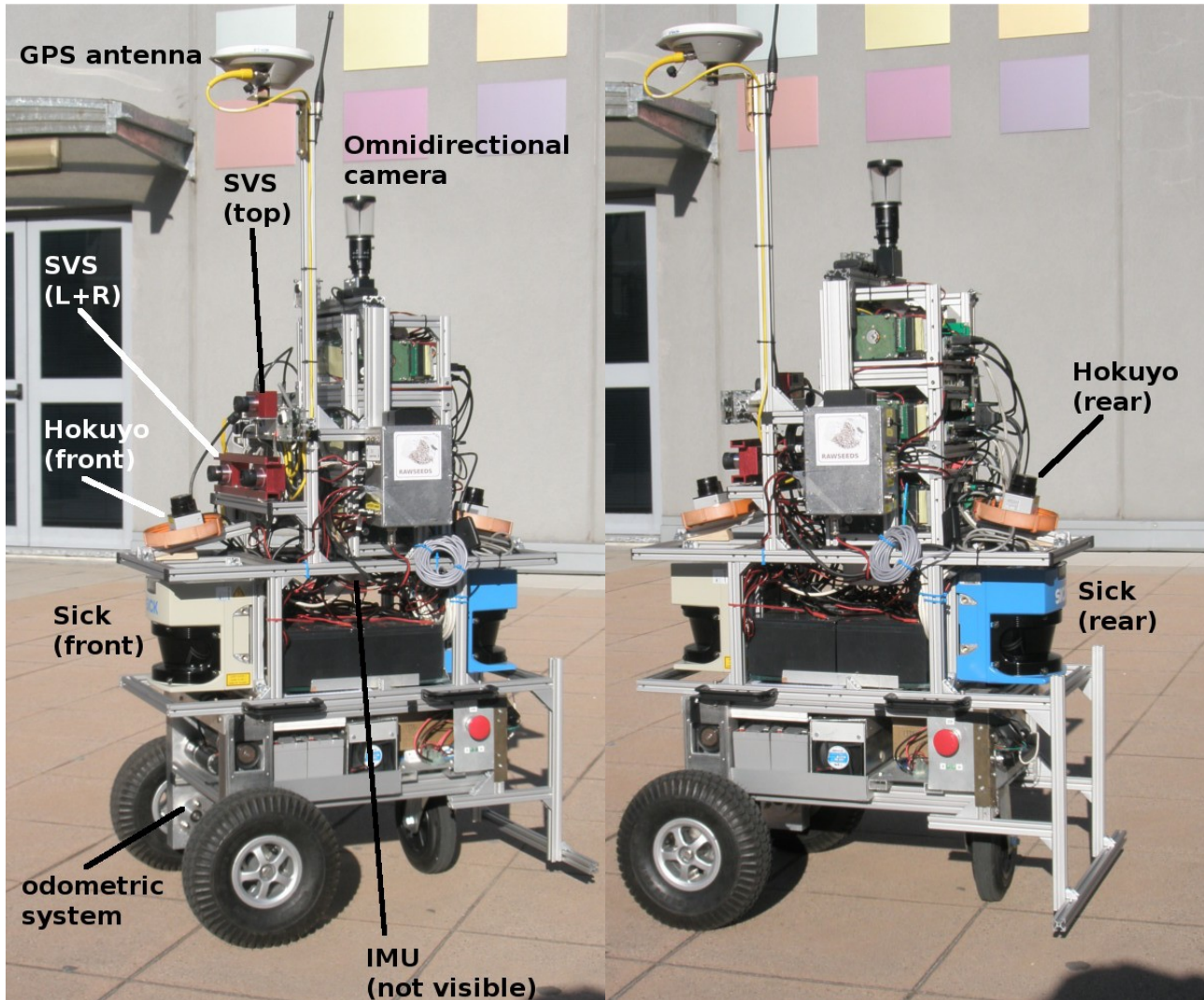
3.1 Sensors used to generate the data

Correct interpretation of the data within the datasets of Deliverable D2.2 requires the knowledge of the type and characteristics of the sensors used to acquire them. This section describes such sensors.

3.1.1 Description of the sensor systems

We repeat here, for convenience, the list of sensors mounted onboard the Robocom robot for indoor and outdoor data gathering. This list has been taken from Deliverable D1.2 (Outdoor Roadmap). In comparison to D1.2, one item has been subject to a minor modification, and one sensor has been added. The modified item is the omnidirectional camera, where the optics remained the same as in D1.2, but the camera was switched from an Unibrain Fire-I to a higher-quality and more configurable Prosilica GC1020C. The added item is the GPS receiver, which was not described in detail in D1.2.

The picture below shows the robot used for the outdoor and mixed data-acquisition activities, and the sensors affixed to it.



The sensors mounted on the robot are the following:

1. Odometric system fitted to the Robocom robotic base.
2. Binocular vision system, composed of a two-camera Videre Design STH-DCSG-VAR system (two FireWire, B/W, 640x480 pixel cameras mounted on a common mechanical frame that allows for an adjustable baseline). Trinocular vision system is realized combining the binocular STH-DCSG-VAR with an additional Videre Design DCSG camera (the same camera used by the STH-DCSG-VAR). Although CMOS, these cameras feature a global shutter, which is important for shooting dynamic scenes or from a moving observer (both things happen in our case).
<http://www.videredesign.com/sthdcsgvar.htm>,
<http://www.videredesign.com/Templates/dcsdg.htm>
3. Color monocular vision is covered by an Unibrain Fire-i 400 camera (FireWire, color, 640x480 pixel). The YUV4:2:2 output stream is transformed to RGB through



suitable postprocessing of the data.²

http://www.unibrain.com/Products/VisionImg/Fire_i_400_Industrial.htm

4. Omnidirectional color vision is obtained by using a Prosilica GC1020C color GigE Vision camera fitted with a hyperbolic mirror built by Vstone. The camera was configured for partial-frame acquisition, with a ROI (Region of Interest) of 640x640 pixels.
<http://www.prosilica.com/products/gc1020.html>,
<http://www.vstone.co.jp/e/EVSC15MR15MR37.pdf>
5. Two Hokuyo URG-04LX laser range finders, mounted respectively on the front and the back of the robot. The scanning planes of the LRSs are tilted down, towards the floor (precise orientation will be given in the following subsection).
<http://www.hokuyo-aut.jp/products/urg/urg.htm>
6. Sick LMS291 and LMS200 laser range finders, mounted on the front and the back of the robot.
[http://mysick.com/partnerPortal/eCat.aspx?
c=1&go=FinderSearch&Cat=Row&At=Fa&Cult=English&Category=Produktfind
er&FamilyID=267&Selections=8641,0,0,8775,0](http://mysick.com/partnerPortal/eCat.aspx?c=1&go=FinderSearch&Cat=Row&At=Fa&Cult=English&Category=Produktfinder&FamilyID=267&Selections=8641,0,0,8775,0)
[http://mysick.com/partnerPortal/eCat.aspx?
go=FinderSearch&Cat=Row&At=Fa&Cult=English&Category=Produktfinder&Fa
milyID=267&Selections=8644,0,0,8775,0](http://mysick.com/partnerPortal/eCat.aspx?go=FinderSearch&Cat=Row&At=Fa&Cult=English&Category=Produktfinder&FamilyID=267&Selections=8644,0,0,8775,0)
7. Xsense MTi inertial measurement unit (USB, 1,7g full scale acceleration, 150deg/s full scale rate of turn).
[http://www.xsens.com/index.php?
mainmenu=products&submenu=machine_motion&subsubmenu=MTi](http://www.xsens.com/index.php?mainmenu=products&submenu=machine_motion&subsubmenu=MTi)
8. Trimble 5700 GPS receiver, with Zephyr GPS antenna. It was used as the *rover* of an RTK-GPS system, in conjunction with a Trimble MS750 used as the *base station* (http://en.wikipedia.org/wiki/Real_Time_Kinematic). The two GPS receivers were connected wirelessly using a Trimble PDL450 radio³.
<http://www.trimble.com/5700.shtml>,
<http://www.trimble.com/zephyrant.shtml>,
<http://www.trimble.com/ms750.html>,
<http://www.trimble.com/pdl450.shtml>.

Please note that (as already underlined in section 2.3) the GPS unit is not to be considered in the same way as the other sensor systems of the robot. It is, infact, the system used for the generation of the **ground truth** describing the actual trajectory of the robot during (some time intervals of) the data gathering sessions.

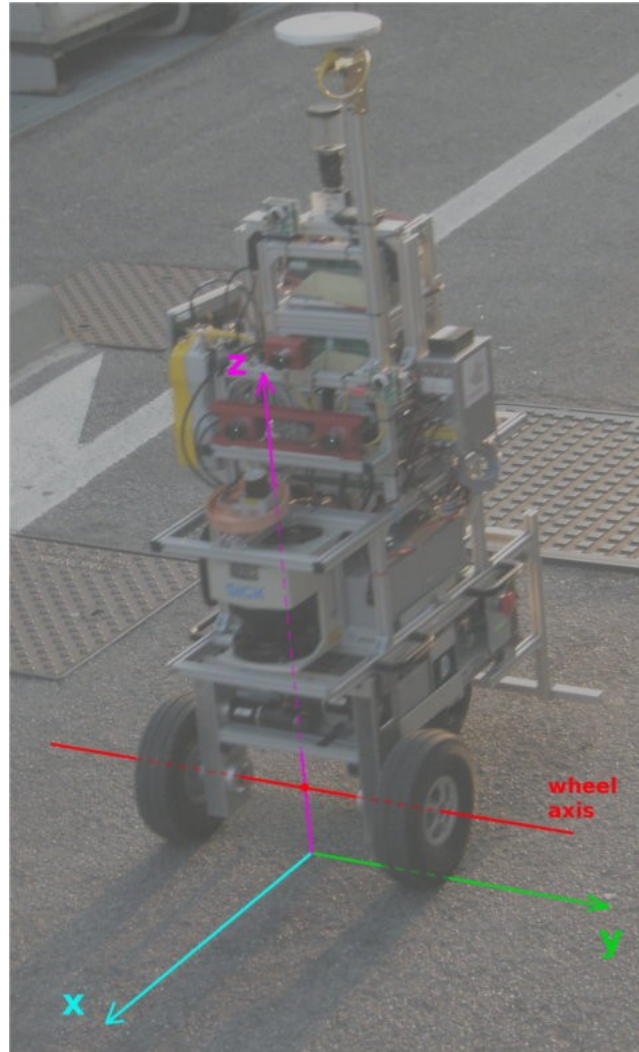
-
- 2 The picture shows *two* frontal cameras (one of which is less visible because it is almost covered by the pole supporting the GPS antenna): however, during the recording of each dataset only one of them was in use. During the data acquisition phase, the upper camera was abandoned in favour of the lower one to try to eliminate some minor defects in the output streams. Although such defects proved to be due to the design of that camera model, the lower camera was left in use and the upper one was abandoned.
 - 3 The short whip antenna which is visible in the pictures beside the larger GPS antenna is used by the Trimble 5700 to receive the correction signals generated by the base station.



3.1.2 Relative pose of onboard sensors

To use the RAWSEEDS datasets it is necessary to know the relative pose of the sensors that generated the streams included into the datasets. This section will provide such information. All the poses will be given with reference to the **odometry reference system** shown in the following picture.





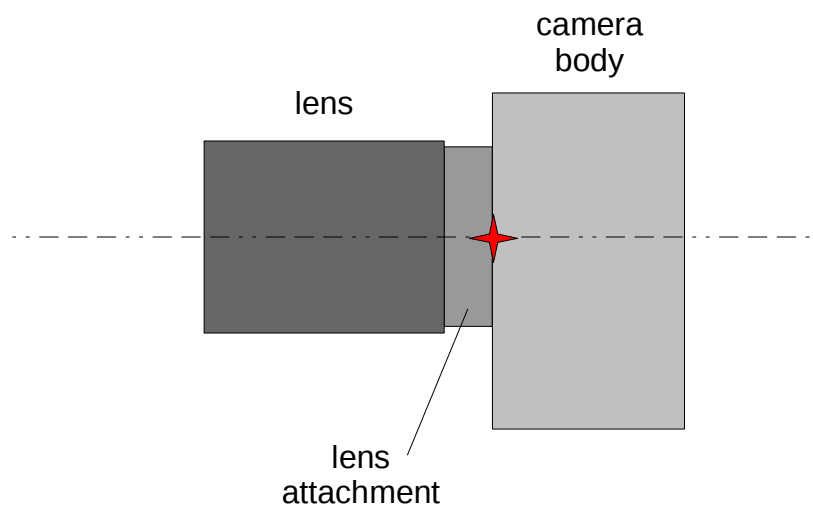
As can be seen from the picture, the origin of the odometry reference frame is the vertical projection on the floor plane of the median point of the wheel axis, and the z axis is vertical. Therefore, both the x and y axes lie on the floor. The angle called "theta" in the file formats described in the preceding sections is measured starting from the x axis, growing (as usual) counterclockwise when seen from above the ground.

In the following part of this section we will give the positions of the sensors as measured in the reference system just described. We will consider the sensors one at a time, specifying for each of them the position and the orientation. However, it is first necessary to specify the points on the sensors that the given positions are referred to. We will start, then, by defining such measured points for each category of sensors.

Cameras (SVS, frontal, omnidirectional)



Point measured: intersection between the optical axis and the plane (perpendicular to it) to which the threaded attachment for the lens is affixed. In the following picture the point is represented by a red star.



GPS

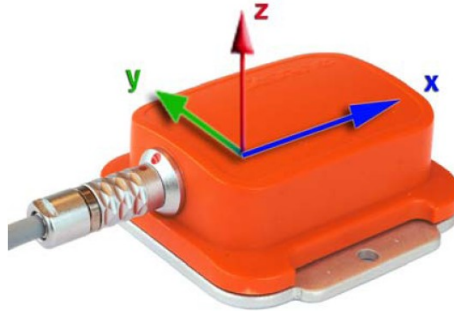
Point measured: intersection between the axis of the threaded hole on the base of the GPS antenna and the plane of that base.

Laser range finders (Sick, Hokuyo)

The center of the rotating mirror reflecting the laser light defines a circumference. Point measured: center of such circumference.

Inertial Measurement Unit

Point measured: median point of the line joining the two fixing holes, on the metal base of the sensor. Please note that the Xsens MTi has its own internal reference system, as shown in the picture below (and indicated on the enclosure of the sensor).



The MTi is positioned on the robot in such a way that each of its own axes is oriented as the axis of the robot's odometry reference system bearing the same name. In other words, between the odometry reference frame and the IMU's frame there is only a translation, but no rotations.

Below is a list of the poses of the sensors in the robot's odometry reference system defined above. All linear measurements are in mm, with a tolerance of $\pm 1\text{mm}$; all angular measurements are in degrees, with a tolerance of $\pm 1.5^\circ$.

FRONTAL camera

For the Bovisa_2008-09-01_Static dataset *only*:

$x = -185\text{mm}$

$y = -53\text{mm}$

$z = 1070\text{mm}$

Orientation: horizontal optical axis, camera pointing towards $x = +\infty$, long side of the CCD horizontal

For *all the other* datasets:

$x = -73\text{mm}$

$y = 183\text{mm}$

$z = 843\text{mm}$

Orientation: horizontal optical axis, camera pointing towards $x = +\infty$, long side of the CCD horizontal

GPS antenna

$x = -21\text{mm}$

$y = 164\text{mm}$

$z = 1375\text{mm}$

Orientation: standard positioning (antenna disc horizontal, threaded hole on the lower side of the disc)

**HOKUYO_FRONT**

x = 62mm

y = 7mm

z = 700mm

Orientation: sensor pointing towards $x = +\infty$, scan plane tilted towards the floor of a 12.5° angle by rotating the sensor around a line parallel to the y axis and passing through the aforementioned coordinates

HOKUYO_REAR

x = -495mm

y = -1mm

z = 704mm

Orientation: sensor pointing towards $x = -\infty$, scan plane tilted towards the floor of a 12.5° angle by rotating the sensor around a line parallel to the y axis and passing through the aforementioned coordinates

IMU

x = -224mm

y = -7mm

z = 537mm

Orientation: metal baseplate below the sensor and horizontal, connector pointed towards $x = -\infty$ (note: as already said, between the odometry reference frame and the IMU's own frame there is only a translation)

ODOMETRY

x = 0mm

y = 0mm

z = 0mm

Orientation: please see the picture in the preceding part of this section

OMNIDIRECTIONAL CAMERA

x = -268mm

y = 2mm

z = 1083mm

Orientation: vertical optical axis, camera pointing towards $z = +\infty$, long sides of the CCD parallel to the y axis (note: only a 640x640 pixel portion of the CCD has been used; the bottom side of the image produced corresponds to the side of the CCD nearer the front of the robot)

**SICK_FRONT** (LMS291)

x = 48mm

y = 0mm

z = 450mm

Orientation: horizontal scanning plane, sensor pointing towards $x = +\infty$ **SICK_REAR** (LMS200)

x = -495mm

y = 1mm

z = 454mm

Orientation: horizontal scanning plane, sensor pointing towards $x = -\infty$ **SVS_RIGHT** (i.e., the camera of the SVS pair positioned on the side of $y = -\infty$)

x = -52mm

y = -79mm

z = 745mm

Orientation: horizontal optical axis, camera pointing towards $x = +\infty$, long side of the CCD horizontal (note: distance between the symmetry axes of the lenses of the SVS stereo pair = 182mm, along the y axis)**SVS_LEFT** (i.e., the camera of the SVS pair positioned on the side of $y = +\infty$)

x = -52mm

y = 103mm

z = 745mm

Orientation: horizontal optical axis, camera pointing towards $x = +\infty$, long side of the CCD horizontal (note: distance between the symmetry axes of the lenses of the SVS stereo pair = 182mm, along the y axis)**SVS_TOP**

x = -72mm

y = 9mm

z = 868mm

Orientation: horizontal optical axis, camera pointing towards $x = +\infty$, long side of the CCD horizontal

* _ * _ * _ * _ *

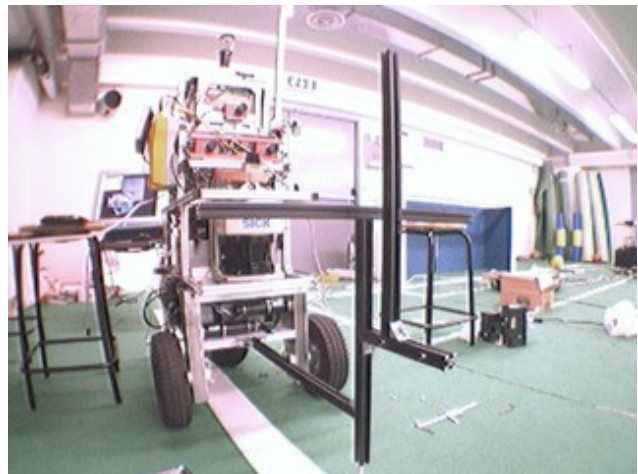
The sensor positions listed above have been measured manually with great care. As a



verification, and as a means to estimate the positions of the *pinhole* of the front-looking cameras, we also performed a second measurement with a completely different approach. This second procedure is described as follows:

1. A test panel sporting a calibration pattern, with an associated reference system, has been positioned in a known position (measured manually) with respect to the odometry reference system. In this way, the transformation (i.e., the rototranslation) between odometry system and pattern system was known.
2. The calibration pattern on the test panel has then been localized using the data from the front-looking cameras: this has been done with the same Matlab toolbox used to calibrate the cameras, described in section 3.2, with the intrinsic calibration parameters listed in that section. The transformations between the reference systems of each camera and that of the pattern were therefore assumed to be known.
3. Finally, for each camera the rototranslation from the odometry system to the camera system was obtained by composing the transformations from odometry system to pattern system and from pattern system to camera system.

The picture below illustrates how the measurement was set up in practice.





The supporting frame for the test panel was accurately oriented to be parallel to the yz plane, and the fact that the horizontal lines on the panel were actually horizontal in space was verified with a spirit level.

The transformations resulting from the measurement process just described are given below. All measurements are in mm; as indicated, there is a scale factor of 100 (1.0e+02) to be applied to the figures.

SVS_RIGHT

1.0e+02 *			
-0.00018873976115	-0.00012716588320	0.00999740997162	-0.28891913553997
-0.00999821864154	0.00000354020289	-0.00018870999696	-0.78021086775186
-0.00000113953863	-0.00999919078251	-0.00012721004810	7.45475315985781
0	0	0	0.01000000000000

(x = -52mm, y = -79mm, z = 745mm)

SVS_LEFT

1.0e+02 *			
-0.00011494258769	-0.00012276408761	0.00999858575901	-0.27257910097409
-0.00999916242081	0.00006090079616	-0.00011420146811	1.02903746880466
-0.00005949019942	-0.00999906095950	-0.00012345381466	7.45603663850162
0	0	0	0.01000000000000

(x = -52mm, y = 103mm, z = 745mm)

SVS_TOP

1.0e+02 *			
-0.00004812638837	-0.00015595506141	0.00999866800477	-0.48082391577554
-0.00999966821128	0.00006646633279	-0.00004709448845	0.09149382295187
-0.00006572301712	-0.00999856290901	-0.00015626976545	8.66619209088593
0	0	0	0.01000000000000

(x = -72mm, y = 9mm, z = 868mm)

FRONTAL (second one of the two positions described in the preceding part of this section)

1.0e+02 *			
-0.00018994384512	-0.00010075588936	0.00999768821210	-0.54371123460904
-0.00999810183678	-0.00004146196243	-0.00019036955377	1.87843237911609
0.00004337046267	-0.00999940644021	-0.00009994921980	8.40933923376386
0	0	0	0.01000000000000

(x = -73mm, y = 183mm, z = 843mm)

As can be seen by comparing the values in the fourth column of each matrix with the



manual measurements given in the first part of this section (and reported under the matrix between parentheses for convenience), there is a remarkable correspondence between the camera positions obtained with the two methods on the y and z axes. Such positions can therefore be considered reliable.

On the x axis, no correspondence was expected due to the different measured points: an arbitrary physical point for the manual measurements and the *pinhole* for the second set of measurements. However, considering that the measurements along the x axis are expected to be only slightly less reliable than those along the y and z axes, the camera positions given above can be considered as good estimates of the *pinhole* positions for the front-looking cameras.

3.2 Calibration procedures

This section describes the procedures followed to generate the calibration data which are included into the datasets of Deliverable D2.2. As already said in section 2, the datasets also include all the data that an user needs - if she so desires - to repeat the calibrations: either with the same images used by RAWSEEDS or with other images from the same image stream. Please note that the calibration procedures adopted by RAWSEEDS were modified in accordance with the indications expressed by Deliverable D3.1: all calibration data included into Deliverable D2.2 comply with such indications.

All camera calibration data have been determined using the Camera Calibration Toolbox for Matlab by Jean-Yves Bouguet, available at http://www.vision.caltech.edu/bouguetj/calib_doc/.

3.2.1 Calibration of the stereo rig

We need to distinguish two tools, both available in the Camera Calibration Toolbox for Matlab. The first aims at the calibration of single cameras (*calib_gui*), while the second one is devoted to the calibration of stereo rigs (*stereo_gui*). In the stereo tool, one can activate/deactivate an optimization on the parameters; this optimization bases on the pattern poses available for the stereo rig calibration. It has also to be noted that the calibration of stereo rigs requires that the same set of points, from the same calibration patterns, has to be visible from both the cameras of the rig. We have therefore a trade-off between selecting pattern poses for maximizing the quality of the calibration of the intrinsics for each single camera, and selecting pattern poses for maximizing the quality of the calibration of the extrinsics of the stereo rig. In the first case one aims at getting a good coverage, in terms of the pattern in the different images, of the whole image. On the other hand, one needs to make the pattern always visible from all cameras; this could prevent a good coverage for the image of some camera.

In order to reach the highest calibration quality, we devised two approaches, briefly sketched hereafter.

Approach 1

- 1.1 collect a set of images, for each camera, devoted to the calibration of the intrinsic parameters (*images_for_intrinsics*);



- 1.2 collect a set of images, for each camera, devoted to the calibration of the extrinsic parameters (images_for_extrinsics);
- 1.3 run the single-camera tool to compute the intrinsics, on the images_for_intrinsics;
- 1.4 run the stereo-rig tool to compute the extrinsics on the images_for_extrinsics, without optimizations;
- 1.5 return the intrinsics, as determined on images_for_intrinsics, and the extrinsics, as determined on images_for_extrinsics.

Approach 2

- 2.1 collect a set of images devoted to the calibration of the extrinsic parameters (images_for_extrinsics);
- 2.2 run the stereo-rig tool to determine the extrinsics on the images_for_extrinsics, with all optimizations;
- 2.3 return the intrinsics and the extrinsics determined on images_for_extrinsics.

It has to be noted that, when saying "collect a set of images", we do not mind whether this is implemented by grabbing images one by one, e.g., by using a program such as Coriander for Linux, or by passing through a large set of images of a previously taken movie and individually selecting the images that are suitable for a given task, i.e., calibration of intrinsics.

As it can be seen below, the results are in favor of Approach 2, i.e., activating the optimizations on the images for the extrinsics turns into better results, in term of the intrinsics, than working on images collected for the intrinsics. The comparison have been performed on the pair SVS_R - SVS_L. We report hereafter the results of the two approaches; in blue approach 1 and in red approach 2.

```
SVS_L with imageforintrinsics
SVS_L with imageforextrinsics plus optimization

fc = [ 669.575836258164372 ; 669.575836258164372 ]; fc_error = [ 0.901559199070125 ; 0.901559199070125 ];
fc = [ 669.11252 ; 669.11252 ]; fc_error = [ 0.74954 ; 0.74954 ];

cc = [ 320.762090800492501 ; 240.979796780157358 ]; cc_error = [ 1.970679476711263 ; 1.229320133006431 ];
cc = [ 322.91567 ; 237.87556 ]; cc_error = [ 1.66719 ; 1.04037 ];

alpha_c = 0.000000000000000; alpha_c_error = 0.000000000000000;
alpha_c = 0.00000; alpha_c_error = 0.00000;

kc = [-0.303314122231926 ; 0.175745849239687 ; 0.000754747672358 ; 0.001042150117293 ; 0.000000000000000 ];
kc = [-0.29430 ; 0.13462 ; 0.00163 ; 0.00116 ; 0.00000 ];

kc_error = [ 0.006543592559733 ; 0.024108612358091 ; 0.000331497179418 ; 0.000291978929520 ; 0.000000000000000 ];
kc_error = [ 0.00520 ; 0.02146 ; 0.00030 ; 0.00025 ; 0.00000 ];

SVS_R with imageforintrinsics
SVS_R with imageforextrinsics plus optimization

fc = [ 662.981018447727251 ; 662.981018447727251 ]; fc_error = [ 0.784560214382271 ; 0.784560214382271 ];
fc = [ 664.04186 ; 664.04186 ]; fc_error = [ 0.74811 ; 0.74811 ];

cc = [ 307.146795057570500 ; 213.565270242765820 ]; cc_error = [ 1.529577250037452 ; 0.996620686938592 ];
cc = [ 308.83852 ; 212.19053 ]; cc_error = [ 1.52851 ; 1.05893 ];

alpha_c = 0.000000000000000; alpha_c_error = 0.000000000000000;
```



```
alpha_c = 0.00000;          alpha_c_error = 0.00000;

kc =      [-0.282551328978809 ; 0.108840211697894 ; 0.000097961865276 ; -0.000825377675953 ; 0.000000000000000 ];
kc =      [-0.28151 ;          0.10142 ;          0.00038 ;          -0.00105 ;          0.00000 ];

kc_error = [ 0.003352545321727 ; 0.009233136833339 ; 0.000268393297885 ; 0.000214345462253 ; 0.000000000000000 ];
kc_error = [ 0.00509 ;          0.01563 ;          0.00029 ;          0.00032 ;          0.00000 ];
```

For the sake of completeness, we also include the data for camera SVS_T, though no comparison have been performed between the two approaches, for this camera.

```
SVS_T with imageforextrinsics plus optimization
fc = [ 665.92359 ;          665.92359          ]; fc_error = [ 0.71269 ;          0.71269          ];
cc = [ 320.59554 ;          208.32816          ]; cc_error = [ 2.03149 ;          1.33006          ];
alpha_c = 0.00000;          alpha_c_error = 0.00000;
kc =      [-0.29398 ;          0.13796 ;          0.00093 ;          -0.00115 ;          0.00000 ];
kc_error = [ 0.00610 ;          0.02302 ;          0.00038 ;          0.00026 ;          0.00000 ];
```

We come now to the extrinsics, determined with the stereo-rig tool, on the 3 binocular rigs that can be built with the trinocular system available.

```
Extrinsic parameters (position of right camera wrt left camera):
Rotation vector: om = [ 0.00097 0.00607 -0.00537 ]; om_error = [ 0.00201 0.00323 0.00016 ];
Translation vector: T = [ 181.06493 -0.33483 0.70925 ]; T_error = [ 0.23946 0.22217 1.22599 ];

Extrinsic parameters (position of top camera wrt left camera):
Rotation vector: om = [ 0.00443 0.01448 -0.00587 ]; om_error = [ 0.00196 0.00303 0.00020 ];
Translation vector: T = [ 88.10214 121.07591 21.13757 ]; T_error = [ 0.30883 0.31771 1.34206 ];

Extrinsic parameters (position of right camera wrt top camera):
Rotation vector: om = [ -0.00343 -0.00836 0.00048 ]; om_error = [ 0.00021 0.00021 0.00015 ];
Translation vector: T = [ 93.16413 -121.46916 -20.77566 ]; T_error = [ 0.27170 0.26475 0.18538 ]
```

The calibration of the trinocular stereo rig is tackled as the calibration of two binocular stereo rigs (SVS_R - SVS_L + SVS_R - SVS_T), so we will end up with the extrinsics of each rig (right+left, right+top). As one could calibrate also SVS_L - SVS_T, we checked the quality of the two different estimates one could get about SVS_T - SVS_R. Overall we need both SVS_L and SVS_T referred to the SVS_R frame. If we determine SVS_L with respect to SVS_R, then one simpler option is to calibrate SVS_T w.r.t. SVS_R; the alternative is to calibrate SVS_T w.r.t. SVS_L, and then to compose this roto-translation with SVS_L w.r.t. SVS_R.

```
rtLR =
1.0e+02 *
0.00999967159282 0.00005372884307 0.00006067328165 1.81064930000000
-0.00005366996439 0.00999985111183 -0.00000986287089 -0.00334830000000
-0.00006072537036 0.00000953691370 0.00999981107205 0.00709250000000
0 0 0 0.01000000000000

rtTR*rtLT
ans =
1.0e+02 *
0.00999966768348 0.00005399282988 0.00006108186503 1.81030076344405
-0.00005393043103 0.00999984919152 -0.00001037571335 -0.00277966103405
-0.00006113696528 0.00001004595142 0.00999980806567 0.00681970701751
0 0 0 0.01000000000000
```

The rotation sub-matrix is quite similar, and also the translation vector. The



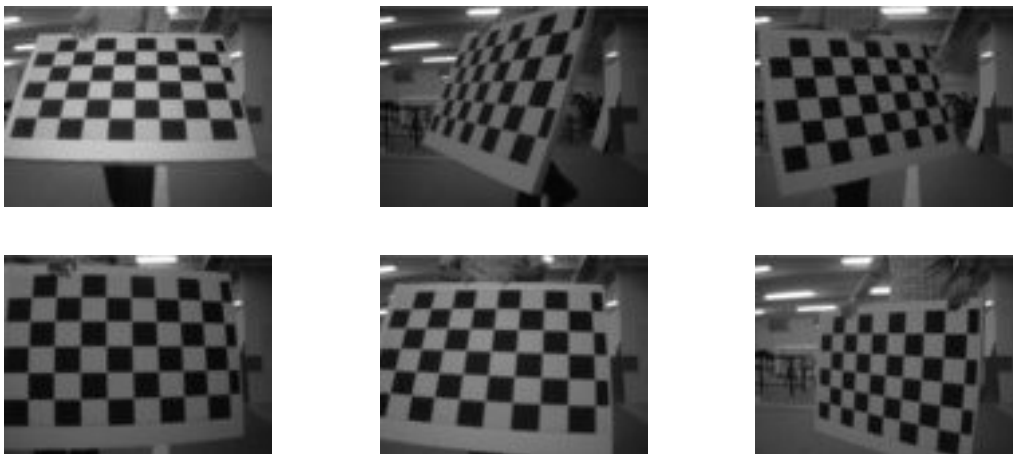
difference between the translation part of the two ($rtLR - rtTR * rtLT$) is:

```
0.00034853655595m => 0.34853655595mm  
-0.00056863896595m => -0.56863896595mm  
0.00027279298249m => 0.27279298249mm
```

Concluding, the overall calibration procedure we followed is as follows:

1. collect a set of images so that all cameras can observe the same set of pattern points;
2. calibrate the extrinsics and intrinsics for the pair SVS_L and SVS_R, with the stereo-rig tool and optimization for both the cameras;
3. calibrate the extrinsics and intrinsics for the pair SVS_T and SVS_R, with the stereo-rig tool and optimization for both the cameras;
4. selects the best of the two intrinsics for SVS_R obtained from previous steps.

As a sample of the kind of images used to calibrate the stereo rig, the picture below shows a subset of the images used to calibrate the left camera of the SVS. The complete set of images is available with the datasets. Please note that visual quality of the images below is low due to the format changes and the resizing necessary to include them into this document.



3.2.2 Calibration of the frontal camera

This device is a low-cost webcam, which has been mounted in order to allow researchers tackle the difficulties introduced by using such a low-quality device as a sensor. For a higher quality stream, to be used for monocular research, please refer to one of the streams of the trinocular stereo system.

For the frontal camera, two different calibrations are available, as after the gathering



of the first outdoor dataset the camera was exchanged with a new sample, mounted in a different position on the robot (please see section 3.1.1 for details).

```
FRONTAL (pose for dataset 20080901)
fc = [ 195.54728 ; 195.54728 ; ]; fc_error = [ 0.39384 ; 0.39384 ; ];
cc = [ 173.62676 ; 131.11679 ; ]; cc_error = [ 0.47297 ; 0.39630 ; ];
kc = [ -0.34212 ; 0.14684 0.00085 0.00000 -0.03196 ];
kc_error = [ 0.00322 ; 0.00477 0.00024 0.00000 0.00195 ];
alpha_c = [ 0.00000 ]; alpha_c_error = [ 0.00000 ];

FRONTAL (pose for all the other datasets)
fc = [ 195.72427 ; 195.72427 ; ]; fc_error = [ 0.36552 ; 0.36552 ; ];
cc = [ 171.91864 ; 127.41018 ; ]; cc_error = [ 0.46904 ; 0.34770 ; ];
kc = [ -0.34296 ; 0.15023 0.00036 -0.00000 -0.03407 ];
kc_error = [ 0.00351 ; 0.00597 0.00032 0.00000 0.00280 ];
alpha_c = [ 0.00000 ]; alpha_c_error = [ 0.00000 ];
```

As a sample of the kind of images used for calibration, the picture below shows a subset of the images used to calibrate the frontal camera. The complete set of images is available with the datasets. Please note that visual quality of the images below is low due to the format changes and the resizing necessary to include them into this document.



3.2.3 Calibration of the omnidirectional camera

This device is a catadioptric camera, i.e., a normal camera with its optics (the dioptric part) and a catoptric part (the reflective part, i.e., the mirror). The mirror part is a commercial device from the Japanese company Vstone; its shape is hyperbolic, and, when combined with a perspective projection, allows to get images from a Single View Point, virtual in this case, because of the mirror. SVP projection has useful properties, and can be calibrated similarly to what is done in the context of normal dioptric cameras.

To calibrate the catadioptric omnidirectional camera, two main toolboxes are available. The one we used is the one whose usage is easier (the tool allows to avoid clicking on all the image points of the calibration pattern). The description of the projection model that this toolbox is the one given in the document "Projection



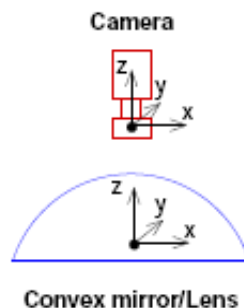
Model" by Christopher Mei, available at

http://www-sop.inria.fr/icare/personnel/Christopher.Mei/articles/projection_model.pdf

The article describing the chosen approach to the calibration is "Single View Point Omnidirectional Camera Calibration from Planar Grids" by Christopher Mei and Patrick Rives, available at

http://www.robots.ox.ac.uk/~cmei/articles/single_viewpoint_calib_mei_07.pdf

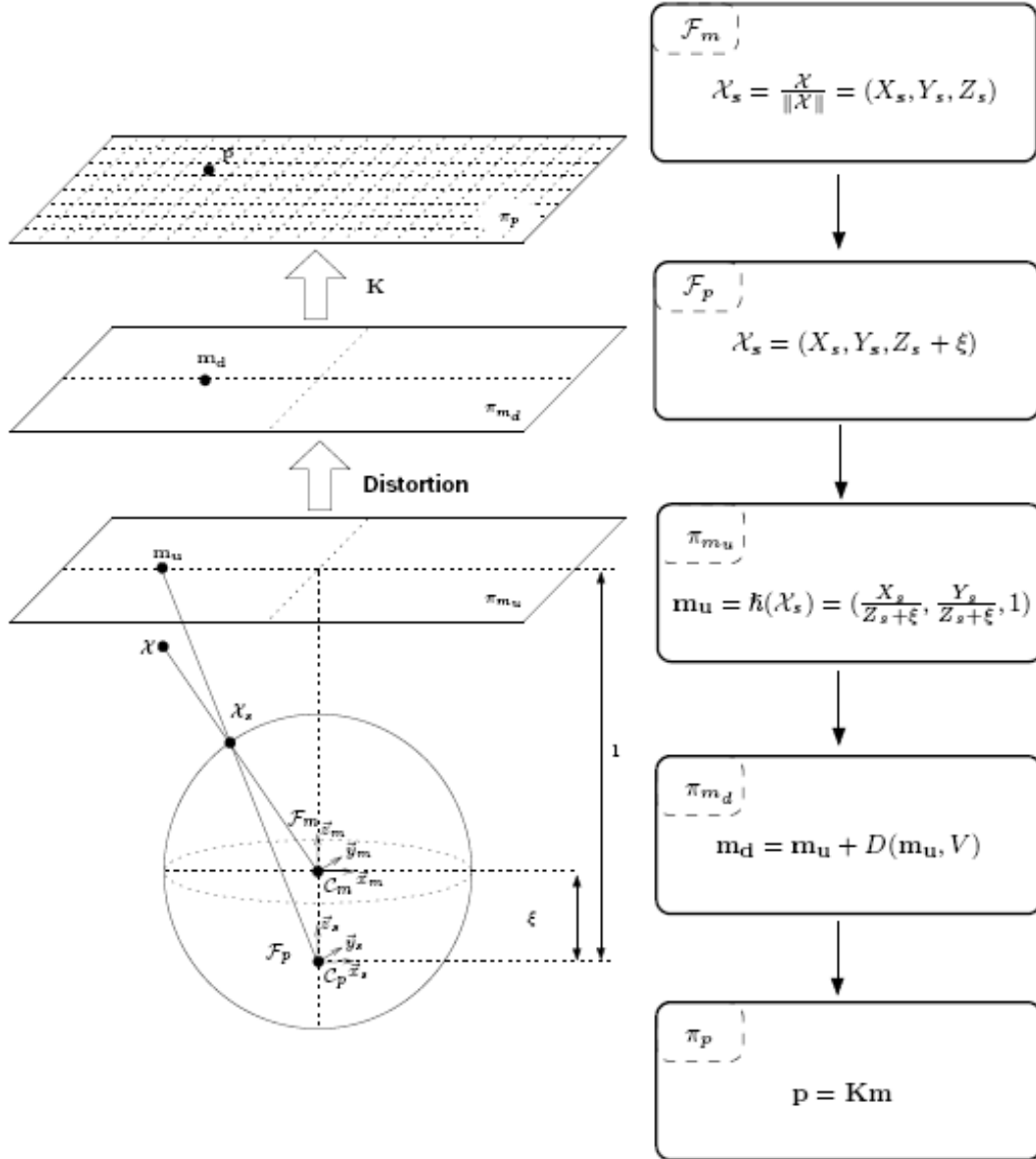
For the convenience of the user, we will now copy into this document the description of the projection model we used. Please note that such description has been directly lifted from "Projection Model" by Christopher Mei: use the original document for reference. The following figure shows the choice of axes done for the model.



The projection of 3D points can be done following the steps outlined in the following figure,







with the relationship between (ξ, γ) and the mirror values detailed in the table below:

	ξ	γ
Parabola	1	$-2pf$
Hyperbola	$\frac{d^2}{\sqrt{d^2 + 4p^2}}$	$\frac{-2pf}{\sqrt{d^2 + 4p^2}}$
Ellipse	$\frac{d^2}{\sqrt{d^2 + 4p^2}}$	$\frac{2pf}{\sqrt{d^2 + 4p^2}}$
Planar	0	$-f$
Perspective	0	f
d : distance between focal points $4p$: latus rectum		

1. world points in the mirror frame are projected onto the unit sphere,



$$(\mathcal{X})_{\mathcal{F}_m} \rightarrow (\mathcal{X}_s)_{\mathcal{F}_m} = \frac{\mathcal{X}}{\|\mathcal{X}\|} = (X_s, Y_s, Z_s)$$

2. the points are then changed to a new reference frame centered in $C_p = (0, 0, \xi)$,

$$(\mathcal{X}_s)_{\mathcal{F}_m} \rightarrow (\mathcal{X}_s)_{\mathcal{F}_p} = (X_s, Y_s, Z_s + \xi)$$

3. they are then projected onto the normalised image plane,

$$\mathbf{m}_u = \left(\frac{X_s}{Z_s + \xi}, \frac{Y_s}{Z_s + \xi}, 1 \right) = h(\mathcal{X}_s)$$

4. we then add radial and tangential distortion,

$$\mathbf{m}_d = \mathbf{m}_u + D(\mathbf{m}_u, V)$$

5. the final projection involves a generalised camera projection matrix K (with γ the generalized focal length, (u_0, v_0) the principal point, s the skew and r the aspect ratio)

$$\mathbf{p} = K\mathbf{m} = \begin{bmatrix} \gamma & \gamma s & u_0 \\ 0 & \gamma r & v_0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{m} = k(\mathbf{m})$$

h lifts a the point from π_{m_u} to the sphere :

$$h^{-1}(\mathbf{m}_u) = \begin{bmatrix} \frac{\xi + \sqrt{1 + (1 - \xi^2)(x^2 + y^2)}}{x^2 + y^2 + 1} x \\ \frac{\xi + \sqrt{1 + (1 - \xi^2)(x^2 + y^2)}}{x^2 + y^2 + 1} y \\ \frac{\xi + \sqrt{1 + (1 - \xi^2)(x^2 + y^2)}}{x^2 + y^2 + 1} - \xi \end{bmatrix}$$

Calibration results for the catadioptric camera, obtained by using the above model, are the following.

OMNI

```
gammac = [ 274.95570  274.95570 ] ± [ 0.35796  1.33785 ]
cc       = [ 326.13594  313.86426 ] ± [ 1.45036  0.00418 ]
xi       = [ 1.00000 ] ± [ NaN ]
kc       = [ 0.02868  -0.00489  0.00072  -0.00042  0.00000 ];
kc_error = ± [ 0.00488  0.00362  0.00058  0.00046  NaN ]
alpha_c = [ 0.00000 ] ± [ NaN ]
```

As a sample of the kind of images used for calibration, the picture below shows a subset of the images used to calibrate the omnidirectional camera. The complete set of images is available with the datasets. Please note that visual quality of the images below is low due to the format changes and the resizing necessary to include them into this document.



3.3 Description of the datasets

What follows is an overview of the outdoor datasets of Deliverable D2.2. The datasets are accessible through the internet, with the procedure described in section 2.1 of this document. In the following of this section, the title of the subsection describing each specific dataset corresponds to the name of the directory containing the dataset on the RAWSEEDS server.

The datasets of Deliverable D2.2 belong to two categories: *outdoor* datasets and *mixed* datasets. The first category includes datasets that were recorded by the robot while it followed a path that did never enter into buildings. The second category includes datasets associated to paths that brought the robot in and out of buildings. While outdoor datasets are more suitable to test purely outdoor algorithms such as those involved in the design of "intelligent vehicles", mixed datasets allow the testing of more sophisticated, multi-purpose algorithms. To help the users select the datasets, both online and in this section of this document the datasets have been explicitly subdivided into two sets: outdoor ones and mixed ones.

Each of the datasets is composed of data gathered by the robot on various paths, partially overlapping and organized into multiple *loops* to help the testing of SLAM (Simultaneous Localization And Mapping) algorithms. One of the key performance elements for such algorithms is, in fact, the ability to correctly "close the loop" when the robot returns to a previously visited zone: i.e., the ability to correctly detect that the zone presently explored has been visited before and to update the map built by the algorithm accordingly.

The location in which all the datasets of Deliverable D2.2 have been acquired is the Bovisa campus of Politecnico di Milano, already described in Deliverable D1.2. The picture in the next page shows a satellite view of the area (source: Google Maps; the



"A" flag is set on via Durando 10, Milan, Italy). In particular, from such picture emerge the dimensions of the area and the presence of wide-open areas and low buildings. A second image is also provided, highlighting the presence of an area of rough terrain (paved by dirt, small stones, sand, and occasional grass): to widen the kind of environments represented into the datasets, this area was intentionally traversed with the robot while acquiring some of the datasets. While describing those datasets in the following sections of this document, we will point out this characteristic.





Each data acquisition session had an approximate duration of 40 minutes (exact durations can be obtained by examining the timestamps included in all the data streams of the datasets). The time of the day for each data acquisition experiment has been chosen by examining the expected constellations of GPS satellites, in order to maximize the quality of the received GPS signals and thus to extend as far as possible the areas and the time spans on which a good robot localization was available from the ground truth RTK-GPS system. The RTK-GPS base station was positioned on the roof terrace of the long campus building adjacent to Via Durando: such terrace is visible in the pictures as a grey rectangle (partly occupied by a smaller roofed building) within the red/brown roof area of the main building. Of course the rover of the RTK-GPS system was onboard the robot.



3.3.1 Outdoor datasets

Outdoor datasets are those associated to paths of the data-gathering robot that were completely set in the outdoors. No building was accessed by the robot.

3.3.1.1 Bovisa_2008-10-04_Static

Path

The following pictures show the path of the robot. For clarity, it has been subdivided into two parts, but actually there were no stops between the first part (left) and the second (right). Each path starts from the red circle and ends at the red arrow.



Start time

October 4, 2008, 3:55PM.

Presentation of the dataset

This dataset is static (i.e., does not include moving objects such as people) and purely outdoor (i.e., the robot did never enter into buildings). The explored environments include:

- Wide-open outdoor spaces among low buildings, comparable to moderately sparse urban environments at street level. Parked cars are present here.
- Fairly narrow outdoor passages between buildings, comparable to more cramped urban environments at street level. Sometimes irregular fences flank



the robot's path.

- A tract of rough terrain, with floor composed of dirt, sand, small stones and occasionally grass. Besides this tract, piles of rubble and discarded materials can be seen (this is a fairly new campus, and in this area the University is still building).
- A moderately-slanted concrete ramp, connecting street level with a low terrace.

Terrain is smooth, except on the rough terrain part where the robot was shaking (due to the stones it encountered under its wheels) and subject to abrupt deviations. Occasionally (especially while going up or down the sidewalks) the robot has encountered small floor discontinuities (such as low steps). Some small hole was encountered both on roads and on the ramp.

Known defects of the dataset (if any)

12-second gap (i.e., missing frames) in the SVS_T datastream from timestamp 1223135815.597387 to timestamp 1223135828.399478 (timestamp format is, as usual, seconds.microseconds).

Notes (if any)

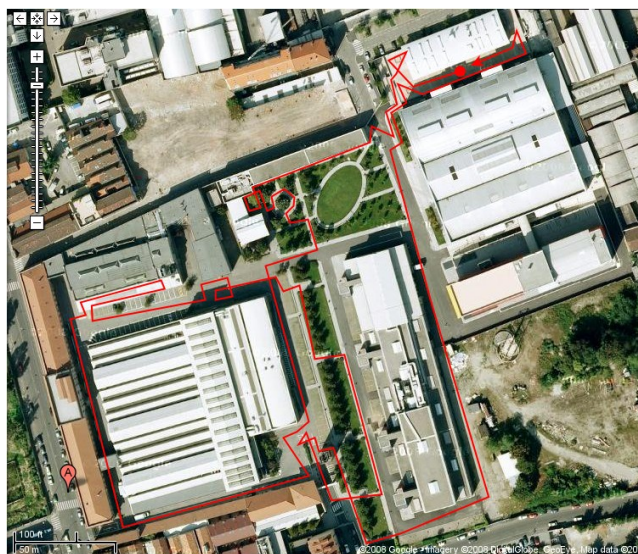
No notes.



3.3.1.2 Bovisa_2008-10-07_Dynamic

Path

The following picture shows the path of the robot. The path starts from the red circle and ends at the red arrow.



Start time

October 7, 2008, 4:45PM.

Presentation of the dataset

This dataset is dynamic (i.e., includes moving objects such as people) and purely outdoor (i.e., the robot did never enter into buildings). The explored environments include:

- Wide-open outdoor spaces among low buildings, comparable to moderately sparse urban environments at street level. Parked cars are present here.
- Fairly narrow outdoor passages between buildings, comparable to more cramped urban environments at street level. Sometimes irregular fences flank the robot's path.
- A tract of rough terrain, with floor composed of dirt, sand, small stones and occasionally grass. Besides this tract, piles of rubble and discarded materials can be seen (this is a fairly new campus, and in this area the University is still building).
- A moderately-slanted concrete ramp, connecting street level with a low



terrace.

- A tract of street-like sidewalk (the straight red line on the lower left part of the map).
- A passage within an outdoor space with some exhibits (big sculptures made from section of tubes), covered by a roof but with a whole side absent. This is the almost horizontal tract which turns back on itself, on the upper left of the map.

Terrain is smooth, except on the rough terrain part where the robot was shaking (due to the stones it encountered under its wheels) and subject to abrupt deviations. Occasionally (especially while going up or down the sidewalks) the robot has encountered small floor discontinuities (such as low steps). Some small hole was encountered both on roads and on the ramp.

Known defects of the dataset (if any)

No known defects.

Notes (if any)

During data acquisition, wheel slippage occurred between timestamps 1223391319.x and 1223391322.x. This makes this dataset especially challenging for some classes of algorithms.



3.3.1.3 Bovisa_2008-10-11b_Static

Path

The following pictures show the path of the robot. For clarity, it has been subdivided into two parts, but actually there were no stops between the first part (left) and the second (right). Each path starts from the red circle and ends at the red arrow.



Start time

October 11, 2008, 5:35PM.

Presentation of the dataset

This dataset is static (i.e., does not include moving objects such as people) and purely outdoor (i.e., the robot did never enter into buildings). The explored environments include:

- Wide-open outdoor spaces among low buildings, comparable to moderately sparse urban environments at street level. Parked cars are present here.
- Fairly narrow outdoor passages between buildings, comparable to more cramped urban environments at street level. Sometimes irregular fences flank the robot's path.
- A tract of rough terrain, with floor composed of dirt, sand, small stones and occasionally grass. Besides this tract, piles of rubble and discarded materials can be seen (this is a fairly new campus, and in this area the University is still building).



- A moderately-slanted concrete ramp, connecting street level with a low terrace.

Terrain is smooth, except on the rough terrain part where the robot was shaking (due to the stones it encountered under its wheels) and subject to abrupt deviations. Occasionally (especially while going up or down the sidewalks) the robot has encountered small floor discontinuities (such as low steps). Some small hole was encountered both on roads and on the ramp.

Known defects of the dataset (if any)

On one occasion (while exiting the pathway around the elliptical grass area, in the first of the two images above) the back wheel of the robot entered the grass and was blocked by the small step leading back to the concrete path. A quick intervention by the driver solved the problem, but introduced a non-static element into the OMNI and SICK REAR streams. The robot was stuck between timestamps 1223739949.x and 1223739952.x.

12-second gap (i.e., missing frames) in the SVS_L datastream from timestamp 1223741420.718308 to timestamp 1223741433.520670 (timestamp format is, as usual, seconds.microseconds). Fortunately, this time interval is very near to the end of the dataset.

Gap (i.e., missing frames) in the SVS_T datastream from timestamp 1223741415.450907 to timestamp 1223741428.252935 (timestamp format is, as usual, seconds.microseconds). Fortunately, this time interval is very near to the end of the dataset.

Notes (if any)

The dataset was recorded almost at sunset. The sun was very low (at the height of the roof of the lower buildings), which is a particularly critical situation for laser range finders based on infrared lasers such as the Sick and Hokuyo units mounted on the robot.



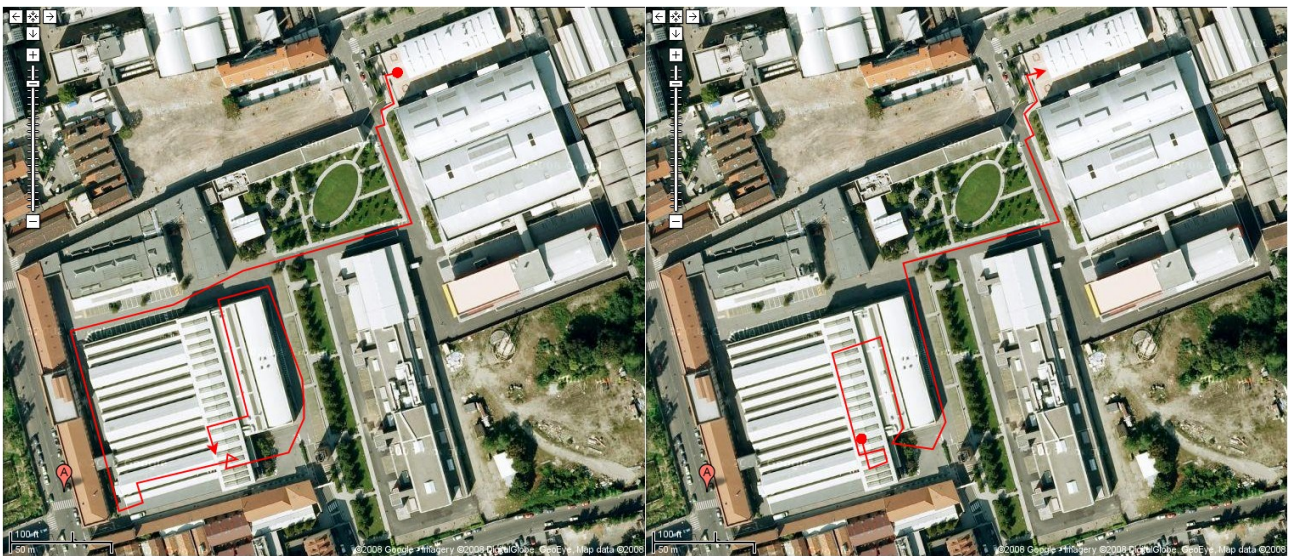
3.3.2 Mixed datasets

Mixed datasets are associated to paths of the data-gathering robot that are set partly outdoors and partly within one or more buildings. The passage from indoors to outdoors and *vice versa* occurs multiple times throughout the datasets, i.e. not only one time as could be the case if the robot simply started outdoor and entered a building, or the reverse. This makes the datasets more useful and challenging.

3.3.2.1 Bovisa_2008-09-01_Static

Path

The following pictures show the path of the robot. For clarity, it has been subdivided into two parts, but actually there were no stops between the first part (left) and the second (right). Each path starts from the red circle and ends at the red arrow.



Start time

September 1, 2008, 3:00PM.

Presentation of the dataset

This dataset is static (i.e., does not include moving objects such as people) and mixed (i.e., covers both outdoor and indoor environments). The explored environments include:

- Wide-open outdoor spaces among low buildings, comparable to moderately



sparse urban environments at street level. Parked cars are present here.

- Fairly narrow outdoor passages between buildings, comparable to more cramped urban environments at street level. Sometimes irregular fences flank the robot's path.
- A moderately-slanted ramp, connecting street level with a low terrace.
- The inside of a University building. The building includes:
 - various kinds of hallways and doors leading in and out of the building;
 - wide corridors with exhibits and models (this is a campus where students study design);
 - narrow corridors with vending machines;
 - a wide environment with two large staircases leading to an upper level;
 - open and closed doors, the former leading to widely different environments (not explored): from small lavatories to large classrooms.

Terrain is smooth for the outdoor parts, and very smooth for the indoor parts. Occasionally (and especially while entering or exiting the building) the robot has encountered small floor discontinuities (such as low steps). Some small hole was encountered both on roads and on the ramp.

Known defects of the dataset (if any)

No known defects.

Notes (if any)

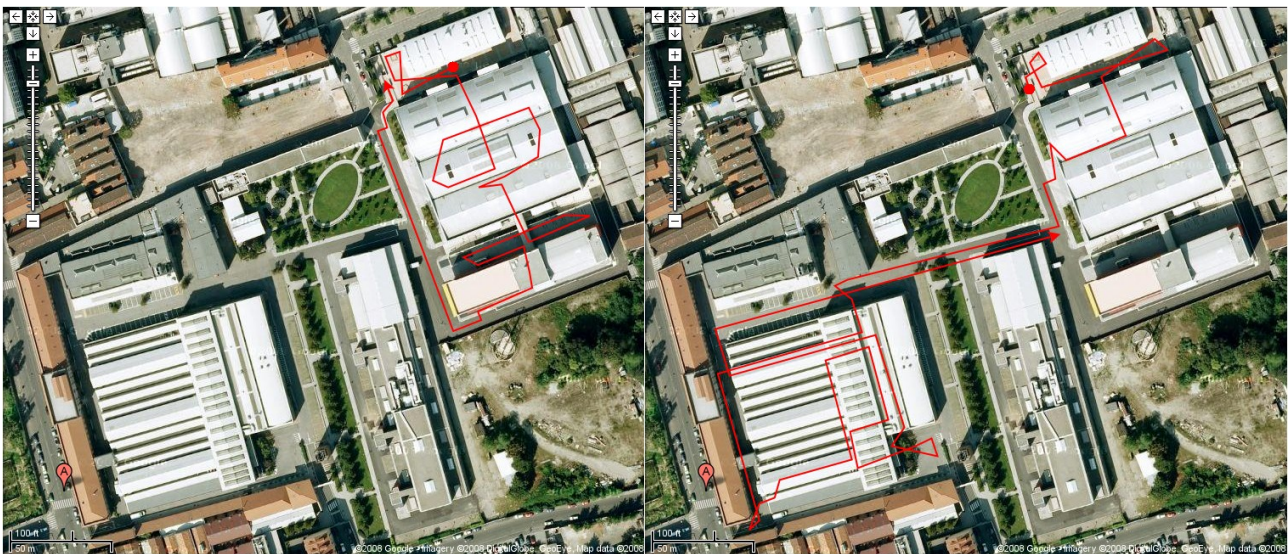
People were present but extremely sparse: for this reason the dataset has been considered as "static". Actually, the dataset was collected at the end of summer 2008, when first-semester courses had not started yet: so only few students were present in the campus.



3.3.2.2 Bovisa_2008-10-06_Dynamic

Path

The following pictures show the path of the robot. For clarity, it has been subdivided into two parts, but actually there were no stops between the first part (left) and the second (right). Each path starts from the red circle and ends at the red arrow.



Start time

October 6, 2008, 4:20PM.

Presentation of the dataset

This dataset is dynamic (i.e., includes moving objects such as people) and mixed (i.e., covers both outdoor and indoor environments). The explored environments include:

- Wide-open outdoor spaces among low buildings, comparable to moderately sparse urban environments at street level. Parked cars are present here.
- Fairly narrow outdoor passages between buildings, comparable to more cramped urban environments at street level. Sometimes irregular fences flank the robot's path.
- Three moderately-slanted ramps, connecting street level with the entrances and exits of buildings. Two of this ramps are made of concrete and have turns, the third is straight and made of perforated metal.
- The inside of two University building. The first building (the one on the left in the maps) includes:



- various kinds of hallways and doors leading in and out of the building;
- wide corridors with exhibits and models (this is a campus where students study design);
- narrow corridors with vending machines;
- a wide environment with two large staircases leading to an upper level;
- open and closed doors, the former leading to widely different environments (not explored): from small lavatories to large classrooms.

The second building (the one on the right in the maps) includes:

- a small hallway, partly surrounded by glass walls;
- two internal (but open to the sky) terraces, with benches;
- narrow corridors;
- a wide hallway with two large holes in the ground within which two staircases rise, a wide bridge between such holes, a wall of glass doors, and several columns and pillars of different types and dimensions.

Terrain is smooth for the outdoor parts, and very smooth for the indoor parts. Occasionally (and especially while entering or exiting the building) the robot has encountered small floor discontinuities (such as low steps). Some small hole was encountered both on roads and on the ramps.

Known defects of the dataset (if any)

No known defects.

Notes (if any)

No notes.



3.3.2.3 Bovisa_2008-10-11a_Static

Path

The following pictures show the path of the robot. For clarity, it has been subdivided into three parts, but actually there were no stops between the first part (upper left) and the second (upper right) or between the second and the third (lower left). Each path starts from the red circle and ends at the red arrow.



Start time

October 11, 2008, 3:05PM.



Presentation of the dataset

This dataset is dynamic (i.e., includes moving objects such as people) and mixed (i.e., covers both outdoor and indoor environments). The explored environments include:

- Wide-open outdoor spaces among low buildings, comparable to moderately sparse urban environments at street level. Parked cars are present here.
- Fairly narrow outdoor passages between buildings, comparable to more cramped urban environments at street level. Sometimes irregular fences flank the robot's path.
- Two moderately-slanted ramps, connecting street level with the entrances and exits of buildings. Two of this ramps are made of concrete and have turns, the third is straight and made of perforated metal.
- The inside of two University building. The first building (the one on the left in the maps) includes:
 - various kinds of hallways and doors leading in and out of the building;
 - wide corridors with exhibits and models (this is a campus where students study design);
 - narrow corridors with vending machines;
 - a wide environment with two large staircases leading to an upper level;
 - open and closed doors, the former leading to widely different environments (not explored): from small lavatories to large classrooms.

The second building (the one on the right in the maps) includes:

- a small hallway, partly surrounded by glass walls;
- two internal (but open to the sky) terraces, with benches;
- narrow corridors;
- a wide hallway with two large holes in the ground within which two staircases rise, a wide bridge between such holes, a wall of glass doors, and several columns and pillars of different types and dimensions.

Terrain is smooth for the outdoor parts, and very smooth for the indoor parts. Occasionally (and especially while entering or exiting the building) the robot has encountered small floor discontinuities (such as low steps). Some small hole was encountered both on roads and on the ramp.

Known defects of the dataset (if any)

3.5s gap (i.e., missing frames) in the OMNI datastream in the last part of the dataset, starting at timestamp 1223733231.416639 (timestamp format is, as usual, seconds.microseconds).

Notes (if any)

Sunny day.



4. Actions taken to comply with the recommendations of WorkPackage 3

The aim of WorkPackage 3 within RAWSEEDS is that of verifying that the quality of the datasets generated by the project is compliant with the quality standard requirements of the project. The Deliverables generated by this WorkPackage have been D3.1 (*Preliminary data certification*), and D3.2 (*Final data certification*). The first analyzed in depth the properties of some preliminary datasets generated by WorkPackage 2 (*Acquisition of sensor data*), while the second did a similar work on finalized datasets. The aims of WorkPackage 3 were:

- to point out any defect in the datasets and/or in the procedures used to gather them (including those related to sensor calibration);
- to suggest corrective actions for the above defects.

D3.1 was presented for internal review in advance of the time when the first part (i.e. the one relative to outdoor environments) of the final datasets was due, so that the corrective actions suggested could be implemented in time for the present deliverable. This mechanism worked as expected, i.e., WorkPackage 2 built on the verification and validation work of WorkPackage 3 to optimize its data-gathering activities in order to obtain the best results. D3.2 was aimed at verifying and certifying the quality of the datasets generated by WorkPackage 2, and at suggesting possible improvements to them and to the associated documentation.

The following Sections take into consideration the problems and recommendations outlined by D3.1 and D3.2, and shortly describe the actions taken to address the points raised by such Deliverables.

4.1 Actions taken in accordance with Deliverable D3.1

In this Section, all the issues raised by D3.1 will be listed, and the corresponding corrective actions will be described.

Lack of documentation. All the documentation requested or suggested is now available, either within this document or online along with the datasets (depending on the type of documents).

Formal defects in the data (e.g., non-uniform file names). Corrected.

Timing and data loss problems. Largely corrected through two actions:

1. substitution of the magnetic hard disks which caused most of the problems (by going into protection state when the robot encountered mechanical shocks) with electronic Solid State Disks;
2. in-depth review and tuning of the operating parameters both of the acquisition software and of the operating system used (Linux).



Camera calibration problems. Calibration procedures have been revised to meet the requests from WorkPackage 3. Calibration for the all the datasets of D2.2 has been done with the new procedures.

Odometry reference system. Although this was not explicitly written in Deliverable D3.1, WorkPackage 3 suggested a switch from the odometry reference system initially chosen (and used in the datasets examined in D3.1) to the new convention used in this document. This has been done, and all the datasets included into D2.2 are based on the new reference system.

4.2 Actions taken in accordance with Deliverable D3.2

Bias in the odometry data. Has been corrected with an improved calibration.

Documentation of wheel slippages and gaps in the data streams in this document. Done.

Filename switch for the Left and Right trinocular streams in some datasets. Corrected.

One image streams used .pgm format instead of .png. Corrected.

Use of .tar compression instead of .tar.bz2 for image streams. File processing is currently ongoing, will be completed in a few days.

Creation of "index" files for image streams. Ongoing, to be completed in a few days.

In addition to the above actions, an expanded description of the calibration methodologies used for the omnidirectional camera was inserted into this document to comply with a remark from WorkPackage 3 expressed via e-mail.