Evaluation of Methods for Robotic Mapping of Cultural Heritage Sites

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Abstract: In archaeological studies the use of new technologies has moved into focus in the past years creating new challenges such as the processing of the massive amounts of data. In this paper we present steps and processes for smart 3D modelling of environments by use of the mobile robot Irma3D. A robot that is equipped with multiple sensors, most importantly a photo camera and a laser scanner, enables the automation of most of the processes, including data acquisition and registration. The robot was tested in the Würzburg Residence. Methods for automatic 3D color reconstructions of cultural heritage sites are evaluated in this paper.

Keywords: laser scanning, 3D modeling, multi-sensors

1. INTRODUCTION

Archaeology is a historical science of high social interest. It studies the human being and its legacy, such as buildings, tools and art. Cultural heritage sites can be found all over the world and they tell us the story of humanity in different areas of the world. Remote sensing has become state of the art in modeling archaeological sites. This way of digitization of entire buildings or areas gives as a unique oportunity to preserve the current state of prehistoric builings and to join forces of experts all over the world. Collecting the data is tedious work. It includes finding the best position for a laser scan, moving the equipment to the position and georeferencing of the scanning position. Letting a robotic system take over this work reduces the time spent in the field by 75 % and decreases the impact to the sites. We present the robot Irma3D, that was designed to create in a tele-operated fashion digital 3D models of environments. This paper describes the setup and the capabilities of the robot and the steps to create these 3D models automatically from multiple sensor sources. The entire process is demonstrated by means of experiments carried out at cultural heritage sites.

In previous work we presented results of tests at Ostia Antica and the Würzburg Residence that showed that the robot can help to automate the process of reconstructing 3D environments. In this paper we focus on the quantitative evaluation of the results. For this purpose we use the data acquired in the Würzburg Residence and evaluate the final model using an additional sensor, the iSpace system from Nikon. The Würzburg Resdience is unique baroque palace in the city center of Würzburg, Germany that was named a UNESCO World Heritage Site in 1981. The Würzburg Residence is ideally suited for the experiments as the large halls allow the setup of the iSpace system so that the entire environment can be observed by this high precision localization system.

In this paper we describe the data collection with the robot Irma3D in this renowned historic sites, the post-processing needed to create a full 3D color model and evaluate the quality of the resulting model comparing different mapping algorithms.

2. EXPERIMENTAL SETUP AND DATA ACQUISITION

Hardware The data was acquired with the mobile robot Irma3D (Intelligent Robot for Mapping Applications in 3D). Irma3D is a small, battery-powered, light weight three wheeled vehicle. It consists of a modified Volksbot RT 3 chassis with two front wheels. Each is actuated by an individual 150 W DC Maxon motor. The motors are powerful enough to move the robot at a maximum velocity of 2.2 m/s The third wheel is in the back of the chassis and is swivel-mounted and thus completely passive as it follows the directions of the front wheels. The high-powered electrical two-wheel drive powered by two 150 W DC Maxon motors is equipped with rotary encoders to measure wheel rotations. This information is used to provide pose estimates of the robot via odometry.

Fig. 1. Irma3D in the Imperial Hall of the Würzburg Residence. Visible in the background is one of the transmitters of the iSpace localization system and a box with two of the reflective targets used for calibration. The handvector bar is used to measure distinctive points in the environment that are used to evaluate the quality of the final model.
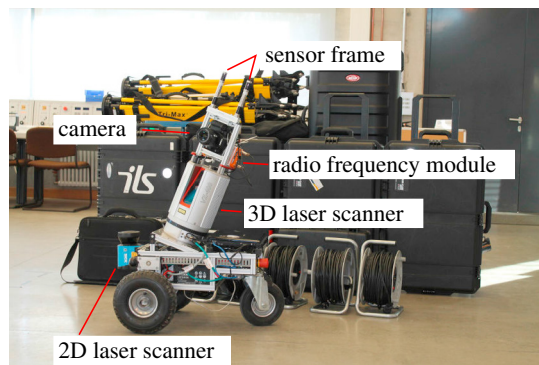
Fig. 2. The Irma3D robot with the setup used in the Residence.

The pose estimates are improved using data from the Xsens MTi IMU device that is also attached to the robotic platform. For obstacle avoidance when moving autonomously a Sick LMS 100 2D laser scanner is added to the front of the robot. This sensor can also be used to improve the localization of the robot. The central sensor of Irma3D is the 3D laser scanner VZ-400 by RIEGL Measurement GmbH. The scanner is mounted on top of the Volksbot RT 3 chassis. Attached to the top of the scanner is a Canon 1000D DSLR camera. After a 3D scan has been acquired the camera is used to acquire color information for the point cloud. Also mounted on top of the laser scanner is an iSpace sensor frame.

iSpace is a high-precision position and tracking system from Nikon Metrology Nikon Metrology (2014). The optical laser based system consists of several transmitters. These are mounted on a wall or on tripods to cover the experimental area both indoors and outdoors. The rotating head of each transmitter emits two perpendicular fan-shaped laser beams at a unique distinguishable frequency near 40 Hz. The vertical openng angle of the laser beams is limited to 40 degrees and the detectable range lies between 2 to 55 meters. Several sensor frames can be located within the system. A sensor frame consists of at least one detector, a photo diode with a horizontal opening angle of 360 degrees and a vertical opening angle of 90 degrees. A small radio frequency module transmits the sensor data wirelessly to the base station of the iSpace system, a PC running the iSpace control software. A sensor frame with one detector is sufficient to acquire 3D position information. To measure also the rotation and to increase the accuracy of the position data the sensor frame used on the robot has a total of four detectors. A sensor frame with two detectors, the handvector bar, is used to measure points in the environment to evaluate the quality of the resulting model. The iSpace system differs from other position and tracking systems as the transmitters do not actively observe the position of the sensor frames. Instead, each sensor frame receives the laser data from the transmitters and sends the information on to the control PC. The control PC calculates the elevation and azimuth angles between all detectors for a sensor frame and each visible transmitter based on the received data defining a straight line between transmitter and detector. Given the relative transformation between the transmitters the length of the lines is calculated using triangulation. To determine the position of the transmitters a calibration procedure using a few hundred points from a special sensor frame is applied. An optimization process calculates the position of all transmitters in a self-defined coordinate system. Three points, the origin, a point on the x-axis and a point on the y-axis allow the user to define its own coordinate system. In typical environments the iSpace system is able to perform measurements at a sampling rate of 40 Hz with a maximum error of [±0.25]mm. In practice environmental factors such as size, reflection of the surface and occlusions of the transmitters have to be taken into consideration.

Experimental environments   The robot was tested in two halls in the Würzburg Residence, namely the White Hall and the Imperial Hall. The Residence Palace in Würzburg Germany was labeled a UNESCO World Cultural Heritage site in 1981. Being built from 1720 to 1744 with the interior finished in 1780 it is now one of Europe's most renowned baroque castles Bayerische Verwaltung der staatl. Schlösser, Gärten und Seen (2014). It was laboriously reconstructed after being heavily damaged during World War II. Not destroyed during the war remained the large unsupported trough vault above the main stair-case designed by architect Balthasar Neumann, the Garden hall with ceiling paintings by Johann Zick, the white hall with the impressive stucco work by Antonio Bossi and the Imperial hall with frescos by Giovanni Battista Tiepolo. With its large colorful paintings by the Venetian painter Giovanni Battista Tiepolo and fine stucco work by stuccoist Antonio Giuseppe Bossi in many of the almost 400 rooms the Würzburg Residence is a unique example of baroque style.

Experiments were carried out in both the White hall and the Imperial hall, two large halls with impressive 3D structure. Together with the colorful paintings in the Imperial hall the environment can only be captured by the combination of two technologies, e.g., laser scanning and photography.

Data collection   To capture the entire environment, data has to be collected at several locations. This is especially crucial due to the restricted field of view of the camera. Accordingly the robot is moved to a scanning location and stops there for data collection. The Riegl VZ-400 laser scanner works in a way that it emits a beam of light into a specific direction. After the light is reflected from a distant object and returns to the scanner, the time between sending and receiving is used to calculate the distance to this object. The sensor is able to capture 125.000 points per second with an opening angle of $360° \times 100°$. Thus, a typical laser scan with a resolution of 0.04° to 0.03° takes between 3 and 5 minutes. To achieve the full 360° horizontal field of view, the scanner head is rotated around its vertical axis. This feature is used to capture the full 360° degrees with the camera. After the scan is taken, the scanner head is rotated in discrete steps to take 12 pictures with a resolution of 3888×2592 at each scanning location. Assuming that the transformation between the camera and the laser scanner is known the point cloud from the laser scanner can then be enhanced with the information from the camera. The calibration procedure used to determine this transformation between camera and the laser scanner is described in detail in Borrmann et al. (2014).

The data acquired at different positions has to has to be brought into one common coordinate system. This process is called point cloud registration. In robotics research methods have evolved over the past years that are specifically designed to register point clouds collected by a mobile robot.

3. SCIENTIFIC APPROACH

3.1 Calibration of the localization sensors

To achieve precise pose estimates for the 3D laser scanner the localization sensors of the robot have to be calibrated to the laser scanner. The method used for odometry, IMU and the 2D laser scanner is explained in Elseberg et al. (2012). In this paper robotic mapping methods using a 3D laser scanner are evaluated using the iSpace system. To localize the robot in the iSpace coordinate system an iSpace sensor frame is attached to the VZ-400 laser scanner. After setting up the transmitters of the iSpace system several reflective markers were attached to objects in the environment. The centers of the markers are measured with the iSpace handvector bar, thus determining their position in the iSpace coordinate system. These markers show up nicely in the reflectance data of the laser scanner. To measure their precise position first a full scan of the environment is carried out. The RiScan Pro Software is used to detect the markers in the environment. An automatic procedure exists, but due to the fact that it creates a high number of false detections the markers were selected manually from the data as they are easily visible due to their high reflectivity. In a second step, fine scans of the markers are performed. The software controls the scanner automatically to scan the area around the selected markers with a very high resolution. If the existence of the marker can be verified, its precise position in the local coordinate system of the scan is calculated. Third, the coordinates of the markers in the coordinate system defined by iSpace are imported as control points and the scans registered to these control points based on the marker position. This yields the position and orientation of the laser scanner in the iSpace coordinate system at the time the scan was taken. Additionally, the pose of the sensor frame is also recorded. In the following poses will be treated as transformation matrices $\mathbf{T}$, consisting of the rotation $\mathbf{R}$ and the translation $\mathbf{t}$. Repeating this procedure for n scans gives n pairs of poses for the Riegl laser scanner $\mathbf{T}_{r,i}$ and the sensor frame $\mathbf{T}_{m,i}$. From these poses the transformation $\mathbf{T}_{m \to r}$ between the coordinate systems is calculated as:

$$\mathbf{T}_{m \to r,i} = \mathbf{T}_{r,i} \mathbf{T}_{m,i}^{-1}. \tag{1}$$

To reduce noise the average over all transformation matrices $\mathbf{T}_{m \to r,i}$ is calculated as:

$$\bar{\mathbf{T}}_{m \to r} = \frac{1}{n} \sum_{i=0}^{n-1} \mathbf{T}_{m \to r,i}. \tag{2}$$

This procedure works for the translation but is not guaranteed to yield valid solutions for the rotation, i.e., an orthogonal matrix with determinant one. Instead we search for the nearest orthonormal matrix by projecting $\bar{\mathbf{R}}_{m \to r}$ onto $SO(3)$ Horn et al. (1988). Let $\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3$ be the eigenvectors and $\lambda_1, \lambda_2, \lambda_3$ the eigenvalues of the square matrix

$$\mathbf{HHs} = \bar{\mathbf{R}}_{m \to r}^T \cdot \bar{\mathbf{R}}_{m \to r} \tag{3}$$

then the final rotation matrix is calculated as:

$$\hat{\mathbf{R}}_{m \to r} = \bar{\mathbf{T}}_{m \to r} \cdot \left(\frac{\mathbf{e}_1 \cdot \mathbf{e}_1^T}{\sqrt{\lambda_1}} + \frac{\mathbf{e}_2 \cdot \mathbf{e}_2^T}{\sqrt{\lambda_2}} + \frac{\mathbf{e}_3 \cdot \mathbf{e}_3^T}{\sqrt{\lambda_3}} \right) \tag{4}$$

Afterwards, for each new scan position the position of the laser scanner in the iSpace coordinate system is calculated:

$$\hat{\mathbf{T}}_{r,i} = \hat{\mathbf{T}}_{m \to r} \mathbf{T}_{m,i}. \tag{5}$$

3.2 Pairwise scan registration

In robotics research methods have evoved over the past years to join data from several positions automatically. Commonly used for this task is the Iterative Closest Point (ICP) algorithm Besl and McKay (1992). The algorithm takes advantage of the fact that robots usually have a rough estimate of their current pose (position and orientation). Starting from such initial pose estimates the algorithm calculates effectively the correct transformation between two point clouds by means of minimizing distances between corresponding points. Corresponding points are chosen based on Euclidean distances. The algorithm is described in Algorithm 1.

Algorithm 1 The ICP algorithm

Require: point clouds m and d
1: find point correspondences
2: minimize for rotation $\mathbf{R}$ and translation $\mathbf{t}$

$$E_{\text{ICP}}(\mathbf{R}, \mathbf{t}) = \frac{1}{N} \sum_{i-1}^{N} ||\mathbf{m}_i - (\mathbf{R}\mathbf{d}_i + \mathbf{t})||^2$$

3: **return** pose $(\mathbf{R}, \mathbf{t})$
4: iterate 1 and 2

Given a registered point cloud M and a point cloud D with an initial pose estimate the ICP first tries to find for each point $\mathbf{d}_i$ from D the point $\mathbf{m}_i$ in M that is closest to d_i. Then one needs to solve for a transformation $(\mathbf{R}, \mathbf{t})$ (translation $\mathbf{R}$ and orientation $\mathbf{t}$) that minimizes the error function E_{ICP}. Nüchter et al. (2010) presents several minimization methods. These two steps are iterated to find the best transformation between the two point clouds. For best results a threshold t_{dist} is introduced and all point pairs with a distance larger than t_{dist} are discarded from the calculations.

In practise this procedure is adopted as follows. Using the first scanning position as reference the nth scan is always registered against the $(n-1)$th scan. This way all scans are sequentially transformed into the same coordinate system.

3.3 Global optimization

Small local errors for the registration of each pair add up and lead to larger errors for long sequences. To overcome this issue a global optimization was proposed by Borrmann et al. (2008).

Given a graph of correspondencing scans for each pair point pairs are determined and the new error function E_{opt} solves for transformations for all scans simultaneously:

$$E_{\text{opt}} = \sum_{j \to k} \sum_{i} ||\mathbf{R}_j \mathbf{m}_i + \mathbf{t}_j - (\mathbf{R}_k \mathbf{d}_i + \mathbf{t}_k)||^2 \tag{6}$$

Methods to minimize E_{opt} are presented in Nüchter et al. (2010). In the experiments global optimization is performed using a complete graph connecting all scans. The implementation used here is freely available from the *The 3D Toolkit* (3DTK) Andreas Nüchter et al. (2014).

3.4 Acquiring initial pose estimates

ICP and the global optimization rely on initial pose estimates to determine the correct transformation between laser scans. Different methods to acquire pose estimates are described in the following.

Odometry   On mobile robots pose estimates are usually attained from odometry. Odometry for wheeled robots such as Irma3D is based on calculating the distance traveled by the robot based on wheel rotations. For this purpose the the relation between the count c of the wheel encoders and the wheel rotations are related to each other using a factor f. Knowing the diameter d of the tires the distance traveled by one wheel is calculated as $\Delta s = \pi \cdot d \cdot f \cdot c$. Considering the distance B between the two wheels and the distances traveled by each wheel $\Delta s_l, \Delta s_r$ the pose at time step n (x, y, θ) of the robot is calculated as:

$$\theta_n = \theta_{n-1} + (\Delta s_r - \Delta s_l)/B$$
$$x_n = x_{n-1} + 0.5 \cdot (\Delta s_r + \Delta s_l) \cdot \cos -\theta_n \qquad (7)$$
$$y_n = y_{n-1} - 0.5 \cdot (\Delta s_r + \Delta s_l) \cdot \sin -\theta_n$$

The quality of these measurements depends highly on the behavior of the robot on the ground. If the floor is slippery and the wheels spin uncontrolled the estimates lack precision. To increase the precision of the position estimates the xSens IMU is attached to the robot and the thus measured accelerations are integrated into the position estimates. This is especially helpful for rotations. Odometry works sufficiently when short distances are covered and the robot follows smooth trajectories. With increasing path lengths, many rotations and frequent stops along the trajectory errors sum up.

2D SLAM   When searching for the next best scanning position it happens that the robot is started and stopped several times leading to bad odometry results. To overcome this problem roboticists commonly use SLAM (Simultaneous Localization and Mapping) solutions. The SLAM problem is the problem of localizing itself in a map while creating it at the same time. Commonly used for SLAM approaches are grid maps built from 2D laser scanners. We use the 2D SICK laser scanner and the GMapping Grisetti et al. (2007) ROS ROS module to create an initial map. GMapping uses Rao-Blackwellized particle filters where each particle holds its own map of the environment. The movement of the robot and last observation are used to predict the next possible state thus maintaining a map of the already explored environment.

Feature-based registration   If no pose estimates were acquired during data collection the remaining option is to determine them directly from the data. Apart from range information modern laser scanners often capture the amount of light that is returned to the sensor. This information, known as reflectance value, can be used to detect features in the data. Conditioned by the buildup of the laser scanning platform the points are captured as range, reflectance and spherical coordinates. This facilitates the generation of a panorama image using the spherical coordinates and the reflectance information. The 3D data is thus projected onto an image. Different projection methods are evaluated in Houshiar et al. (2012). The panorama generation enables the use of image based feature matching methods.
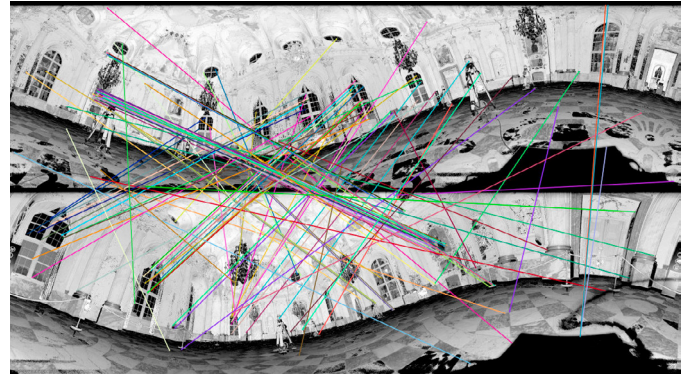

Fig. 3. Illustration of a scan pair with Mercator projection and matched features.

These methods analyze the image and create a description of areas with high changes in intensity. The most common features are SIFT (Scale invariant feature transform). They also show superior performance for feature-based point cloud registration. As the SIFT feature detector works in gray-scale images the panorama images from reflectance values of laser scans are ideally suited for feature matching. For the automatic registration of point clouds using these panorama images corresponding features are detected in the panorama images of scan pairs. Feature correspondences found in two reflectance panoramas are used to calculate pairwise transformation matrices of the point clouds with a RANSAC-like Fischler and Bolles (1981) approach. For this purpose the algorithm identifies the feature in one image that is the closest to the sampled feature from the other image based on a comparison of their descriptors (see Figure 3).

The registration proceeds by testing a subset of 3 point pair matches and examining the two triangles that are defined by these points. The algorithm translates the triangles so that their centroids lie at the center of the common reference frame. The orientation that minimizes the error between the points is then computed by the closed form solution proposed by Horn (1987).

4. EXPERIMENTAL RESULTS

Weißer Saal   During first experiments in the White Hall of the Residence the robot was manually driven to 9 positions to collect data. The starting position was close to the door leading to the Imperial Hall. The other 8 positions were chosen in the corners of the hall facing once towards the wall and once the other way to account for the tilted mount of the laser scanner. Fig. 4 illustrates some of the localization methods, showing scan positions, marked by a black line, and the resulting 3D model. It is obvious that the pose estimates from odometry contain large errors. In an environment such as the one used here, they still suffice as initial pose estimates for ICP, in more complex environments, however, they easily render the registration impossible. The map generated from Gmapping seems to represent the environment well. The structure of the hall is clearly visible. Some faulty black lines are seen in the center of the hall. Using the pose estimes to position the 3D scans directly reveals some inaccuracies as the walls from different scans do not align perfectly. This is illustrated by using different colors for the individual scans. Applying

(a) Odometry + IMU   (b) Gmapping
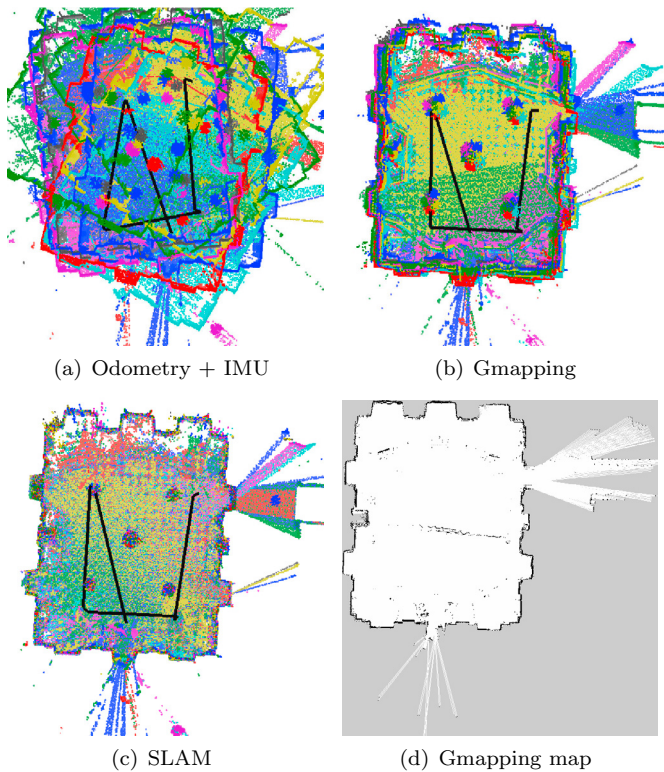

(c) SLAM   (d) Gmapping map

Fig. 4. Floor plan of the White Hall. Projection of the 3D point cloud without the roof using poses from odometry and IMU (a), Gmapping (b), slam6D with pose estimates from Gmapping (c). Each scan is drawn in a different color. The black line connects the scan positions. (d) shows the map created from Gmapping using the 2D laser scanner.

Fig. 5. The final 3D model of the White Hall in the Würzburg Residence.

the global optimization on top of the pose estimates from Gmapping improves the results visibly. Not only the walls ovarlap but also the color distibution in the maps changes. Close to the individual scanning positions the density of the color of that scan becomes higher, while in the other maps the distribution is more random. This effect is the same, when comparing the results with start estimates from different methods. The final 3D model is displayed in Fig. 5 or can be seen at `http://youtu.be/_wPug_So_iE`.

Kaisersaal   To achieve a quantitative evaluation of the methods the iSpace system is set up before data collection in the Imperial hall. Six transmitters are set up and calibrated to define a coordinate system as depicted in Fig. 6. iSpace is then able to measure the robot position high precisely using the sensor frame attached to the top of the laser scanner. Furthermore, points in the environment are measured using the handvector bar to evaluate the quality of the final model (cf. Fig. 1).
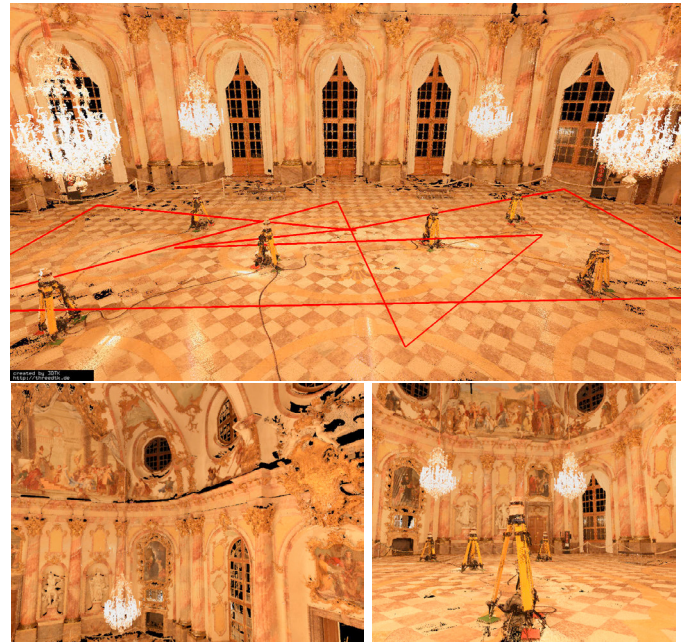

Fig. 6. Final 3D model of the Imperial Hall with transmitters and robot poses.

The robot was manually driven to 11 scanning positions. For the registration methods the pose of the first scan in anchored in the iSpace coordinate system. At each scanning position the position of the robot was recorded using the iSpace system. Figure 7(a) shows the scan positions determined using the different localization systems. Again, odometry has large errors. All other systems yield similar pose estimates. After applying the global optimization to all of these estimates the final results are identical.

For a quantitative evaluation of the pose estimates 7 distinct points in the environment were measured using the iSpace handvector bar. These points were identified in each individual point cloud and transformed into the iSpace coordinate system using the pose estimates calculated with the different localization methods. For each scan the average of the distances between the transformed points and the globally measured point coordinates are calculated. Points that cannot clearly be identified in the point cloud are ignored in the averaging. The results are plotted in Fig. 7(b). As expected, the error for odometry pose estimates is tremendous. A registration is still possible due to the fact that the environment contains of a single large hall. However, this asks for two phases of the ICP method, first with a maximum distance of 250 cm between point pairs and then with a maximum distance of 100 cm to generate a correct model. Even though at first sight GMapping produces a feasible map, the missing accuracy becomes obvious here. This is caused by several factors, the limitations of the 2D laser scanner, the computational requirements to perform the 2D registration continuously and the use of a voxel map with inherent loss of precision. Decreasing the voxel size increases automatically the computational requirements.

Despite the promised accuracy of the iSpace system, the error in the model using this system directly for localization is surprisingly high. Possible reasons for this are interferences from the large windows and the glass chan-

deliers. Additionally, the rotational accuracy promised by the system is not as high as the positional accuracy. However, small rotation errors have already a large impact on the final model given the large distances to the walls. Furthermore, to capture as much as possible from the environment, the robot was moved to the corners of the hall, where the transmitter coverage was not optimal. For each positional measurement the system calculates an uncertainty, which is shown in Fig. 7(c). It can be seen that the large errors for the reference points correspond to the scans with high uncertainty. Feature-based registration yields the best initial pose estimates. They differ only very slightly from the final results. The remaining error is caused by three factors. First, not all points could be measured with high precision. Second, some of the reference points were in areas that were hard to capture with the laser scanner due to the reflective properties of the material. In combination with the low resolution in areas far away from the laser scanner the points manually selected points lack precision. Third, the registration methods use the first scan as reference. The errors in the localization of this scan are therefore propagated to the remaining scans. Nevertheless, the evaluation shows, that the error is minimal for the ICP approach independent of the method used for pose estimates. In the future we will work on increasing the robustness of the approach by analyzing the scene to choose the most appropriate option for generating the pose estimates. The final model of the Imperial Hall is depicted in Fig. 6. A video is available at `http://youtu.be/jKVxlLvu7Pk`.

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(a)   (b)   (c)
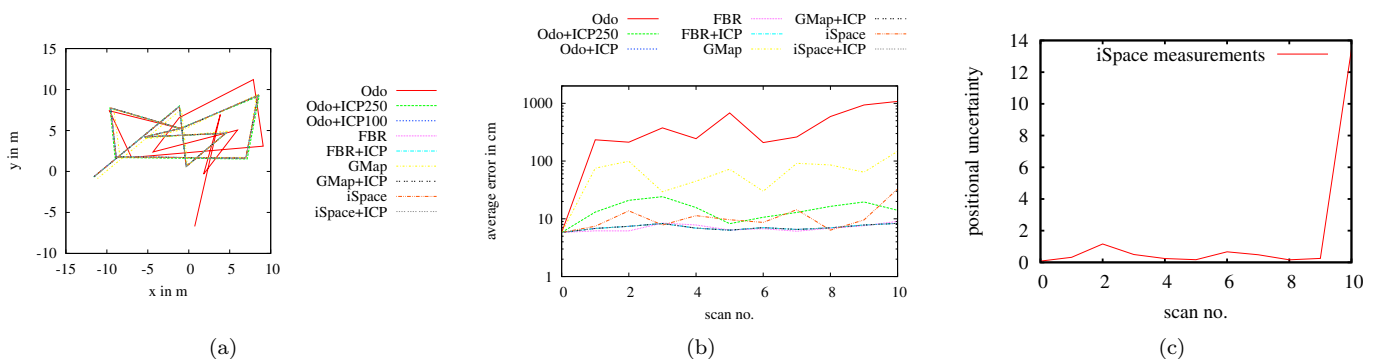
Fig. 7. Evaluation of the iSpace measurements. (a) The poses using the different localization methods. Odo = Odometrie and IMU, ICP = Global optimization with a maximum distance of 100 cm between points, ICP250 = Global optimization with a maximum distance of 250 cm between points, GMap = GMapping, FBR = Feature-based registration using the Mercator projection, SIFT features and the SIFT descriptor for panorama matching. (b) Average error in cm of the measured control points for the map generated using the different mapping methods. (c) Positional uncertainty calculated from the iSpace system for each scan position.