# RADLER - A RADial LasER scanning device

Dorit Borrmann and Sven Jörissen and Andreas Nüchter

**Abstract** In recent years a wide range of 3D measurement devices for various applications has been proposed. Each of them has its own benefits and limitations. This paper proposes a modified unicycle with a 2D laser scanner attached to the wheel axle, thus creating a radial 3D scanning pattern. This novel low-cost device combines the advantages of wheeled scanning equipment with those of wearable or hand-held devices. After presenting the hardware setup and the sensor integration, the results are evaluated using three test scenarios and a terrestrial laser scanner for comparison.

## 1 Introduction

In recent years, optical 3D measurement devices have undergone a rapid development. With increased speed and accuracy on the one hand and decreased weight and hardware costs on the other hand they are on the way of becoming the standard measurement tool in many disciplines. For measuring large areas in a timely manner mobile scanning solutions are the method of choice. Laser scanners as well as camera systems mounted on cars, trolleys, backpacks or aerial vehicles have been developed depending on specific requirements.

Mobile mapping systems consisting of sensors mounted on cars are the state of the art for mapping urban environments. However, they are limited to areas that are accessible by car. Robotic solutions [10] or solutions with scanners mounted on carts, like the viametris iMMS [12, 11], the Google Street View Trolley [5], or the NavVis 3D Mapping Trolley [9] are applicable in smaller alleys. At stairs as well as dirt or gravel roads these systems still meet their limits. Airborne laser scanning is not restricted to specific terrain and thus has advantages, but it is not available in roofed environments or tunnels or gives unsatisfying results in areas with a lot of trees or bushes. Backpack mounted systems, also known as personal laser scanning, such as “The Cartographer” by Google [4], the Zebedee 3D sensor system [1], the Leica Pegasus:Backpack [8] or our own backpack mobile mapping system [6], have been presented as ideal solutions to overcome these issues for indoor mapping. While all of them perform great for said requirements and tasks, all come with disadvantages such as high weight of the backpack, high hardware costs or low range (Zebedee 3D, 15-30 m).

A different approach was recently presented in form of the ”Classical Mechanics Scanner” [7]. Although it is simple and easy to operate, steering the wheel is not possible since the localization is only performed in an intrinsic manner, which requires

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the path to be straight. Additionally, it needs to be regularly pushed for a continuous movement, making the operation exhausting for long scans. Therefore, the field of application is very limited, especially considering challenging and rough terrain. While camera systems meet their limits in changing lighting conditions and featureless environments, the main drawback of full 3D laser scanners is still the respectable price range and the weight. Inspired by the concept of a surveyor's wheel, this paper presents a low-cost 3D scanning solution, RADLER[1] (a RADial LasER scanning device), that consists of a 2D laser scanner mounted on the axle of a unicycle (cf. Fig. 1). The wheel rotation creates a radial 3D scanning pattern. Moving on the ground leads to a smoother trajectory than hand-held or backpack systems. Nevertheless, with the large pneumatic wheel, RADLER can be operated on rough terrain and even stairs if the operator stands above the wheel. Additionally, it is lightweight, highly portable and easy to operate.

**Fig. 1** First author operating RADLER[1] (RADial LasER scanning device).

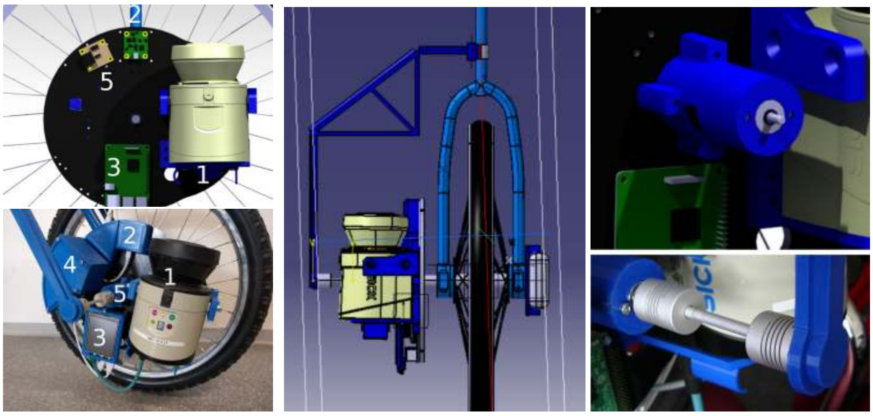
## 2 Technical approach

RADLER is a low-cost scanning device that combines the advantages of wheeled 3D measurement equipment with those of hand-held or wearable devices. It consists of a modified unicycle with an attached handle for easy maneuverability, as seen in Fig. 1. It is light-weight and moves smoothly on the ground due to the large pneumatic wheel, which also allows it to be used in rough terrain and even on stairs, when the operator is rather pulling than pushing.

### *2.1 Hardware setup*

The sensors, namely a SICK LMS141 LiDAR sensor, a PhidgetSpatial Precision 3/3/3 IMU, a Raspberry Pi 3 single board computer (SBC) with display and a Phidget rotary encoder ISC3004, are mounted on a base plate that is connected to the wheel axle as seen in Fig. 2. Counterweights on the other side help to keep the wheel in balance during operation. For best stability, the weights move the center of gravity onto the wheel (cf. red line in Fig. 2(b)). The rotary encoder is fixed

[1] https://en.wikipedia.org/wiki/Shandy#Radler




(a) Sensor plate (b) Center of gravity (c) Wheel encoder

**Fig. 2** The sensor setup of RADLER. (1) SICK LMS141 LiDAR sensor, (2) PhidgetSpatial Precision 3/3/3 IMU, (3) Raspberry Pi 3 with Display, (4) Cable Box, (5) Phidget optical rotary encoder ISC3004 and encoder high speed.

with respect to the unicycle frame via a support structure and connected via the PhidgetEncoder High Speed to the SBC through USB. A coupler releases the axial stress from the encoder during rotation. The LMS141 with a maximum operating range of 40 m at a scanning frequency of 25/50 Hz and resolution of 0.25 / 0.5 ° is mounted with its scanning plane parallel to the wheel's axle and connected to the SBC via Ethernet. The Raspberry Pi 3 is configured as a WiFi access point, such that easy communication via *ssh* is possible. The wheel encoder is used for simple odometry and later on fused with the IMU to get a precise trajectory. RADLER is powered through a 11.1 V 1000 mAh lithium polymer battery, which is also directly mounted on the base plate, giving 11.1 V for the laser scanner and 5 V via a DC-DC converter for the SBC, that allows an operation time of about 40 to 50 min.

## 2.2 Sensor integration

The Raspberry Pi 3 integrates the sensors using ROS (the Robot Operating System). The laser scanner rotates around the wheel axis to create a radial 3D point cloud while moving forward at the same time. This ensures multiple measurements between full 360 degree rotations to provide enough overlapping data needed by our continuous-time SLAM algorithm [2]. The quality of the resulting 3D point cloud is thus heavily dependent on the quality of the laser scanner pose when unrolling the 2D scan slices.

Let the unicycle coordinate system $\mathscr{U}$ be located in the center of the axis with $x$ pointing forward, $z$ pointing upward and $y$ pointing away from the sensor plate. Let $T_{\mathscr{U}\to\mathscr{G}}$ be the transformation from $\mathscr{U}$ into the global coordinate system $\mathscr{G}$, $L$ the circumference of the tire, and $C$ the counts per revolution, i.e., the encoder count for a full 360° wheel rotation, then the change in pitch angle $\Delta\vartheta$ of the unicycle and the forward movement $\Delta x_{\mathscr{U}}$ of the unicycle are determined from the wheel encoder counts $c_t$ between time steps $t-1$ and $t$ as

$$\Delta\vartheta = \frac{-2\pi}{C} \cdot c_t \quad \text{and} \quad \Delta x_{\mathscr{U}} = \frac{L}{C} \cdot c_t. \tag{1}$$

IMUs are prone to drifting effects. To reduce the impact of the drift on the map quality, only the yaw $\psi$ and roll $\varphi$ angles are considered. Let $R_{\mathscr{I}\to\mathscr{G}}$ describe the orientation of the IMU in the global coordinate system, then

$$\begin{pmatrix} p_x & p_y & p_z \end{pmatrix} = R_{\mathscr{I}\to\mathscr{G}} \cdot \begin{pmatrix} 0 & 0 & 1 \end{pmatrix}^T \tag{2}$$

describes the $z$-axis of $\mathscr{I}$ in the global coordinate system. Thus the orientation of the unicycle is determined as

$$\psi = \text{atan2}(p_y, p_x) \quad \text{and} \quad \varphi = \angle \left(\begin{pmatrix} p_x & p_y & p_z \end{pmatrix}, \begin{pmatrix} p_x & p_y & 0 \end{pmatrix}\right). \tag{3}$$

The pitch angle is determined in a similar matter using the $y$-axis in the global coordinate system as

$$\vartheta = \text{atan2}(q_y, q_z) \quad \text{with} \quad \begin{pmatrix} q_x & q_y & q_z \end{pmatrix} = R_{\mathscr{I}\to\mathscr{G}} \cdot \begin{pmatrix} 0 & 1 & 0 \end{pmatrix}^T. \tag{4}$$

$\vartheta$ is used to calibrate the wheel encoder as described in the next section.

Let $T_{\mathscr{L}\to\mathscr{U}}$ be the transformation from the scanner coordinate system $\mathscr{L}$ into the unicycle coordinate system, then the initial transformation for any point $p_{\mathscr{L}}$ in scanner coordinates into the global coordinate system is given as

$$p_{\mathscr{G}} = T_{\mathscr{I}\to\mathscr{G}} \cdot T_{\mathscr{L}\to\mathscr{U}} \cdot p_{\mathscr{L}}, \tag{5}$$

where the rotational part of $T_{\mathscr{I}\to\mathscr{G}}$ is given by $(\varphi, \vartheta, \psi)$ and the translational part is given by

$$\Delta x_{\mathscr{G}} = \Delta x_{\mathscr{U}} \cdot \cos\psi, \quad \Delta y_{\mathscr{G}} = \Delta x_{\mathscr{U}} \cdot \sin\psi, \quad \Delta z_{\mathscr{G}} = 0. \tag{6}$$

The initial transformation does not consider any differences in height and is limited by the accuracy of the encoder and the IMU. Algorithmic solutions are necessary to reduce the impact of these limitations. Here the continuous-time SLAM approach from [2] is used. As this approach is based on the ICP (iterative closest point) algorithm, it benefits from the design of RADLER. The radial rotation allows the 2D laser scanner to measure in front and behind simultaneously, increasing the density and the amount of overlap in the scene.

### 2.3 Sensor calibration

For accurate odometry, it is important to determine $C$ and $L$ from (1) as precise as possible. While the circumference of the tire $L$ can be easily measured, the counts per revolution $C$ of the encoder need to be calibrated. To this end, Madgwick fused and filtered quaternions from the IMU data are used. Fig. 3 shows an exemplary plot of the calculated angular pitch position of the IMU versus the encoder ticks. Detecting peaks in the angular positions allows for calculating the difference in encoder ticks per revolution. These differences are filtered based on the median and then averaged to calculate the number of ticks per revolution. Finally, the offset corresponding to the initial orientation of the encoder is determined. The respective pose of the wheel is then calculated with odometry for movements along the wheel plane and IMU data for the orientation of the wheel as described before. To compensate for systematic errors in the wheel encoder due to environmental influences such as temperature, the automatic calibration procedure is repeated for each experiment.

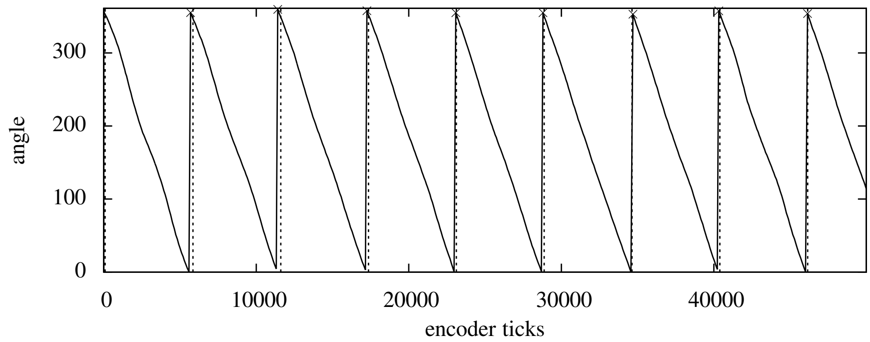



**Fig. 3** Determination of encoder RPM with IMU data. The continuous line shows the IMU angles, the crosses mark the detected peaks while the dashed lines represent the zero-crossings based on the calibrated encoder.

## 3 Experimental results

To evaluate the performance of RADLER, three test scenarios in different environments were performed. The first and second experiments were conducted in the $1^{st}$ floor of the University of Würzburg's computer science ("The Hallway") and old mathematics building ("The Circle"), respectively, the third experiment at the Randersacker chapel[2] ("The Chapel"). Scans obtained with a Riegl VZ-400 laser scanner serve as ground truth for "The Hallway" and "The Chapel".

1. "The Hallway" Being the simplest movement consisting of a straight line over approximately 200 m on a smooth surface with no slope. The data set results in

[2] http://www.wuerzburgwiki.de/wiki/Maria-Schmerz-Kapelle_(Randersacker)

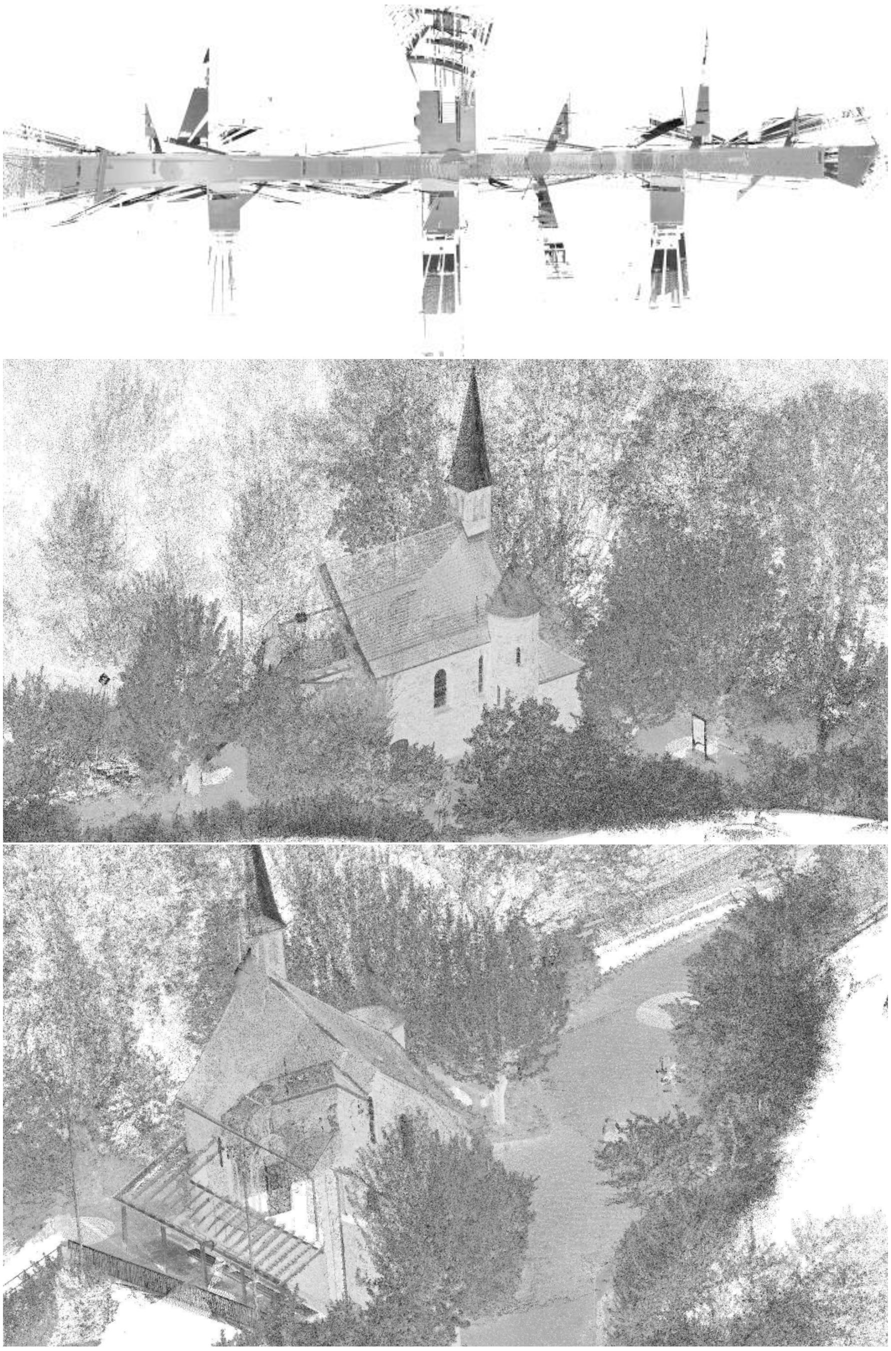


**Fig. 4** Ground truth data acquired with a Riegl VZ-400 terrestrial laser scanner. Top view from ”The Hallway” and two perspectives from ”The Chapel”. The grey values represent the reflectance of the materials.

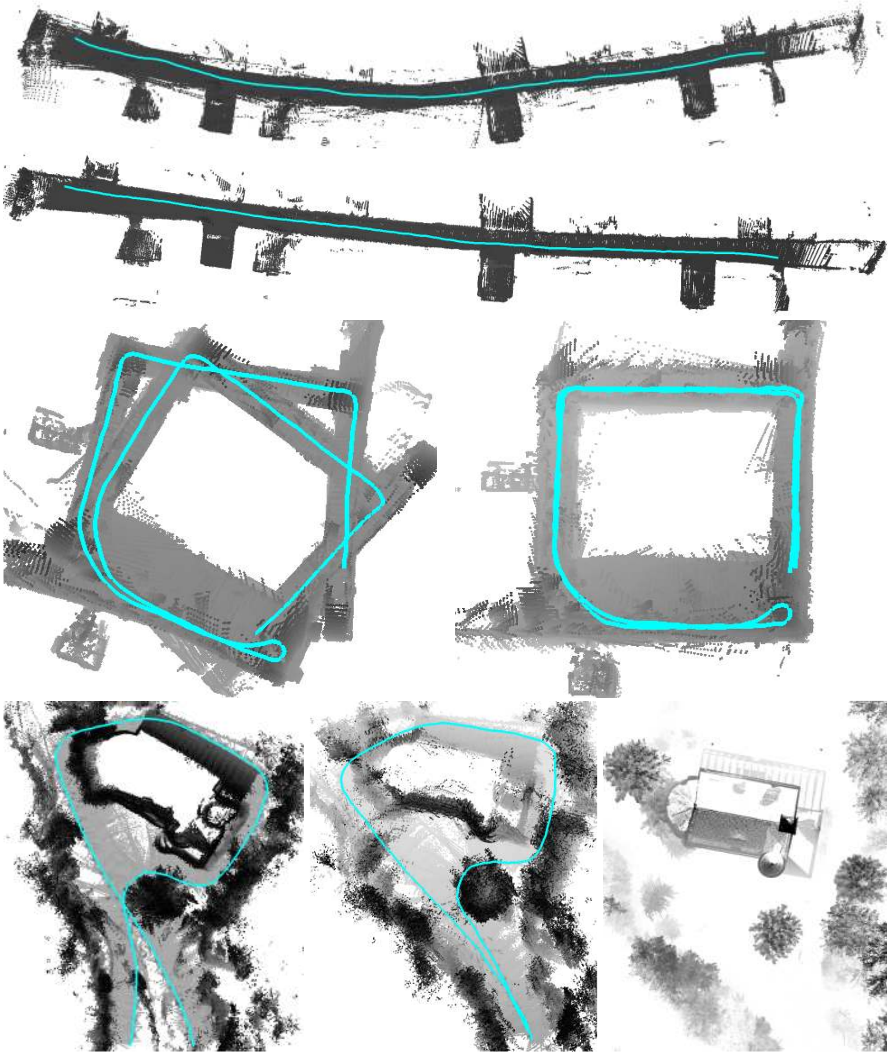


**Fig. 5** Topview showing the results from the experiments: first, the initial trajectory, second, the results from the continuous-time SLAM algorithm. From top to bottom: "The Hallway","The Circle" and "The Chapel". The noisy appearance of the indoor data sets results from reflecting surfaces such as glass. The initial trajectory of "The Chapel" data set is planar. After correction, the true 3D structure of the surface becomes clear when looking at the shading. As the chapel is lower than the starting position the shading by height has less impact on the roof of the chapel which is therefore lighter in color. The third image shows the reference data set collected with a Riegl VZ-400 laser scanner.

around 3.5 million points. Typically for an office building, the hallway consists of multiple doors and glass facades, yielding problems for laser scanners due to reflections and ghost projections (partly visible in Fig. 4 (top) and Fig. 5 (top)).
2. ”The Circle” Again, the surface was smooth without slope, a full circle there and back was conducted for this experiment to compensate the limited field of view of the unicycle. The IMU drift is strongly present, but was removed by the continuous-time SLAM. The full data set results in around 6.3 million points.
3. ”The Chapel” Being the last data set, it is also the most challenging with a gravel-like surface and slopes. Starting at the highest point and descending to the level surroundings of the chapel, a final ascend back to the starting point was done. Since the initial trajectory was only 2D, the differences in elevation were corrected using the SLAM algorithm and the global consistency was improved. The data set consists of around 3.5 million points.

Fig. 4 shows the Riegl scans from ”The Hallway” as a top view and ”The Chapel” from two different sides. The gray values of the points represents the reflectance of the materials. The results shown in Fig. 3 were obtained after about 150 iterations of the continuous time-SLAM algorithm. To calculate the point-to-point distance, the RADLER data was first matched to the ground truth using the ICP algorithm, implemented in 3DTK [3]. The points are colored with the point-to-point distance on the shown color scale, ranging from 0 m to 1 m.
”The Hallway” compares well to the ground truth, especially in the first three quarters of the way from left to right in Fig. 3 (top). Black color marks points with a point-to-point distance greater than 1 m. They almost exclusively appear in the last quarter, which is a result of the large glass front at the end of ”The Hallway’. RADLER scans mostly towards one side causing one wall to be sparsely covered. Without a loop closure the ICP algorithm contracts the data towards one side and thus bending the trajectory.

Fig. 5 shows top views of the last two experiments with the originally obtained trajectory as well as the improved trajectory after few iterations of the continuous-time SLAM. The closed loop helps to improve the trajectory significantly, compared to the previously mentioned deviation for ”The Hallway”. Having the longest trajectory, ”The Circle” still converges nicely to the rectangular shape of the building. Blurry edges in the top view show the necessity of further improvements in calibration. For longer trajectories a single offset and static RPM values appear not to be sufficient. A solution is here the integration of the IMU values using a Kalman filter.

”The Chapel” also compares well to the ground truth with less outliers compared to ’The Hallway’. Though the rough terrain does not seem to influence the quality of the output in a negative way, the closed loop within the path made a proper correction of the trajectory with our SLAM algorithm possible. The major drawback in the outdoor scene comes from the limited range of the laser scanner and the lower density at increasing distances. The roof of the chapel is also hardly covered by points. To increase the density, the unicycle could be moved much slower than in the current experiments or the trajectory could be followed twice. It would also be an option to exchange the LMS141 for a model with a greater maximum measuring distance, but this would increase the cost of the hardware drastically.

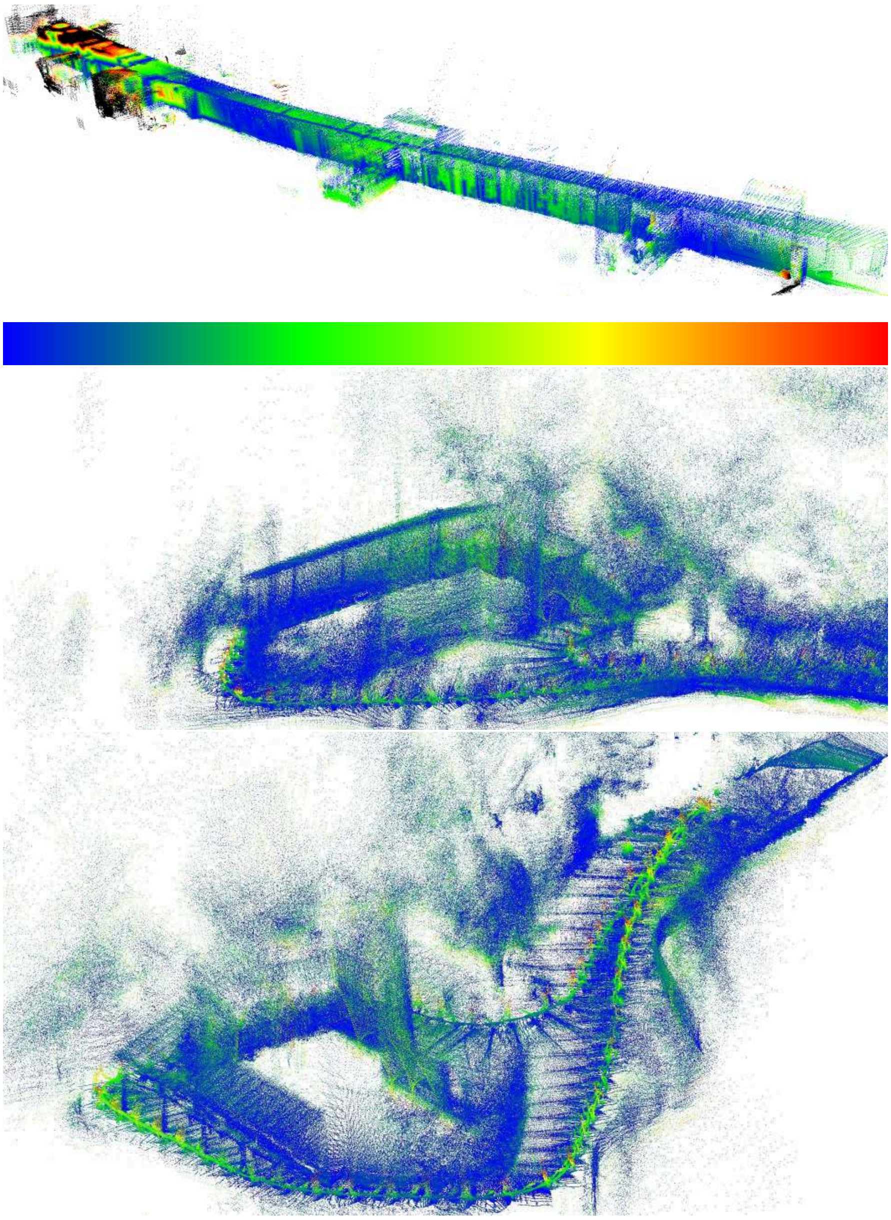


**Fig. 6** Registered point clouds for ”The Hallway” and two perspectives from ”The Chapel”, respective to Fig. 4. The color represents the shown scale, ranging from 0 m (blue) to 1 m (red) point-to-point distance.

## 4 Conclusions

This paper presents a new, low-cost way of generating 3D point clouds without the utilization of a classical 3D laser scanner. A modified unicycle with a 3D laser profiler, an IMU and a wheel encoder was used to generate 3D point clouds and the results were optimized using out continuous-time SLAM algorithm. The experiments and the discussion show, that the results are already promising and meaningful 3D point clouds are generated. But needless to say, a lot of work remains to be done. In the future, we plan on implementing a Kalman filter for sensor fusion of IMU and wheel encoder to improve the accuracy of the odometry. Additionally, a GPS sensor could be integrated to provide a better initial trajectory for our continuous-time SLAM algorithm. Also, the mounting system of the sensors needs to be improved in order to overcome some drawbacks a classical unicycle provides, such as the clearance within the main axis.

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