Mobile Robot Localization and Mapping by Scan Matching using Laser Reflection Intensity of the SOKUIKI Sensor

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Abstract— **This paper describes a new scan matching method for mobile robot localization and mapping. The proposed method "Intensity-ICP" uses Laser Reflection Intensity obtained by a laser range scanner named "SOKUIKI sensor". Compared with conventional scan matching methods which are effective just in geometric featured environments, Intensity-ICP is effective in both geometric featured and featureless environments if there are some features like colors or materials. This method can build a map with Laser Reflection Intensity data. The map will be effective to robust localization because it has abundant information; not only geometric data but also Laser Reflection Intensity.**

Fig. 1. SOKUIKI Sensor "URG-04LX" [2]

I. INTRODUCTION

Mobile robot self-localization is indispensable for navigation and map building. According to sensor characteristics, they can be divided into two groups; self-localization using internal and external sensors. Self-localization using internal sensors is called dead reckoning. Odometry is a typical example of dead reckoning. Other examples of dead reckoning use gyros and acceleration sensors. On the contrary, self-localization with external sensors uses ultrasonic sensors, cameras, laser range scanners such as "SOKUIKI sensors" [1], and so on.

Recently, self-localization using external sensors is popular, because they cancel accumulated error from internal sensors. Using ultrasonic sensors, fast processing is possible owing to the small amount of information received from sensors. However, the accuracy is not suitable for self-localization in geometrically complex environments. With cameras, we can obtain abundant information of environments, however, heavy computational loads are required for image processing. Also, illumination effects are big problems in real applications. Compared with these sensors, SOKUIKI sensors can get abundant information, and are robust to illumination effects. Besides, they furnish geometric data of environments directly, the computing process is simple and fast. Therefore, they are frequently used in self-localization.

Scan matching is used extensively in self-localization using a SOKUIKI sensor. We can localize the current position of a robot using scan matching which is a method to align current scan data to map of environments. Almost all conventional scan matching methods use geometric features of environments. Therefore, they are effective just in geometric featured environments and noneffective in environments without geometric features. So they could not be applied to localization tasks, for example, in corridors just having flat walls and no pillars.

To cope with the above-mentioned problem, this paper proposes a new scan matching method using Laser Reflection Intensity. We named this method "Intensity-ICP". Laser Reflection Intensity depends on surface colors and materials of scanned objects. Therefore, compared with conventional scan matching methods using only geometric features, the proposed Intensity-ICP is effective in both geometric featured and featureless environments if there are some features like colors or materials. In this paper, Laser Reflection Intensity is obtained by a SOKUIKI sensor "URG-04LX" which is made by HOKUYO AUTOMATIC CO., LTD. [2] and shown in Fig.1.

This paper describes Intensity-ICP using scan data of 2 dimensional geometric space, however it is also applicable to that of 3 dimensional geometric space.

II. RELATED WORKS

Scan matching methods can be classified into two types; local matching and global matching. Local matching needs initial position and is useful for position tracking. Global matching doesn't need initial position and is useful for global localization. Typical examples of local matching are ICP [3] and IDC [4]. Examples of global matching are Signature-based Scan Matching [5], CCF [6], LineMatch [7], APR [8], and so on. In mobile robot localization, local matching is frequently used because the initial position is supplied by odometry. Intensity-ICP is also a local matching method.

Intensity-ICP aligns two scan data, same as almost all conventional scan matching methods. But there are simultaneous scan matching methods [9] which simultaneously aligns three or more scan data at once. An advantage of simultaneous scan matching is it has no accumulated error. However, it has huge processing burden.

ICP, which is the most basic scan matching algorithm, uses

TABLE I

SPECIFICATIONS OF URG-04LX USED IN THIS STUDY

Detectable range	0.02 ~ 5.5 m *
Distance resolution	1 mm
Intensity range *	Approx. 0 ~ 40,000
Scanning angle	240 degrees
Angle resolution	Approx. 0.70 degrees *
Scanning time	100 ms/scan
Interface	USB2.0 FS mode (12 Mbps) RS232C (Max. 750 kbps)

(* : specially changed from normal URG-04LX)

only geometric coordinate values of scan points. There are other methods more robust than conventional ICP, which use not only coordinate values but also other feature quantities.

Color-ICP [10] is an extended ICP algorithm which uses colors and textures of object surfaces as feature quantities. A similar method is proposed in [11]. However colors and textures obtained by cameras are not invariant feature quantities because cameras are sensitive to ambient light. So Okatani et al. [12] proposed a method which supports variance of reflect by lighting conditions. These methods need two sensors in total; a SOKUIKI sensor and one camera, or two cameras. However, Intensity-ICP proposed in this paper needs only one SOKUIKI sensor.

Simultaneous 2D images and 3D geometric model registration [13] aligns 2D camera images to 3D geometric model. 3D geometric model is made from Laser Reflection Intensity edges of 3D range image which was got from 3D SOKUIKI sensor. This method and Intensity-ICP are similar, because both use Laser Reflection Intensity. However, this method aligns camera images, but Intensity-ICP aligns scan data.

As stated above, Intensity-ICP is a new scan matching method, which needs only one SOKUIKI sensor, and uses both geometric coordinate values and Laser Reflection Intensity of scan data as feature quantities.

III. SCAN MATCHING USING LASER REFLECTION INTENSITY

A. The method to obtain Laser Reflection Intensity

In this paper, we use a SOKUIKI sensor "URG-04LX" (in the following, spelled "URG") to get scan data. The firmware of URG is specially modified to get Laser Reflection Intensity. The specifications of URG are shown in Table I. Angle resolution of normal URG is approximately 0.35 deg., but that of URG used in this study is 0.70 deg. to obtain Laser Reflection Intensity.

Then we describe an example of Laser Reflection Intensity data. We scanned with URG in the environment shown in Fig.2. URG is mounted on a mobile robot, and there are black and white boards as scanned objects in front of the robot. URG scanned a horizontal plane. As a result of the scan, Laser Reflection Intensity data shown in Fig.3 is obtained. In Fig.3, the robot position is at the origin of the graph, and the right scale bar shows Laser Reflection Intensity by colors. It is indicated that scan points on the white boards have high Laser Reflection

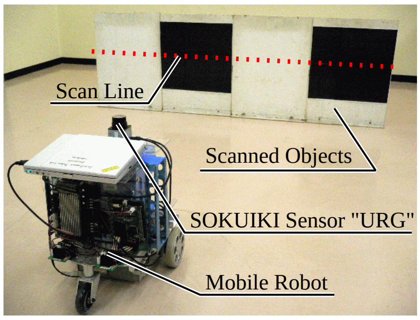


Fig. 2. Scan Environment

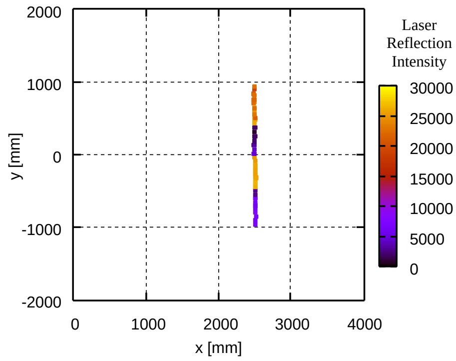


Fig. 3. Example of Laser Reflection Intensity data

Intensity and the ones on the black boards have low Laser Reflection Intensity.

B. Properties of Laser Reflection Intensity

Laser Reflection Intensity is not an invariant feature quantity. It depends on not only surface colors and materials of scanned objects but also distances and angles from URG to scanned objects. Therefore, the position of URG also affects on Laser Reflection Intensity.

Then in this paper, we treat only cases in which distances between input scan position and reference scan position are short enough not to affect Laser Reflection Intensity. From this, we consider Laser Reflection Intensity as an invariant feature quantity.

C. ICP algorithm

Intensity-ICP algorithm is designed by expanding ICP algorithm. Therefore to introduce the proposed Intensity-ICP, we describe conventional ICP algorithm at first. Scan matching using ICP algorithm is a method to minimize the matching error using the total squared geometric distance between the points in an input scan and the corresponding points in a reference scan. ICP uses initial relative position between an input scan and a reference scan which is supplied by odometry. In a lot of cases, map data is used as a reference scan.

The definition of evaluation value is shown in Eq.(1), which is the total squared geometric distance between the points in an input scan and the corresponding points in a reference scan. The equation of homogeneous coordinate transformation is given in Eq.(2).

$$
\begin{aligned}
e^{(m)} &= \sum_{i=1}^{N} |\boldsymbol{p}_{k_i^{(m)}} - \boldsymbol{q}_i^{(m)}|^2 \\
&= \sum_{i=1}^{N} \{x_{diff}^2 + y_{diff}^2\} \\
&= \sum_{i=1}^{N} \{(x_{\boldsymbol{p}_{k_i^{(m)}}} - x_{\boldsymbol{q}_i^{(m)}})^2 + (y_{\boldsymbol{p}_{k_i^{(m)}}} - y_{\boldsymbol{q}_i^{(m)}})^2\} \qquad (1)
\end{aligned}
$$

e : evaluation value
$\boldsymbol{p}$: reference scan points
$\boldsymbol{q}$: input scan points
(m) : number of iterative calculation
N : number of scan points
k_i : point number in a reference scan which correspond to number i in an input scan
x, y : geometric coordinate values of scan points
$diff$: difference of parameters

$$
\boldsymbol{q}_i^{(m+1)} = \boldsymbol{T}^{(m)} + \{\boldsymbol{R}^{(m)}(\boldsymbol{q}_i^{(m)} - \boldsymbol{c}^{(m)}) + \boldsymbol{c}^{(m)}\} \qquad (2)
$$

$\boldsymbol{T}$: translation vector of homogeneous coordinate transformation matrix
$\boldsymbol{R}$: rotating matrix of homogeneous coordinate transformation matrix
$\boldsymbol{c}$: mounted position of a SOKUIKI sensor (center of scan), rotation center of $\boldsymbol{R}$
If the SOKUIKI sensor mounted on the origin of robot coordinate, $\boldsymbol{c}^{(1)} = 0$.

The procedure for iterative calculations of ICP algorithm is explained as follows.

In the first step, the algorithm transforms an input scan coordinate using homogeneous coordinate transformation matrix. The matrix is calculated from initial relative position between an input scan and a reference scan which is supplied by odometry.

In the second step, it searches corresponding points in a reference scan which correspond to each input scan point. A reference scan point which has the shortest squared geometric distance to an input scan point of all reference scan points is corresponded.

In the third step, it calculates homogeneous coordinate transformation matrix which minimizes evaluation value by nonlinear optimization method such as the steepest descent method or Newton's method. The evaluation value is total squared geometric distance between the points in an input scan and the corresponding points in a reference scan.

After the third step, it returns to the first step, and transforms an input scan coordinate using homogeneous coordinate transformation matrix which was calculated in the third step. And then, it iteratively calculates these steps.

In these steps, the result of calculating homogeneous coordinate transformation matrix converges. And calculating homogeneous coordinate transformation matrix means localizing scan position. The position is self-localized position of the robot.

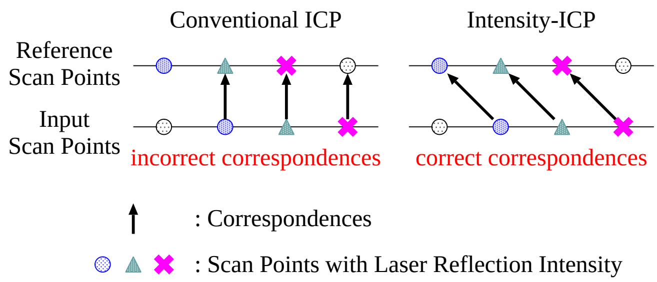


Fig. 4. Intensity-ICP algorithm

D. *Intensity-ICP algorithm*

As explained above, Intensity-ICP algorithm is an extension of ICP algorithm. An operation image of Intensity-ICP algorithm is shown in Fig.4. Each point such as ◯, △, × shows scan data points with Laser Reflection Intensity. ◯, △, × mean high, middle, and low level of Laser Reflection Intensity, respectively. In geometric featureless scan data like Fig.4, corresponding between scan points which have the same Laser Reflection Intensity values is correct. That is to say, it is correct that ◯ correspond to ◯, △ correspond to △, and × correspond to ×, respectively. Conventional ICP scan matching algorithm doesn't consider Laser Reflection Intensity, so it can not correspond correctly. But Intensity-ICP considers Laser Reflection Intensity, so it can correspond correctly.

The proposed Intensity-ICP is 3 dimensional ICP, because of Laser Reflection Intensity. Specifically, breakdown of 3 dimensions are 2 dimensions of geometric coordinate values (x, y) and 1 dimension of Laser Reflection Intensity. However, homogeneous coordinate transformation is same as Eq.(2) because coordinate transformation is in 2 dimensions. Evaluation values on Intensity-ICP are considered in 3 dimensions. Specifically, this method considers Laser Reflection Intensity, and searches corresponding points which have the shortest geometric distances and the smallest differences of Laser Reflection Intensity between input scan points and reference scan points. This is the key point of the proposed Intensity-ICP.

The definition of evaluation value is shown in Eq.(3), which is the total squared geometric distance and difference of Laser Reflection Intensity between the points in an input scan and the corresponding points in a reference scan. It is extended from Eq.(1).

$$
\begin{aligned}
e^{(m)} &= \sum_{i=1}^{N} |\boldsymbol{p}_{k_i^{(m)}} - \boldsymbol{q}_i^{(m)}|^2 \\
&= \sum_{i=1}^{N} \{x_{diff}^2 + y_{diff}^2 + w \times l_{diff}^2\} \\
&= \sum_{i=1}^{N} \{(x_{\boldsymbol{p}_{k_i^{(m)}}} - x_{\boldsymbol{q}_i^{(m)}})^2 + (y_{\boldsymbol{p}_{k_i^{(m)}}} - y_{\boldsymbol{q}_i^{(m)}})^2 \\
&\quad + w(l_{\boldsymbol{p}_{k_i^{(m)}}} - l_{\boldsymbol{q}_i^{(m)}})^2\} \qquad (3)
\end{aligned}
$$

l : Laser Reflection Intensity of each scan point
w : weighting factor of Laser Reflection Intensity

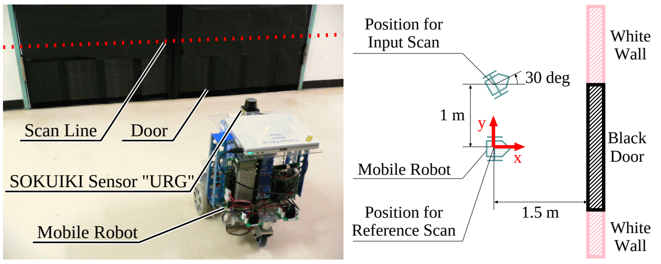


Fig. 5. Experimental environment of localization

Units of x and y are mm. The value of w is decided from the experimental data. As shown in Table I, Laser Reflection Intensity range of URG is approximately 0 $\sim$ 40,000. Considering this by some trials, the value of w is defined as 0.0002. A difference of Laser Reflection Intensity between black and white objects scanned from the distance of 1 m is approximately 30,000, and the value is nearly equivalent to 425 mm. However, the optimum value of w depends on scan data.

IV. Experiments

We experimentally evaluated the performance of the proposed Intensity-ICP. Newton's method is employed as nonlinear optimization method in Intensity-ICP algorithm.

We experimented on localization and mapping. In localization experiments, it is proved that Intensity-ICP is effective even in geometric featureless environments if there are some features like colors or materials. In mapping experiment, we succeed to build a map with Laser Reflection Intensity data.

A. Localization

At first, we experimented on localization in geometric featureless environments. In order to show the effectiveness of Intensity-ICP in geometric featureless environments, we compared self-localization tasks by conventional ICP scan matching and Intensity-ICP scan matching.

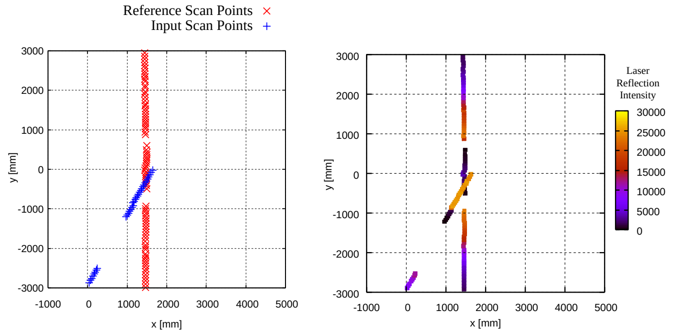
Experimental environment is shown in Fig.5. The left side is a picture of experimental environment, and the right is a top plan view, respectively. This is an environment without geometric features. There is only one feature, the color of the door is different from that of the wall. And shown in Fig.5, URG is mounted on a mobile robot.

In this environment, URG scanned twice. First, URG scanned at the front of the door as a reference scan. And the position of the robot at this time is defined as origin of the world coordinate. Next, the robot was moved manually to $(x, y, \theta) = (0\ mm, 1000\ mm, 30\ deg.)$ on the world coordinate, and the scanning is performed again to obtain an input scan.

Then, the robot localized the position where URG got an input scan by scan matching. The correct coordinate value of the position is $(x, y, \theta) = (0\ mm, 1000\ mm, 30\ deg.)$.

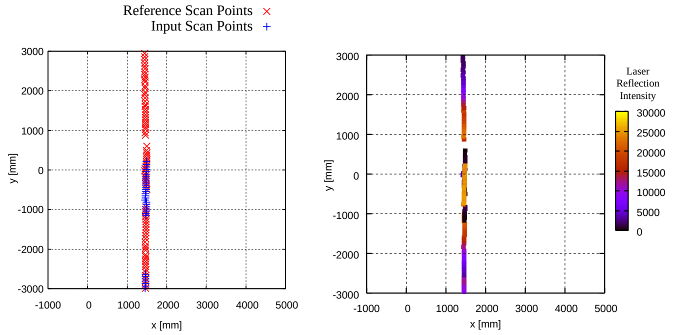
In this experiment, we didn't use odometry. The initial relative position between an input scan and a reference scan, which is given to scan matching algorithm, is $(x, y, \theta) = (0\ mm, 0\ mm, 0\ deg.)$.

Fig.6 shows scan data before matching. Fig.7 shows the result of conventional ICP scan matching and Fig.8 shows the result



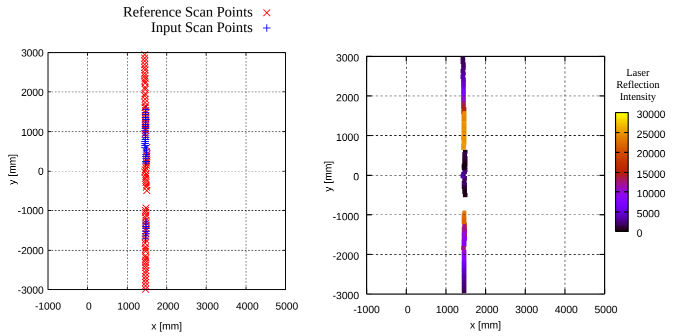
(a) scan classes (b) intensity data

Fig. 6. Scan data before matching



(a) scan classes (b) intensity data

Fig. 7. Result of ICP scan matching



(a) scan classes (b) intensity data

Fig. 8. Result of Intensity-ICP scan matching

of Intensity-ICP scan matching, respectively. In each figure, red points in the left graph show a reference scan and blue points show an input scan. The right scale bar shows Laser Reflection Intensity by colors.

Fig.7 shows what seems to be correct matching. However, the result coordinate value of localization by ICP scan matching is $(x, y, \theta) = (40\ mm, -567\ mm, 29\ deg.)$. It is incorrect for the error approximate 1500 mm away from correct position. In contrast, the result coordinate value of localization by Intensity-ICP scan matching is $(x, y, \theta) = (30\ mm, 972\ mm, 29\ deg.)$, which is correct value though there is an error approximate 30 mm. So Fig.8 shows correct matching.

Therefore, it is proved that Intensity-ICP scan matching can correctly align scan data and correctly localize even in geometric featureless environments.

B. Mapping

Next, we experimented on mapping by Intensity-ICP scan matching. Two methods to remove outliers in scan matching are implemented to Intensity-ICP scan matching [14]. A map with Laser Reflection Intensity data was built in this experiment.

Experimental environment is shown in Fig.9. The left side is a top plan view of experimental environment, and the right is a picture of experimental environment which is taken at "Camera Position" of the top plan view. The robot ran around this environment by human control. The robot obtained odometry data and scan data from URG at intervals, and built a map after running. Considering properties of Laser Reflection Intensity, Intensity-ICP scan matching uses not all map points as reference scan but only scan points obtained on the previous position, which are previous input scan points, as reference scan.

A map built by Intensity-ICP scan matching is shown in Fig.10. Laser Reflection Intensity is shown by colors in this map. It is succeeded to build a map with Laser Reflection Intensity data.

For comparison, a map built by only odometry without scan matching is shown in Fig.11. The map built by odometry is distorted because of accumulated error. However, the map built by Intensity-ICP scan matching is accurate compared with the map built by odometry. In addition, the map built by Intensity-ICP has abundant information; not only geometric data but also Laser Reflection Intensity, and it is useful for robust localization.

C. Considerations

It is proved that Intensity-ICP is effective in both geometric featured and featureless environments. Conventional scan matching methods is not effective in geometric featureless environment, but Intensity-ICP is effective in also geometric featureless environments if there are some features like colors or materials.

We succeeded to build a map with Laser Reflection Intensity data. The following advantages will exist in localization using a map with Laser Reflection Intensity data.

- Even if scan points of a SOKUIKI sensor are sparse, the method can localize correctly because the map has abundant information; not only geometric data but also Laser Reflection Intensity.
- The method can remove outliers robustly using Laser Reflection Intensity as a feature quantity.
- Laser Reflection Intensity data is useful to compute the initial position of global localization.

V. Conclusions and Future Works

We proposed a new scan matching method, Intensity-ICP, considering Laser Reflection Intensity as an invariant feature quantity in this paper. Then we proved effectiveness of the method, and succeeded to build a map with Laser Reflection Intensity data which will be effective to robust localization.

But indeed, Laser Reflection Intensity is not an invariant feature quantity. Therefore, it is convenient to convert Laser Reflection Intensity into reflection property values of scanned objects. These values change depending on only object colors and materials. The values are calculated by converting Laser Reflection Intensity using a previously defined conversion table. This conversion is convenient because reflection property values are invariant feature quantities.

Alternatively, another method using derivative values of Laser Reflection Intensity as invariant feature quantities is effective explained in [13].

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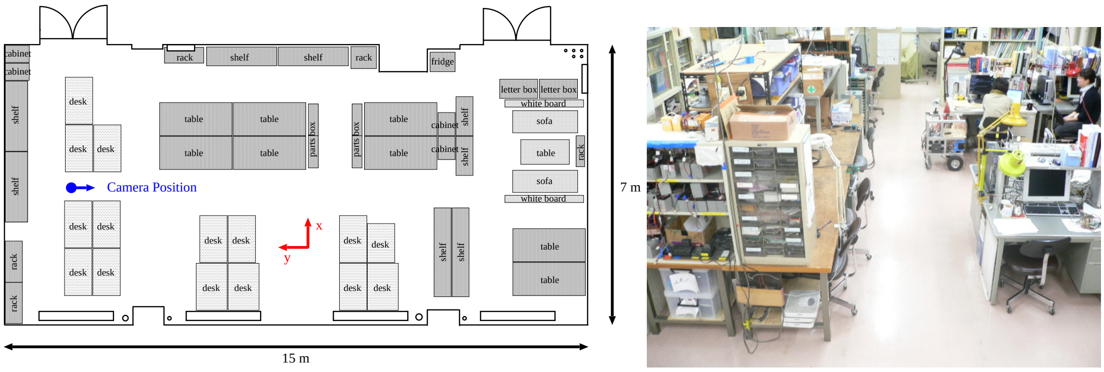

Fig. 9. Experimental environment of mapping

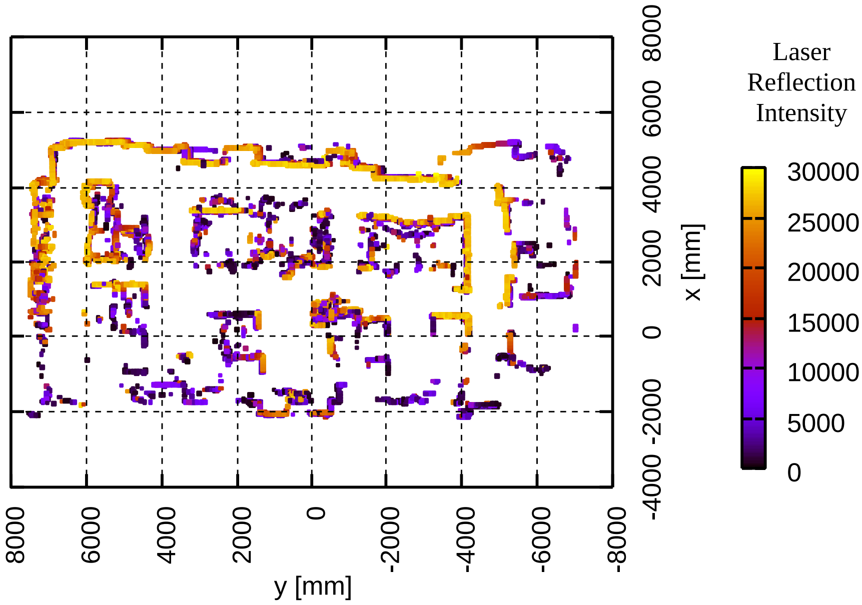

Fig. 10. Map built by Intensity-ICP scan matching

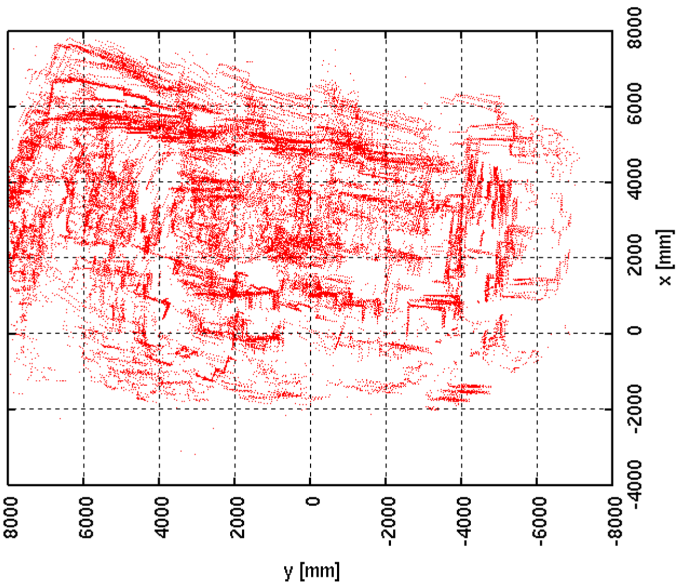

Fig. 11. Map built by odometry