Map Building for Mobile Robots using a SOKUIKI Sensor
-Robust Scan Matching using Laser Reflection Intensity-

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Abstract: This paper describes map building using a new scan matching method, Intensity-ICP. The method uses Laser Reflection Intensity of a laser range scanner named "SOKUIKI sensor". So compared with conventional scan matching methods which are effective just in geometric featured environments, Intensity-ICP is effective in both geometric featured and non geometric featured environments. We also propose two methods to remove outliers in scan matching. Laser Reflection Intensity and geometric constraint are used in these methods. As the result of using Intensity-ICP scan matching and outlier removing methods, an accurate map can be built. In addition, the map has abundant information; not only geometric data but also Laser Reflection Intensity, and it is useful for robust localization.

Keywords: SOKUIKI Sensor, Scan Matching, Map Building

1. INTRODUCTION

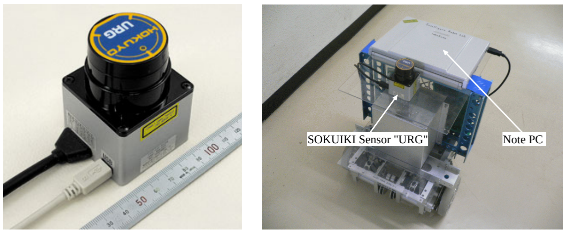
Map building technology is indispensable for mobile robots. Accurate self-localization is needed for automatic map building without operations by human. Odometry is often used for wheeled robot localization, but it has big accumulated errors. So localization method using a laser range scanner named "SOKUIKI sensor" [1] is under intense study in recent years. Because range data of SOKUIKI sensors is accurate and robust for ambient light, localization using a SOKUIKI sensor is dependable.

Scan matching methods are extensively used in localization using a SOKUIKI sensor. Scan matching is a registration method which aligns current scan data to map scan data of environments. But 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. For example, they could not be applied to localization tasks in corridors just having flat walls and no pillars. So we suggested a new scan matching method using Laser Reflection Intensity which is effective in both geometric featured and non geometric featured environments [2]. This method was named Intensity-ICP.

This paper describes map building using Intensity-ICP scan matching. And we propose two methods to remove outliers in scan matching. These methods are useful for map building. Laser Reflection Intensity and geometric constraint are used in these methods.

Scan data of 2 dimensional geometric space is used for map building in this paper.

2. INTENSITY-ICP ALGORITHM



(a) URG-04LX (b) Mobile Robot

Fig. 1 SOKUIKI Sensor and Mobile Robot

Table 1 Specifications of URG-04LX(intensity data ver.)

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)

This paper reviews briefly Intensity-ICP algorithm [2]. Intensity-ICP algorithm uses geometric coordinate values and Laser Reflection Intensity of scan data as feature quantities, which are obtained by a SOKUIKI sensor.

In this paper, scan data is obtained by a SOKUIKI sensor "URG-04LX" (in the following, spelled "URG") which is made by HOKUYO AUTOMATIC CO., LTD. [3] and shown in Fig.1(a). And URG is mounted on a mobile robot shown in Fig.1(b). The firmware of URG is specially modified to get Laser Reflection Intensity. The specifications of URG used in this study are shown in Table 1. Angle resolution of normal URG is approximately 0.35 degrees, but that of intensity data version URG is 0.70 degrees to obtain Laser Reflection Intensity.

Intensity-ICP algorithm is an extension of ICP algorithm [4]. An operation image of Intensity-ICP algorithm

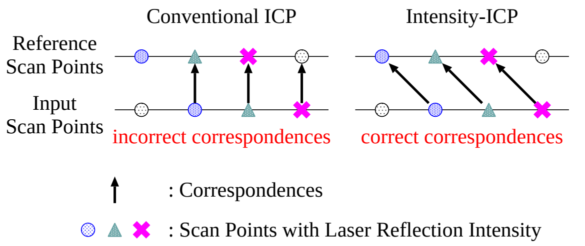


Fig. 2 Intensity-ICP algorithm

is shown in Fig.2. 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.2, 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.

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.

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.

The definition of evaluation value is shown in Eq.(1), 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. The equation of homogeneous coordinate transformation is given in Eq.(2).

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

e : total squared geometric distance and difference of Laser Reflection Intensity (evaluation value)
$\boldsymbol{p}$: reference scan points
$\boldsymbol{q}$: input scan points
(m) : number of iterative calculations
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
l : Laser Reflection Intensity of each scan point
w : weighting factor of Laser Reflection Intensity

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

$\boldsymbol{T}$: 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, $\boldsymbol{c}^{(1)} = 0$.

Units of x and y are mm. The value of w is decided from the experimental data. As shown in Table 1, 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.

The procedure for iterative calculations of Intensity-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 and the smallest squared difference of Laser Reflection Intensity 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.

3. PROBLEMS AND SOLUTIONS IN MAP BUILDING

3.1 Distortion of Scan Data

SOKUIKI sensors are laser range scanners, so they measure distances using laser. Therefore scan data is distorted for some scanned objects which have particular laser reflection surface characteristics. For example, high reflectivity objects such as metals and translucent objects such as plastics. Distorted scan data is outlier of scan matching, and reduces accuracy of matching.

This problem occurred on every SOKUIKI sensor using any measurement method, because all SOKUIKI sensors use laser. At least, it is confirmed that the problem occurred on URG and LMS200 (made by SICK).

For accurate scan matching and map building, it is preferable to remove distorted scan data.

The cause of distorted scan data on URG is measuring by phase-contrast method. URG adjusts the output voltage of APD (Avalanche Photodiode), which is a light receiving unit, by AGC (Auto Gain Control) [1]. If the output voltage of APD exceeds control capability of AGC, URG can not get waveform and phase of reflection laser. It means URG can not measure accurate distances and scan data is distorted. But the other side, distorted scan data can be removed by cutting scan points which exceed control capability of AGC.

The Laser Reflection Intensity values obtained by URG are equivalent to the output voltage of APD. However, it is wrong that high Laser Reflection Intensity is regarded as exceeding control capability of AGC. Because the Laser Reflection Intensity values are controlled by AGC, if the Laser Reflection Intensity values are high, it can not be accurately determined if it is exceeding control capability of AGC or not. Therefore, high Laser Reflection Intensity is a necessary but not sufficient condition of exceeding control capability of AGC.

Through many trials, it was found that scan points which are close to URG and have high Laser Reflection Intensity are more likely to exceed control capability of AGC. Therefore, distorted scan data will be removed by cutting scan points which are close to URG and have high Laser Reflection Intensity values.

The above method is implemented and evaluated by experiments. In this implementation, scan points which are close to URG in 1 m and whose Laser Reflection Intensity values are over 27,000 are cut. Experimental environment is shown in Fig.3. There is a shelf made of unpainted stainless steel on left side of the robot, and a shelf painted in cream color on right side of the robot. Scan data before removing distortion is shown in Fig.4, and scan data after removing distortion is shown in Fig.5. Laser Reflection Intensity is shown by colors. The origin of graph coordinate is position of URG (center of scan). In Fig.4, it is found that scan points located on nearly 90 degrees to URG are distorted. Scan points situated on the shelf made of unpainted stainless steel on left side of the robot are distorted up to 100 mm. And in Fig.5, distorted scan points are clearly removed. Therefore, it can be said that suggested method to remove distorted scan points is effective.

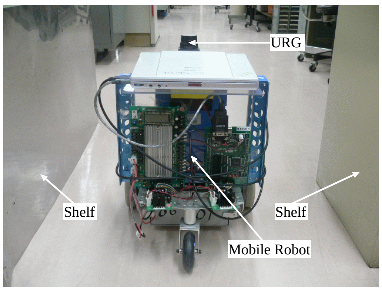


Fig. 3 Experimental environment of removing distortion

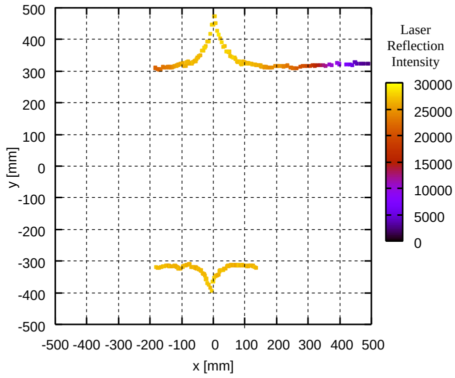


Fig. 4 Scan data before removing distortion

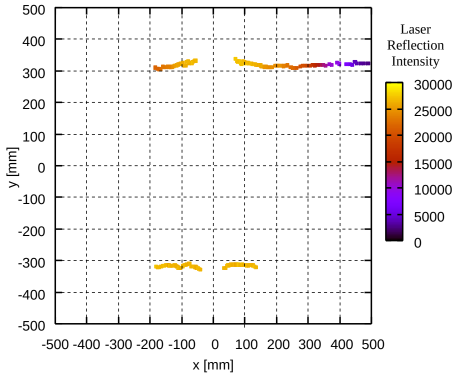


Fig. 5 Scan data after removing distortion

3.2 Input Scan Points which have No Corresponding Reference Scan Points

In map building by scan matching, a map is built by adding input scan points which are nonexistent in reference scan points. So there are some input scan points which have no corresponding reference scan points. This is a very big problem for scan matching. More specifically, correct scan matching can not be done without removing some input scan points which have no corresponding reference scan points. Because input scan points which have no corresponding reference scan points are outliers of scan matching, and cause incorrect correspondences [5].

In [6], M-estimation was used on ICP algorithm to reduce adverse effects of incorrect correspondences. M-estimation can reduce adverse effects of incorrect correspondences, however it can not remove input scan points which have no corresponding reference scan points.

Therefore, M-estimation can not completely remove adverse effects of incorrect correspondences, and matching results are not accurate.

A method, which picks up correspondences for good evaluation value by random sampling and uses only selected correspondences, doesn't adapt to ICP algorithm. Because ICP algorithm needs not only correspondences which have good evaluation value but also those with bad evaluation value. That is, ICP algorithm needs almost all correspondences independently of evaluation value. It is required for removing incorrect correspondences to cut correspondences which have just vastly different evaluation value from other correspondences. However, it is effective to correspond by random sampling and evaluate by LMedS [7].

In [8], incorrect correspondences were removed by threshold of evaluation value. [9] used only correspondences which have moderately small evaluation value. Based on these methods, correspondences which have vastly different evaluation value from other correspondences are removed. Standard deviation of evaluation value on all correspondences is calculated when searching for corresponding points, and twice value of the standard deviation is used as threshold of evaluation value for removing correspondences which have vastly different evaluation value from other correspondences. It isn't necessary sorting correspondences by evaluation value, because of using standard deviation.

In addition, we suggest a new algorithm to remove incorrect correspondences by bidirectional search for corresponding points. This algorithm searches for correspondences from input scans to reference scans and also from reference scans to input scans, and uses correspondences which are just matched on bidirectional searches. It isn't effective to use bidirectional search in the beginning of iterative calculations, but it improves accuracy of scan matching to use bidirectional search after a certain level of convergence.

The bidirectional search algorithm doesn't work well if intervals of each scan point are short, so scan points must be thinned to suitable intervals. In this implementation, scan points are thinned to 50 mm intervals.

An operation image of bidirectional search algorithm to remove incorrect correspondences is shown in Fig.6. Arrows show closest points (correspondences) of each point. Solid line arrows mean correspondences which are matched on bidirectional searches, and dotted line arrows mean correspondences which are not matched on bidirectional searches. It turns out that using only correspondences which are matched on bidirectional searches can align accurately.

In [10], some correspondences are removed by threshold of evaluation value and correspondences which correspond to the end of scan points are cut. The effect of suggested bidirectional search algorithm is similar to [10], but bidirectional search algorithm is more effective. That is, bidirectional search algorithm is effective on input scan points which have no corresponding reference scan points caused by occlusion or distortion removing described above.

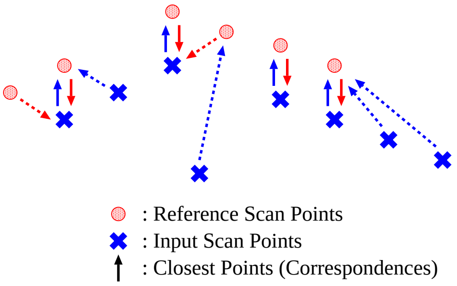


Fig. 6 Bidirectional search for correspondences

4. MAP BUILDING

Distortion removing and bidirectional search algorithm are implemented to Intensity-ICP scan matching. Newton's method is employed as nonlinear optimization method in Intensity-ICP algorithm. And we experimented on mapping by Intensity-ICP scan matching. A map with Laser Reflection Intensity data was built in this experiment.

Experimental environment is shown in Fig.7. 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.

Laser Reflection Intensity is not an invariant feature quantity [2]. 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.

Therefore, 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.8. Laser Reflection Intensity is shown by colors in this map. We 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.9. 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.

5. FUTURE WORKS

As shown in the above-mentioned, 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 [11].

6. CONCLUSIONS

This paper described map building method using Intensity-ICP scan matching. And we proposed two methods to remove outliers in scan matching. Laser Reflection Intensity and geometric constraint are used in these methods. As the result of using Intensity-ICP scan matching and outlier removing methods, an accurate map can be built. In addition, the map has abundant information; not only geometric data but also Laser Reflection Intensity, and it is useful for robust localization.

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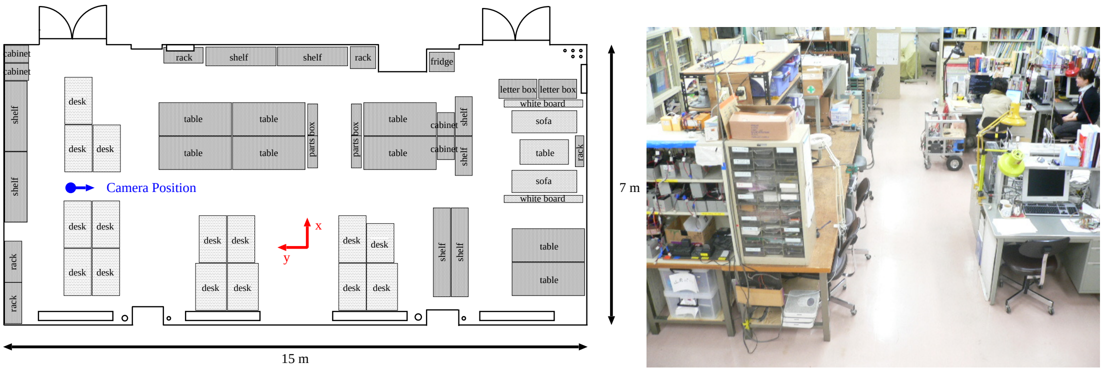

Fig. 7 Experimental environment of mapping

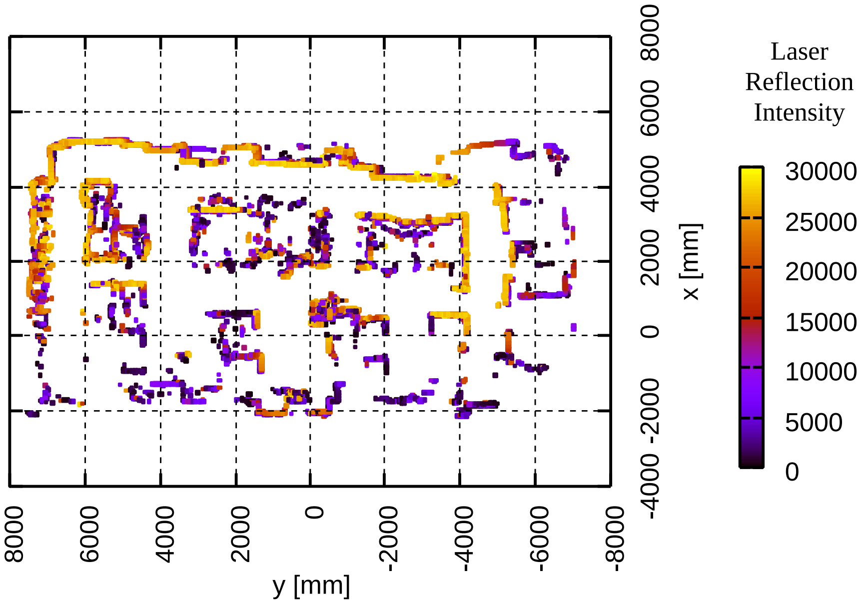

Fig. 8 Map built by Intensity-ICP scan matching

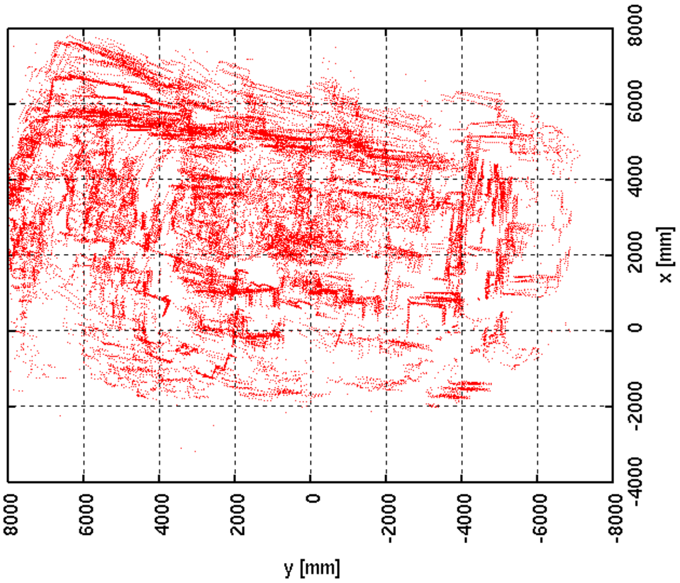

Fig. 9 Map built by odometry