Development of Compact and Light-weight LRF Based Positioning Sensor for Mobile Robot Localization

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***Abstract*— In this paper, we describe our positioning system based ultra-compact Laser Range Finder (LRF) for mobile robot. The system consists of reflectors as landmark and a laser range finder (LRF) named "Pos-URG". The landmarks are randomly and sparsely placed in environment, and their position and posture are known. Pos-URG has map data which consists of pose information and relation information between each landmark, which are sorted in ascending order of distance value between each other landmarks. When the Pos-URG finds multiple number of landmarks, the set of landmarks in map which correspond the detected landmarks is searched. The searching is done using not only each landmark's position and posture but also relations between them. Then, Pos-URG's position and posture is calculated with coordinate transform from sensor coordinates to map coordinates. The most important characteristic of this proposed searching method is its low computational time and it enables the method to be implemented into low-cost and low-spec CPU which is assembled into Pos-URG.**

I. INTRODUCTION

Many researches about self-position estimation methods have been published because knowing the position is a fundamental issue for mobile robots.

In general, two types of self-positioning methods exist, one estimates absolute position at each place and another revises accumulated odometry. For these estimation, external sensors (e.g., Sokuiki sensor[1],[2], Vision camera[3] and GPS[4]) and internal sensors (e.g., Gyro sensor, Motor encoder of wheel(odometry)) have core role. Especially GPS is widely used in outdoor environment because it can provide absolute position while using other sensors demands much computational burden on mobile robot to estimate self-position. GPS, however, is not easy to be used in indoor environments. Recently indoor GPS is widely developed, though its accuracy cannot satisfy the demands of autonomous robots. NAV200 (SICK Co., Ltd.) is also positioning system based on LRF. The system consists of LRF and reflector, and estimate self-position by comparing detected reflector's position with their pre-registered position. Its cost and size, however, are not suited for small-sized mobile robots.

Under such background, we developed ultra-compact positioning system based LRF for mobile robot localization. In this paper its construction and algorithm are described.

II. OUTLINE OF THE PROPOSED SYSTEM

The proposed positioning system consists of a SOKUIKI sensor "Pos-URG", which is one of LRF produced by Hokuyo Automatic Co., Ltd., and multiple reflector placed in environment. Firstly reflectors are randomly and sparsely placed in environment as landmarks. Then their position, posture, distance between each reflector and its vector orientation are registered to Pos-URG as map data.

The Pos-URG equipped with mobile robot measures the environment where the robot moves. When multiple landmarks are detected, corresponding set of landmarks in the map is searched, then the sensor's position and posture are calculated with coordinate transform from sensor's coordinate to map's coordinate (See Fig.1).

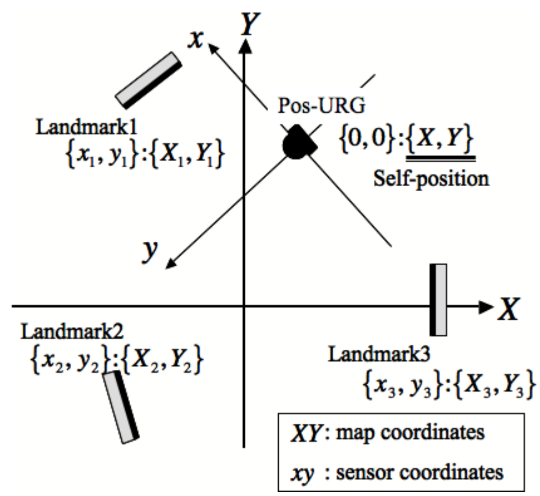

Fig. 1. Outline of sensor's processing

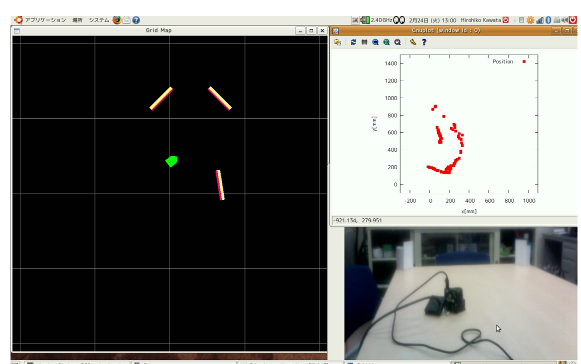

Fig. 2. Display of Pos-URG's data

The map data uses a tree data structure because the data includes each landmark's position and relation between each landmark. Each node has landmark's position and posture etc., and each edge has distance between landmarks and

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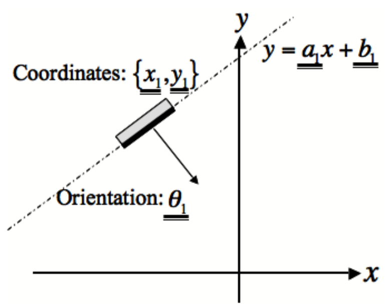
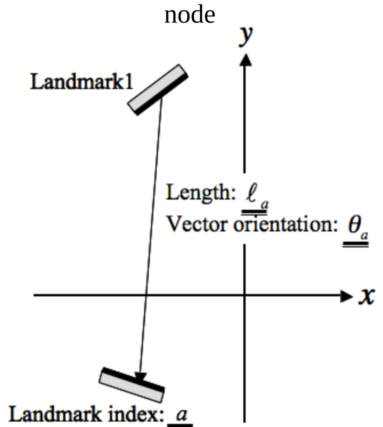
its vector orientation. The cost of searching in such data structures is low meaning that computational burden can be decreased. It means that the proposed method is suitable for low-spec CPU which is adopted by low-cost and compact sensor.

The sensor's position and posture which correspond to robot's position and posture can be obtained. Thus the mobile robot can be free from computational burden of positioning. Fig.2 shows our system's GUI window displaying sensor's output.



(a) Position and posture information of each landmark for node



(b) Relation information between each landmark for edge

Fig. 3. Contents of map data (Each underlined data are included in map data)

III. Algorithm of Searching

A. Landmark map data

Fig.3 shows meaning of each element included in map data.

Node's data is as below,

1) position(x, y coordinates)
2) posture(orientation of reflection surface)
3) border line of visible area(slope a and interception b of linear equation $y = ax + b$)

Edge's data is as below,

1) index number(order of node)
2) distance(between itself and landmark of parent node)
3) vector orientation(from landmark of parent node to itself)

When N landmarks are registered to map, all landmark has $N-1$ sets of the value which is sorted in ascending order of distance each.

Pos-URG outputs its position and posture in the same coordinate system as the map.

B. Search algorithm

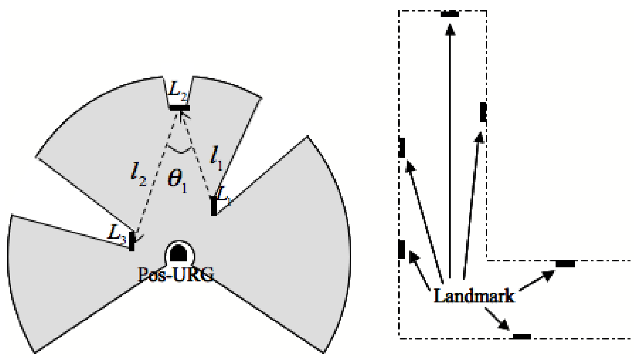
Searching and association of landmarks exploits the rotational order in which scan readings are acquired by the Pos-URG. The sensor scans from right to left, so the first landmark detected from the right is labeled as L_1, the next on its left is labeled as L_2 and so on. Searching will proceed in the order of the detected landmarks $\{L_1, L_2,..., L_n\}$. An example of an scan is presented in Fig.4(a). Fig.4(b) shows a representation of a virtual map in which landmarks are located (the wall lines are not stored on the map).

We define a connection map M_{a-i} where the landmark a was found and then related landmark i is connected to a.

The proposed searching algorithm is as below (refer to Fig.5 and Fig.6),

1) When n reflectors are detected, they are divided into n clusters and numbered as$\{L_1, L_2,..., L_n\}$. (See Fig.4(a))
2) When $n>1$, L_1 is associated to one of landmark in map M_{1-1}, otherwise processing return to 2nd step (See Fig.6(a)).
3) Distance l_1 between L_1 and L_2 is calculated, then a search area is built with radius l_1 and sensor accuracy margin. Using the edge distance information on the map, candidate landmarks falling in the search area are sorted in ascending order according to their edge distance from M_{1-1}. If n=2, processing go to 6th step. (See Fig.5(a))
4) Distance l_2 and angle θ_1 from L_2 and L_3 is calculated, then a search area is built at a distance of l_2 and at an angle θ_1 and using the sensor's accuracy margin as radius. If there is a landmark falling in the search area then it is associated to map M_{1-3}. This search uses the edge's vector orientation data stored on the map. (See Fig.5(b))
5) If M_{1-n} is detected by continuing the processing, searching succeeds. Otherwise processing returns to 2nd step (See Fig.6(b)).
6) Parameter of *Helmert Transformation* is calculated using coordinates of $\{M_{1-1}, M_{1-2},..., M_{1-n}\}$ and $\{L_1, L_2,..., L_n\}$ with least-squares method. Finally candidate of sensor's position and posture is calculated with *Helmert Transformation* of $\{0, 0\}$. (See Fig.5(c))
7) Validity of the obtained result is evaluated by relation of sensor's position and orientation of reflection surface. (See Fig.7(a))
8) The processing from 2nd to 7th step are done for all landmarks in map.
9) If multiple results are obtained, only plausible results are output if it can be judged by previous data. (See Fig.7(b))

The most important advantage of this proposed method is low computational burden. When N landmarks are registered in map and n landmarks are detected, the 2nd step is processed maximally $N \times (N-1)$ times. However most of searching are finished at that time, because sparse and random arrangement of reflector reduce the possibility to satisfy the searching condition. Furthermore the effect of ascending sort cannot be missed, that is, searching process can be interrupted when distance between each landmark is over max range of Pos-URG. Most of following searching processing is also interrupt quickly because of restricted search condition. Once searching succeeds, next searching target is limited within near of the first position from next searching. If initial position is given in advance, searching area can be limited from first process. These fact indicates that the proposed method is suitable for low-spec CPUs.



(a) Pos-URG detect landmarks in real environment. (The sensor's scan area is shadowed.)

(b) Each landmark's position information has been given to Pos-URG as *map data*.

Fig. 4. Example of search environment

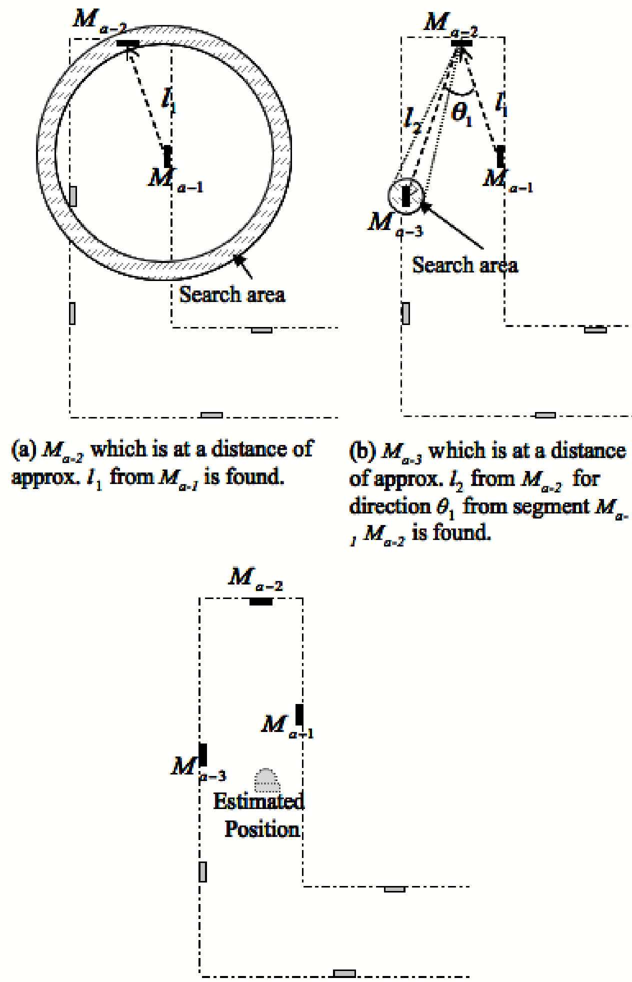
C. Evaluation of validity

Fig.7 shows how to evaluate validity of obtained result which is described in the 7th step of algorithm in previous section.

As shown in Fig.7(a), when Pos-URG is at back of reflector or the sensor's orientation is similar to that of the reflection surface, the sensor cannot detect the reflector. The search process which was explained in previous section, however, cannot exclude such case. Thus framework for checking the case which is explained below is introduced. As already shown in Fig.3(a), map data has orientation of reflection surface and slope and interception of linear equation which is constructed by the reflection surface. To judge if the sensor can detect the reflector or not can be done by using these elements and the sensor's position and orientation.

As another irregular case, the searching method outputs two candidates of position when the number of detected reflectors is two as shown in Fig.7(b). Furthermore several candidates may be obtained. In such cases, the most plausible candidate is chosen for final result by previous or historical results.

When final result cannot be uniquely determined in spite of using those checking frameworks, all candidates are output.

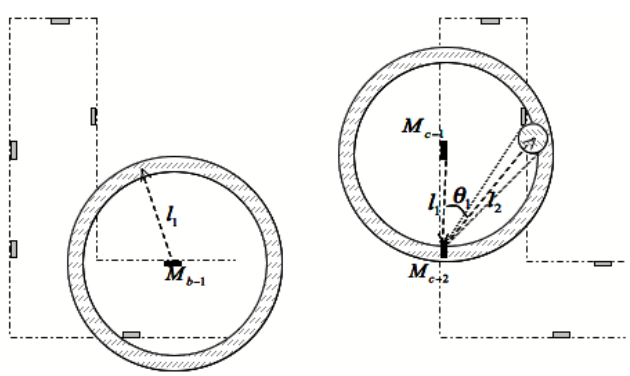


(a) M_{a-2} which is at a distance of approx. l_1 from M_{a-1} is found.

(b) M_{a-3} which is at a distance of approx. l_2 from M_{a-2} for direction θ_1 from segment $M_{a-1}M_{a-2}$ is found.

(c) Self-position is estimated by matching result.

Fig. 5. Successful search in case of Fig.4



(a) Map does not have landmark M_{b-2} which is at a distance of approx. l_1 from M_{b-1}.

(b) Map does not have landmark M_{c-3} which is at a distance of approx. l_2 from M_{c-2} for direction θ_1 from segment $M_{c-1}M_{a-2}$, although it has M_{c-2} which is at a distance of approx. l_1 from M_{c-1}.

Fig. 6. Failed search in case of Fig.4

In such case, candidates will be squeezed to one after moving and sensing of sensor.

IV. Structure of the Proposed Sensor System

A. Choice of reflector

One advantage of the proposed searching method is that failure in detecting an existing reflector (e.g.:occlusion) does not influence the result. However to recognize an object which is not reflector as landmark causes fail searching. Thus reflector as landmark must be completely of a special material which can be stably extracted.

One solution is to form landmark specific shape. Though it is hard to realize because its matching process will be complex and exact detecting of shape will be hard when the landmark is far from sensor.

LRF generally measures distance from time of flight (TOF) or difference of phase (AM-CW) between transmitted laser and received one. Optical intensity of received laser changes depending on the flying distance and material which reflects the laser, while optical intensity of transmitted one is almost constant. This property of LRF is widely used for recognizing the difference of object. Especially intensity of received laser which is reflected by reflector in condition when the angle of incidence is from 0 to 45 degrees keeps high level in spite of reflector's distance from sensor. In case of other specular material, intensity from metal declines with increasing of distance, and that from mirror is high when the mirror is at exactly positive position of the sensor. For these reasons, it was judged that a reflector is most suitable for landmark.

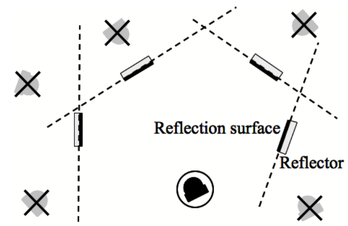
From various kinds of reflectors, the proposed system selects reflexible reflector sheet "3M^{TM} Diamond Grade$_{TM}DG^3$ 4090 series"(Sumitomo 3M Limited). This reflector's features are its high processability and reflection property.

The reflectors must be placed sparsely and random. The sparse means that three or four landmarks should be detected by sensor at any time. The random placement reduces the number of candidate obtained by the searching.

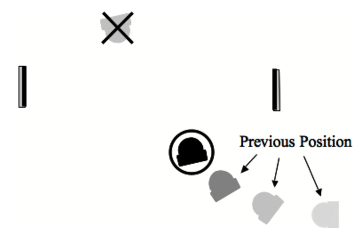
B. LRF(SOKUIKI sensor)

SOKUIKI sensor URG series (URG-04LX [Classic-URG], UBG-04LX-F01 [Rapid-URG], UHG-08LX [Hi-URG], UTM-30LX [Top-URG]) which is supplied by Hokuyo Automatic Co., Ltd. is widely known and adopted for mobile robots for its compactness and high performance. Now these sensors output just distance and intensity. The proposed system uses these sensors which are added function of self-positioning by changing their firmware.

In this paper, special type of Rapid-URG (Rapid-rURG) was used for stable detection of reflector. The Rapid-rURG has Pin Photo Diode (PPD) as its optical receive device, while normal SOKUIKI sensors have Avalanche Photo Diode (APD) for high sensitivity. The Rapid-rURG can only detect materials whose reflection property is very high because sensitivity of the PPD is lower than that of APD. Thus only reflector can be detected stably as shown in Fig.9, where two reflectors and specular stainless board are placed in front of and 1[m] far from the Rapid-rURG. The reflectors are clearly detected, while the stainless board is not at all.



(a) Judge by position of sensor and landmark



(b) Judge by sensor's posture

Fig. 7. Judge validity of calculated sensor's position

Fig. 8. Rapid-URG whose optical device is replace by Pin Photodiode (Rapid-rURG)

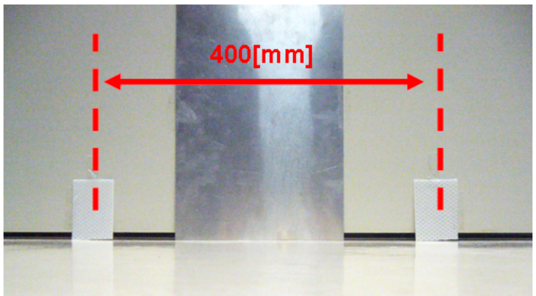
TABLE I
SPECIFICATIONS OF $Rapid-rURG$

Optical source	Near infrared laser(785nm)
Optical receive device	Pin Photodiode
Detectable distance	0.1 to12[m]
Accuracy	±10[mm]
Scanning angle	240[degrees]
Angle resolution	Approx. 0.35[degrees]
Scanning rate	40[Hz]
Dimension	W60 D70 H60[mm]
Weight	200[g]
I/F	USB, RS-232C
CPU	Renesas : H8SX 1653 48MHz

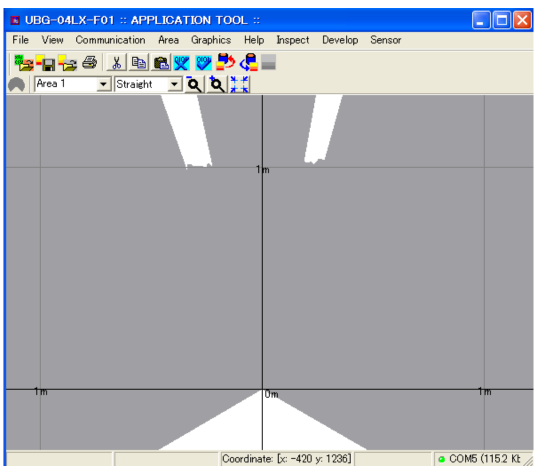
Fig.8 presents the Rapid-rURG, and TableI describes its specifications. The detection area is increased from 5.6[m] (max range of Rapid-URG) to 12[m] by restricting its sensing object. Other properties do not change from Rapid-URG.

C. Storing of Map data

The map data is stored in flash ROM of CPU. Now the data is include in source code, and written to the flash ROM with other code. In near future, it will solely written by PC application, on which user input reflector's position and posture using GUI. In other method, the sensor will have map storing mode, which the sensor automatically detect reflectors and store all information to itself.



(a) Environment



(b) Result of scanning

Fig. 9. Comparison with reflector and stain-less board

Fig. 10. Reflexive Reflector Sheet

V. Experiment and Discussion

The proposed method was implemented into Rapid-rURG as Pos-URG, then repeatability was evaluated in environment shown in Fig.11. Fig.12 shows the sensor's position and posture where the evaluation was done and Table.II shows the results.

Ten landmarks information were given to the sensor. The processing time in case that three landmarks were detected was about 2[msec], whose details are that clustering process took about 200[usec], 10×9[units] first search step took about 900[usec], remaining searching process took about 400[usec] and calculation of coordinate transform and validity check took about 500[usec]. The fist search step needs more time when the number of given landmarks increases. For example, if the number is 100, the processing time may take 99[msec] by simple calculation. The true computational cost, however, will be reduced by some steps as followings.

1) The map data is already sorted by distance value.
2) The searching can be interrupted when the distance value is more than sensor's maximum range. In the next version of firmware, such relation information will not be given to the map data.
3) Only first search from sensor's start up or lost of self-position needs full search. Namely landmarks in the map which should be searched is limited to one whose position near the self-position, and the number of such landmarks is a few because of sparse placement of landmarks.
4) Full search is not necessary if initial self-position is given.

The searching process except the first step of that does not need much more time even when the number of landmarks in the map increases as expressed before. Furthermore the implemented processing does not include approximation by omitting decimals, however the H8SX, which Pos-URG uses as CPU, does not have FPU. So to reduce dramatically the processing time is available by integral approximation if the sensor's accuracy is not sacrificed. It will be considered as one of future works. As a result, the proposed method achieved one of goal that low-spec CPU can process in real time.

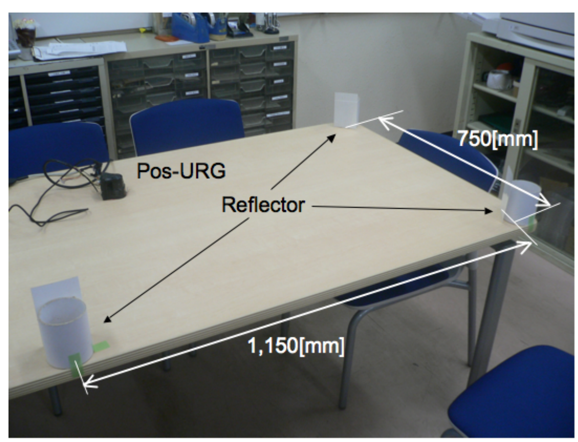


Fig. 11. Environment for experiment

As TableII shows repeatability of posture at every points seems very good. Although that of horizontal was not stable, while that of vertical comparatively well-balanced.

TABLE II
REPEATABILITY OF POS-URG(SIGMA)

Real Position	Horizontal [mm]	Vertical [mm]	Posture [degree]
Point 1 with 3 landmarks	10.29	2.76	0.021
Point 2 with 2 landmarks	71.89	0.28	0.28
Point 3 with 3 landmarks	62.97	0.83	0.08
Point 4 with 2 landmarks	4.7	6.0	0.015
Point 4 with 3 landmarks	7.39	10.26	0.033

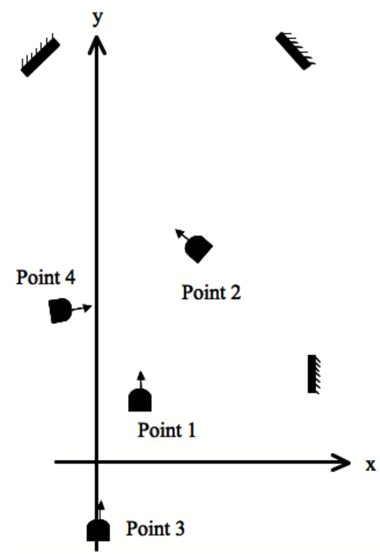


Fig. 12. Position and posture of Pos-URG where the repeatability was confirmed

Investigation of such result is one of future work. Anyway, target repeatability 100[mm] was achieved.

For comparison of accuracy, repeatability was obtained with changing number of landmarks at Point4. It was anticipated that less landmarks causes low accuracy, however obtained result was contrary, that is, the case of two landmarks was better than the case of three landmarks. Its reason guessed that accumulation of error from sensor was reduced by decreasing the number of the landmarks. This is one of the most important problems which must be investigated and settled.

Finally, any false result were not obtained at any points.

As other future works, the followings are given.

- Increasing accuracy
- Preparation of PC utility software for proposing reflector placement and maintenance
- Automatic map data registering function
- Increasing sensor's detection area and making its angle resolution minutely
- Implement to normal type of the sensor for obstacle avoidance

As already mentioned, sparse and random placement of reflectors is an important factor for this proposed system, however it is hard for user to do so by himself in wide environment. Thus function of automatic proposing placement of reflector will be helpful. Furthermore automatic map data registering function is also useful. For these purposes, PC utility software must be developed.

At present, the size of the reflectors is big in order to detect them from a certain distance. This, however, imposes limitations for the environment. Not only increasing sensor's detection area but also making its angle resolution minutely is big issue for stable detection and minimizing of reflector's impact on the environment. It is considered that at least 4 times the present resolution will be necessary.

To use Rapid-rURG involves a blessing and a curse, that is, being able to detect only reflectors stably also means that the sensor cannot be used for obstacle avoidance. One solution for that is to use a normal sensor in parallel, though it increases cost. A better solution is that sensor has both functions which are self-positioning and normal measuring. So method to detect reflectors stably by a normal sensor must be developed and it is the most important future work.

VI. SUMMARY

In this paper, the development of compact and light weight self-positioning sensor system was proposed.

Self-positioning is done by landmark matching using reflectors as landmarks and a previously constructed map. The map, which has a tree data structure, is given to the sensor in advance. An advantage of the proposed method is its low computational burden because of efficient and restricted searching condition based on the placement of landmarks. So it is suitable for low-spec CPU which is generally used by small sensor.

High grade reflex reflector was selected as landmark, and SOKUIKI sensor URG series which is typical small LRF nowadays was chosen as sensor.

The proposed method was implemented into the sensor itself, and evaluated its property. Finally future works were described.

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