Graph SLAM based Mapping for AGV Localization in Large-Scale Warehouses

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***Abstract*—The operation of industrial Automated Guided Vehicles (AGV) today requires designated infrastructure and readily available maps for their localization. In logistics, high effort and investment is necessary to enable the introduction of AGVs.**

Within the SICK AG coordinated EU-funded research project PAN-Robots we aim to reduce the installation time and costs dramatically by semi-automated plant exploration and localization based on natural landmarks. In this paper, we present our current mapping and localization results based on measurement data acquired at the site of our project partner Coca-Cola Iberian Partners in Bilbao, Spain. We evaluate our solution in terms of accuracy of the map, i.e. comparing landmark position estimates with a ground truth map of millimeter accuracy. The localization results are shown based on artificial landmarks as well as natural landmarks (gridmaps) based on the same graph based optimization solution.

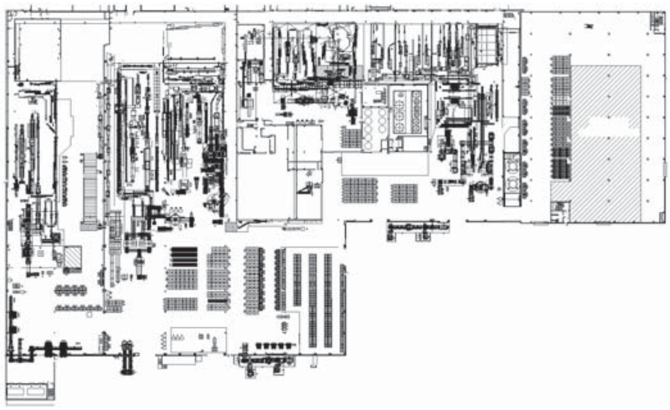

Figure 1. CAD drawing of production and warehouse facilities of Coca-Cola Iberian Partners in Bilbao, Spain.

I. Introduction

A high degree of automation has been reached in logistics and factories in general. However, the simple task of moving standard-sized goods on pallets from one point to another is done by manually driven forklift trucks in most cases. One major obstacle for operators with today's Automatic Guided Vehicles (AGV) are high introduction costs. They sum up from following facts:

- installation for localization-supporting infrastructure, e.g. reflectors
- manual measurement which need to be performed by land surveyors in order to create an highly accurate navigation map for AGVs.
- closing time of production during the transition time from manual forklifts to AGVs

Manual forklifts are being known for low efficiency, high energy consumption and listed among the most frequent causes of severe accidents in factories. Consequences of driving errors range from fatalities to damaged goods and/or delays in production.

If operators opt for AGVs there are many systems to choose from. Unlike manual forklifts, AGVs can support the vision of flexible, efficient, green and safe operation. Energy consumption can be subject to optimization techniques, e.g. preventing waste of energy due to unnecessary long ways, emergency breaking, etc. AGVs are equipped with safety devices to avoid collisions at all time.

An overview of AGV systems is given in [1]. They commonly rely in their localization on artificial landmarks, reflectors, installed only for that purpose. The planning and design of a reflector layout, i.e. positions, has to be done carefully in order to 1) sufficiently cover the warehouse and enable accurate localization for any AGV anywhere in the warehouse, and 2) avoid symmetries in order to enable a unique association of the observed landmarks to the reflectors in the map.

The latter is a fundamental property exploited in the global localization task: It is highly desirable that even immediately after a power on the AGV knows its position in the warehouse. Obviously, installation cost increases with the number of installed reflectors: Production plants can cover large spaces, in turn a large number of reflectors, up to 10,000 per plant, can be required.

After a tedious design of the reflector layout, modifications can be unavoidable if changes are done in the facility, e.g. installation of a new rack. Operators often dislike the inflexibility of the existing approach. A simple mapping procedure is therefore highly desirable, too.

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Figure 2. Aerial view of production and warehouse facilities of Coca-Cola Iberian Partners in Bilbao, Spain. Taken from Apple Maps.

System Setup

Within the PAN-Robots project we developed a mapping system that overcomes the requirements of manual measurements of any installed reflectors.

Currently, the localization is done by virtue of a 360 degree laser scanner (SICK NAV 350) mounted on the top of the AGV at the same height where the factory reflectors are installed, scanning a horizontal plane parallel to the factory ground. A digital map of the installed reflector positions must be available to the AGV typically with millimeter-range precision, currently provided by a land surveyor.

By conducting a mapping procedure, i.e. scanning the interior of the warehouse on manually-predefined paths a suitable map for localization is generated. We review our Graph SLAM based map generation in Section II under the aspect of using industrial sensors such as the SICK NAV 350 and the given environment of a warehouse.

The warehouse we used to record our measurement data at Coca-Cola Iberian Partners, Bilbao, Spain, is shown in Figure 2. The digital maps of the reflector positions are available for the performance evaluation.

As contour-based localization system we use Adaptive Monte Carlo Localization (AMCL) [2], [3] in combination with P-L-ICP [4] and give some details in Section III.

Contribution

Our contributions are as follows: First, we present our measurement setup and data recorded in a real warehouse at our project partner Coca-Cola Iberian Partners, Bilbao, Spain. The warehouse is fully operational with a fleet of 12 AGVs which rely on 172 reflector installations at a height of roughly 5 m. The warehouse covers an area of approx. $130\,\mathrm{m} \times 100\,\mathrm{m}$ with three parts / building sections.

A comparison of our reflector position estimates from the mapping procedure and the reference reflector map of the installation is presented along with our results in Figure 4.

Related Work

The problem of enabling academic solutions for the industrial environments has been investigated by the authors in previous work [5], [6], [7]. Previous work investigated the usage of particle filter based grid SLAM implementations. However, in our experiments the limitations of this approach motivates another approach using Graph SLAM.

The usage of Graph SLAM is well established for a number of problems [8]. Recent work, e.g. [9] uses a combination of Graph SLAM and gridmap-based localization.

II. Gridmap Estimation using Graph SLAM

Currently GMapping [10], [11], is considered state of the art for particle filter-based mapping. It generally performs well for small loop closures, however, in large environments, the probability of failed loop closures increases depending on the maximum laser range. A single failed loop closure can lead to a diverged map estimation. Commonly to filter-based approaches, there are no options to influence the behavior of the filter at run-time.

On the other hand, Graph SLAM frameworks, e.g. g2o [12], have several advantages over filter based approaches. Because of global optimization, also large loop closures can be handled very well. Even if the front-end fails to associate common structures, manual constraints can be quickly inserted into the optimization to obtain a valid map estimate after the process. Interestingly for commercial application, g2o is currently released under BSD license. There are several applications for g2o apart from 2D SLAM, e.g. Bundle Adjustment, 3D SLAM and Generalized ICP among others.

A. Hybrid Localization

In many cases, customers are conservative in their choice of localization techniques and still rely on reflector-based techniques. So it is favorable that g2o allows to solve the feature-SLAM problem as well as the grid map estimation problem jointly in one seamless process. Enhancements of current reflector layouts can be done more sparsely using hybrid mode localization technique employing reflector landmarks and contour data at the same time. Consequently, there is only a small gap left to avoid reflectors completely and use exclusively contour data if requested by the customer.

B. Incremental Graph SLAM

The fundamental processing pipeline of our Incremental Graph SLAM is as follows:

First, a scan matcher is used to estimate the motion between two consecutive scans from the laser scanner. Visual odometry has proven to be very robust if the laser range is high enough, so we do not use wheel encoder or other data from motion sensors, e.g. IMUs.

The motion estimate is added to the graph while the scan is analyzed for features, i.e. reflectors. Detected reflectors are associated with reflector landmarks already existing in the graph (map). After this step the graph can be optimized, thus the current position estimate is updated using the latest feature information.

Due to low drift of the visual odometry we can postpone the optimization to be done not after each scan but every N-th time.

From a structural point of view, explicit loop closure edges connecting poses are not necessary to obtain a consistent map. The data association registers seen reflectors to already mapped reflectors according to simple distance criteria.

Given the optimized graph and the associated scans for the nodes, a complete occupancy grid map can be reconstructed by projecting the laser scans from the position estimates in the graph.

A fundamental problem of Graph SLAM is the memory growth depending on the number of scans in contrast to a (more or less) fixed size map in GMapping. This can be avoided using node reduction techniques recently proposed, e.g. [13].

III. Results

In this section we report the accuracy of our mapping and localization approach.

A. Mapping Accuracy

Figure 3 shows the generated gridmap for the Coca-Cola Iberian Partners plant in Bilbao. Due to the scanning in a height of approx. 5 m most of the storage area is not captured in the map thus vast empty spaces can be seen in the middle of the plant's logistic area. In the lower right part two racks are visible loaded with pallets. The walls appear to be straight and even the separation of the left hall area and the middle part is clearly mapped. This map was subject to indirect quantitative evaluation in terms of localization accuracy described in the next section.

To evaluate the accuracy directly we refer to the current reflector installation layout which is used in today's production and measured in millimeter accuracy. The reflector positions are taken as ground truth and we compare them to the detected reflector positions in the map. The result is depicted in Figure 4. The mean distance of the estimated reflector positions is about 3 cm with a maximum deviation below 10 cm.

The reflector observations with higher deviation can explained by a larger distance at which they were seen. In case of reflector #65 the distance from the scanner was about 43 m. In practical localization implementations this reflector observation would not be used.

B. Localization Accuracy

To be able to further evaluate the accuracy of the generated maps we used them in the contour localization and report the accuracy of the localization. The results are shown in Figure 5. It can be seen that both trajectories align very well with the reference trajectory obtained by the SICK NAV350 reflector localization system. Also, the results are very similar in terms of position accuracy and angular accuracy.

IV. Summary and Future Work

In this paper we have shown that in industrial environments Graph SLAM in combination with AMCL provides a viable solution to enable far more flexible logistics due to the independence of a reflector installation. The localization accuracy based on the Graph SLAM map is roughly equal

Figure 3. Gridmap of production and warehouse facilities of Coca-Cola Iberian Partners in Bilbao, Spain.

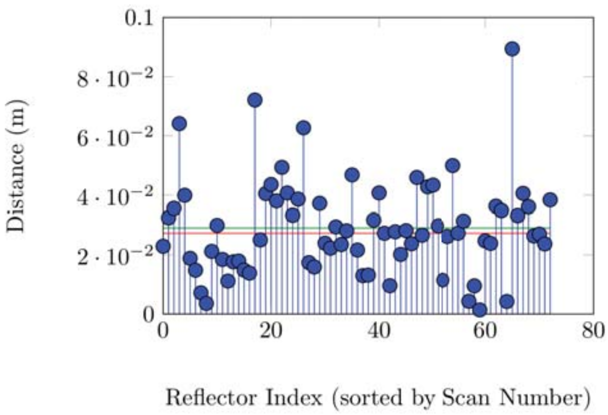

Figure 4. Comparison of estimated reflector position accuracy in distance to next ground truth reflector. Mean at 2.9 cm (green line) and median at 2.7 cm (red line) is shown as well.

to the reference particle filter based SLAM implementation. That enables the method to be applied to even larger plants where filter-based approaches are very likely to fail due to unsuccessful loop closures. This needs to be verified in future works.

Promising localization approaches dealing with more dynamic environments are described by Tipaldi et al. [14] and Valencia et al. [15]. While Tipaldi et al. estimate several dynamic gridmaps at runtime, Valencia et al. use a Normal Distribution Transform (NDT) representation at different timescales for localization. Both report improvements in robustness in changing environments compared to AMCL.

Acknowledgment

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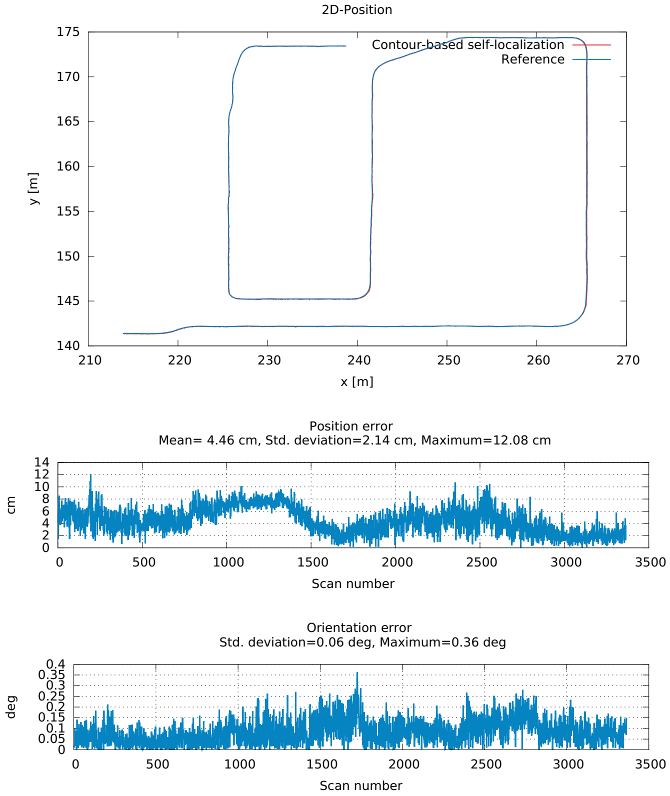
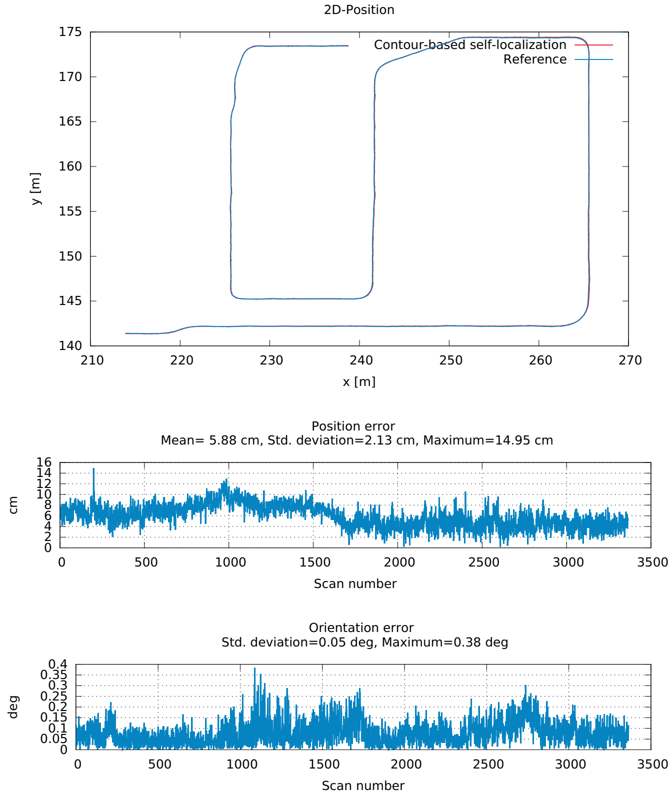


(a) Trajectory and accuracy of the contour localization using the map created with GMapping.



(b) Trajectory and accuracy of the contour localization using the map created with Graph SLAM.

Figure 5. Evaluation of localization accuracy.

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