Strategies for 3D Data Acquisition and Mapping in Large-Scale Modern Warehouses

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***Abstract*—Today modern manufacturing and logistic processes rely in most instances on manual forklifts. Being known for low efficiency, high energy consumption and listed among the most frequent causes of severe accidents in factories, the SICK AG coordinated EU funded research project PAN Robots aims to replace them in large scale with Automated Guided Vehicles (AGV). Major obstacles for operators with current AGVs are high initial costs, e.g. registration of all pallet positions and reflectors which needs to be performed by highly trained professionals in order to create an accurate navigation map for the AGVs. Simultaneous Localization And Mapping (SLAM) is the scientific approach to initial mapping. In this paper, we present 3D mapping strategies dedicated for the warehouse environment with multiple Laserscanners. Preliminary results are shown based on measurement data captured at the site of our project partner Casbega, Madrid, Spain.**

I. Introduction

In factories in general a high degree of automation has been reached. However, in most warehouses pallets loaded with goods are transported by manual forklifts. The pallets have to be picked up from the factory's palletizer and stored in the warehouse until the designated truck is stocked with the goods the customer ordered. Manual forklift are prone to errors while driving leads to accidents and/or damaged goods. Automatic Guided Vehicles (AGVs) are an alternative but still costly in their introduction. Today's AGVs rely in their localization on artificial landmarks, reflectors, installed only for that purpose [1]. The planning of reflector positions has to be done carefully in order to sufficiently cover the warehouse and enable accurate localization for any AGV anywhere in the warehouse. On the other hand regular patterns have to be avoided in order to enable a unique association of the observed landmarks to the reflectors in the map or layout. Last but not least, the installation cost increases with the number of installed reflectors, so the factory operator aims to have a reliable system with as few reflectors as possible. Nevertheless smooth, efficient and accurate operation with as few as possible energy consumption (preventing waste of energy due to unnecessary long ways, emergency breaking, etc.) and of course no collisions are highly desired, too.

Now, whenever a new plant is build or an existing one is extended or modified the reflector layout has to be revised. After the construction is finished the relevant points of interest, e.g. pallet positions in the racks and pickup places have to be defined manually because the construction realization cannot be assumed to be exact.

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Within the project the aim is to develop a 3D mapping system that overcomes the requirement of having manual registration procedures of common warehouse elements including any installed reflectors.

Common elements found in warehouses are

- construction elements
  - racks
  - poles
  - piles
  - walls
  - windows
  - doors for humans / gates for AGVs/manual forklifts
- special areas
  - pickup places
  - pallet positions in the racks
  - block storage/free stacks
  - Maintenance area / battery station
  - drivable corridors / paths
  - dedicated / shared walkways for pedestrians
  - safety zones, e.g. in front of picking places
- dynamic objects
  - AGVs
  - manual forklifts
  - tricycles
  - pedestrians
- static objects
  - obstacles
  - pallets
  - fire extinguisher
  - reflector positions

In regular operation after plant exploration, the tasks or missions the AGVs are assigned by a control center. Each AGV is supposed to localize itself anytime and move to the given first operating point of the mission. Of course, transporting the load to the designated destination requires localization, too.

Currently, the localization is done by virtue of a 360 degree Laserscanner – 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

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ground. A digital map of the installed reflector positions must be available to the AGV typically with high precision, i.e. millimeter range.

By conducting a suitable form of 3D mapping and scanning the interior of the warehouse we try to calculate a 3D representation of the entire warehouse in order to detect the points of interest i.e. pallet positions by means of segmentation, detection and extraction algorithms. A suitable map for localization is generated in that process, too.

Contribution

We try to sketch a complete solution for the mapping problem in modern warehouses according to the requirements of warehouse operators under economic and ecologic constraints in order to generate the digital map in a green, efficient and safe manner. As the project is still in a early stage we draft our approach and show some preliminary results based on a measurement campaign done at the beginning of the project.

First we discuss the various requirements on a 3D mapping procedure by analysing the applications localization and semi-automated plant exploration that rely on the map in Section II.

While there exist straight-forward solutions for the generation of maps for localization applications, we extend on the necessary steps of processing the acquired measurements towards the extraction of points of interest that the AGV control center requires for setup and operation.

Secondly, we present measurement data recorded in a real warehouse at our project partner Casbega. The warehouse is fully operational with a fleet of over 40 AGVs which rely on 285 reflector installation at a height of roughly 5 m. The warehouse covers an area of approx. 200 m $\times$ 150 m with corridors describing a regular grid in most regions. The reference reflector map of the installation is presented along with our preliminary results in Fig. 6.

Three kinds of measurement setups were investigated.

a) A regular AGV otherwise used for normal operation was redesigned on site for the measurement campaign: Using the AGV as a moving platform sideway-Laserscanners measure the environment. Data fusion with the regular localization information results in a 3D map. The AGV was manually steered through the corridors in lawnmower fashion in order to cover as much of the warehouse area as possible. The traveled distance was approx. 1,800 m.
b) A rotating 3D Laserscanner is used to measure the environment from static, pre-defined positions. It is depicted in Fig. 2.
c) Using the fork of a forklift to scan the shelf or rack from top to bottom.

The techniques and methods are discussed in detail in Section III.

The overall goal is to avoid a reflector installation at all in future warehouses. However, as a first setup it is also desirable to generate the digital map of the installed reflectors without the need of a land surveyor.

For the time being we make use of the existing reflector layout as a reference and detect the reflector landmarks in SLAM manner without a priori knowledge except their exceptional reflectivity using the first mapping approach a).

Feature-based SLAM algorithms provide a suitable solution to approach the goal. In Section IV the estimated SLAM solution implemented according to [2] based on data gathered in measurement setup a) is compared to the manually measured reflector positions. The estimated trajectory is also presented.

Finally, the paper gives a conclusion and closes with issues for future work.

Related work

Previous works for mapping generally discussing large areas (not corridors), focus on natural environments with little or no artificial symmetric and repetitive structures. Not much recent work has been spent on mapping in warehouses. An exception is [3]. They use a similar approach but the autonomous vehicles are equipped with Inertial Measurement Units (IMUs) and wheel odometry which we are trying to avoid at the moment to keep the system at reasonable costs. Furthermore mapping and localization is based on OccupancyGrids which are either not precise enough due to the quantization or not fast enough if the grid is very tight. Additionally the mapped area is significantly smaller and 2D (planar) only.

II. REQUIREMENT ON THE MAPPING

The digital 3D map is supposed to serve multiple purposes:

- for localization of the AGVs: an environmental map representation has to be provided that supports smooth operation of the AGV fleet,
- for plant exploration: racks, pallet position, pickup places, safety areas have to be defined precisely.

A. Plant exploration

In the 3D point cloud, points of interest have to be extracted, e.g. describing the possible pallet positions of each rack in the global coordinate system of the warehouse.

The proposed processing pipeline is illustrated in Fig. 1. First, the point cloud is acquired using one or multiple of the techniques presented in Section III. Then a segmentation will be done, including plane segmentation and clustering of the remaining points. The clusters are processed in a feature extraction stage where e.g. rack positions should be identified semi-automatically.

B. Localization Requirements

Requirements for the Localization are derived from the application and the current layout of the warehouse, e.g. are there broad drivable corridors for 1) maneuvering at a pallet position and 2) collision avoidance. If the drivable corridors are very small, high accuracy and very precise localization solution is required at all times.

However, today's AGVs are equipped with safety Laserscanners that immediately stop the AGV if an obstacle is persistently detected in the statically, pre-defined safety areas

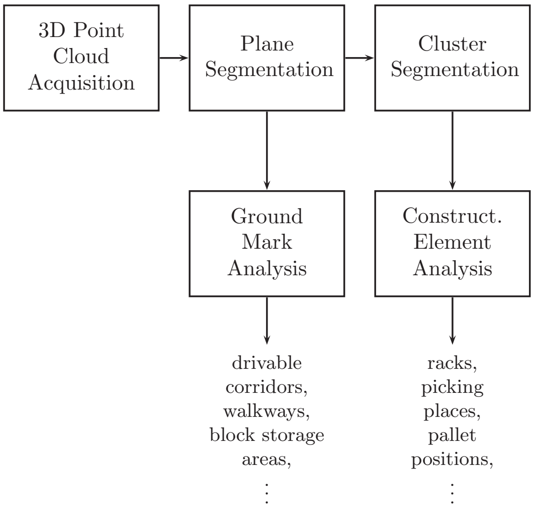

Figure 1. Warehouse element recognition pipeline consisting of multiple segmentation steps and feature extraction.

Figure 2. 3D Laserscanner prototype by SICK.

realized in the safety Laserscanner. Nevertheless, an emergency breaking causes 1) stress to the mechanical structure of the AGV (which weights about 7,000 kg), 2) inflicting wear on the tires 3) stress to the factory ground that leads to potholes on routes with heavy traffic.

AGVs passing each other must not collide, that results in a requirement to the map of a given precision depending on the width of the drivable corridor and the width of the involved AGVs. However, plant operators have an interest to maximize the storage area thus decreasing the drivable areas to a minimum.

III. Acquiring the 3D map: Measurement Setups

A. The Mapping AGV

In order to have a complete 3D perception a regular AGV is equipped with Laserscanners as shown in Fig. 3. The Laserscanners are mounted on the vehicle to achieve an optimal coverage of the environment.

Figure 3. The mapping AGV equipped with multiple Laserscanners. On top blue coated NAV350 – encircled in yellow – with 360° horizontal field of view, in the middle attached gray coated LMS500 – encircled in blue – to scan the environment perpendicular to the direction of the AGV heading.

The Laserscanner on top of the AGV represents the regular localization sensor SICK NAV 350 scanning a 2D plane parallel to the ground. Its measurement parameters are summarized in Tab. I.

The Laserscanners installed at the sides are SICK LMS500 with a field of view of a horizontal plane perpendicular to the driving direction and to the ground. Thus, the racks are captured while the AGV passes by.

However, the point density is highest for elements in the rack on the same height level while its decreasing for measurements higher or lower than that. The measurement parameters are summarized in Tab. I.

Projecting the measurement data of the side Laserscanners according to their mounting positions and the current AGV's position estimate results in a 3D point cloud of the warehouse as shown in Fig. 4.

This method usually results in locally consistent maps if the host vehicle's motion is adequately measured. Note that we do not use the odometry of the AGV itself. The mapping system should be easily installed on any AGV or other host

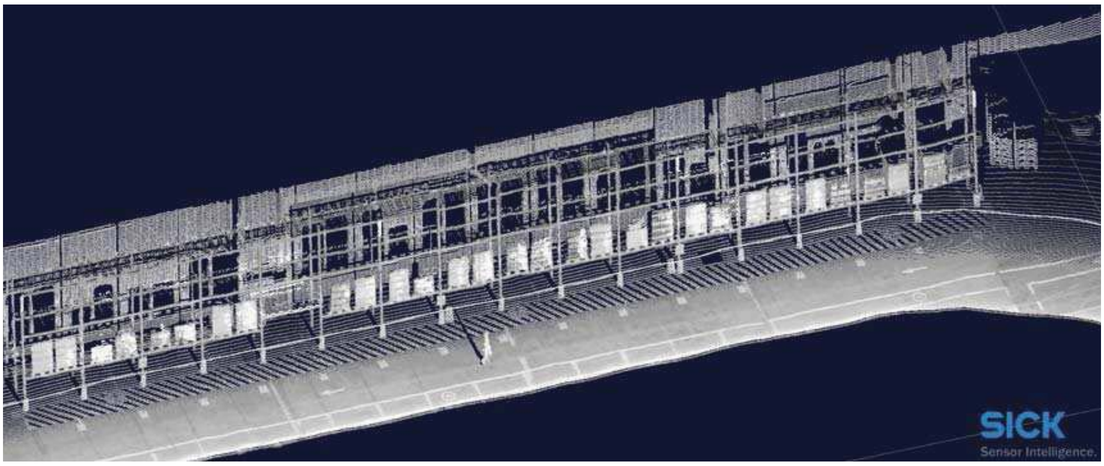

Figure 4. The measurement data recorded by the mapping AGV with support of the current NAV build-in reflector localization.

Table I. LASERSCANNER PARAMETERS

	SICK NAV350	SICK LMS500
Scan frequency	8 Hz	100 Hz
Angular resolution	$\frac{1}{4}$ °	$\frac{2}{3}$ °
Angular field of view	360°	190°
Maximal range on 10% reflectivity	35 m	40 m

vehicles that may have no odometry sensors at all.

Visual odometry from the NAV350 Laserscanner should be sufficient if the accelerations are not too deviant. However, the problem of calibration remains, especially under the given installation the overlapping scanning region is very small. We use TrimmedICP [4] to feed an Extended Kalman Filter [5] and use its solution as visual odometry input for the Feature SLAM.

The drive-by approach offers the advantage that comparable low shadowing appears and the time consumption for gathering measurement data can be reduced if predefined automated trajectories are driven. So little to no manual engagement is required in the end.

B. SICK 3D Laserscanner

Utilizing a 3D Laserscanner the environment can be perceived without a moving host vehicle as shown in Fig. 2

Of course, gathering all measurement data from one position results in most consistent 3D scans. Calibration is done at manufacturing of the 3D Laserscanner.

However, due to the polar measurement principle of a Laserscanner the point density decreases with range. Obstacles may cause very large shadows if they are close, e.g. AGVs being around or pallets close to the 3D Scanner. Low hanging lights at the ceiling causing large "holes" in the warehouse ceiling that moves with the position of the 3D Scanner which renders the ceiling next to useless for registration as shown in Fig. 8.

In order to cover the whole warehouse area a lot of measurement positions had to be defined and conducted. It has been shown, e.g. [6] that these single position measurements can be successfully concatenated by means of scan matching and registration. However, depending on the structure and symmetry of the environment the distance between two measurement positions must be less than 2 m. Additionally, planning the position, conducting the measurements and quality assessment of the registration involves a high degree of manual engagement which would be desirable to avoid.

C. Top Down Scanning

By scanning while the fork moves up and down a complete 3D representation of the shelf can be acquired as well. Mounting a Laserscanner on a "pilot pallet" pointing at the shelf while an additional sensor measures the distance to the ground. Data fusion led to the measurement results that are shown in Fig. 5 for a LMS100 installed on the "pilot pallet".

This method results in minimal shadowing. The point density is constant at each height of the rack.

However, it takes substantially more time than method a) but might be automated as well. Additional scan matching and registration would have to be applied to the vertical swaths as well as in the method b).

IV. PRELIMINARY RESULTS

A. 3D Point Cloud Acquisition

For the discussion of our preliminary results we focus on Fig. 4 for method a) – drive-by scanning –, Fig. 8 for method b) – 3D Laserscanner based scanning – and Fig. 5 for method c) – top-down scanning using the fork of the AGV.

As pointed out before all data was recorded at Casbega in a real warehouse environment while regular operation was going on.

Fig. 4 is generated by showing the data of only one LMS500 mounted at the side of the AGV and utilizing the reflector-based localization solution of the regular AGV operation.

The difference in the sampling rate of the devices (100 Hz for LMS500 and 8 Hz for NAV350 Localization solution) is compensated by means of linear interpolation.

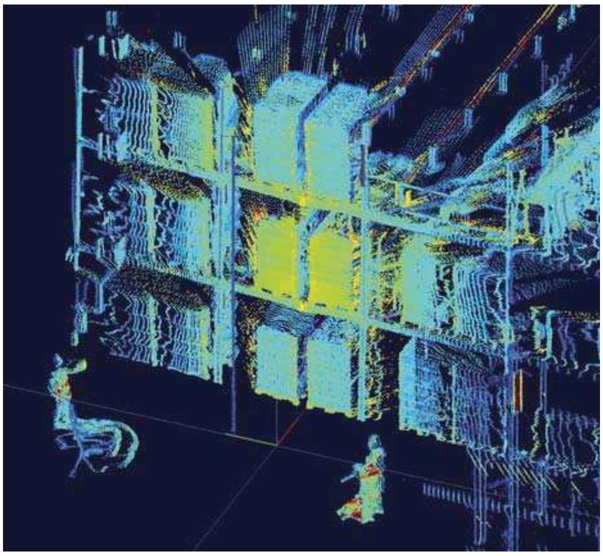

Figure 5. Top-down scan swath of a gravity rack using a SICK LMS100. False color indicate reflectivity (RSSI) - blue represents low RSSI, red high RSSI values.

Comparing a) and c) it is obvious that in c) the ground is missing. The markings on the ground floor visible through reflectivity (Receive Signal Strength Indicator – RSSI) values as shown in Fig. 4 give valuable information for the extraction of safety zones (marked as diagonal strips), pedestrian walkways which is clearly not the case for method c) and also not in b) – because the point density around the 3D Scanner position is very low on the ground.

The rack structure is well recognizable in Fig. 4, however the pallet loads seem flat because of the perpendicular arrangement of the LMS500 on the AGV. On the other hand, even the pallet pockets are perceivable in that swath. Although this 3D reconstruction is done by virtue of the reference positions calculated by utilizing the reflector layout, straight lines, e.g. the ground markings in driving direction are not completely straight, instead they seem to oscillate a bit. Another weakness visible in this figure is the problem of dynamic objects: in this case a pedestrian walked while the AGV was driving by. The person's shape is a bit distorted in the reconstruction due to the relative movement of the AGV and the person. Of course the measurement points reassembling the person could be removed easily however the missing information by the dropped shadow cannot be reconstructed easily. One radical solution to this issue would be to restrict access for dynamic objects to the mapping area.

For the 3D Laserscanner we observe a quite detailed reconstruction without the need for localization, however the figure shows only one scanner position. As pointed out before 1) shadowed regions 2) large distances between measurement positions and 3) repetitive structures, e.g. poles in the rack renders the scan matching and registration very difficult. An example for the registration of two positions is given in Fig. 9 using techniques described in [6], [7].

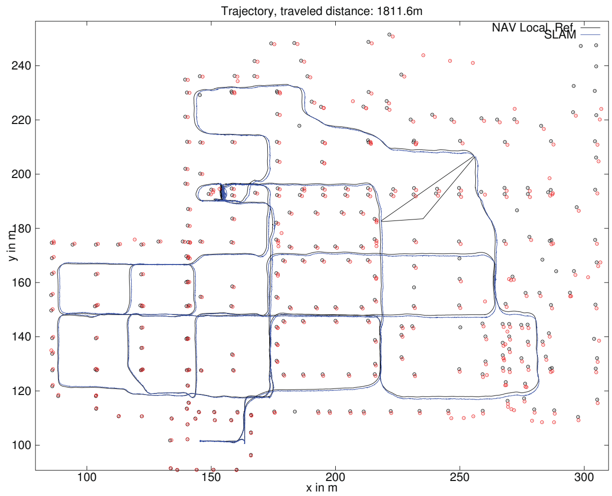

Figure 6. Result map and trajectory. Black circles are positions of reflectors in the reference map, red circles are the map entries generated by the employed Feature SLAM

B. *Feature SLAM*

A feature based SLAM approach according to [5] was applied to the contour measurement data gathered by the NAV350 Laserscanner. In a preprocessing stage a reflector detection was applied and then the recognized features were directed to the Feature SLAM together with the visual odometry output. Due to the low sampling rate of 8 Hz a intra-scan motion compensation was applied to the contour points as well.

The conventional approach consists of data association, extended Kalman filtering and particle filtering.

The result was the estimated trajectory of the host vehicle and the digital map with the estimated reflector positions as shown in Fig. 6. For comparison the reference reflector map is shown in black circles and the trajectory solution as calculated by the reflector localization of the regular operating system is shown in black as well.

We can basically state a success regarding our first goal to being able to localize without exact knowledge of the reflector positions. Our SLAM solutions follows the solution of the reflector localization over the whole distance of 1.8 km.

For quantitative analysis of the results the absolute difference in position and heading over the frame index is shown in Fig. 7. This result resembles a typical SLAM result, first we explore unknown territory so the absolute error rises due to drift, but as soon as we return to some previously seen regions the error decreases again due to the successful data association.

Mean error in position is around 0.8 m and the heading error below 0.6° which is a promising start for further investigations.

V. Conclusion

In this work we conducted and investigated measurement techniques to enable 3D mapping of a warehouse environment. Requirements to the map are discussed. The measurement

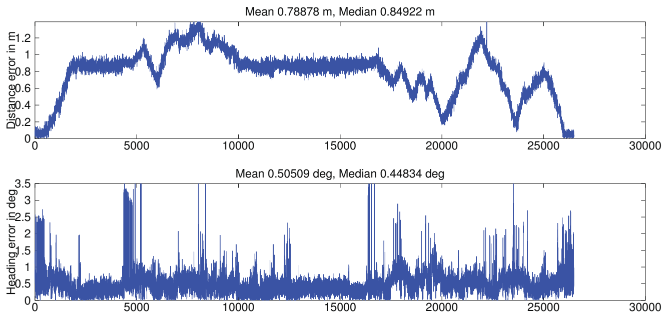

Figure 7. Absolute Error in Position and Heading of the Trajectory.

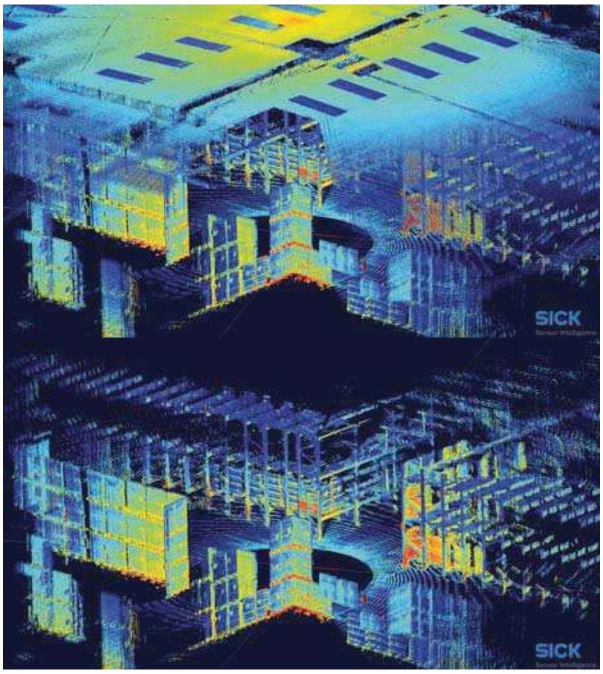

Figure 8. Measurement result for 3D Laserscanner at one position, note the repeating structures of the racks (back) and pallet blocks (front). Upper image shows the full scan, while in the lower image the point cloud is clipped at a height of approx. 5 m in order to have a complete view on the racks.

strategies were presented and advantages and disadvantages pointed out supported by real measurements.

Preliminary results using acquired data for the localization application were presented underlining the feasibility of the approach and the potential for further research in the PAN-Robots project.

VI. Future Work

Clearly, reflector installations are still expensive and inflexible. So the digital map and the localization that uses it should be based on natural landmarks. Promising results are shown with FLIRT features [8] and occupancy grid maps [9]. However, there exists also the graph-based SLAM solutions based directly on point clouds. Furthermore, the feasability of direct 3D mapping approach has been shown [10]. Investigation of applicability in the warehouse context will be carried out in the near future.

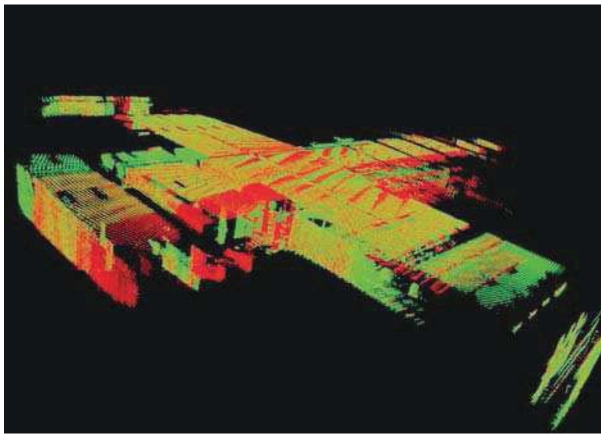

Figure 9. Result for a successful scan registration of two scans (in red resp. green) of the 3D Laserscanner at two positions. Distance between positions was approx. 2 m. Consistency is observable, e.g. at the left side where one part of the warehouse wall was covered at one scanner position and the other part from the other position. Together they result in a straight wall with some overlap that is colored in yellow.

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