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Bouguerra A, Andreasson H, Lilienthal A, Åstrand B, Rögnvaldsson T. An Autonmous Robotic System for Load Transportation. In: IEEE Conference on Emerging Technologies & Factory Automation, 2009. ETFA 2009. Piscataway, N.J.: IEEE; 2009. p. 1-4. IEEE Conference on Emerging Technologies and Factory Automation, 2009.

DOI: http://dx.doi.org/10.1109/ETFA.2009.5347247
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An Autonomous Robotic System for Load Transportation

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Abstract

This paper presents an overview of an autonomous robotic system for material handling. The system is being developed by extending the functionalities of traditional AGVs to be able to operate reliably and safely in highly dynamic environments. Traditionally, the reliable functioning of AGVs relies on the availability of adequate infrastructure to support navigation. In the target environments of our system, such infrastructure is difficult to setup in an efficient way. Additionally, the location of objects to handle are unknown, which requires runtime object detection and tracking. Another requirement to be fulfilled by the system is the ability to generate trajectories dynamically, which is uncommon in industrial AGV systems.

1 Introduction

The process of loading, unloading and transportation of materials is one of the key issues for every production site and has a great impact on costs. Automated Guided Vehicles (AGVs) are robotic transporters that have been designed to help industries achieve high productivity at minumum cost. Typical examples include automotive factories, warehouses, paper mills, and mines [4, 2, 6]. AGVs come essentially in two forms today: AGVs guided by wires in the floor and AGVs guided by visual markers in the environment (e.g., reflective markers). AGVs that rely on floor-planted wires require the deployment of a specific infrastructure (wires). Moreover, they are restricted to follow those wires, like a train on rails. AGVs using reflective markers to navigate have the drawback of requiring additional infrastructure but can modify their paths, e.g., to navigate around obstacles.

There have been several works aiming at extending the functionalities of traditional AGVs. Typical added functionalities include high-level decision making and flexible path planning on top of traditional wire-guided AGVs [7], task scheduling (see, e.g., [9]), environment-specific perception using laser scanners to recognize ceiling details and pallets [5], and vision-based navigation that exploits naturally occurring visual features [3].

This paper presents an overview of an ongoing research effort by the universities of Örebro and Halmstad in Sweden together with Danaher Motion Särö, Linde Material Handling, and Stora Enso Logistics to develop a system of **M**ultiple **A**utonomous forklifts for **L**oading and **T**ransportation **A**pplications (MALTA) [8]. The ultimate goal of the project is to develop modularized components for continuous operation of autonomous transportation vehicles. Initially, the system will be tested on forklift trucks adapted to handle paper reels in a production facility (mill) and warehouse terminals with the following characteristics. First, the controlled forklift trucks are to be operating safely in dynamic environments where humans and other autonomously and manually driven vehicles can exist. Second, the system must be able to compute dynamic vehicle paths online to ensure a more time-optimal flow of material. Finally, the proposed system is required to achieve flexible positioning of the load (paper reels) in different settings that include containers, lorry trailers, cargo trains, and on the floor.

The remainder of the paper is organized as follows. Section 2 gives a description of the working environment, while section 3 is devoted to presenting the system. Section 4 summarizes our first test cases, and section 5 includes a discussion of the open research issues.

2 The Environment

Figure 1 shows pictures of paper warehousing terminals, where MALTA vehicles are intended to operate. The left picture shows stacks of paper reels that are temporarily stored before they are transported to customer sites using cargo trains and trailer-trucks. The warehouse environment is characterized by the presence of manually driven trucks fitted with clamps used to load and unload paper reels. The handled paper reels can weigh up to 5000 kg and have a diameter in the range of 950 - $1800mm$ and a height in the range of 550 - $2800mm$. They are covered

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Figure 1. A warehouse of paper reels. Left) Stacked paper reels waiting to be loaded. Middle) Reels to be unloaded in the warehouse terminal. Right) A concrete pillar that has the same cylindrical shape as a paper reel.

with a protection paper/plastic and have printed labels that can be read with a bar code reader. Paper reels are stacked in the warehouse for intermediate storage. Due to the high stacks of paper reels, setting up tradition AGV reflector-based localization becomes almost impractical.

The environment includes also trailer-trucks used to transport paper reels from the paper mill to the terminal. When trailer-trucks arrive at the warehouse, their cargo is unloaded in predefined areas of the terminal by clamp-fitted trucks (see the middle picture in figure 1). The paper reels are unloaded either on the floor or on top of other reels. The clamp-fitted trucks are also assigned to loading containers, truck-trailers, and wagons of cargo trains. The activities of loading/unloading are performed in parallel, which makes the environment highly dynamic.

The pictures in figure 1 show also some of the difficulties that the system must cope with in order to achieve its assigned tasks correctly. For instance, the cylindrical shape of the pillar support shown in the right picture can be mistakenly detected as a paper reel. Another example is of stacks that are not perfectly aligned vertically.

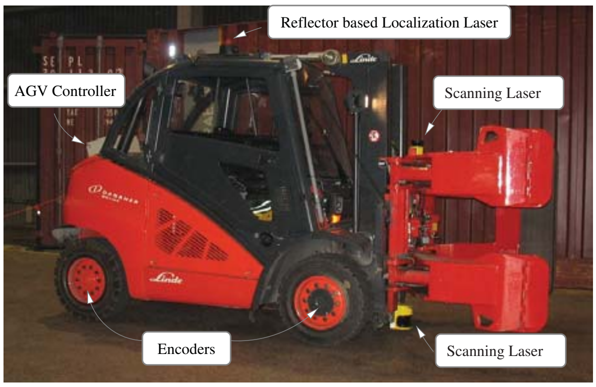

Figure 2. A modified forklift truck retrofitted with an AGV controller and a reflector-based localization laser for guidance purposes. Two front scanning-lasers are used for reel detection and safe navigation.

3 System Description

The autonomous system that we are currently developing is based on a modified Linde H 50 D diesel forklift truck that has a load capacity of 5000 kg (see figure 2). The standard version of the truck was modified by shortening the mast and replacing the forks with a clamp. The truck was retrofitted with an off-the-shelf AGV control system developed by Danaher Motion. The AGV control system comprises a set of hardware and software components (PC, IO modules, field bus controller, rotating laser ranger, etc.). The control system interfaces the actuators and sensors of the truck through the already built-in local CAN network. To detect paper reels and obstacles, two extra scanning lasers were incorporated into the truck (see figure 2). The modules of the system are shown in figure 3, and they are described in the following subsections.

3.1 Vehicle Module

The AGV controller comprises a set of hardware components that include an onboard PC running Linux and a set of IO modules used as interfaces to control the truck. Communication between the different components of the controller is implemented using the CanOpen protocol.

The main task of the AGV controller is to navigate the truck from an initial location to a goal location. To do so, an operator defines and uploads a layout of drivable paths specified as collection of line segments and B-splines. The controller achieves navigation tasks by following an appropriate path. The position of the truck can be tracked using a spinning laser (installed on the top of the truck) and reflective markers installed in the environment. To support dynamic navigation, the system accepts runtime trajectories specified as B-splines.

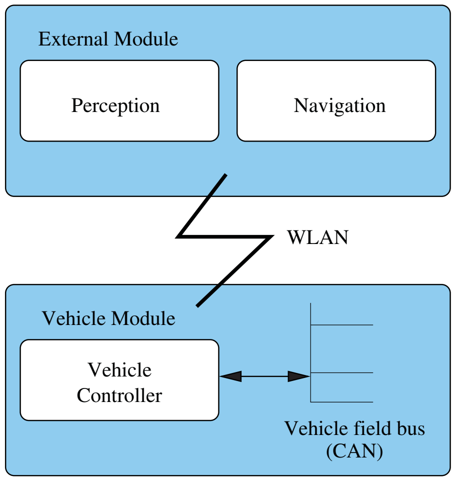

Figure 3. Modules of the MALTA system. The AGV controller implements navigation using reflective markers. The AGV controller is connected to the CAN network of the vehicle. The external module includes a perception component to detect paper reels and obstacles and a navigation component for generating dynamic paths.

3.2 External Module

The external module includes two main components: perception and navigation. The main aim of the perception component is the detection and tracking of paper reels, while the navigation component aims at generating runtime trajectories needed to achieve tasks of loading and unloading of paper reels. The trajectories are represented by cubic B-splines and they are executed by the AGV controller. The navigation component will also be responsible for ensuring safe motion, i.e., obstacle detection and avoidance. The functionalities of both components are implemented as a set of Player drivers [1] that run on an external PC. Communication between the onboard PC of the AGV controller and the external PC is implemented by a set of TCP/IP protocols using a wireless radio network.

Paper reel detection

Paper reels are modeled as circles whose positions and diameters are determined using laser range-data. The method used to detect paper reels is based on Taubin's work for fitting a circle to data points [10]. To extract the data points, laser range scans are processed as follows. First, range scans are divided into segments, if the distance between two consecutive scan points is larger than a predefined threshold. Second, the circle fitting algorithm is applied for each extracted segment to obtain reel position and diameter. Finally, all paper reels that have a diameter falling outside a predefined interval of acceptable reel diameters are rejected.

Paper reel tracking

To estimate the reel position in a global coordinate frame, the global pose estimate of the truck, which is provided with the reflector-based laser localization system, is combined with the paper reel detection method. Essentially, the tracker keeps a global map of detected paper reels, such that the global position of each paper reel is updated using a Kalman Filter.

The data association process (i.e., establishing the correspondence between sensed reels and the reels in the global map) is performed using the Euclidean distance to associate the closest reel in the map with the sensed one, unless the distance is greater than a predefined threshold. If no corresponding reel in the global map is found, a new paper reel is added to the map. To improve the position estimate of the reels, especially when the truck is turning quickly, the truck pose estimate is interpolated using the time stamp of both the laser and the localization readings. To avoid to track/update reels that are outside of the loading/unloading area, reels that fall outside this region are simply neglected.

4 Test Cases

The autonomous vehicle system described in this paper builds upon different commercially-available subsystems. The first conducted step was the integration of a modified forklift truck and an AGV control system to create an automated vehicle. Therefore, the initial tests were aimed at verifying the correct and reliable operation of the integrated AGV system. The second series of tests aimed at the evaluation of the perception component using off-line data, while the objective of the last series of tests was the verification of the functionalities of the entire system.

AGV Verification Tests

The integrated AGV system performs navigation by following predefined static paths. This means that the position of the reel and its size together with a path segment leading to it have to be known in advance in order to pick up a paper reel. In these tests, paper reels were successfully loaded and unloaded from 10 different fixed positions with different elevations. The tests were successfully repeated several times over a period of 4 months.

Evaluation of the Perception Component

While performing the previous AGV verification tests, data from the laser range-finder and AGV reflector-based localization was logged for the purpose of evaluating the reel detection and tracking component. Using the predefined positions as ground truth, the obtained results showed that the estimated absolute reel-position error (for the 10 different positions) was $0.027m$ with a standard deviation $\sigma = 0.013m$ (the results depend on the AGV's positioning accuracy). This was achieved by combining measurements using a Kalman filter for each of the ten reel poses. Only measurements performed at a distance less than $8m$ were considered. Please note that the error in reel position (which, in our case, is less than 2% of reel diameter) was taken into account when opening the clamp to pick up reels.

Evaluation of the Entire System

The goal of these tests was to evaluate the extended capabilities of the original AGV system with runtime perception and navigation capabilities. The tests consisted in transporting a set of reels from a loading zone to a container. The reels were placed by a manually-driven truck inside the loading zone, i.e., the positions of the reels were not initially known to the system. This scenario was one of the first requirements to fulfill by the system.

To achieve the assigned task, the closest detected reel was selected as target to approach and pick up using an online-computed path (B-spline) starting at a predefined point. Similarly, the transportation of the reel into the container was carried out by following a path including a return B-spline and a set of predefined segments. To ensure that the target reel was appropriately picked up, i.e., to avoid the situation of the clamps hitting the reel when turning, the truck was forced to drive straight at the final part of the B-spline. The tests were successfully run a significant number of times to ensure that the entire system was working correctly.

5 Discussion and Conclusion

We have presented an overview of our ongoing work of developing an autonomous robotic material-transportation system. The goal is to have a fleet of autonomous and manually-driven forklift trucks operating in dynamic production environments with intermediate storage as well as loading of containers and train wagons. The system is built on top of a retrofitted forklift truck with an "off-the-shelf" AGV control system together with extra sensors. The AGV navigation system works very reliably under normal conditions and is able to navigate the truck with an accuracy of approximately $1cm$.

However, there are two main evident limitations that need to be addressed in the AGV system. First, the infrastructure used for the reflector-based localization is difficult to setup in an efficient way, due to the high stacks of paper reels that will obscure the reflectors, see figure 1. Therefore, the indoor localization has to be addressed in a different manner, e.g., by laser scanners or cameras pointing to the ceiling. One observation is that paper reels are rather easily detected in 2D laser scans and could therefore be suitable as landmarks in the context of SLAM.

The second limitation of the AGV control system is its use of predefined paths, which means that the truck is not allowed to change path at runtime. A solution to this limitation is to generate and follow paths online. However, this raises the issue of safe navigation, as there are many unsafe and dangerous locations around the working site that are impossible to detect using a 2D laser scanner alone (e.g., a one meter drop down to the train tracks). This is currently addressed by providing predefined locations, where on-line path generation is allowed. Another open issue is the detection and handling of stacked reels that are not aligned vertically and that could also be sitting on more than one reel. Our intention is to use advanced 3D sensing modalities to detect and handle such situations.

Acknowledgment

We would like to thank Danaher Motion, Linde Material Handling, and Stora Enso for their contribution to the MALTA project. We also would like to acknowledge the support of the Swedish KK foundation.

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