MALTA: A System of Multiple Autonomous Trucks for Load Transportation

A. Bouguerra* H. Andreasson* A. Lilienthal* B. Åstrand† T. Rögnvaldsson*†
*Örebro University, Sweden
†Halmstad University, Sweden

Abstract— **This paper presents an overview of an autonomous robotic material handling system. The goal of the system is to extend the functionalities of traditional AGVs to operate 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 that the system be able to detect and track object positions at runtime. Another requirement of the system is to be able to generate trajectories dynamically, which is uncommon in industrial AGV systems.**

Index Terms— **Autonomous Vehicles, Load Handling, AGVs**

I. INTRODUCTION

There is great demand for efficient material transport in many industrial environments. Typical examples include automotive factories, warehouses , paper mills, and mines [7, 5, 9]. One direction for responding to such demand has been the incorporation of automated robotic vehicles in the cycle of material handling, including loading, the actual transportation, and unloading of the material. A mobile robotic solution has a great potential to offer improvements in terms of costs, safety, efficiency, flexibility and availability. Automation of the full material handling cycle is generally a very challenging task, and robotic solutions are available today only for simple loading and unloading tasks in controlled and largely static environments.

This paper presents an overview of an autonomous truck system for loading, unloading, and transporting of material in highly dynamic environments. The system is being developed as part of the MALTA research project (**M**ultiple **A**utonomous forklifts for **L**oading and **T**ransportation **A**pplications) [11] at Örebro University and Halmstad University in Sweden, together with Danaher Motion Särö, Linde Material Handling, and Stora Enso Logistics. 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 in dynamic environments shared with humans and other autonomously and manually driven vehicles ensuring safe operation. 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.

Automated Guided Vehicles (AGVs) are robotic transporters that have been deployed considerably for material handling in industrial settings. 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 with wires in the floor require both specific infrastructure (wires) and are restricted to follow those wires, like a train on rails. AGVs with reflective markers have the drawback of requiring additional infrastructure but can modify their paths, e.g., to navigate around obstacles.

Most of the scientific literature tends to focus on specific functionalities of industrial robotic vehicles, e.g., guidance, vision, and task scheduling (see, e.g., [12]). Among the few papers that describe complete functional AGV systems is the RETRARO project [10] that targeted the development of a flexible robotic transporter for a textile production unit. The system was implemented on top of traditional wire-guided AGVs with a special focus on adding high-level decision capabilities and flexible path planning.

The ROBOLIFT project [3], a collaboration between Elsag Bailey and Fiat-OM Carelli Elevatori, was an early project aiming at using computer vision instead of wires in the floor for navigation. The truck followed lines painted on the floor using a camera mounted on the forklift canopy roof. The ROBOLIFT project demands in terms of computing power needs and warehouse management systems could not be easily met at the time, which made it difficult to fully utilize the potential of an autonomous truck. A valuable conclusion from the ROBOLIFT project was that successful development of an autonomous forklift truck requires a close technical and commercial partnership, a good understanding of customer needs (i.e., focus on the real needs that add value to the customer).

The system described by Kelly *et al.* in [6] can be considered among the first systems targeted at developing automated vehicles that do not depend on any artificial guidance infrastructure. The developed AGV system uses vision to achieve navigation tasks, by exploiting naturally occurring visual cues. To guide the vehicle continuously in the working facility, the system uses visual servo controllers and online trajectory generation algorithms. The system was tested in an auto assembly plant for a period of approximately 100 hours.

The University of Hannover and STILL Gmbh [8] together developed an autonomous forklift truck for a warehouse application with navigation using laser scanners and ceiling details and with pallet recognition. It navigates along static paths, like traditional AGVs with beacons, but does not require additional infrastructure like beacons or wires in the floor. There is a very similar commercial autonomous forklift truck system available from Siemens that also navigates using laser scanner and ceiling details. It uses manual "teach-in", i.e. a driver guides the vehicle once and then the vehicle follows this path. Another forklift AGV system is the warehouse transportation system described in [1]. The system comprises an automated forklift equipped with two laser scanners at the front and the rear that allow for 360° range scanning in 2D. The authors consider the problem of optimal location assignment in dynamic warehouses and navigation along static paths. The laser scanners are utilized for mobile robot self-localization, pallet detection, and obstacle avoidance.

A recent project that, like the MALTA project, aims at going well beyond the current Automated Guided Vehicle (AGV) systems is the autonomous forklift project Robo-Forklift at MIT [2]. The Robo-Forklift project, however, has a slightly different focus than the MALTA project: it is directed at a military application scenario (the project can be motivated by saving lives in war and not by efficiency arguments); it looks at voice communication; and it focuses on situation awareness with image input, using a lot of computing power.

The MALTA project focus is on operating in dynamic environments with both humans and other trucks, some manual and some autonomous (see section II for a description of the targeted working environment), and on research problems that are essential to reach a civilian implementation in the near future.

This paper is organized as follows. In section II, we give a description of the working environment. Section III is devoted to presenting the system. Next, section IV describes our simulation tool. Section V summarizes our first test cases, and section VI includes a discussion of the open research issues.

II. THE ENVIRONMENT

As stated above, one of the targeted application environments of the MALTA project are paper production facilities and warehousing terminals. Figure 1 shows few pictures of the targeted working environments. For instance, the first picture is of a warehousing terminal where paper reels are temporarily stored before they are transported to customer sites using cargo trains and lorries. Please note the cylindrical shape of the pillar support shown in the bottom picture, which can be mistakenly detected as a paper reel. This is one of the challenges to the onboard perceptual system.

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 - $800mm$ and a height in the range of 550 - $2800mm$. They are covered with a protection paper/plastic and have printed labels that can be read with a bar code reader.

The environment includes also lorries used to transport paper reels from the paper mill to the terminal. When lorries arrive at the warehouse, clamp-fitted trucks are assigned to unload their cargo in predefined areas of the terminal. 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, lorry trailers, and wagons of cargo trains. The activities of loading/unloading are performed in parallel, which makes the environment highly dynamic.

III. 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 SICK laser rangers 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.

A. *The AGV Controller*

The task of the AGV controller is to provide traditional AGV functionalities. Basically, the controller comprises a set of hardware components that include an onboard PC running Linux and a set of Input/Output modules used as interfaces to control the truck. Communication between the different components of the controller is implemented using the CanOpen protocol.

The main functionality 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 Bsplines. 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 allow for dynamic navigation, the system also accepts runtime trajectories specified as B-splines.

B. *External Module*

The second module of the autonomous system 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 Bsplines 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 [4] that run on an external PC. Communication

Fig. 1. A warehouse of paper reels. Top) Stacked paper reels waiting to be loaded. Middle) A lorry to be uloaded in the warehouse terminal. Bottom) A concrete pillar that has the same cylindrical appearance as a paper reel.

Fig. 2. The industrial truck used in the MALTA project. The truck is retrofitted with an AGV controller and a reflector-based localization laser for guidance purposes. Two Sick lasers are also added to the truck for the purposes of reel detection and safe navigation.

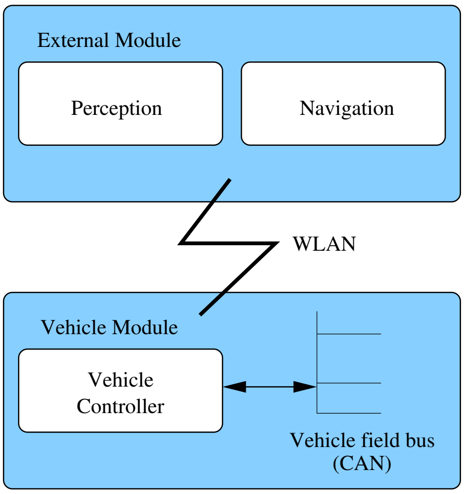


Fig. 3. The modules of the MALTA autonomous system organized into two separate modules that are connected through WLAN. The first module includes the AGV controller that implements a traditional AGV functionalities (navigation using reflective markers). The AGV controller is connected to the CAN network of the vehicle. The second module includes two main components: perception and Navigation. The aim of these two components is to provide autonomous functionalities for detecting paper reels and genearting dynamic navigation paths.

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: Laser range data (coming from the SICK S300 laser) was used for finding the position and diameter of the paper reels as circles. The reels in the warehouse are always standing up. The method used to detect paper reels is based on Taubins work for fitting a circle to data points [13]. 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. 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

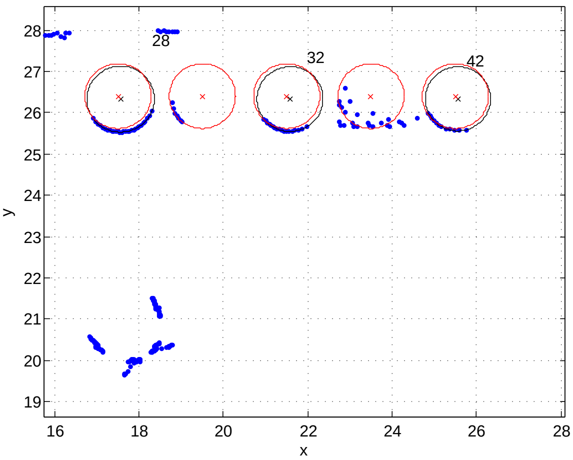


Fig. 4. Paper reels detected by Taubins circle fit method (black). True paper reel positions from AGV control system (red). The range laser also detect the truck paper reel clamps (left bottom).

are rejected.

Figure 4 shows an example situation where paper reels are detected by the perception system. Black circles represent estimated reels from the laser data, while red circles represent ground truth reels that have different vertical positions. For instance, reel number two, from the right, is placed on a high stack of pallets, which resulted in the laser scanner to see the pallets instead of the reel. On the other hand, reel number four, from the right, is not detected, because the clamp was obstruction the laser ranger from getting a sufficient number of scan points of the reel. The laser readings shown in the bottom left corner of the figure represent the obstructing clamp.

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 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.

IV. SIMULATOR/VISUALIZATION TOOLS

For development and debugging purposes of the autonomous vehicle system, without the necessity of using a six ton truck, a 3D simulator has been developed (see figure 5). The simulator is based on the Gazebo, which is part of the Player project [4]. To replicate the navigation interface of the onboard AGV control system, we have implemented a driver to follow trajectories specified as B-splines. The simulated truck is also equipped with a clamp that can be used programmatically to load and unload simulated paper reels. We also developed a client interface to visualize the working environment of the vehicle as well as the raw and processed data (perception information).

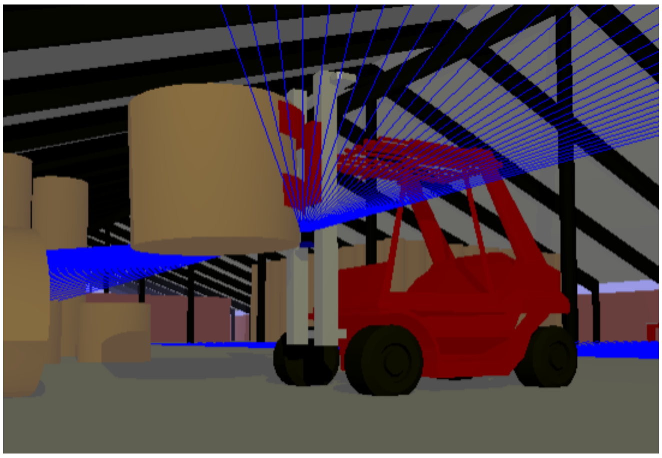


Fig. 5. A snapshot of a simulation of a Linde truck picking up a paper reel in the context of the MALTA project settings.

V. 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 first 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 to pick up a paper reel, the position of the reel and its size together with a path segment leading to it have to be known in advance. In this tests, paper reels were successfully loaded and unloaded from 10 different fixed positions with different elevations. The tests were 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 on the logged data showed that the estimated absolute reel-position error (for the 10 different positions) was $0.027m$ with a standard deviation $\sigma = 0.013m$. 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. It is worth mentioning that the results are dependent on the AGV's positioning accuracy. Please note that the error in reel position (which, in our case, is less than 2% of reel diameter) is taken care of 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 placing a set of reels by a manually-driven truck inside a loading zone. This means that the positions of those reels were not known to the system. This scenario was one of the first requirements that the system should be able to fulfill.

After the reels were placed in the loading zone, the truck was asked to pick them up and place them in a container (see figure 6). To achieve the assigned task, the truck started driving towards a predefined point (point A in the figure) where online-computed paths (Bplines) can be started from. While approaching point A, the perception component was busy acquiring and tracking paper reels inside the loading area. Once at point A, the closest reel was selected as target to approach and pick up. To do so, the online navigation module requested the position of the selected reel and generated and sent a Bspline to the AGV controller, which in turn ordered the truck to follow the generated trajectory. When the truck reached the target reel, the AGV controller proceeded with the loading operation of the reel. Similarly, the transportation of the reel in the container was carried out by following a path including a return spline (to point A) and a set of predefined segments. To ensure that the target reel was picked up appropriately, i.e., avoid the situation of the clamps hitting the reel when turning, the truck was forced to drive straight at the final part of the spline.

VI. DISCUSSION AND CONCLUSION

We have provided an overview of our ongoing work with developing an autonomous robotic material-transportation system. The intended goal is to have a fleet of autonomous forklift trucks operating in dynamic production environments with intermediate storage, loading of containers and train wagons. The system is also intended to work in close cooperation with manual trucks as well as other autonomous trucks. 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 limits in the "off-the-shelf" AGV system that need to be addressed. 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. Figure 7 shows initial results of using reels as landmarks. The positions of the reels are anyway required in terms of loading/unloading operations. The major problem is that the locations of the reels are in constant change, which would make data association difficult. One possible solution to the data association issue is to use the unique bar-code tag of each reel to identify it. However, we do not have the possibility to read it on the fly while passing by. Yet, another motivation for using reels for SLAM is that the 2D laser range-finders (both in the front and the back), required for safety regulations, can be used to extract reel landmarks.

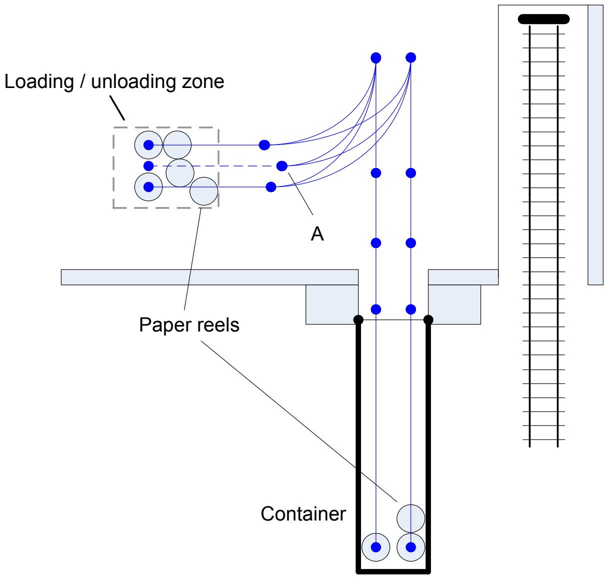
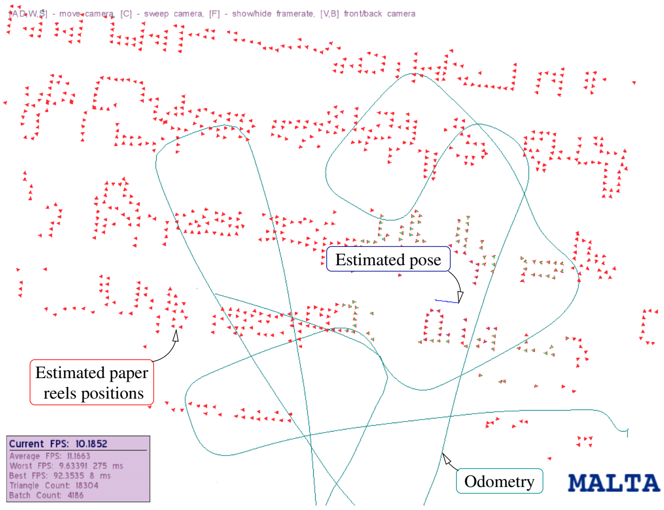


Fig. 6. Loading paper reels from unknown positions inside a loading zone and unloading them in a container. Lines with bullet ends are predefined path segments used by the AGV control system to navigate. The online generated Bspline starts at the first point of the dashed line (i.e., point A).

The second limitation of the "off-the-shelf" AGV control system is it use of predefined paths, which means that the truck is not allowed to change path at runtime. Driving safely the truck with an online generated path is a main issue 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. Up to now reels have been detected using only 2D laser data. Other sensing approaches will be required when stacked reels are handled. One open issue is to detect and handle stacks that contain reels which are slightly shifted horizontally and that could also be sitting on another stack. This is a very dangerous situation, since the connected stack might overturn when lifted. Our intention is to use advanced 3D sensing modalities to detect and handle such situations, e.g., 3D laser scanning and stereo vision.



```
[A,D,W,S] - move camera, [C] - sweep camera, [F] - show/hide framerate, [V,B] front/back camera
```

```
Current FPS: 10.1852
Average FPS: 11.1663
Worst FPS: 9.63391 275 ms
Best FPS: 92.3535 8 ms
Triangle Count: 18304
Batch Count: 4186
```

Fig. 7. Results of a landmark-based SLAM using paper reels (triangles) as landmarks of the environment. The raw odometry and the current pose estimate are also shown.

ACKNOWLEDGMENT

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

REFERENCES

[1] L. Armesto, J. Tornero, and Juan Carlos Torres. Transport process automation with industrial forklifts. In *Symposium on Robots and Control*, pages 655–660, 2003.

[2] Agile Robtics: Autonomous Forklift. http://www.csail.mit.edu/node/549.

[3] G. Garibotto, S. Masciangelo, M. Ilic, and P. Bassino. ROBOLIFT: a vision guided autonomous fork-lift for pallet handling. In *Proceedings of the 1996 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 96)*. IEEE, September 2003.

[4] B.P. Gerkey, R.T. Vaughan, K. Stoy, A. Howard, G.S. Sukhatme, and M.J. Mataric. Most valuable player: a robot device server for distributed control. volume 3, pages 1226–1231 vol.3, 2001.

[5] A. Helleboogh, T. Holvoet, and Y. Berbers. Testing agvs in dynamic warehouse environments. In *Environments for Multi-Agent Systems II, Second International Workshop*, pages 270–290, 2005.

[6] A. Kelly, B. Nagy, D. Stager, and R. Unnikrishnan. An infrastructure-free automated guided vehicle based on computer vision. *IEEE ROBOTICS AND AUTOMATION MAGAZINE*, 14(3):24–34, 2007.

[7] A. Kochan. Robotic production assistants for working alongside the human operator. *Assembly Automation*, 22(1):26–28, 2002.

[8] D. Lecking, O. Wulf, and B. Wagner. Variable pallet pick-up for automatic guided vehicles in industrial environments. In *Proceedings of 11th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, pages 1169–1174, 2006.

[9] J. Marshall, T. Barfoot, and J. Larsson. Autonomous underground tramming for center-articulated vehicles. *J. Field Robot.*, 25(6-7):400–421, 2008.

[10] M. Mellado, E. Vendrell, A. Crespo, P. Lopez, J. Garbajosa, C. Lomba, K. Schilling, H. Sttzle, and R. Mayerhofer. Application of a real time expert system platform for flexible autonomous transport in industrial production. *Computers in Industry*, 38(2):187 – 200, 1999.

[11] MALTA Project. http://aass.oru.se/Research/Learning/malta/index.html.

[12] T. A. Tamba, B. Hong, and K. Hong. A path following control of an unmanned autonomous forklift. *Journal International Journal of Control, Automation and Systems*, 7(1):113–122, 2009.

[13] G. Taubin. Estimation of planar curves, surfaces, and nonplanar space curves defined by implicit equations with applications to edge and range image segmentation. *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, 13(11):1115–1138, Nov 1991.