AUTOMATED GUIDED VEHICLE SURVEY

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Contents

1. Introduction

Automated Guided Vehicles (AGVs) are vehicles capable of autonomously navigating their environment. AGVs are used for a variety of applications, such as transportation of materials, forklifts, automation of port operations, etc. A variety of localization technologies are used in commercially available AGVs, such as guide wires, magnetic beacons, retroreflective beacons for laser guidance, and more. Localization is also an active research area in the academic community, and new localization technologies have been developed that are yet to be deployed on AGVs.

One of the key differences between these navigation technologies is the amount of infrastructure that is required to be built into the environment the AGVs operate in. Some technologies, such as guide wires, require physical wires to be laid along every path that the AGVs will take, while other solutions such as SLAM systems developed in academia don't require any modification of the environment. However, one must also consider the reliability and robustness of these systems if they are to be deployed.

In this document, we provide a survey of localization technologies that are currently in use on commercial AGVs, as well as those developed by the research community. Some common applications of AGVs are also outlined. A survey of commercially available AGVs, their applications, and the localization technologies they use is also included.

2. AGV Systems

2.1. **Introduction.** In this section, we give an overview of several common types of AGVs and their applications. A brief summary of some important topics related to AGV systems is also given.

2.2. **Popular AGV Types / Applications.** AGVs are generally used to transport objects around their environment. There are several popular types of AGVs for accomplishing this in various ways. In this section, we provide a brief overview of several popular types of AGVs.

2.2.1. *Forklifts.* Handling of palletized objects is a popular application of AGVs. Many manufacturers produce forklift type AGVs for this type of application. In most cases, forklift AGVs are not capable of autonomously positioning themselves correctly to lift a pallet due to the accuracy required. These AGVs require a human operator to manually align the forklift. After this manual step, automatic transportation of the load is possible.

A recent system was demonstrated by the University of Hannover in collaboration with forklift manufacturer STILL that is capable of autonomous alignment and lifting of pallets. This work is presented in [1].

2.2.2. *Towing Vehicles.* Many AGVs are designed to tow a load, such as a trailer that needs to be transported between two locations. Such AGVs can often tow extremely heavy loads, though typically they must operate on flat ground or very small grades. This is one of the most common types of AGVs.

2.2.3. *Unit Load.* Unit load AGVs are designed to carry a specific load on top of the vehicle. These sometime include a means for getting a load from a conveyor belt or being loaded by a crane. Once loaded, the unit load AGV is capable of autonomously transporting it's load to a given desitnation.

2.2.4. *Light Load.* Another popular application for AGVs is the transportation of smaller objects, which can be more applicable for non-industrial settings. "Light Load" AGVs are designed to transport a variety of small objects through indoor environments. Example applications for such AGVs are hospital applications, and mail delivery.

2.3. **Free Ranging vs. Fixed Path.** One important distinction between different types of AGVs is the difference between free-ranging vs. fixed path AGVs. Some navigation technologies such as guide-wire navigation restrict AGV movement to a fixed set of paths laid out in the environment. Other technologies, such as laser based navigation techniques allow the robot to move along arbitrary paths within its environment, provided that it remains within the boundaries of its area of operation. This doesn't necessarily mean that the AGVs' environment must be augmented to a lesser degree in the case of free-ranging AGVs, just that a greater range of motion is allowed vs. fixed path AGVs.

2.4. **AGV Control Systems.** AGVs are often deployed in groups, where many AGVs will operate in the same area. An important problem that needs to be solved for such a system is how to effectively control multiple AGVs in an efficient manner while avoiding collisions and traffic congestion. This is a large part of what many AGV providers supply with an AGV system. Such control systems will not be covered in this document; the focus will instead be on localization technologies.

2.5. **AGV Safety Systems.** Safety is one of the primary concerns of many AGV manufacturers. Modern AGVs are equipped with a variety of safety equipment to ensure that collisions with people, the environment, and other AGVs can be avoided.

SICK Laser scanners can be used to accurately detect people or obstacles in the path of the AGV, and are used by many AGV manufacturers to cause the vehicles to slow and stop when obstacles are present in the path. The sensor is typically mounted near ground level so that most obstacles are within view of the sensor.

Other sensors, such as Infrared distance sensors or ultrasonic (sonar) distance sensors are sometimes used instead. Many AGVs are also equipped with physical bump sensors which will stop the vehicle if a physical collision occurs. Finally,

emergency stop systems are also common in AGVs, allowing users to stop AGV motion by pressing a button.

2.6. **Automatic Charging Systems.** AGVs are usually powered by batteries, and so they must be periodically recharged. Many AGV producers have developed automatic charging systems that allow AGVs to autonomously recharge themselves when necessary. This can occur either using a system that physically swaps batteries on the AGV, allowing it to go back to work immediately, or by docking the AGV and charging the the battery while it is still inside of the vehicle.

3. Navigation Technologies

3.1. **Introduction.** In this section, we present the most popular techniques for localization of commercial AGV systems. A brief description of each technique and its related issues is given.

3.2. **Inductive Guide Wire.** This navigation technique involves placing wires in the floor of the work area that correspond to the routes the AGVs will travel upon. The AGVs include sensors that can detect these wires, and the navigation consists of following the wires embedded in the floor to the destination. Junctions and multiple paths are handled by embedding multiple wires, and activating different wires depending on the desired path of the AGV. An example of how this method works is shown in figure 1.

This was one of the earliest methods of AGV navigation, but it appears to be less popular in modern AGVs. The technique requires a large amount of augmentation of the environment, as wires must be embedded in the floor for each path that an AGV can travel upon.

3.3. **Optical Guidepath.** A similar technology is optical guidepath navigation. This method also involves fixed paths, but instead of a wire on the floor, an stripe of ultraviolet reactive material is applied to the floor. This can be paint or UV reactive tape. The vehicles that are to follow this guidepath are equipped with ultraviolet light emitters and detectors. The control system for the vehicle identifies the stripe on the floor, and makes the necessary adjustments to the vehicle heading to remain on the guidepath.

This navigation method requires less augmentation of the environment than guide wire localization. However, AGVs are still restricted to fixed paths using this method.

3.4. **Magnetic Beacons.** This method involves small magnetic beacons embedded in the floor of the AGV's workspace. As with the guide wire method, the environment's floor must be augmented extensively to allow AGV operation. This technique is used in conjunction with the vehicle's wheel odometry, and often also inertial guidance using a gyroscope. The vehicle's pose is tracked with respect to a predefined map of the workspace using odometry and/or the inertial guidance

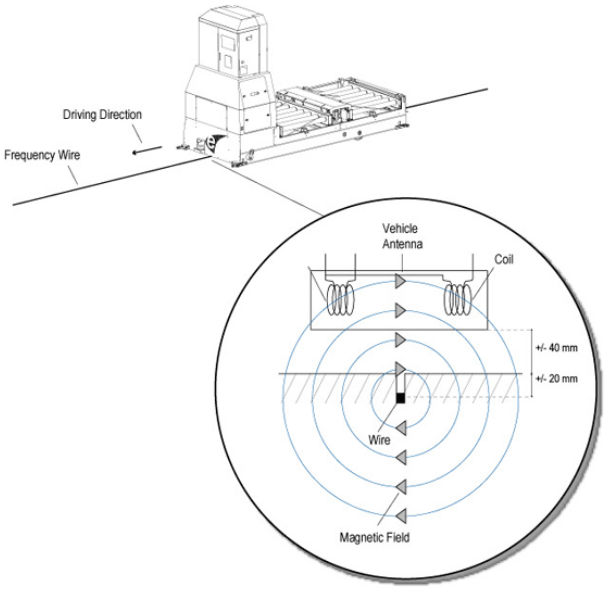

FIGURE 1. AGV Platforms can follow guide wires embedded in the floor. SOURCE: Egemin Automation USA Web Site [2]

system. This map also includes the positions of the magnetic beacons that are embedded in the floors. The vehicle is equipped with a sensor that can detect these magnets, and the readings of the poses from these are used to correct the pose of the robot. The magnets serve as fixed landmarks in known positions with respect to the map, so any drift that takes place in the odometry or inertial guidance can be corrected. One AGV company that uses this technique is Frog AGV Systems, and they claim this system to be as accurate as laser based localization systems[3]. A figure demonstrating how magnetic beacons can be used for localization is shown in figure 2.

In contrast to guide-wire navigation and optical guidepath navigation, this method does not restrict AGVs to movement along fixed paths. The AGVs can move freely throughout the environment as long as they remain in the areas augmented with magnetic markers.

3.5. **Barcodes.** Kiva systems uses a very similar technique, but instead of a grid of magnetic beacons, a grid of optically detectable barcode-like markers is placed on the floor. These barcodes are detected optically, and are used in much the same way as the magnetic beacons described above.

3.6. **Retroreflective Laser Guidance.** In this technique, retroreflective beacons are placed about the work space of the robots, where they will be in view of a scanning laser range finder. The AGV is provided with a map of the work space that includes the locations of the beacons. The pose of AGV with respect to its

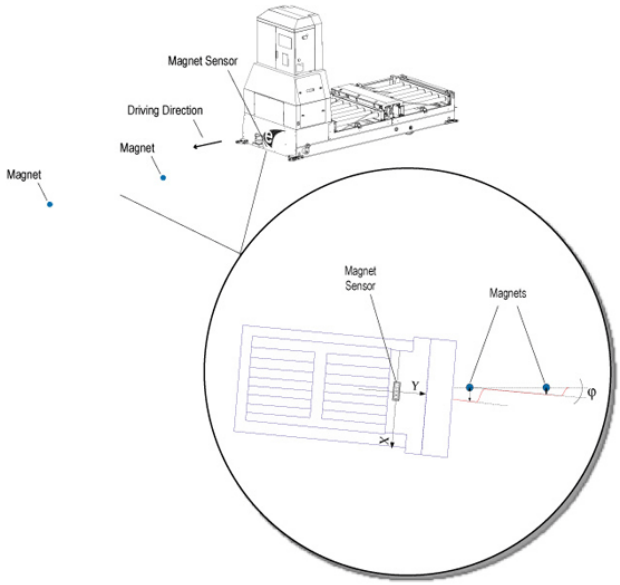

FIGURE 2. Magnets embedded in the floor can be used for platform localization. SOURCE: Egemin Automation USA Web Site [2]

map is computed using the beacon locations. This technique has the advantage that the floor need not be modified when changes to the workspace are made; only the map that the AGVs use to localize must be updated. An example of how such a system works is shown in figure 3.

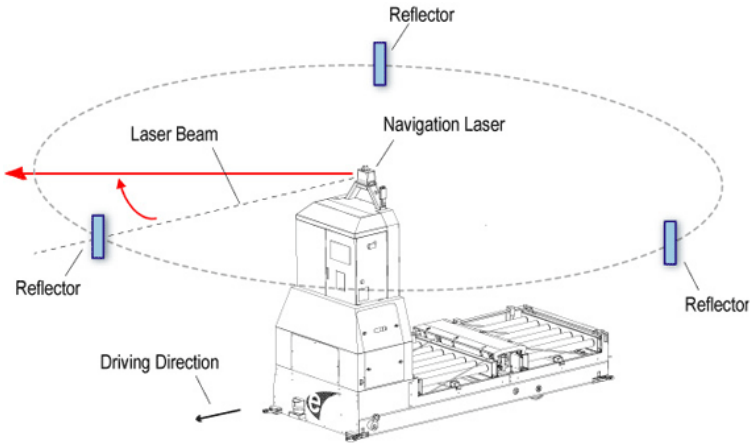

FIGURE 3. An example of how a laser scanner can be used with retroreflective beacons for localization. SOURCE: Egemin USA Web Site [2]

Typically, a manually generated map of the environment is used to define the locations of the retroreflective beacons. This map is also sometimes used to define the routes on which the AGVs may travel, as shown in figure 4.

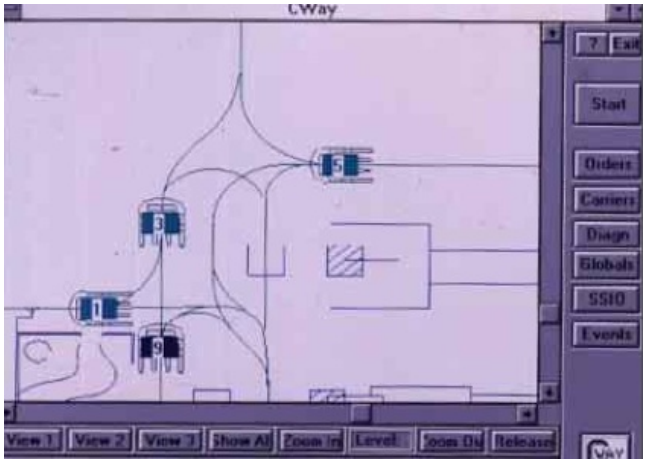

FIGURE 4. A CAD map defining AGV routes. SOURCE: NDC Technology Au Web Site [4]

This method also doesn't necessarily restrict the AGVs to fixed paths; they are capable of localization and navigation in any area where two to three reflective markers are visible.

3.7. **Vision.** One AGV Vendor, Seegrid, uses a vision based technique to localize their robots. Seegrid AGVs are equipped with a multi-camera array. Points in the environment can be triangulated by identifying the same physical point using multiple cameras. Using this technique, the multi-camera system is used to build up a 3D occupancy grid of the area the AGV is to operate in. An occupancy grid in 3D can be thought of as modeling the world by a grid of small cubes. Each cube is marked with its probability of being occupied or free. Once this grid has been built up for the whole environment, the AGV can localize and avoid obstacles by using this model of the environment. Seegrid claims that their system localizes to within 50mm. An example of what such an occupancy grid looks like is shown in figure 5.

3.8. **Infrared Landmark Based Localization.** Another method of localization is localizing infrared light sources at known locations. Evolution Robotics' [6] NorthStar system is one example of this. Evolution's system has two parts: a projector and a receiver. The projector emits Infrared light, and is aimed at the ceiling. The projected light is detected by an IR receiver onboard a mobile platform. By triangulating it's pose based on the emitted light pattern, the mobile device can be localized with respect to the projector.

FIGURE 5. Seegrid's Vision based localization system builds a 3D occupancy grid using a camera array. SOURCE: Seegrid Web Site [5]

The accuracy of this approach depends on a variety of factors, primarily the distance between the emitter and the receiver, as well as the reflectivity of the environment. Accuracy for use in a home environment is 1cm-4cm for position, and 1 degree - 2 degrees for heading under recommended usage. Accuracy for asset tracking applications in larger environments (such as a warehouse or commercial store) is up to 15cm under recommended usage. [6]

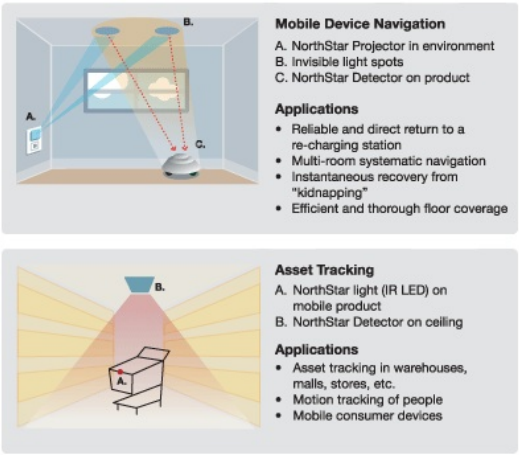

FIGURE 6. Evolution Robotics' NorthStar System. SOURCE: Evolution Robotics Web Site [6]

A similar product is Hagisonic's Stargazer system [7].

4. Research Localization Methods

4.1. **Introduction.** This section focuses on localization techniques that have been developed by the robotics research community. Robot localization and mapping has been a very active field, and many successful approaches have been demonstrated. Because the focus of this document is AGV localization technologies, only localization techniques for indoor vehicles will be presented. Specific attention is given to research results that have been demonstrated in real-world environments, and systems that have been shown to be able to provide highly accurate localization while being robust.

4.2. **Extended Kalman Filter.** The Extended Kalman Filter is a popular localization algorithm. A detailed description of the underlying technique is beyond the scope of this document, but can be found in [8].

One of the most accurate localization results from the research community uses this technique. This system was developed by Patrick Jensfelt at KTH, and is presented in [9]. It consists of a mobile robot that was used for marking booth locations at the Stockholm International Fair. The system utilizes a SICK laser range finder, and requires no augmentation of the environment. One of the key features of this system is that it is capable of operating in very large indoor environments, such as an exhibition hall that is 70m by 270m. The average localization error was 28mm, making this one of the most accurate localization methods available for a large indoor areas.

This system uses a feature-based approach to the localization problem. The environment in which the robot localizes is a very large, open exhibition hall. There are many columns/pillars with several shapes that exist throughout the environment. The features used for localization are the walls, as well as these pillars. The iterative closest point (ICP) algorithm [10] is used to accurately match the laser scans with the pillars.

The map used by this system is a manually generated CAD (Computer Aided Design) map of the environment. This map can be easily edited using standard commercial CAD packages, allowing it to be easily kept up to date when there are changes to the environment. The accuracy of the map used was 1cm-2cm.

The features that are detected are tracked, and an Extended Kalman Filter (EKF) is used to localize the robot. The robot's wheel odometry is used in conjunction with the features that are detected to maintain an accurate pose estimate.

4.3. **SLAM.** SLAM stands for Simultaneous Localization and Mapping. This has been an active research area for many years, and includes many map building techniques, utilizing a variety of sensors. Many techniques have been developed that are capable of map building and localization [8]. This problem has been addressed for a variety of environments, including indoor environments, outdoor environments, and underwater environments. Because mapping and localization are performed concurrently in these techniques, this is a more difficult problem

than localization alone. A survey of some SLAM techniques is presented in [11] and [12].

Note that SLAM is a harder problem than localization alone, because a map is not provided. Instead, the map must be estimated by the robot. SLAM is generally not applied to AGVs, as it is a more recently developed approach, and has had less testing in industrial settings.

5. Survey of Commercial AGV Systems

5.1. **Bluebotics.**

5.1.1. *URL.* http://www.bluebotics.com

5.1.2. *Description of Vehicles.* Bluebotics is a Switzerland based robotics company that produces a variety of robots, including several AGVs. The most traditional AGV that Bluebotics produces is a small forklift type AGV, made in conjunction with Esatroll. The vehicle is called the Paquito, and is capable of lifting up to 1200kg.

Bluebotics also produces the AMV-1 "Autonomous Modular Vehicle". This platform is capable of transporting small loads of up to 150kg. It is "modular" because several attachments for carrying different payloads are available, such as small goods, or a chair module for transporting a person.

Several non-AGV robots are also produced by Bluebotics, such as the Shrimp III mobile robot, which is suitable for all-terrain use, and several "entertainment" robots.

5.1.3. *Description of Applications.* The Paquito AGV forklift is targeted at the material handling market, such as transportation of palletized goods. The AMV-1 is suitable for smaller loads, and is targeted at the hospital/healthcare market, and other applications that require handling of small loads.

5.1.4. *Navigation Technology Used.* Bluebotics has a proprietary localization technology called ANT. ANT localizes using the laser range finder for localization, and does not require reflectors. No details about the localization method used are published.

5.1.5. *Photo.* Photos of Bluebotics platforms are shown in figures 7 and 8.

5.2. **Danaher Motion (Formerly NDC Technology).**

5.2.1. *URL.* http://www.danahermotion.com http://www.ndc.se

FIGURE 7. The Bluebotics Paquito. SOURCE: Bluebotics Web Site [13]

FIGURE 8. The Bluebotics AMV-1. SOURCE: Bluebotics Web Site [13]

5.2.2. *Description of Vehicles.* Danaher Motion's current line of AGV products includes their modular "NDC8" technology, which is a modular AGV control system. AGV suppliers can purchase this control system (with sensors, as well as controllers for AGVs) to integrate into their own AGVs.

Danaher Motion also produces a system called Pick-n-Go, which allows forklifts / trucks to follow users for use in order picking applications. Details of how the autonomous person-following is achieved were not published.

5.2.3. *Description of Applications.* Danaher Motion's technologies are not standalone AGVs, but AGV control systems and sensors [14]. These products are targeted at AGV suppliers, and are meant to be integrated into vehicles produced by others.

5.2.4. *Navigation Technology Used.* Danaher Motion's NDC8 AGV Control System supports several types of navigation, including guide wires, magnetic tape or beacons, or laser guidance [14].

Danaher Motion's laser localization system is called "LazerWay". This system consists of a scanning laser range finder on each vehicle, and retroreflective targets positioned around the environment. A manually generated CAD model of the environment is used. This type of system is described in detail above at the retroreflective laser guidance section.

5.2.5. *Photo.* Photos are shown in figures 9 and 10.

FIGURE 9. A forklift equipped with Danaher Motion's Pick-n-Go system. SOURCE: Danaher Motion Web site [14]

FIGURE 10. Danaher Motion's LazerWay Sensor. SOURCE: Danaher Motion Web site [14]

5.3. **Egemin Automation.**

5.3.1. *URL.* http://www.egemin.com/

5.3.2. *Description of Vehicles.* Egemin produces a variety of AGVs for different material handling tasks. Forklift type AGVs are available in a variety of shapes and sizes for transporting pallets and other loads. Tug type AGVs and unit load AGVs are also available for transporting large or heavy loads.

Egemin also produces some smaller AGVs for handling smaller loads. The Packmobile AGV is a small vehicle equipped with a small rack of shelves. This vehicle can carry loads of small objects. A specialized version of this vehicle is also produced for mail distribution.

5.3.3. *Description of Applications.* Egemin's forklift, tug, and unit load AGVs are targeted at industrial material handling. Some of the highlighted applications include automotive industry, food processing, paper handling, and warehouse distribution systems [2].

The Egemin packmobile is targeted at smaller material handling jobs such as the healthcare industry or cleanroom operations. The mailmobile device is intended for mail delivery applications.

5.3.4. *Navigation Technology Used.* Egemin Automation's industrial AGVs can use guide wires, magnetic beacons, or laser based localization with retroreflective targets. These methods are as described above in the Navigation Technologies section.

The Packmobile and Mailmobile AGVs both use optical guidance by following a ultraviolet reactive line (either paint or tape).

5.3.5. *Photo.* Photos of Egemin AGVs are shown in figures 11, 12 and 13.

FIGURE 11. An Egemin Packmobile AGV. SOURCE: Egemin Web Site [2]

FIGURE 12. An Egemin Forklift AGV. SOURCE: Egemin Web Site [2]

FIGURE 13. An Egemin tug AGV. SOURCE: Egemin Web Site [2]

5.4. **Esatroll.**

5.4.1. *URL.* http://www.esatroll.com

5.4.2. *Description of Vehicles.* Esatroll produces a wide range of vehicles, including many sizes of unit load AGVs, forklift AGVs, and custom AGVs. Vehicles are available for payloads ranging from 200kg to 16 tons.

5.4.3. *Description of Applications.* Esatroll's AGVs are targeted at the industrial material handling market.

5.4.4. *Navigation Technologies Used.* Esatroll AGVs can use wire guidance, magnetic beacons, or retroreflective laser guidance, depending on the application. Magnetic guidance is typically preferred for outdoor systems or indoor systems where reflectors may be often occluded. Wire guided AGVs are also available for simple applications where fixed paths are sufficient. These methods are described above in the Navigation Technologies section.

FIGURE 14. An Esatroll Forklift AGV. SOURCE: Esatroll Web Site [15]

FIGURE 15. An Esatroll Unit Load AGV. SOURCE: Esatroll Web Site [15]

5.4.5. *Photo.*

5.5. **Frog AGV Systems.**

5.5.1. *URL.* http://www.frog.nl

5.5.2. *Description of Vehicles.* Frog AGV Systems manufactures a variety of AGV platforms, including box runners and pallet movers. Frog also designs custom vehicles for customers' applications that have unusual requirements such as extremely heavy or large loads.

In addition to full AGV systems, Frog also distributes AGV components. This includes sensors, such as Frog's Magnetruler sensor for detecting their magnetic beacons or various obstacle avoidance sensors. They also sell their FROG-box vehicle controller, which can interface with sensors and wheel odometers to calculate vehicle position, drive the AGV, and communicate with the AGV control system. The SuperFROG AGV control system is also available. This system controls a multiple AGV system, and handles traffic flow, job assignment, and other tasks.

5.5.3. *Description of Applications.* Frog AGVs are targeted at material handling applications for industrial settings. Highlighted industry applications include automotive, healthcare, metal industry, pharmaceuticals, and food distribution [3].

5.5.4. *Navigation Technology Used.* Frog AGV systems produces AGVs that can localize using any of several localization methods, including inductive wires, their proprietary magnetic beacon system, or laser guidance. The technology used depends on the application and environment in which the AGVs will be operating.

The Frog name stands for Free Ranging On Grid, which refers to Frog's proprietary navigation technology. This technology consists of a grid of small magnets embedded in the floor throughout the AGVs' work area. The AGVs track their position using gyroscopes as well as wheel odometry, and correct errors using measurements taken on the magnets embedded in the floor.

5.5.5. *Photo.* Photo of a Frog AGVs are shown in figures 16 and 17.

FIGURE 16. A pallet carrying AGV. SOURCE: Frog Web Site [3]

FIGURE 17. A large custom Frog AGV. SOURCE: Frog Web Site [3]

5.6. **HK Systems.**

5.6.1. *URL.* http://www.hksystems.com/agv/

5.6.2. *Description of Vehicles.* HK Systems produces a variety of AGVs for the industrial market. This includes several models of unit load and forklift type AGVs, and some.

5.6.3. *Description of Applications.* Some of the highlighted applications include material handling for aerospace, automotive, clean room, food processing, manufacturing, pharmaceuticals, and warehousing.

5.6.4. *Navigation Technology Used.* HK Systems uses a magnetic guidance type navigation system, which they called the Eagle System. HK Systems AGVs can also be equipped with retroreflective laser guidance systems. Both of these techniques are described in the navigation technologies section above.

5.6.5. *Photo.* An example of an HK Systems AGV is given in figure 18.

FIGURE 18. An HK Systems unit load AGV. SOURCE: HK Systems Web site [16]

5.7. **JBT Corporation.**

5.7.1. *URL.* http://www.jbtc-agv.com/

5.7.2. *Description of Vehicles.* JBT Corporation produces a variety of AGVs, including forklift type AGVs, Tugger AGVs, and Unit Load AGVs. They produce ten configurations of forklift type AGVs for handling different sided pallet loads in various environments. Several unit-load type AGVs are available, which can include conveyors or lifts if required by the application. JBT's tug type AGVs can be configured to tow a variety of platforms and loads. Custom AGVs can also be produced to suit a customer's application.

5.7.3. *Description of Applications.* The primary application is material handling in an industrial setting. Some of the highlighted applications include automatic trailer loading, raw material handling, supply delivery, and pallet handling [17].

5.7.4. *Navigation Technology Used.* JBT Corporation supplies AGVs that use laser based navigation. The method used is as described in the navigation section above.

5.7.5. *Photo.* Photos of JBT Corporation AGVs are shown in figures 19, 20, and 21.

FIGURE 19. JBT Corporation Tug AGV. SOURCE: JBT Corp Web site [17]

5.8. **Kiva Systems.**

5.8.1. *URL.* http://www.kivasystems.com

FIGURE 20. JBT Corporation Pallet Handling AGV. SOURCE: JBT Corp Web site [17]

FIGURE 21. JBT Corporation Fork AGV. SOURCE: JBT Corp Web site [17]

5.8.2. *Description of Vehicles.* Kiva makes small AGVs that are designed to fit under specially designed racks of equipment. These AGVs are equipped with a special mechanism that is capable of lifting the fully loaded rack of equipment, and moving while supporting this load. The AGVs come in two sizes to lift two different sizes of racks.

5.8.3. *Description of Applications.* Kiva's AGVs are used for distribution systems. Their system is designed to bring racks of products to human workers. The human workers then pack and ship the goods from the equipment racks. Many of the AGVs operate concurrently in a warehouse to bring the products to the workers.

Example applications are distribution centers for online purchases, such as Zappos (online shoe retailer), and Walgreens (pharmacy).

5.8.4. *Navigation Technology Used.* Kiva Systems' AGVs navigate using their wheel odometry, corrected by barcode markers placed on the floor of their area of operation. This technology is described above in the barcode section. Detailed accuracy information is not published.

5.8.5. *Photo.* A photo of a Kiva robot is shown in figure 22.

FIGURE 22. A Kiva Systems AGV, shown with human and rack. SOURCE: Kiva Systems Web site [18]

5.9. **Mobile Robots.**

5.9.1. *URL.* http://www.mobilerobots.com/

5.9.2. *Description of Vehicles.* Mobile Robots manufactures a variety of robots, some of which are suitable for use as AGVs. Robots from this company are popular as research platforms in the academic community. Some of these platforms are advertised for use as AGVs for material handling. These vehicles are smaller than most industrial AGVs, the smallest of which handles 10kg, the largest up to 100kg.

Additionally, Mobile Robots sells their ARCS Robot controllers for use in other AGVs, such as the RMT Robotics ADAM AGV.

5.9.3. *Description of Applications.* These robots are targeted at smaller material handling tasks. Some of the highlighted applications include transportation of medical specimens, as well as delivery of manufactured goods [19].

5.9.4. *Navigation Technology Used.* Mobile Robots' AGVs localize using a Monte Carlo Localization approach, but the specific details of the localization system are proprietary. Information and references on Monte Carlo Localization are described in the Navigation Technologies section above. A SICK Laser Scanner, an internal gyro, and wheel odometry are used to accurately estimate the AGV's position with respect to it's environment. These AGVs can be used to build a map of their environment; a manually generated map need not be used. The claimed accuracy of the system is +/- 150mm.

5.9.5. *Photo.* Photos of Mobile Robots' platforms are shown in figures 23 and 24.

FIGURE 23. Mobile Robots' Powerbot Platform. SOURCE: Mobile Robots Web site [19]

FIGURE 24. Mobile Robots' Patrolbot Platform. SOURCE: Mobile Robots Web site [19]

5.10. **NDC Technology Australia.**

5.10.1. *URL.* http://www.ndcta.com.au/

5.10.2. *Description of Vehicles.* NDC Technology Australia is a partner of Danaher Motion (Formerly NDC Technology). As described in the Danaher Motion section of this document, Danaher provides AGV control systems and sensors that AGV suppliers can use in their vehicles. NDC Technology Australia is one such supplier, and produces a variety of AGVs using Danaher Motion's technology.

A variety of AGVs are available, including several forklifts of varying capacities, several pallet conveyor AGVs, as well as several heavy load AGVs.

5.10.3. *Description of Applications.* NDC Technology Australia's AGVs are targeted at the material handling market for industrial settings. Pallet transportation, paper reel moving are some of the highlighted applications[20]. Custom AGVs can also be designed for specialized applications.

5.10.4. *Navigation Technology Used.* As a partner of Danaher Motion, the AGVs produced here use Danaher Motion's navigation technologies (see the Danaher Motion section of this document). Several navigation technologies are supported, including guide wires, magnetic beacons, and laser guidance. However, laser guidance is used in over 95% of their systems[20].

5.10.5. *Photo.* Photos are shown in figures 25, 26, and 27.

FIGURE 25. An NDC Technology Forklift AGV. SOURCE: NDC Technology Web site [20]

5.11. **RMT Robotics.**

5.11.1. *URL.* http://www.rmtrobotics.com http://www.adam-i-agv.com/

FIGURE 26. An NDC Technology Pallet Conveyor AGV. SOURCE: NDC Technology Web site [20]

FIGURE 27. An NDC Technology Heavy Load AGV. SOURCE: NDC Technology Web site [20]

5.11.2. *Description of Vehicles.* RMT Robotics makes an AGV called the ADAM. This AGV is capable of autonomously transporting relatively small goods placed on top of the platform. The platform is round, and approximately 1m in diameter. It's payload is up to 150kg.

5.11.3. *Description of Applications.* This AGV is targeted at material handling tasks. The highlighted application is transportation of automotive tires in a tire manufacturing setting [21].

5.11.4. *Navigation Technology Used.* The ADAM uses a MobileRobots ARCS PC in conjunction with a SICK laser range scanner. This system does not use retroreflective targets, but instead by matching laser scans of the environment to a prebuilt map. The claimed accuracy for this system is +/- 150mm for position and +/- 1 degree for orientation under normal operating circumstances [21]. The positional accuracy can be increased to 15mm for specific points by using a target. Please see the Mobile Robots section of this document for more information.

5.11.5. *Photo.* A photo of the ADAM AGV is shown in figure 28.

FIGURE 28. RMT Robotics' ADAM AGV. SOURCE: ADAM Web site [21]

5.12. **Seegrid.**

5.12.1. *URL.* http://www.seegrid.com

5.12.2. *Description of Vehicles.* Seegrid currently produces two types of AGVs: a tug type AGV, and a pallet carrier type AGV. The GT3 tug AGV is capable of hauling carts between specified locations. The GP8 pallet carrier is capable of autonomous navigation, but a human operator must position the fork on the pallets in order to pick up a pallet. Autonomous navigation to another point and autonomous drop-off is then possible.

5.12.3. *Description of Applications.* Seegrid's AGVs are targeted at the material handling market, such as distribution centers.

5.12.4. *Navigation Technology Used.* Seegrid's AGV use a vision based localization technique, as described above in the Navigation Technologies section. This technique utilizes a multi-camera rig to build up a 3D occupancy grid of the environment. Once such a map has been generated, the vehicle can localize itself with respect to this map. The claimed accuracy for this system is 50mm. This occupancy grid is used for localization.

Note that Seegrid AGVs are also equipped with SICK laser scanners for collision avoidance. These sensors are not used for localization.

5.12.5. *Photo.* A photo of a Seegrid AGV is shown in figure 29.

FIGURE 29. A Seegrid GT3 Tugger type AGV. The camera array is on top of the pole. SOURCE: Seegrid Web site [5]

5.13. **Snox Engineering Group.**

5.13.1. *URL.* http://www.snox.com

5.13.2. *Description of Vehicles.* Snox produces a range of AGVs, including a tug type AGV, a box carrier, a forklift. The snoxCart AGV can be used either as a carrier for loads of up 800kg, or it can be used as a tug type AGV for loads of up to 2.5 tons. The snoxStacker AGV is a forklift type AGV capable of lifting pallets weighing 600 kg or more depending on configuration. Custom AGVs can also be designed for other applications.

Snox also sells their Snoxbox controllers, which allow AGVs (even AGVs from other manufacturers) to be upgraded. These controllers are capable of localizing via guide wires, magnetic guidance, or laser guidance. This allows outdated AGVs, or vehicles that are no longer supported to be used with modern navigation systems.

5.13.3. *Description of Applications.* Snox's AGVs are aimed at the industrial material handling market. Highlighted applications include several manufacturing scenarios[22].

5.13.4. *Navigation Technology Used.* Snox AGVs can localize by using guide wires, magnetic guidance, or laser guidance. The Snoxbox controller can localize using any of these methods if equipped with appropriate sensors. The technology used is decided depending on the application at the time of installation.

5.13.5. *Photo.* Photos of Snox AGVs are shown in figures 30 and 31.

FIGURE 30. A snoxCart tug type AGV. SOURCE: Snox Web site [22]

FIGURE 31. A snoxStacker forklift type AGV. SOURCE: Snox Web site [22]

5.14. **Swisslog.**

5.14.1. *URL.* http://www.swisslog.com/

5.14.2. *Description of Vehicles.* Swisslog manufactures an AGV called the TransCar. The Transcar is designed to fit several designs of standard hospital carts. The carts are lifted by the AGV, and automatically transported between user specified locations. The TransCar is capable of transporting loads of up to 450 kg. The vehicle is capable of autonomous navigation, as well as obstacle and person avoidance.

Swisslog also produces equipment that allows the AGV to automatically call an elevator. This allows the AGV to access multi-story buildings.

5.14.3. *Description of Applications.* Swisslog's AGVs are targeted at the healthcare industry. These AGVs are meant to transport goods throughout hospital environments [23].

5.14.4. *Navigation Technology Used.* Swisslog's AGVs localize using data from SICK laser rangefinders and a manually generated map. Swisslog provides an application for manually generating maps for use in localization. The details of the localization technique used are not published in their literature.

5.14.5. *Photo.* A Swisslog TransCar AGV is shown in figure 32.

FIGURE 32. The Swisslog TransCar AGV, carrying a hospital cart. SOURCE: Swisslog Web Site [23]

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