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Roger Bostelman
Tsai Hong
Intelligent Systems Division
Engineering Laboratory

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Roger Bostelman, Tsai Hong

Abstract

This paper provides a literature review of docking research, an area that has relatively few research articles as compared to generic automatic guided vehicle (AGV) or mobile robot research. Docking refers to the arrival and stopping at a position relative to another object. Docking can include positioning the vehicle or the equipment onboard the vehicle relative to another object, for example a tray station, trailer, or pallet. The paper is expected to be useful to ASTM Committee F45 for development of docking and navigation standards and to industrial vehicle research communities as basis to further docking research. The paper covers research on vehicle control for docking and on the use of sensors combined with intelligent vehicle control. Docking research on AGV or mobile robots with onboard robot arms is also included. Other related research described includes flexible cells and docking of other than ground vehicles, e.g., unmanned surface vehicles. Closing the survey is a discussion of patents related to docking and an extensive list of references.

Index Terms: survey, dock, docking, AGV, mobile robot, docking patents, standards.

Introduction

Automatic guided vehicles (AGVs)[1] are used in a variety of industrial settings, including factories and hospitals, to transport materials from one location to another. AGVs move automatically using preprogrammed stop points, typically 1) navigating via laser triangulation [1] using offboard path planning and vehicle control. Mobile robots provide similar functionality, although they typically use simultaneous localization and mapping [2] and/or other fiducial-following methods with onboard path planning and vehicle control.

AGVs and mobile robots are designed to execute pickup/delivery services between pickup/delivery stations. To do so, the vehicle must be able to navigate between stations and perform precise docking maneuvers. Docking can be referred to as the arrival and act of stopping at a position relative to another object prior to performing a load transfer or other object-connection (e.g., assembly) operation between an AGV or mobile robot and another vehicle or equipment/object, for example with a roller table, rack, trailer, cabinet, or object. Docking requires more precise control than navigation to avoid collision with the station or the load and to ensure a correct load transfer or connection with the object. Without such precise control, docking maneuvers can damage the load, the station, and the vehicle [3]. Mandel and Duffie also state that current docking accuracy is limiting the industrial applications of AGVs and mobile robots. [4]

Precise docking control requires generic definitions of terms. Within ASTM Committee F45 Driverless Automatic Guided Industrial Vehicles [5], ASTM subcommittee F45.91 has drafted, in working document WK48954, definitions for many terms, including 'dock' and 'docking':

- dock, n—target location where the vehicle interacts with another object.
- docking, v- the arrival and act of stopping at a position relative to another object.

Such generic definitions will allow vendors and users to utilize the exact same terminology when discussing the various capabilities of AGVs and mobile robots. Docking operations could include not only docking of the vehicle (AGV or mobile robot) but also docking of equipment onboard the vehicle

[1] Disclaimer: NIST does not endorse products discussed within this paper nor manufacturers of these products. Products mentioned are for information purposes only and are not expressed as an endorsement for them or their manufacturer.

such as an apparatus or a robot arm, with other vehicles or facility equipment. Safety during both navigation and docking is important.

Industrial vehicle standards exist [6, 7], or are being developed [8], for safety; but only for AGVs and people/equipment near AGVs. Within at least [6], there are no specific safety requirements for docking operations or methods. However, there are specifications for non-contact safety sensors and bumpers that are used to detect obstacles, equipment, and people near the vehicle. These vehicle safety sensors, however, are not typically designed for use near docking equipment, such as tray stations and racks. They will detect the presence of the equipment and cause the vehicle to initiate an emergency stop[2]. The standard requires powered, load-handling devices to have an interlock when used in conjunction with powered, load-handling stands or devices external to the vehicle. Furthermore, the standard requires a signal confirming proper vehicle alignment prior to activation of any load transfer mechanism.

To complement the above stopping and safety-related standards, ASTM Committee F45 is developing performance-related standards for industrial vehicles. The work is organized according to the following subcommittees: ASTM F45.91 deals with terminology, F45.01 with environmental effects, F45.02 with docking and navigation, and F45.03 with obstacle detection and protection. New working documents are being developed for 'Navigation in Defined Spaces' (WK48955) and 'Docking' (WK50379). These documents, however, are based on minimal background research on the theory and methods behind vehicles, and their onboard equipment, docking with another object.

This paper includes results of a search of relevant scholarly research and industrial patents using the term 'dock' and of interviews with industry contacts. The beginning docking research section includes prior general literature reviews on navigation and docking. Following are specific research discussions on control, sensors with intelligent vehicle control, and mobile robots with robot arms. Sensors combined with intelligent vehicle control change the control methodology to include environmental sensing for planning and actuation. Moreover, the addition of an onboard robot arm provides further complexity to vehicle controls. Other related research is then provided covering manual, multi-robot, space, and surface vehicle challenges. A section on cross-docking is provided to ensure that there is no confusion in vehicle docking and the term cross-docking which typically covers material handling directly from receiving to shipping areas in distribution facilities. Lastly, five patents on docking-related equipment are discussed: a sensory interactive docking module, a robot arm onboard a vehicle for material handling, an automatic charging system, a docking platform, and docking station.

These results provide a basis for developing new docking-related performance standards for industrial vehicles, such as AGVs and mobile robots. The paper also discusses research associated with cross-docking. Cross-docking is a concept associated with material handling and distribution in which goods move directly from receiving to shipping. We have included a section on cross-docking because it includes unstructured navigation and docking. A list of references is then provided to allow the reader to delve further into specific docking research areas of interest.

Docking Research

Docking research has been ongoing in several areas since inception of automated guided vehicles in the 1950's. This section first divides docking research into general literature reviews that provide other compilations of past research, although with different intended focus than this document. Following

[2] Note: areas around docking equipment are called hazard or restricted areas. People should not be present in these areas. But, if they are, the vehicle safety sensors should detect them and cause an emergency stop.

are sections on control, sensors and intelligent vehicle control, mobile robots with robot arms, and other related research. Since docking cannot occur without navigation to the docking location, navigation is also embedded within the surveyed docking research.

General Literature Review

Arkin and Murphy, Rooks, and Vis have compiled general literature reviews describing the state-of-research on navigation and docking. Arkin and Murphy [9] described some of the earliest research methods that were proposed for achieving mobility of autonomous vehicles in the workplace. They presented an overview of the autonomous robot architecture (AuRA), which was designed to facilitate intelligent mobility/navigation. They also described the changes needed to adapt AuRA to new domains for flexible manufacturing systems. The changes included the new types of knowledge and the new motor behaviors required for this domain. Finally, they discussed the results of both simulations of, and real experiments of, navigational planning and reactive/reflexive motor schema-based navigation in that domain.

In 2001, Rooks [10] described different uses of AGVs across a range of industries and applications. For example, he described how at one manufacturing facility, AGVs were used as tugs to tow trailers delivering components to production lines, while at another, they carry both part kits and finished engines to and from assembly dressing lines. At yet another facility, they handled heavy paper rolls and served coating machines. These applications use traditional embedded wire navigation technology. Other guidance techniques were also described, including laser scanners which are being applied in a Belgian fruit and vegetable market to transport pre-packed products to dispatch lines. Specific to docking, Rooks details an automatic docking system and a standard pallet truck that is available as a complete automated package with laser guidance.

Vis [11] discussed literature related to the design and control of AGV systems in four different applications: manufacturing, distribution, trans-shipment, and transportation. The author concluded that new analytical and simulation models were needed for large AGV systems to overcome large computation times, NP (nondeterministic polynomial)-completeness, congestion, deadlocks, and delays in the system and finite planning horizons. The author concluded that more specific research is needed in the design and control of large AGV systems in the application areas of distribution, trans-shipment, and transportation.

Control

Vehicle control is a major research topic for both navigation and docking. The earliest form of AGV navigation was based on following electrical wires buried in the floor, or reflecting lines painted on it; some vehicles still operate using this mode. This made adaptation to changes in production or warehousing processes elaborate and costly because changes in vehicle paths required changes in factory infrastructure to modify the guidance paths. Some newer AGV systems use beacons, which make changes easier, but these systems are typically not yet capable of avoiding obstacles. Very recently, computers have become a common navigation component in AGVs. Practical limitations, however, with either a central or an on-board computer mean that a certain level of autonomy is needed for navigation. For example, a central computer typically stops a vehicle from entering a location occupied by another vehicle. An onboard computer with added intelligence may be capable of surpassing the stopped vehicle. However, in both cases, for computational simplicity, the basic planned paths consist of straight lines or `lanes'. To enable the vehicles to change lanes, without stopping to turn, while staying on the planned path, curves with a continuous curvature are needed. Van der Molen and Geerts [12] describe the application of clothoids to enable changing between lanes.

These clothoids envelope boundaries that encompass the `swipe-out' area occupied by the vehicle during motion.

Ilić [13] examined some of the general principles and analysis methods that are used to design AGVs for automated material handling tasks. Specifically, their research focused on an AGV system (AGVS) that is especially suitable for handling and transporting materials in discrete-product manufacturing. These systems are most applicable for the automation of low-and medium-volume handling situations, where the routing of materials to docking locations is more individualized. Ilić developed a new quantitative method for analyzing these systems giving examples to demonstrate the method.

The application of interpolation-based, approximate fuzzy reasoning methods in direct, fuzzy logic, control systems gives a simplified way to construct the fuzzy rule base for controlling both vehicle speed and steering. In this control method, rules don't risk the chance of not having a conclusion for some of the observations. Kovàcs and Kóczy [14] introduced an approximate, fuzzy-reasoning method based on Kóczy and Hirota [15] interpolation which could be implemented to be simple enough for practical direct, fuzzy-logic, control applications designed to acquire the shortest docking routes. They introduced a steering and collision-avoidance strategy that demonstrated, in simulation, the efficiency of the proposed approximate fuzzy reasoning method in direct fuzzy control. An example simulation output of the speed and steering for the shortest docking distance on the trial guide path is shown in Figure 1.

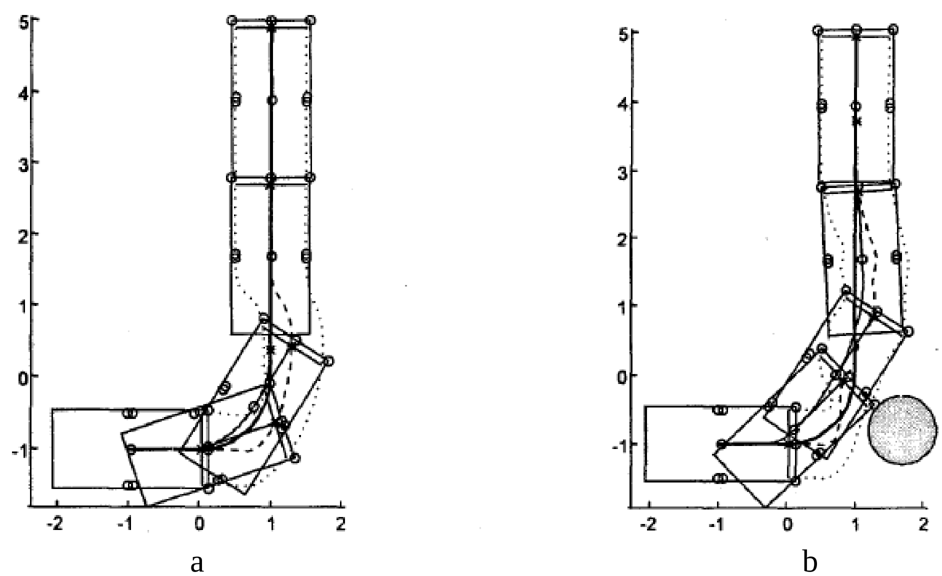

Figure 1 – Simulation of a fuzzy controller used to demonstrate the shortest docking distance on a trial guide path (a) without and (b) with an obstacle to avoid. (courtesy [14] Kovàcs and Kóczy, 1998)

Efficient and effective control of AGVs is vital in relatively expensive semiconductor and liquid crystal display plants because AGV systems often limit the total production capacity. Jang, et al. [16], presented an efficient control methodology for AGV routing in semiconductor and LCD production bays, where AGVs play a central role in material handling. The methodology uses information on the future state of systems to make routing decisions. These highly knowledge-based systems maintain a great deal of information on current and near-future states, such as the arrival and operation completion times of parts - thereby enabling a new approach for production shop control. With the proposed methodology, the cell controller could record future events chronologically and use this information to determine the navigation docking between any part's operation machine and temporary storage. They

showed by simulation that the new control methodology reduced both AGV requirements and flow times of parts.

The design of AGVSs must incorporate not only the vehicle's and guide-path routing, but also some control problems such as collisions and deadlock (i.e., when two or more AGVs are programmed to occupy the same zone or location). Fanti [17] presented a control strategy to avoid deadlock and collisions in zone-controlled AGVSs. In particular, the control scheme managed the assignments of new paths and next zone acquisition. Moreover, he proposed colored, timed Petri nets to model the AGVS structure and dynamics. The model allowed an easy implementation of the control strategy based on the knowledge of the current system state. Later, Dotoli and Fanti [18] presented a novel control strategy that manages vehicle paths, both current and following, to avoid deadlock and collisions of vehicles and their acquisition of the next zone. They also tested colored petri nets for dynamic vehicle modeling and to monitor vehicle performance. They implemented several simulations of AGVs with varying fleet sizes to test the effectiveness of the proposed control strategy and compare it to their previous work.

Beyond path routing, Henson, et al. [19] considered steering as a challenge to docking. They developed a novel, partially heuristic technique that allowed relatively accurate docking for Ackerman-steered vehicles. Multiple experiments were performed to better understand and analyze the heuristic element of the technique and validated via simulation. The results demonstrated that the vehicle's steering characteristics impact docking precision which may prove valuable in attempting to remove the heuristic element.

Berman and Edan [20] developed decentralized control of an autonomous AGV used for material handling. Their goal was to improve overall system flexibility and robustness. Their approach addressed all aspects of AGVS functionality, including: system management, navigation, and docking for load transfer. Hierarchical, fuzzy, behavior-based control, which is a reactive navigation scheme was expanded to multi-robot control in semi-structured environments by incorporating an a priori path optimization and right-of-way determination.

Similar to Berman, Herrero-Perez and Martinez-Barbera [21] proposed a methodology for modeling and controlling a flexible material handling system (MHS) which included multiple AGVs that was suitable for Flexible Manufacturing Systems. "The AGVs incorporated artificial intelligence techniques to: 1) facilitate the configuration and adaptation of the vehicles when there are layout modifications and 2) simplify the interaction between them using simple coordination models. In order to achieve higher flexibility, the MHS made use of decentralized navigation control, which increases autonomy and scalability, and a distributed Petri net for solving task allocation and traffic control problems." In order to facilitate the integration with the manufacturing processes, tasks dispatched by manufacturing cells were allocated by the MHS which took into account pending transportation tasks and the system's current performance. [22] The system was tested in a real factory and in 2010 was in operational use.

Buyurgan et al. [23] presented the development of an architecture for real-time routing of AGVs to dock locations in a "random flexible manufacturing system". The AGV routing problem was modeled using an evolutionary, algorithm-based, intelligent, path-planning model. The model made vehicle routing decisions for material handling requests to maximize system throughput. A three-layer software architecture was implemented that used hypothetical production data and traditional dispatching rules. The analysis showed that, in many cases, the proposed routing model outperformed the traditional dispatching rules for real-time routing of AGVs.

Villagra et al. [24] presented a control strategy to ensure low jerk variations in AGV path-tracking operations in industrial environments. The system focused on robustness, performance, and ease-of-configuration of the vehicle maneuvers. The authors state that robustness was improved by combining algebraic techniques for robust, intelligent, feedback control with differential flatness. The system was easily configured by defining a velocity profile that was decoupled from the geometric path. Some simulated results showed dramatic improvement with respect to more standard, flatness-based controllers.

Lucas et al. [25, 26] looked to improve duration, accuracy, and stability features of precise docking tasks for an AGV fork-lift truck that interacted with objects. A fork-lift truck typically performs docking maneuvers to load pallets on conveyor belts. The authors proposed a soft-computing technique based on a “multi-objective, evolutionary algorithm using multiple fuzzy logic controllers” which satisfied imposed constraints for docking tasks.

Balakirsky et al. provided an overview of the National Institute of Standards and Technology/ Institute of Electrical and Electronics Engineers (NIST/IEEE) Virtual Manufacturing and Automation Competition (VMAC). The goals were for competitors to implement a hierarchical-level control framework, to integrate team algorithms, and to port code directly from simulation to a real mobile robot. The overview provided the competition's objectives, history, operation, and the supporting software infrastructure. [27] A picture of the NIST AGV used for the competition is shown in Figure 2.

Figure 2 - NIST AGV used for the NIST/IEEE Virtual Manufacturing and Automation Competition [27] Balakirsky, 2008]

Kirsch et al. [28] suggest that positioning sensors used for accurate localization of AGVs for docking applications are relatively expensive. Also, they suggested that there are drawbacks to the requirements concerning the omnidirectional AGV design, construction, and onboard safety sensors. Instead, they compared three frequently-used algorithms for position tracking using the safety laser range sensors: the Extended Kalman Filter, the Unscented Kalman Filter, and the Monte Carlo Particle Filter. The authors present analysis of AGV positioning accuracy, the time behavior of the algorithms, the AGV movement function, and the measurement function.

As in [28], Villagra and Herrero-Perez [3] provided an in-depth comparison between different control approaches seeking robust AGV guidance in path-tracking load transfer operations. They assumed that tracking errors cannot exceed 10 cm during the docking maneuver to avoid collisions. They compared control strategies seeking to ensure low jerk variations in docking operations of AGVs in industrial environments. The proposed control system focused both on “robustness and performance (slight errors could damage the load or the station)” and on “ease of controller configuration (a reduced set of parameters should be enough to easily adapt to new layouts or production rates)”. Fuzzy and vector pursuit non-model-based control techniques were applied to a new nonlinear model-based control strategy. Simulations were used to demonstrate that the data-driven model for robust feedback control was combined with differential flatness to obtain the AGV control strategy. The results showed AGV path-tracking in industrial environments did not require prior knowledge of physical parameters.

Herrero [29], similar to [20], followed with research on automatic configuration of the initial vehicle position, or waypoint. This waypoint is used to initiate a robust docking maneuver using non-holonomic (Ackerman steered) robotic forklifts used in automated manufacturing. The proper selection of these waypoints is of paramount importance to operate with high industrial accuracy, repeatability, and reliability that is required for industrial load transfer operations. An unconstrained optimization method coupled with probabilistic techniques was the proposed solution. The authors suggest that their proposed method increased the flexibility and adaptability of autonomous robotic forklifts.

Sensors and Intelligent Vehicle Control

Beyond advancing control strategies for AGVs and mobile robots, sensors have also been combined with intelligent vehicle control to solve docking challenges. The various approaches to sensory-interactive, intelligent vehicle control briefly described in this section include:

- Absolute vehicle positioning using bar-codes
- Vision and optical switches to detect lines on floors
- Infra-red sensing
- Fusion of a charge coupled device-camera, odometry sensors, and ultrasonic sensors
- Sensors combined with fuzzy logic and control
- Fixed-mounted video, pan-tilt stereo cameras, and combined range sensors with video with image-based control
- Ultrasonic transducers on the vehicle and receivers on the facility
- Dead-reckoning combined with vision
- Radio frequency identification and magnetic sensors with fuzzy control
- Laser range-finding sensors

Petriu et al. [30] presents two techniques that enhance the applicability of pseudorandom absolute position measurements as a cost-effective AGV upgrade. “An onboard synchronization technique for tracking binary code on the floor led to minimum complexity requirements for the tracks physically laid on the floor where a one-bit-wide pseudorandom code track was added to the AGV guide path.” They suggested that an optimized serial/parallel implementation of the pseudorandom/natural code conversion allowed the best design tradeoff between the cost of the equipment and the time for implementation.

Andersen et al. [31] described the benefits and drawbacks of different strategies for docking and positioning of autonomous vehicles based on visual feedback. They compared three different sensor techniques: magnetic tape with magnetic field sensors, vision used to detect a line on the floor, and an array of optical switches to detect a line on the floor. The sensing techniques were tested extensively

through experiments on a testbed AGV concluding that odometry combined with vision provided the most accurate vehicle positioning.

Vaz et al. [32] presented a sensor-based docking strategy for a non-holonomic, mobile platform used to support material handling operations in industrial-like environments. A low-cost, infrared sensor system was designed and implemented to locate the mobile platform relative to the docking station, where passive reflectors were installed. With this information, trajectories were generated and followed, docking the platform with an accuracy of approximately ± 0.5 cm in x and y, and ± 1° in θ even though the system was designed using relatively low cost sensors. The paper also presented relevant experimental results.

To increase AGV flexibility, Roth and Schilling [33] 1) combined different low-cost sensors such as simple CCD-camera, odometry sensors, and ultrasonic sensors, 2) fused their information with intelligent algorithms, and 3) stored the reference path in the vehicle's onboard computer. This required an effective path-planning strategy, in particular with respect to navigation, collision avoidance, and docking to target stations. The authors suggest that sensors to support these maneuvers need to be robust to survive in the rough industrial environment, cheap to be an alternative to the existing wire guided vehicles, and accurate to meet the performance requirements. The performance of this concept was demonstrated using factory tests as part of the European ESPRIT project RETRARO in the production environment of a wool processing and spinning company.

Induction wire-guided vehicles performed typical material transport in a textile manufacturing without having the flexibility to adapt transport routes to changes in the production process. Mellado et al. [34] developed concepts to overcome these deficits in the RETRARO project. The project included a consortium that developed an on-board, AGV operating-system as a general purpose, real-time, knowledge-based control system. The control and sensor data processing were based on fuzzy logic and real-time expert systems. Both enabled a vehicle to deal autonomously with the typical uncertainties of an industrial working environment. The approach provided good navigation, collision avoidance, and target docking capabilities, based on measurements by cheaper, less accurate sensors.

Nygårds et al. [35] developed an approach to dock a mobile robot or AGV to a pallet. The pallet size was known but the load was not. The pallet had an initial pose (position and orientation) uncertainty on the order of ± 15 cm and ± 20°. The docking error was required to be within ± 1 cm and ± 1° with "very low" failure rate. A combination of a range camera and a video camera was used for docking with the role of the range camera being emphasized. Successful docking was achieved with typical errors of ±5 mm. One weak aspect was the integration with the control system onboard the robot and the sensor association with the robot given that the resolution of a range camera is strongly distance-dependent. A finding in the paper is that this type of docking is feasible and that it can be self-monitoring.

Kim et al. [36] proposed a visual docking approach using image-based control for a non-holonomic mobile robot equipped with a stereo camera on a pan-tilt. The mobile robot was to use only visual feedback to align with a rectangular target. The visual docking process was divided into two stages, approach and docking, and was validated in several simulations. The docking stage was implemented by introducing a virtual target between the final target location and the current mobile robot position.

Minten et al. [37] reported on the complexity of a reactive docking behavior which used a vision algorithm that grew linearly with the number of image pixels. The robot imprinted (initialized) the vision system on a two-colored docking fiducial when leaving the dock, then used region statistics to

adapt the color segmentation to changing lighting conditions. The docking behavior was implemented on a marsupial team of robots, where a daughter micro-rover re-entered the mother robot from an approach zone with a 2 m radius and 140° angular width with a tolerance of ± 5 cm and ±2°, respectively. The authors stated that testing during outdoor conditions (noon, dusk) and challenging indoor scenarios (flashing lights) showed that using adaptation and imprinting was more robust than using imprinting alone.

Feng and Zeng [38] presented the design, operating principle, and system construction of an ultrasonic navigation system for an AGV. They used receiver beacons located at the docking workstations and transmitter beacons mounted on the AGVs which removed the common drawbacks of using ultrasonic sensors. An electromagnetic signal was used for system synchronization based on a time-of-flight counter. To ensure accurate docking, a transducer equalizer was employed to reach a range precision of 1 mm with low-cost ultrasonic transducers. They showed through experimental results that the approach met the requirements of the automatic material handling system of computer integrated manufacturing systems. Tong, F. et al. [39] also investigated ultrasonic, sensor-based AGV docking. They described experimental results obtained on an AGV with a docking precision of around ± 3 mm in x and y and ± 1° in bearing.

Yu et al. [40] researched an intelligent, monocular vision-based AGV system. The embedded system and high-performance algorithms were designed to detect docking landmarks, namely Arabic numerals. The authors describe that their real-time, two-dimensional, camera images were processed using a digital signal processor, including filtering, segmenting, and labeling connected components. Then, the vision system calculated the relative distance and the slope of the guideline. The vision system detected artificial landmark numbers placed along the path side for use in docking. The simulated results of image processing and experimental results on an AGV both demonstrated that the algorithms were efficient and robust.

Andersson and Månsson [41] researched options and found a solution to maneuver and dock an AGV between predefined positions with an accuracy of ± 5 mm using dead-reckoning followed by vision-based tracking. A path-tracking technique they called “Quadratic curve” was used together with the Extended Kalman filter algorithm for location estimation. Their results showed a mean accuracy of 5.1 mm with a standard deviation of 3.0 mm over 30 repetitions of the docking phase. They concluded that odometry was easy to implement, but suffered from sensitivity to both stochastic (floor irregularities, collisions, skid) and systematic (cumulative) errors. The kinematic model was affected by the lack of measurement tolerance in the assessment of vehicle dimensions. The vision-based system proved, as predicted, to be very accurate but also sensitive to light conditions. The low AGV speed (maximum 200 mm/s) combined well with the low vision system resolution and frame rate.

Wu et al. [42] developed a parking-position detection and control system for precise palletized materials transfer between an AGV and a load transfer station. Figure 3 shows the experimental setup. In order to align the AGV roller conveyer with the station using a radio frequency identification tag, it was necessary for the AGV to detect the longitudinal, lateral, and orientation deviations of its body with respect to the station. A pair of magnetic sensors was used to measure the lateral and orientation deviations of the AGV. Fuzzy control was proposed to eliminate these deviations and keep the AGV on its path. A set of optical emitters and receivers was located at specific points on the AGV and the station respectively; they were used to determine the longitudinal position for material transfer, and to coordinate the transmission operation of the AGV and station. The authors performed the transfer experiment of palletized materials hundreds of times on the AGV prototype system. Experimental results

showed their AGV system could achieve the accuracy, repeatability, and reliability needed in industrial applications.

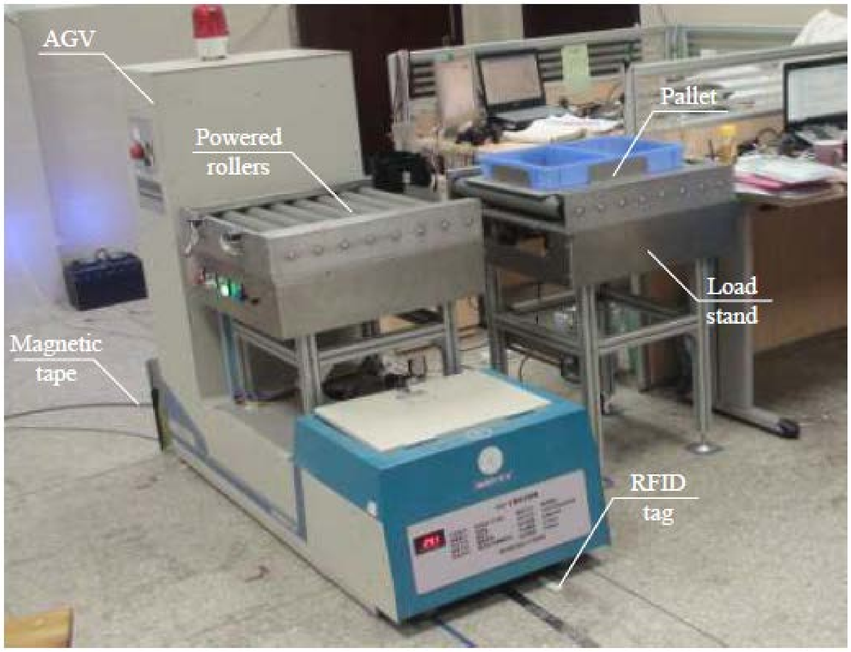

Figure 3 – Experimental setup of precise transfer of palletized materials between an AGV and a load transfer station. (courtesy [42])

Lee et al. [43] suggested a docking solution for AGVs conveying products in medium- and small-scale factory automation systems such as the one used in the Korean processing facility as shown in Figure 4. They dedicated a task manager module to translate high-level tasks into general robot commands for navigation and to reuse developed algorithms without modification. When parked in front of a docking station, the robot detected the docking goal position by using a laser range-finding sensor and segmented out the station legs as shown in Figure 5. When the robot was properly docked with the docking station, it lifted up the pallet, and left the docking station carrying the load.

Figure 4 - Experimental docking in a Korean processing facility [courtesy Lee, 2014]

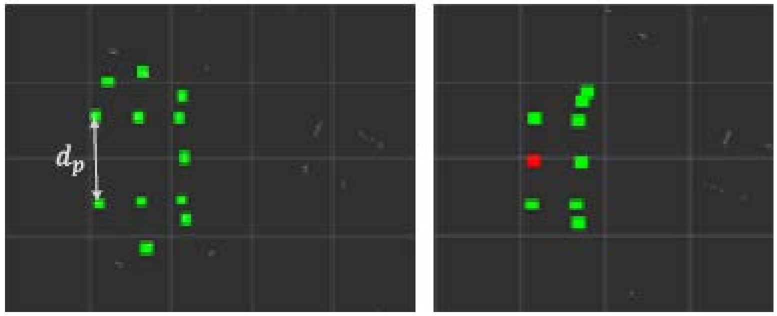

Figure 5 - Results of segmentation for docking where dp is the distance between dock station legs. (courtesy [43])

Xing, et al. [44] designed an AGV including a two-sided, three-level, push-pull, load-transfer mechanism and a Programmable Logic Controller (PLC). The AGV was used for relatively long travel, to transfer a pallet of material to a load stand and back. The AGV followed magnetic tape paths in the floor and located itself with radio frequency identification tags beside the load stand. The PLC 1) detected the docking positions of the AGV and the load stand and 2) controlled the horizontal and vertical movement of the load-transfer mechanism with a stepper motor and an electric push rod. Load-transfer experiments verified the performance of the material transport system.

As with [18] in the Control section, Gayathri, et al. [45] proposed a Petri-net approach although they used a programmable logical controller (PLC) design, which also prevented collisions among AGVs. Their implementation involved a surveillance robot with automatic docking for battery recharging, potentially for home security.

Mobile Robot with Robot Arm

Alessio [46] and Bain [47] suggested that AGVs have limited interaction with workstations. They only transport material to and from workstations; other material-handling equipment at the workstation can transfer the load between the AGV and the workstation's operating envelope. Two manufacturers successfully resolved the limited-interaction problem for their specific applications by equipping AGVs with robot arms for loading and unloading workpieces. The research into autonomous mobile robots for the materials-handling domain was directed at exploring autonomous mobility as a potential solution to the drive-path problem. [46] The TAURO system integrated the movement of a wheelchair with the operation of an onboard manipulator. In this way should the goal be out of the manipulator's reach, the wheelchair would move on a path toward the goal until the manipulator was within reach. [47] A photo of the system is shown in Figure 6.

Figure 6 – The TAURO mobile manipulator. [courtesy Bain, 1986]

Mandel and Duffie [48] proposed a method to compensate for mobile robot docking inaccuracies by modifying the task of an onboard robot arm based on the estimated docking error, which is the offset between the desired and actual docking locations of the mobile robot. The docking error is estimated using a sensor mounted on the robot arm - either a vision system or a touch trigger probe. They presented their algorithms for calculating the spatial docking error for each sensor and for modifying the robot's task accordingly. Additionally, they described a method that would allow the mobile robot to achieve results even in the presence of perturbed data. The calculation of the spatial offset between the actual and the desired locations of the mobile robot using a vision system was implemented and the results of experiments were presented and discussed in [48]. Erwin [49] also explored the challenge of how a robot can achieve the correct position and orientation with respect to the workstation, within the required tolerances for the interaction. He developed docking strategies that used lasers for space applications [4] or visual techniques in flexible manufacturing systems environments.

Other Related Research

Other related research to docking is described in this section as there may be some bearing on ASTM F45 developments considering alternatives to typical industrial docking activities. For example, remote operator-in-the-loop control, assembly cell limitations from the vehicle, space vehicle docking, and autonomous surface vehicle docking.

Barberá et al. [50] developed a remote, operator interface which was linked to the AGV through a wireless Ethernet network. The interface allowed the operator to know both the current tasks and current position of the AGV. It also allowed the operator to send a new task to the AGV, to inform the AGV of new docking stations or layouts, and to send new navigation maps to the AGV. The ideas and algorithms used in this system are common in indoor mobile robotics. The AGV should not collide with objects or obstacles while following the trajectory and should be far enough from the docking station to allow the AGV to reach an adequate pose for docking. Thus, plant operations only stop during the time needed to update the AGV's topological maps.

In a (multi-robot) assembly cell, transport of parts, products, tools, and fixtures is of major importance. In flexible assembly cells, transport has a substantial influence on assembly efficiency because the assembly times are usually much smaller than the transportation times. Storm and Boneschanscher [51] describe research at Delft University of Technology on a multidisciplinary research project named DIAC (Delft Intelligent Assembly Cell). The project goals were the development, implementation, and integration of technology that make up a flexible assembly cell. As part of the project, a prototype flexible assembly cell was built having two assembly robots with overlapping workspaces. A handling system provided the internal transport using reconfigurable pallets for product-specific parts, subassemblies, assembled products, and fixtures. Since both the number of pallets and the buffer space within the cell were limited, the efficiency of the assembly system depended upon the assembly strategy and the capacity of the handling system.

Other potentially relevant docking research was performed by Mandel [4] and Kim et al. [52]. Mandel described the Laser Docking System (LDS) that consisted of passive docking aids (reflectors) placed on the target vehicle in a known location and orientation. These reflectors were acquired and tracked by means of a modulated laser beam located on the interceptor vehicle. The LDS enabled the interceptor vehicle to analyze the return (reflected) signal in order to determine both relative position and relative attitude of the target vehicle during station keeping and docking. Laser ranging experiments were accomplished at the National Aeronautics and Space Administration, and from these experiments have

evolved laser docking concepts. The concepts included angle and attitude measurements that were capable of providing all of the information needed for automatic docking control by the interceptor vehicle. Several designs were compared and plans included the development and testing of: first a breadboard model, then an engineering model, and finally qualification and flight systems.

Kim et al. [36] discussed docking as an important capability for autonomous surface vehicles (ASVs) and as an essential part of a wide class of missions. One such mission was discussed: the emergency response and environmental protection problem of containing a floating pollutant. They proposed a solution in which multiple robots autonomously navigated to surround the surface matter. Before doing so, the robots docked with one another to secure specialized attachments designed to ensnare the contaminant. They described the prototypical, physical, robot system developed to perform this task and detailed the system architecture, sensors, hardware, control system, and visual-processing pipeline. While employing multiple ASVs maximized spatial reconfigurability, their success depended on the reliability of inter-robot docking capabilities. But achieving robust docking was a significant technical challenge because the water continually induced external disturbances on the control system. The system relied primarily on visual-servoing within a control framework using sensor fusion. Accurate disturbance measurements were obtained through traditional sensor modeling and filtering techniques. Since the environment was a priori unknown, varied from trial-to-trial, and proved difficult to model, they applied 1) a model-free, reinforcement learning-algorithm, State-Action-Reward-State-Action (SARSA)(λ), 2) specialized initial conditions, which ensured stable operation, and 3) an exploration guidance approach that increased the speed of convergence. A two-loop control scheme was adopted for visual-servoing to successfully make use of feature descriptors with various (and variable) computational times. The approach demonstrated the docking problem with autonomous ground vehicles and ASVs. The results from several situations were compared, showing that disturbance rejection coupled with SARSA(λ) was an effective approach.

Cross-Docking

Cross-docking is a material handling and distribution concept in which goods move directly from receiving to shipping. In a typical cross-docking system, the primary objective is to eliminate storage and excessive handling. As companies continue to streamline distribution functions, cross-docking is becoming a more widely accepted distribution method. The benefits of cross-docking include reduced inventory, increased customer responsiveness, and better control of the distribution operation. By definition, cross-docking systems require a close connection between receiving and shipping operations. This connection calls for robust hardware and software systems to solve the cross docking problem [53] [Rohrer, 1995]. This concept is included here for completeness and to avoid confusion with the concept of docking. Research topics on cross-docking include:

- literature review [54]
- simulation [54]
- truck docking or scheduling sequence [55]
- application of the Taguchi method [56]
- best sequence of inbound and outbound trucks [57]
- cost-stable scheduling strategy [58, 59]
- optimal route selection [60]

Docking Patents

Lisy [61] invented a warehouse material-handling automation system which included a portable module with which to load and unload material to and from an automatic guided vehicle. The system

operates such that the automatic guided vehicle can calculate its position relative to a destination and follow a route to the destination. In addition, the system operates even when the portable module is displaced or moved from its original position to a new destination. The system includes 1) bar-code targets affixed to the destination, 2) a scanner on the vehicle for scanning the bar-code targets, and 3) a computer on the vehicle for triangulating the vehicle's position relative to a stored path.

McClure, et al. [62] invented a mobile robot or AGV having a multi-jointed robot arm. The robot arm has a gripper and camera mounted at the free end of the arm. The gripper is for engaging, holding, and releasing workpieces. The robot arm transfers workpieces to and from process machines or storage areas. The robot arm finds the workpiece or the place to set it down by looking at two light-emitting diodes placed a known distance and orientation away from the workpiece or set-down place. The robot arm and camera are controlled by a computer onboard the vehicle. The AGV and robot arm are used to transfer workpieces from place to place in an automated manufacturing environment.

The invention also provides for at least two active or passive locating beacons in known positions with respect to the workpiece nest on a process machine. The beacons are detected by the camera and the visual information is then sent to an onboard control computer, which processes the information and guides the robot arm in picking up or depositing workpieces. The visual information also can be used to guide the robot arm in pushing a switch located on the process machine, for the purpose of letting the process machine know that the AGV is ready to load or unload a workpiece. The high degree of manipulative accuracy allows the robot arm to transfer very small parts, such as those associated with integrated circuit manufacture (see Figure 7). Fully automatic parts transfer is, therefore, possible without human assistance.

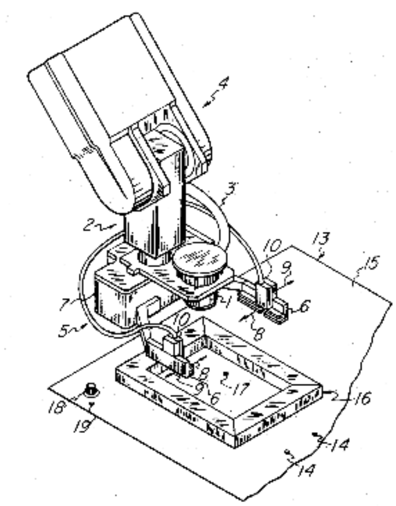

Figure 7 - McClure et al. invention of a robot arm onboard an AGV. [62]

Pinlam, et al. [63] invented an automatic charging system for AGVs, a typical docking activity. The invention provides AGV systems with automatic recharging and a central processor for control. The central processor monitors the AGVs charge states, assigns them to tasks, and determines when to recharge the AGVs. The central processor can optimize the operation of the AGVs to achieve various objectives which can include, for example, maximizing AGV availability, maximizing battery life, and/or maximizing recharging station utilization. Systems and methods of the invention can maximize the utilization of AGV equipment and minimize the number of AGVs required to accomplish a given set of tasks.

Aggarwal [64] invented an integrated wafer transport and transfer device which included a vehicle with an integrated docking platform for holding a wafer carrier such as a FOUP (front opening unified pod) as shown in Figure 8. The docking platform is positioned at the correct height for sealing the FOUP to the load lock of a process tool. Vertical and/or horizontal movement is required in some cases. Methods for delivering wafers to process tools are also described. In a preferred embodiment, wafers are carried inside a FOUP on a cart, such as an automatically guided vehicle or a personally guided vehicle. The cart is docked at a process tool and the FOUP is sealed to the load lock of the tool without removing the FOUP from the cart. After processing on one tool, the cart along with the FOUP can be moved to the next process tool for further processing. The FOUP can stay on the same cart until all processing is completed. This is especially useful for moving priority lots through the fabrication facility quickly.

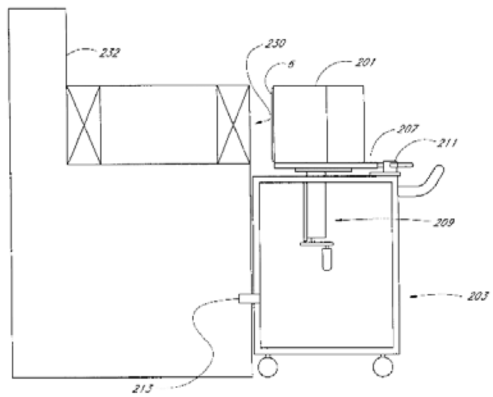

Figure 8 - Aggarwal invention of an integrated wafer transport and transfer device [64]

Pfeiffer [65] invented an AGV docking station that included a station base-unit and a shift unit adapted to move relative to the station base-unit (see Figure 9). Movements occur between an extended position and a retracted position, where movement of the shift-unit from the extended position to the retracted position defines a shift-unit movement direction. The docking station further includes an actuator coupled to the station base unit and the shift-unit, where the actuator is adapted to move the shift-unit between the extended position and the retracted position and at least one locator block coupled to the shift-unit. The docking station stops an AGV travelling in the shift-unit movement direction when a portion of the automated guided vehicle contacts at least one locator block with the shift-unit in the extended position.

In some environments, robots may be used to load and/or unload parts from AGVs. To facilitate reliable unloading, the position of the AGVs relative to the robots should be accurate and repeatable. Previously, AGVs would drive to docking stations affixed to the floor of the factory. Once robots had loaded or unloaded parts from the AGVs, the AGVs would back away from the docking stations and then continue along a pre-determined path. Docking stations may be desired that stop AGVs without requiring reversal of the direction of travel of the AGVs.

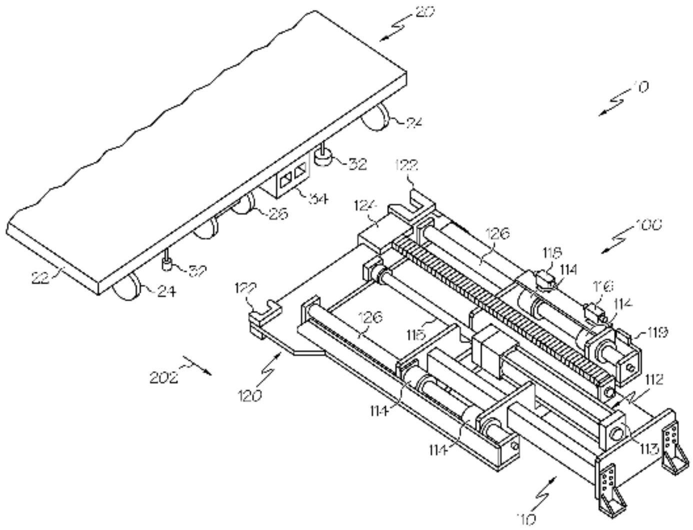

Figure 9 - Pfeiffer invention of a docking station for an AGV which included a station base unit and a shift unit adapted to move relative to the station base unit. [65]

Conclusions

This survey provides a literature review of docking research for AGV or mobile robot research. As being defined in ASTM F45.02, docking refers to the arrival and stopping of a vehicle at a position relative to another object. Docking can include positioning the vehicle or the equipment onboard the vehicle relative to another object, for example a tray station, trailer, or pallet. Research that has been completed in referenced articles within this survey considers control and sensors combined with intelligent vehicle control as the main areas to study based on the number of articles uncovered. Control methods using clothoids, petri nets, and fuzzy logic among other methods were considered to improve vehicle approach and stopping performance for docking. Sensory interaction with intelligent control algorithms provided much research using radio frequency identification, vision, and laser range sensors to provide improved docking performance. Docking research on AGVs or mobile robots with onboard robot arms is also included where some researchers use the relatively precise tolerance of robot arms as a means for improving docking. Other related research is included on flexible cells and docking of other than ground vehicles, e.g., unmanned surface vehicles. Patents uncovered included automatic battery charging, actuated docking systems to attach between the vehicle and dock station, and robot arms onboard vehicles.

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