Autonomous Cargo Transport System

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Abstract

The automation of spotter operations at a Bulk Mail Center poses several challenges to the current technologies of perception, planning, and configuration. Perception systems will be challenged to operate in all-weather conditions and at varying levels of accuracy. Coordinating and safeguarding multiple vehicles, operating at speeds up to 25 miles per hour in the same general area, require a complex global planner. To engage a trailer the vehicle must be designed so that it can acquire trailers of varying length (40, 45 and 48 foot), provide optimal mounting locations for sensors and be configured so that it is relatively easy to maneuver and plan successful trajectories.

Through previous and ongoing research we have developed significant expertise in the areas of real-time control, path planning, perception, and system integration for automating road-worthy vehicles. Although such systems still lack the robustness to function in a completely unconstrained environment, Bulk Mail Center sites provide a unique opportunity to successfully apply and demonstrate an autonomous spotter vehicle. The site can be well represented by a finite (x,y) grid with known landmark (facility, light poles) coordinates, and access is restricted in that unexpected obstacles (personnel, non-automated vehicles) can be limited to a high degree, if not completely, from the operational area of the autonomous system. These and other factors constrain the task so that autonomy is feasible.

This paper will present a proposed automated spotter system by partitioning the problem into three primary tasks - driving, hitching, and docking. A brief overview depicting a typical automated scenario is also provided.

Introduction

Field operations are a major departure from factory operations, offering truly substantive opportunities and compelling motivations for advanced robot worksystems. Task-based architectures are capable of handling the complex planning requirements for multiple vehicles performing the same task within a confined area. Specific technologies have matured to the level that, if the proposed operating environment is well-structured for the tasks, autonomous systems can demonstrate robust and reliable operation. While a relatively unstructured environment demonstrates a high degree of dynamism, or change, the well-structured environment experiences little change or variance.

USPS Bulk Mail Centers (BMC) can be categorized as well-structured environments for autonomous spotter operations. Critical task information, such as locations of loading docks, check-in/out stations, maintenance areas, and refueling pumps, are known in advance with a high degree of accuracy. Pedestrian and non-automated vehicle activity within the automated area can be restricted, and the maximum vehicle speed is low, reducing the complexity and severity of the obstacle detection task. These factors, combined with an accurate site positioning system, reduce the complexity of automating spotter operations, such that it is technically and economically viable with moderate improvements to existing technologies.

This paper, resulting from a design study, presents a solution to the problem of automating spotter operations resulting from a design study. The study approached the problem by separating it into three tasks: driving, hitching, and docking (see Figure 1 to Figure 3). Each task incorporating perception, planning, mechanism, and operations elements. Integration of the various sensor and control systems can be accomplished using many different architectures [Shafer86]. The combination of all basic elements form the autonomous cargo transport system or the ACT system (see Figure 4).

Overview

Automated spotter operations comprises multiple work vehicles following the orders of a central dispatcher in a safe, orderly fashion. The general configuration of a bulk mail center has a single inbound/outbound checkpoint, multiple staging areas, and multiple loading docks. The operation is further structured by grouping in the docks into various categories. A typical cycle for a trailer would be -> pickup at inbound -> dropoff at staging area -> pickup at staging area -> dropoff at dock -> pickup at dock -> dropoff at staging area -> pickup at staging area -> dropoff at outbound (see Figure 5).

The dispatcher would initiate these actions via a 2D plan view of the site displaying the current locations of all trailers and active automated spotters. For the first leg of a trailer's journey (inbound to staging area) the dispatcher would select the inbound location and then select the staging area. The central planner would then compute the best path using the locations of all active spotters and any "off-limits" are and display it for the dispatcher. Upon confirmation, the command would be sent to an available spotter and executed. By selecting a dock as the goal point a trailer could be routed directly to a dock, skipping the staging area.

To ensure safety and efficiency in the operation, close cooperation and coordination between vehicles and the dispatcher are required. To achieve this, the automated vehicles must maintain continuous contact using a specified message protocol. Three types of messages are envisioned: pre-planned, continual, and sporadic. Pre-planned comprises the typical dispatcher interactions where trailers are being moved. Continual messages are similar to a "heartbeat" where transmission are cyclic of period T and result in low-level information such as vehicle position, speed, and status. Sporadic messages occur infrequently, such as emergency stops.

Driving

Driving encompasses the movement of the trailers between hitching and docking tasks at speeds of up to 25 mph. Two primary subtasks occur during driving: navigation and obstacle detection. The complexity of these subtasks is increased by the requirement of "all-weather" and day/night operation. In addition to the primary subtasks, multiple vehicle systems, such as coolant, oil pressure, fuel level, and air pressure, must be monitored to ensure safe operation and to minimize costly downtime due to failure in service.

Navigation

Navigation is the most basic capability of the automated spotter tractor. All tasks utilize the navigation module to compute trajectories between a start point and a goal point. The navigation module consists of a position estimator, the path planner, the execution monitor, and the path tracker. The most basic components of the navigation module are the low-level controller and the position estimator.

The controller accepts commands from the higher level modules, computes the actuator-specific commands, closes the physical control loop, and monitors the actuator performance. Navigation requires the control of the gear shift (an automatic is used in spotter tractors), steering angle, air brakes, and propulsion [Amidi90] in addition to feedback from the mechanical orientation sensor which returns the angle between the tractor and the trailer. The low-level controller combines information from all these sensors to compute the pose of the tractor/trailer combination at any moment in time.

The position estimator provides an estimate of the vehicle's location within the BMC. The accuracy of this estimate greatly impacts the amount of forward planning that can be done and the number of path corrections that the path tracker must execute. As the accuracy increases, the magnitude of path variances can be minimized and the multiple vehicles can operate in closer proximity to each other [Brumitt92].

Two distinct levels of path planners will exist, a central planner that tracks all active vehicles and generates complete route plans for each vehicle. Aside from computing the route plans for all vehicle, the central planner displays the paths of all active vehicles for the A trajectory, or motion, planner will run onboard the vehicle and is responsible for taking the route plans and generating the trajectories required so the automated vehicle is in the correct pose at the correct time [Latombe91]. Execution monitors and path trackers will run onboard the vehicles to support the trajectory planner. These modules verify the accuracy of the travelled path keeping any variance within operational limits.

Various methods of position estimators were examined. The best solution was an RF-based (radio frequency) system, referred to as the Site Positioning System or SPS, using four transmitters and multiple receiving towers (see Figure 5 and Figure 6). This type of system is ideally suited to BMC operation since it can provide "all-weather" operation. Analysis of the navigation problem identified the need for positional accuracy on the order of $\pm$ 10 cm for safe, efficient driving. The SPS is capable of $\pm$ 6 cm accuracy during normal operation and $\pm$ 3 cm operation if the phase difference values for the transmitter/receivers have been logged for a particular location. This logging option provides the increased accuracy necessary for the hitching or docking operations.

Obstacle Detection

Obstacle detection is required to safeguard other vehicles or workers that may intersect the path of the vehicle. It is further complicated by the existence of dynamic obstacles, such as people or non-automated vehicles, in the environment. Early detection of dynamic or static obstacles can be difficult since they may be obstructed by parked trailers or buildings. To bound the problem, the following conditions are enforced.

- Reaction: The vehicle will slow and stop whenever an obstacle is detected in its path, instead of attempting to avoid it. If the obstacle is transient, the automated vehicle will resume motion once its path is clear. If the obstacle remains in the path, a still-frame image from the forward-looking camera will be sent to the dispatcher's console for his determination of the problem.
- Obstacles: Only large obstacles are expected to be encountered. A minimum obstacle size of 1.5 m is used as a reference.
- Dynamic obstacle behavior: Access to the site will be restricted, and therefore, workers in the environment will be alert and able to take appropriate actions to avoid collision with the autonomous vehicles. The central dispatching system will plan the paths of the individual vehicles to avoid conflicts, particularly at intersections where perception sensors can be obscured.

The sensor chosen to support the obstacle detection task is a single-line, forward-sweeping laser rangefinder (see Figure 4) similar to that used in mining navigation research [Shaffer90]. In operation, the sensor cuts a horizontal slice similar to a lighthouse [Singh91]. It is capable of detecting obstacles smaller than the 1.5 m minimum to distances exceeding 50 meters at an update rate of 20 Hz. Its data can be processed in real-time, providing the reaction time necessary to safely stop an automated spotter if an obstacle is detected. The optimal location for this sensor is above the front bumper, using a mechanically stabilized platform.

Hitching

Hitching is the operation where the automated spotter tractor connects or disconnects with the mail trailer. The hitching operation begins after the automated spotter has been driven to a location in front of the target trailer or dock and assumed the initial pose. Hitching comprises two subtasks: air line hookup and trailer loading. The task is localized, in that only the position and orientation of the ACT vehicle with respect to the trailer is important. The individual systems used for this task are shown in Figure 4. This decreased range simplifies the perception recognition and tracking tasks.

Air Line Hookup

Moving the trailer once the automated spotter has hitched to it requires energizing the trailer air lines to release the trailer brakes. Two separate connectors, standard and emergency, are present on the forward face of each trailer. Various options capable of either energizing the brake system or lifting the trailer wheels were evaluated [Fitzpatrick92].

Adding structure to the task by installing a new connector box at a specific location enables automatic connection to the trailer air lines. Centrally locating the new connector box on the forward face of the trailer simplifies the connection. In addition, adding special markings allow it to assist in the trailer loading task discussed in the next section. The box would also be designed to simplify the mating of the spotter to the trailer air lines similar to the hydraulic connectors designed for automatic mating.

A new mechanism must also be appended to the spotter tractor. This mechanism must extend to cover the distance between spotter and trailer, mate with the new connector box, and retract to leave a flexible hose. The height of the box with respect to the fifth wheel would be known so that a simple mechanism can be used (see Figure 2). A camera would be integrated into the system such that the dispatcher could verify the connection if desired. In normal operation, the air line connection would be completely automated.

Trailer Loading

Trailer loading is the physical connection of the automated spotter to a trailer. To accomplish this task the spotter must verify it is attaching to the correct trailer, locate the hitch point, track the fifth wheel hookup to the hitch point, and verify the hitch is secure. This task is complicated by the variety in appearance of trailers. Similar to the dock location task, this task will be simplified by tracking special markings on the air connector box attached to the trailer.

Target tracking using a vision system is used to control mobile equipment. In this instance, a camera controls the spotter motion such that the markings are kept in the center of its image [Thorpe91]. The range is limited so that minimal lighting would be required for night or inclement weather. The vehicle would continue to back up until the fifth wheel slides under the trailer and engages the ball. The trailer is then lifted to the required fifth wheel elevation angle to initiate the automatic air line connection. At the same time, the controller verifies that the safety interlock has positive engagement on the trailer ball.

Both translational and angular alignment errors can be tolerated during this process. The fifth wheel mechanism is designed such that translational errors of ± 3 simply slide the trailer over due to the "V" shape. Angular errors of up to ± 5 can be tolerated by the air line hookup mechanism. Once the trailer has been loaded, the mechanical orientation sensor will provide the feedback to determine the angular orientation between tractor and trailer. At this point the plan for driving away can be generated and initiated.

Docking

Docking places the heaviest demands on the position estimator system of all the tasks. Operational requirements limit the side-to-side translational and angular positioning errors allowable. Even under manual operation it is necessary for trailers to be re-spotted a number of times each shift. While the allowable errors are directly related to the method of trailer loading/unloading that will be used, the most stringent values, associated with docks using conveyors, were used to specify the performance of the docking task. To successfully dock, the ACT vehicle must locate the correct dock and compute its position and orientation, or pose, with respect to that dock.

The normal docking scenario has the ACT vehicle pass in front of the dock at a reduced speed and assume a preferred pose in front of the dock. During the pass-by, the obstacle detection scanner verifies that the dock is open. The trailer is backed up to the dock until contact is made, the trailer is un-hitched, and the spotter drives away. The same control and planning elements, necessary for the navigation task, are used during the docking maneuver. The additional tasks of dock location and pose calculation are described in greater detail below.

Dock Location/Identification

To demonstrate the necessary docking accuracy, it is critical that the centerline of the dock, with respect to the ACT vehicle, be known to a high degree of accuracy. Two methods - sensed versus inferred - can accomplish this task. While inference provides the simplest solution it is a risky choice until the performance of the position estimator is demonstrated under normal operating conditions. Sensing the dock can be accomplished with many methods - many require significant processing to extract features which are then matched against predicted features. Another solution is to mark the dock location in a manner that simplifies the recognition and computation problem.

Identifying the dock location with specialized markings is the best solution. An existing navigation system for automated fork lifts can be used for this purpose. This system utilizes a rotating laser scanner similar to that used for obstacle detection. The difference is that it returns the bar code and the angular position of its center. Multiple bar codes can be detected throughout its 360 scan serving to increase the accuracy of the position estimate for a specific bar code. The ACT vehicle would have one of these scanners mounted on a mast on top of each cab. As the ACT vehicle passes in front of the dock area, it would search for the bar code matching its expected target. Once found, one or two of the bar codes to the left and right of the target would be used to increase the position accuracy.

Ideally, using a highly accurate positioning system and inferring the dock location provides the most economic solution. The SPS does promise the necessary accuracy for location by inference to be successful. This concept would be tested and evaluated during the first implementation.

Pose Calculation

Determining the ACT vehicle's pose with respect to the dock requires the vehicle be able to compute its own pose and calculate the transform to associate this with respect to the dock. As in the dock location task, these calculations may be derived using inference or by actually sensing the dock. In addition, the solution for the location task will also support pose calculation - this includes the sensed and inference options.

Internal feedback used for navigation and control (steering angle, etc.) is used to compute the pose of the spotter with respect to the trailer. This information is then used by the onboard planner to compute the path trajectories required to successfully dock the trailer.

Operations

The overall success of an automated system is heavily dependent on the interface between man and machine. Part of this interface comprises the operations modifications that must be emplaced for the automated equipment to function. In the case of the ACT vehicle, site modifications must be made to acquire the additional information necessary for safe vehicle control and to support the site positioning system. For navigation and control, information such as the overall trailer length and separation distance between the trailer tandem wheels and the rear spotter wheels must be accurately known (see Figure 7). Without this information the vehicle cannot follow the planned path with the necessary accuracy.

Operational modifications must be made at the man - machine interface. This interface occurs in multiple areas. Under normal operations, the most common would be the dispatcher and the dock clerks. The dispatcher would utilize a graphical interface to enter the high level commands into the central planner (see Figure 8). The dock clerks interact with the automated spotter performing such tasks as setting wheel chocks and opening trailer swing doors. The safety of interaction with the automated equipment is heavily dependent on developing a checklist and communications between dispatcher and clerk.

Two-way communications must also be maintained between the central planner and the ACT vehicles. This link serves to confirm proper functioning of the equipment, exchange position information, and transmit commands. Another RF system would be used that is capable of the throughput necessary for data exchange. In addition, redundant transmitter/receiver pairs would be installed to reduce the potential for loss of communications. Full operational considerations are discussed in the design study [Fitzpatrick92].

Summary

The accurate site positioning system makes the autonomous cargo transport system a viable alternative to manual operation. The remaining perception tasks are simplified by restricting the range of their operation and increasing the reliability in prediction. Vehicle control technology are sufficient for the problem. Operational issues, such as the operator interface for the dispatcher, are the focus of significant research and development. These factors together demonstrate that automated spotter operations are technically feasible [Fitzpatrick92]. Due to length limitations, this paper does not address the issues of safety even though they are probably the most critical. Operational changes do provide sufficient structure such that the automated equipment can function both safely and productively.

Acknowledgments

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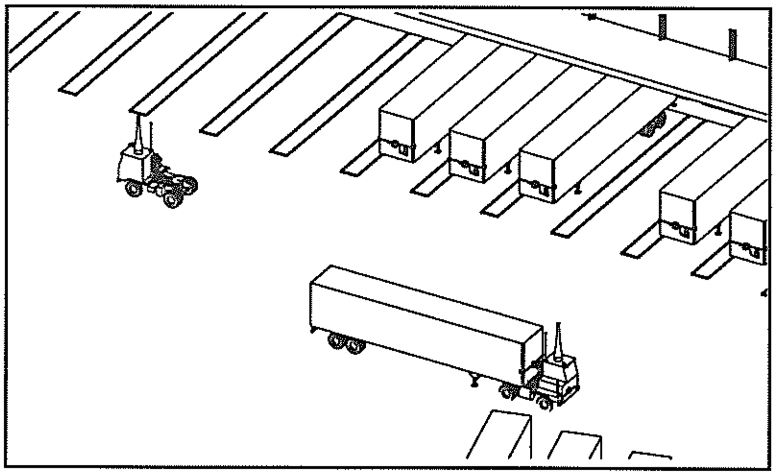

Figure 1: Automated Trailer Handling Scenarios: - driving

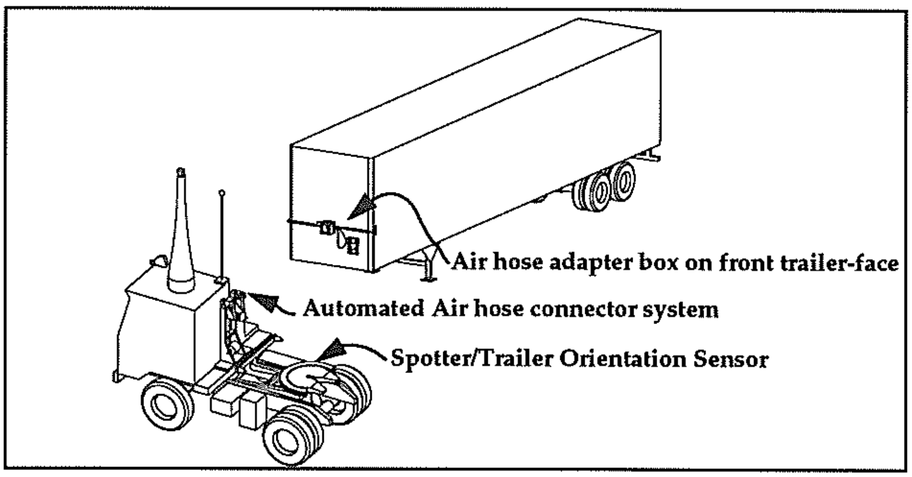

Figure 2: Automated Trailer Handling Scenarios: - hitching

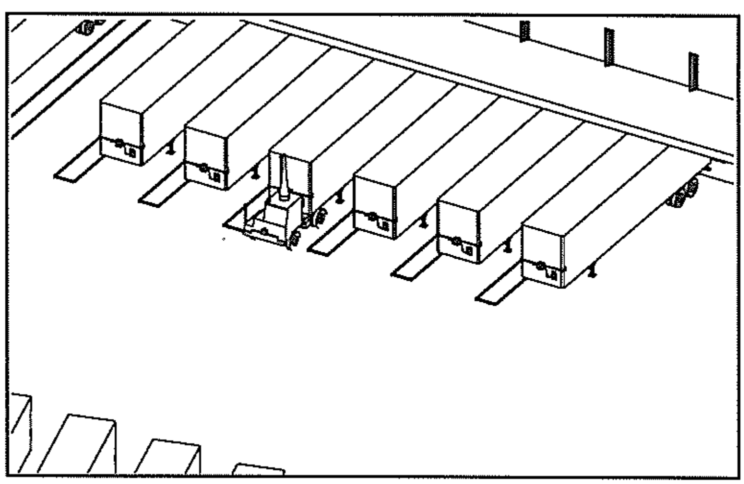

Figure 3: Automated Trailer Handling Scenarios: - docking

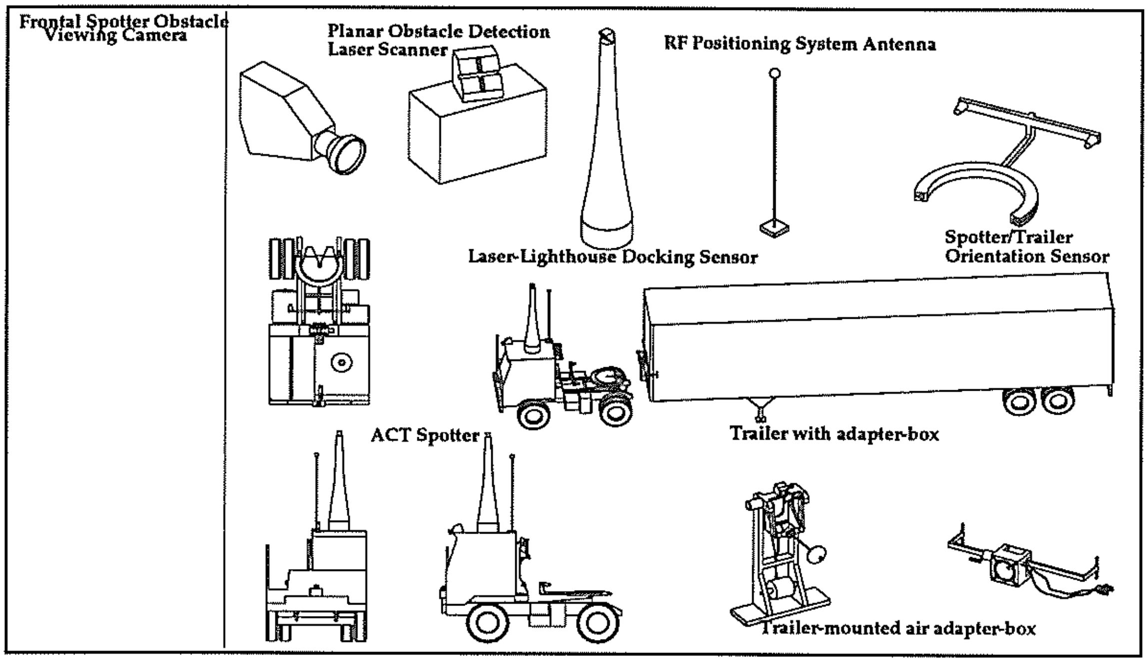

Figure 4: Elements and technologies comprising the ACT system

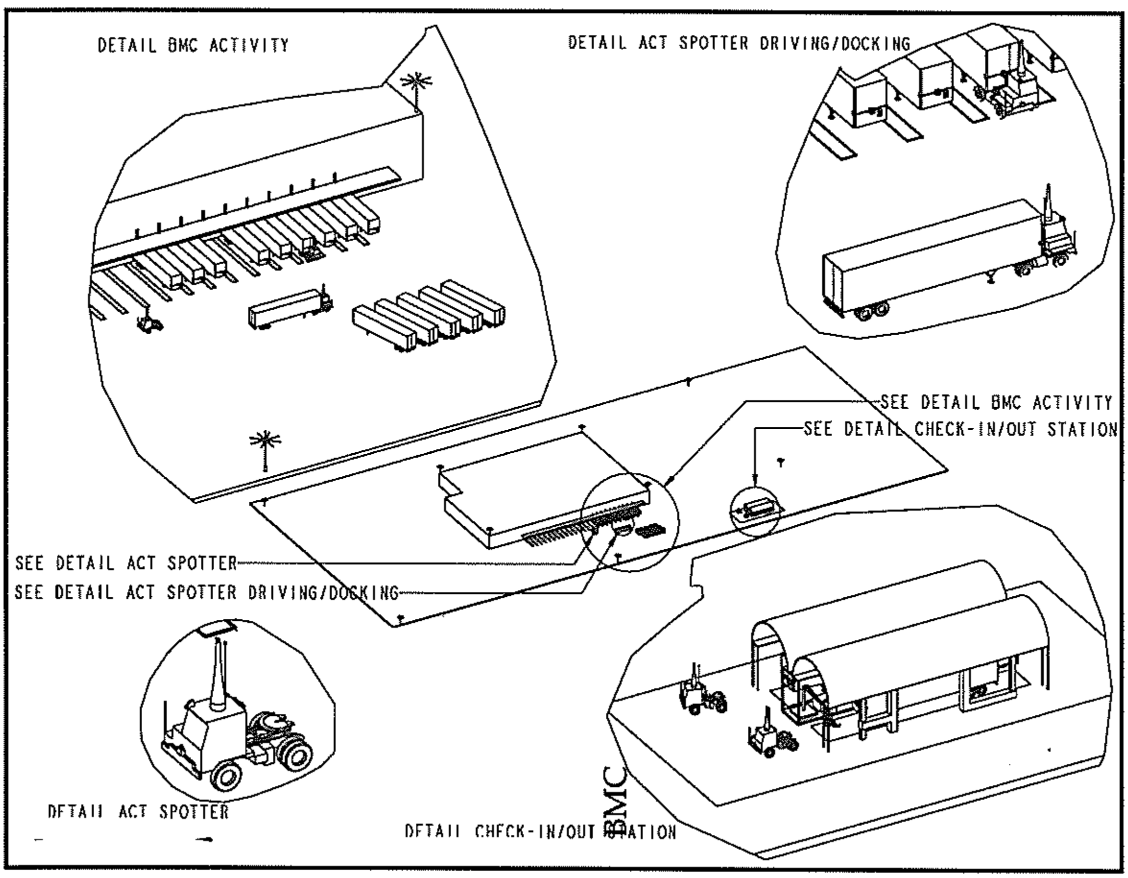

Figure 5: Autonomous Cargo Transport System Operational Scenario

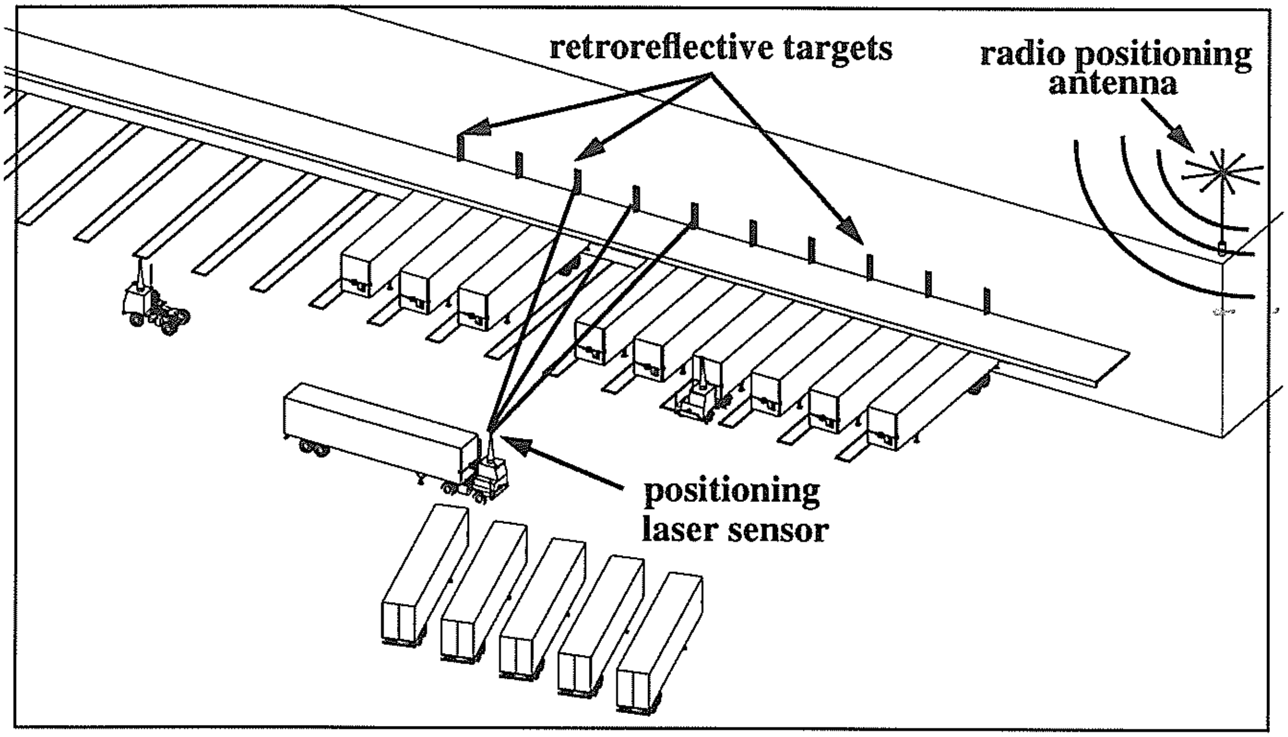

Figure 6: Navigation systems for positioning during driving and docking

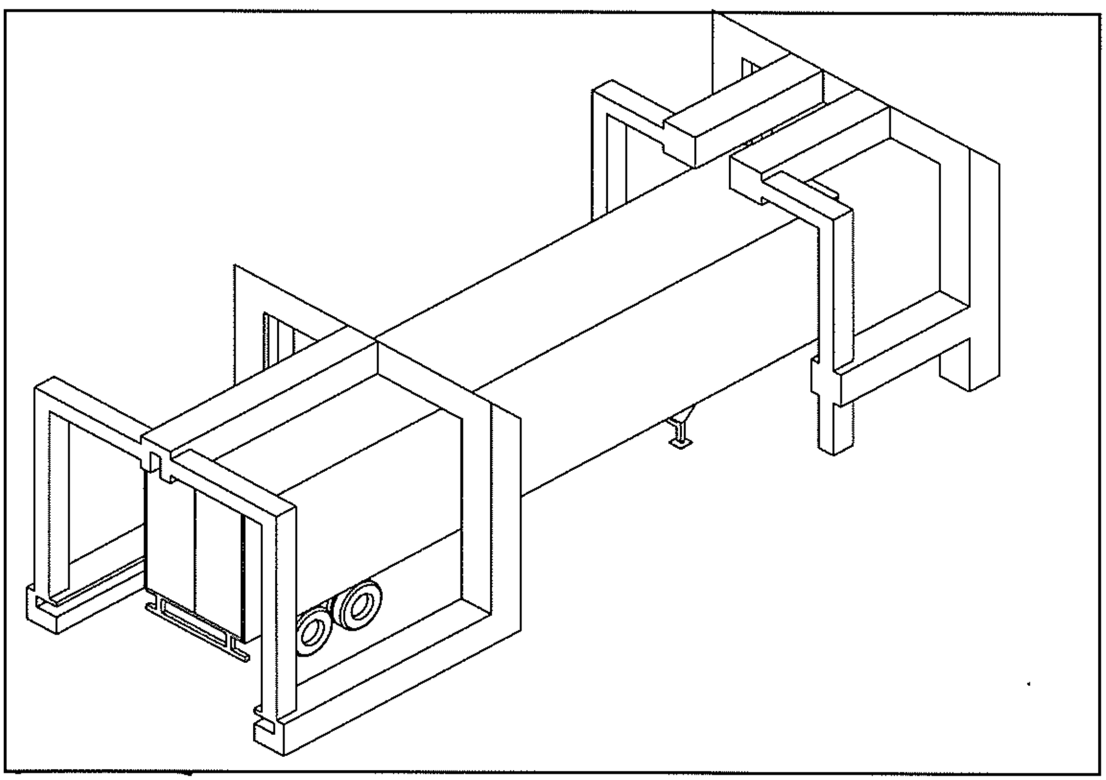

Figure 7: Sensing apparatus to determine trailer parameters upon check-in to the BMC

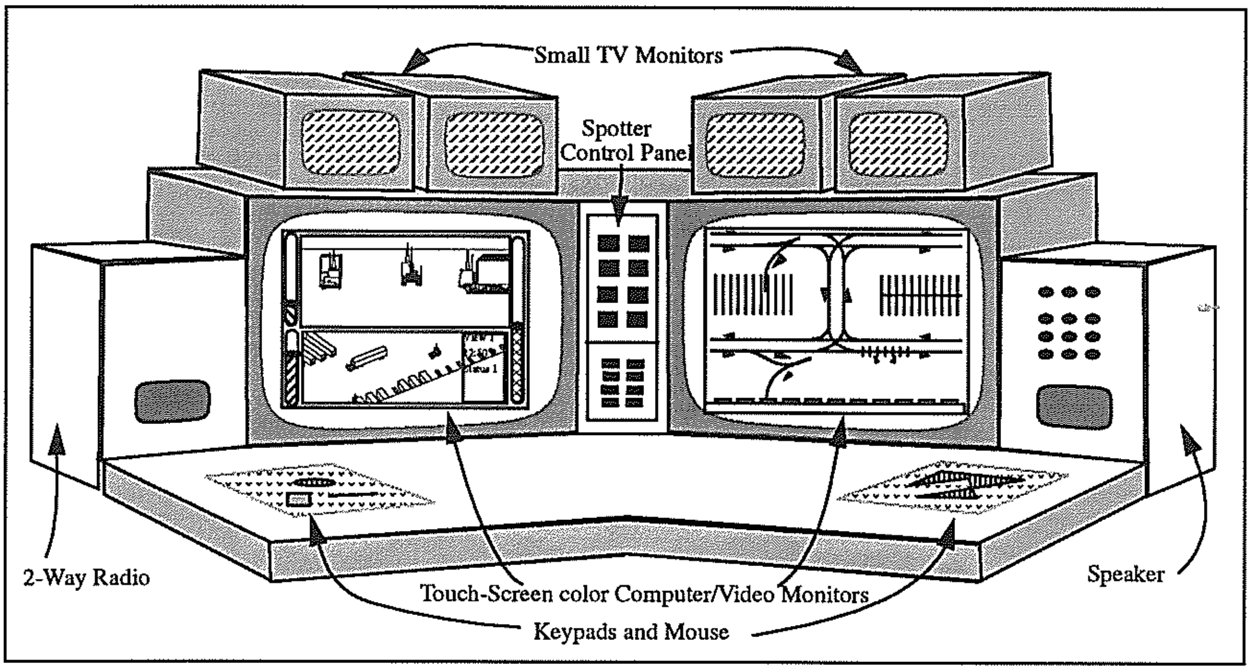

Figure 8: Layout of dispatcher's operator console with central planner display and video overlays

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