DEVELOPING AN AUTOMATIC GUIDED VEHICLE FOR SMALL TO MEDIUM SIZED ENTERPRISES

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Abstract

When choosing material handling equipment, small to medium sized enterprises (SMEs) with highly flexible product mixes seldom consider automatic guided vehicles (AGVs) as a potential solution. When evaluating AGV systems these organizations are often put off by their high cost. Also, the intrusiveness and inflexibility of fixed wire guidance systems are a poor fit for their ever-changing material handling environments. These factors lead to the under-utilization of AGV systems in these enterprises, which can leave them at a disadvantage. An AGV system often proves its worth in a short time as product is moved quickly and safely throughout operations. Since the barrier to the use of AGV systems in SMEs appears to be high initial cost coupled with an the inflexibility of navigable paths, a low cost and flexible alternative to the traditional AGV system is introduced and described.

1 Introduction

The first commercial automatic guided vehicle (AGV) in the United States went into service in a grocery warehouse in 1953 [1]. The nearly 50 years that have passed since have seen many technological improvements in AGV systems, and the systems have been used to automate material handling tasks in many industries. Modern AGV systems, however, represent a significant investment for a firm. The average cost for a single guided vehicle is about $100,000 [1], and a system that includes multiple vehicles, navigation aids, communication hardware, and safety devices can cost several times that amount. This high initial investment has restricted AGV applications almost exclusively to large corporations, so there would seem to be a significant unsatisfied demand for lower-cost systems in SMEs.

The goal of this project is to develop a low-cost AGV system to meet that demand. The prototype AGV currently under development is called the SmartCaddy. It is an automated version of a vehicle that is now a manually guided walk-behind cart called the PartsCaddy manufactured by DJ Products (see Figure 1). The SmartCaddy has been designed with two things in mind, low cost and high flexibility. Low cost has been achieved by using simple, reliable systems that are based on readily available off-the-shelf components. Flexibility has been achieved by designing a modular system with multiple navigation and communication capabilities. The modularity also compliments the desire for low cost, since the vehicle can be configured for a specific application by including only those features that are necessary.

Figure 1. PartsCaddy Manually Operated Vehicle

2 Automatic Guided Vehicle Systems

Guided vehicle systems consist of several components, including the power source, drive and control systems, navigation and communication systems, and safety devices. In this section each of those components are discussed, and the flexible and low-cost design approach to each of these are described.

2.1 Vehicle Power Source and Drive System

Guided vehicles typically operate on battery power, with battery voltages ranging from 12 to 48 VDC. Batteries are commonly lead-acid and are usually sized to last at least 8 hours during normal use. The batteries are often recharged with an on-board charger that can be plugged into any conventional wall outlet [2]. An alternative for vehicles that are required to operate around the clock is a power system that uses batteries that are easily swapped out and can be recharged off-line [3].

The SmartCaddy utilizes three 12-volt battery banks to provide three different voltages: 12 VDC for the lift table, 24 VDC for the control system, and 36 VDC for the primary drive motors. The 12 VDC supply utilizes two batteries in parallel to provide adequate capacity for the lift table hydraulic pump. The batteries are recharged with an on-board charger that charges each 12-volt bank independently. This guarantees proper charging even if the level of discharge in each bank is different. The charger can be plugged into any standard 120 VAC wall outlet.

Most guided vehicles use differential drive where two drive wheels, one on each side of the vehicle, are each driven independently [4]. Further mechanical support for the vehicle is provided by unpowered caster wheels. With this arrangement the vehicle can typically move in either the forward or reverse direction, turn either right or left, or spin around in place. Many vehicles use four-quadrant drives for speed control in which each wheel can be accelerated or decelerated in either the forward or reverse direction. Deceleration is accomplished via dynamic braking where the motion of the vehicle is used to generate power back into the batteries. This provides excellent speed control on ramps or uneven surfaces as well as improving efficiency and therefore battery life [2].

The SmartCaddy uses differential drive with the drive wheels located near the front of the vehicle. Each drive wheel is independently powered by a 36 VDC motor. Two casters provide support for the rear of the vehicle. Two variable speed four-quadrant speed controllers with dynamic braking power the motors. The speed controllers respond to analog control signals from the vehicle controller.

2.2 Vehicle Control

Automatic guided vehicles usually possess some type of on-board programmable control system. These range from simple single-board controllers [2] to complex computers [5]. The vehicle controller analyses inputs from sensors to determine the state of the vehicle, and then manipulates actuators to achieve some desired vehicle behavior. Sensors may include navigation aids, odometry, collision avoidance, safety bumpers, and load height. Actuators may change wheel speeds, activate visual or audible alarms, shut down vehicle power, or alter load height.

For the SmartCaddy it was strongly desired to use an off-the-shelf controller rather than expend the time and money required to develop a custom control system. This desire led to the selection of a standard industrial programmable logic controller (PLC) as a vehicle controller. The PLC operates directly off of the 24 VDC control power, and is equipped with digital and analog inputs and outputs as shown in Table 1. The PLC is responsible for all vehicle control, and is capable of autonomously executing eight different navigation primitives, explained in the following section.

Table 1. PLC Inputs and Outputs

Digital Inputs
- Left odometry sensor
- Right odometry sensor
- Left landmark sensor
- Right landmark sensor

Digital Outputs
- Table lift (pump)
- Table drop (valve)

Analog Inputs
- Left navigation sensor
- Right navigation sensor
- Table position sensor

Analog Outputs
- Left drive motor speed control
- Right drive motor speed control

2.3 Vehicle Navigation

Guided vehicles usually use either fixed path or free-ranging navigation. Fixed path navigation requires that a path be installed within a facility, and that the vehicle be equipped with sensors that are capable of detecting the relative position of the vehicle with respect to the path. The navigation sensors detect any deviation from the path and send signals to the vehicle controller, which then alters the motion of the vehicle to reduce the deviation from the intended path.

For many years the most common fixed path navigation method was wire guidance [6]. With this system a wire was typically installed in a cut in the floor, and the wire was charged with a radio-frequency signal from a transmitter. An antenna on the vehicle was positioned above the guide wire in such a way that the signal from the antenna was proportional to the displacement of the center of the antenna from the center of the guide wire. The signal from the antenna was then used to steer the vehicle down the guide wire.

Although widely accepted and very reliable, wire-guided vehicle systems have some drawbacks. The guide wire and associated transmitter are expensive to install, and multiple paths usually require multiple wires and transmitters, increasing the expense. Also, installing the path initially is disruptive and time consuming, and changing the path to accommodate material flow changes requires removing or abandoning existing wires and installing new ones. Because of these disadvantages, the guided vehicle industry has moved rapidly toward non-wire guided vehicles in recent years [6].

Some non-wire-guided vehicles still use fixed path navigation. The most common systems are tape-guided, where a special tape is applied to the floor as a path for the vehicle to follow. The tape can usually be installed and tested in less than a day, and can easily be removed and reconfigured if changes are needed [2]. Fluorescent, reflective or metallic tapes are often used, and optical or inductive sensors that measure the vehicle's position relative to the tape replace the wire-following antenna.

Another alternative to wire guidance is open path or free navigation. Vehicles that use free navigation compute their position internally by triangulation with optical or radio-frequency beacons, or by using a combination of odometry and inertial (gyroscopic) guidance. Laser triangulation is becoming more popular and is very accurate [6], but it is also quite expensive. Less costly systems using odometry and inertial guidance calculate their position relative to some known departure point, a process known as dead reckoning. This process is susceptible to the accumulation of errors, since even a small error in heading translates into a large position error over long travel distances [7]. Most dead reckoning systems use landmarks placed occasionally along the travel path that act as absolute position references to minimize the accumulation of errors. Landmarks are usually magnetic or optical markings on the floor.

The SmartCaddy is capable of both fixed-path and free navigation. In either mode, steering is performed by varying the speeds of the left and right drive wheels. In the fixed-path navigation mode the vehicle uses a fuzzy control algorithm to follow a 2 in.

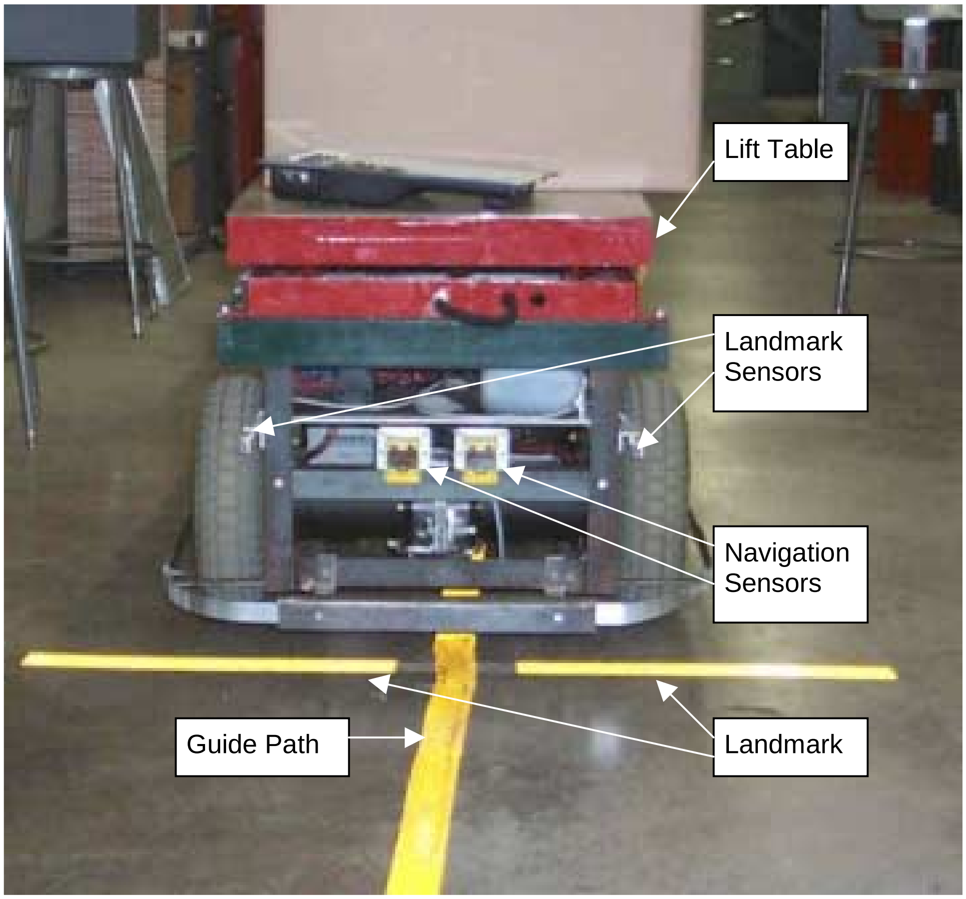

Figure 3. Front View of SmartCaddy Vehicle Showing Sensors and Floor Markings

wide reflective tape applied to the floor. The tape is sensed by two analog optical sensors (see Figure 3). The difference in the signals produced by these sensors is proportional to the deviation of the vehicle position from the center of the tape, and this signal is used by the fuzzy control algorithm to compute steering adjustments. The distance traveled along the tape is determined by monitoring odometry sensors on each of the drive wheels. The sensors produce about 16 pulses per foot of travel. Landmarks, which are reflective tape markers placed perpendicular to the guide path, are used to align the vehicle at the end of a travel segment and to eliminate the accumulation of position errors. Landmarks are detected by digital optical sensors place at the right-front and left-front corners of the vehicle (See Figure 3).

In free navigation the vehicle simply goes straight ahead by maintaining equal speeds on the left and right wheels. Again, the distance traveled is determined by monitoring odometry sensors on each of the drive wheels. Landmarks are also used in free navigation at the end of travel segments to allow the vehicle to correct position errors.

Each navigation mode has four choices of primitive motions, and the eight possibilities are shown in Table 2. Each primitive takes two parameters, a travel distance *d* and a table height *h* (some turn primitives have a travel distance of 0). The vehicle executes the motion primitives as follows:

Table 2. SmartCaddy Motion Primitives

Primitive	**Motion**
LF(*d*, *h*)	Run **L**ine **F**orward
LL(0, *h*)	Turn to **L**ine on **L**eft
LR(0, *h*)	Turn to **L**ine on **R**ight
LB(*d*, *h*)	**L**ine navigate **B**ackward and turn around
FF(*d*, *h*)	Run **F**ree **F**orward
FL(*d*, *h*)	Turn **F**ree **L**eft
FR(*d*, *h*)	Turn **F**ree **R**ight
FB(*d*, *h*)	**F**ree navigate **B**ackward and turn around

- LF(*d*, *h*): Follow the tape line in the forward direction. Once the distance *d* has been traveled, continue moving forward until a landmark is detected. When the landmark is encountered, stop the vehicle and square up to the landmark. When the vehicle is squared, move the table to height *h*.
- LL(0, *h*): Begin turning left by holding the left wheel stationary and driving the right wheel forward. When approximately 75° of rotation have been completed, begin looking for the tape line with the navigation sensors. When the line is found, center the vehicle on the tape. When the vehicle is centered, move the table to height *h*.
- LR(0, *h*): Begin turning right by holding the right wheel stationary and driving the left wheel forward. When approximately 75° of rotation have been completed, begin looking for the tape line with the navigation sensors. When the line is found, center the vehicle on the tape. When the vehicle is centered, move the table to height *h*.
- LB(*d*, *h*): Back up along the tape line in the reverse direction. Once the distance *d* has been traveled, spin the vehicle in place by driving the wheels in opposite directions. When approximately 160° of rotation have been completed, begin looking for the tape line with the navigation sensors. When the line is found, center the vehicle on the tape. When the vehicle is centered, move the table to height *h*.
- FF(*d*, *h*): Free-navigate in the forward direction. Once the distance *d* has been traveled, continue moving forward until a landmark is detected. When the landmark is encountered, stop the vehicle and square up to the landmark. When the vehicle is squared, move the table to height *h*.
- FL(*d*, *h*): Free-navigate in the forward direction. Once the distance *d* has been traveled, begin turning left by holding the left wheel stationary and driving the right wheel forward. When exactly 90° of rotation have been completed, drive both the left and right wheels forward and begin looking for a landmark. When

the landmark is encountered, stop the vehicle and square up to the landmark. When the vehicle is squared, move the table to height *h*.

- FR(*d*, *h*): Free-navigate in the forward direction. Once the distance *d* has been traveled, begin turning right by holding the right wheel stationary and driving the left wheel forward. When exactly 90° of rotation have been completed, drive both the left and right wheels forward and begin looking for a landmark. When the landmark is encountered, stop the vehicle and square up to the landmark. When the vehicle is squared, move the table to height *h*.
- FB(*d*, *h*): Free-navigate straight backward. Once the distance *d* has been traveled, spin the vehicle in place by driving the wheels in opposite directions. When exactly 180° of rotation have been completed, drive both the left and right wheels forward and begin looking for a landmark. When the landmark is encountered, stop the vehicle and square up to the landmark. When the vehicle is squared, move the table to height *h*.

Each primitive is programmed as a subroutine in the PLC that acts as the vehicle controller. The PLC is capable of autonomously executing up to six of the motion primitives in sequence.

2.4 Communication

Most guided vehicles are equipped with bi-directional wireless communication. Messages can usually be sent from a stationary base station to the vehicle to transmit path information. The vehicle then responds with messages to the base station to communicate how the vehicle is progressing along the path.

The SmartCaddy uses a wireless Ethernet connection to communicate with a base station computer that can be placed anywhere on the same network. A laptop computer equipped with a wireless Ethernet adapter is installed on board the SmartCaddy, and the laptop is in turn connected via cable to the vehicle control PLC. The recent proliferation of wireless Ethernet adapters and hubs has made them an excellent, low-cost choice for this type of communication [8]. The SmartCaddy uses the popular IEEE 802.11b (11 Mbit) standard.

In a typical scenario, the laptop will request path information from the base station via the wireless connection and will receive a command to move the vehicle from its current station to a specific destination station. The laptop is equipped with a navigational database that contains, for each possible station-to-station move, a list of primitives that are necessary to complete the movement.

These primitives are then communicated by the laptop to the PLC using the Modbus RTU protocol. The Modbus protocol is a well-established, public domain serial communication protocol that has been used for years in industrial control. The PLC used in the SmartCaddy has a Modbus port as a standard feature, so the serial communication has been implemented at very low cost.

As the PLC executes the motion primitives, the laptop (also using the Modbus link) monitors the vehicle odometry data and the number of primitives that have yet to be executed. In this way the laptop can maintain a near-real-time representation of the vehicle's progress. When all of the motion primitives in the current group have been completed the laptop sends another group of six or less. This process continues until all of the primitives for the designated path have been transmitted to the PLC and executed. The primitives can be programmed in any combination, so a path between stations can contain both line-following and free navigation segments. Once the requested path has been completed, the laptop requests the next destination from the base station and the process is repeated.

2.5 Safety Systems

Safety devices are obviously necessary on any vehicle that is not directly observed and operated by a human being. The safety standard for guided industrial vehicles with automated functions is ASME/ANSI Standard B56.5 and includes the following requirements [9]:

- Emergency stop upon
  - Manual actuation of emergency stop button
  - Actuation of safety bumper (the bumper must activate with a force of 8 lbs. or less and the vehicle must stop within the collapsible range of the bumper)
  - Deviation from guide path of 3 in. or more when following a closed path
  - Deviation from intended path of 6 in. or more in free navigation
  - Loss of guidance reference
  - Loss of speed control
  - Processor fault (watchdog timer)
- Required braking functions
  - *Emergency brake* - a mechanically set fail-safe brake that stops the vehicle in emergency situations prior to striking an obstruction or upon vehicle system failure.
  - *Parking brake* - a brake to prevent inadvertent movement of a stationary vehicle
  - *Service brake* - a braking system to proved controlled deceleration and stopping during normal vehicle operation
- Audible and/or visual warning signals must activate
  - Prior to and during vehicle motion
  - Prior to and during movement of vehicle lifting device

The safety systems for the SmartCaddy are currently under development, and will comply with the requirements stated above. A safety bumper wrapped with a tactile switch is currently being designed and installed, and systems are under development for emergency braking, audible and visual warnings, and monitoring the automatic guidance functions.

3 Current Development Activity

The SmartCaddy vehicle described in this paper is in the prototype stage, and three projects are currently underway to further its development. A student design team is currently working on improving the safety systems of the vehicle, including the design and installation of the aforementioned safety bumper. Another student design team is currently finalizing the hardware and software for the wireless Ethernet connection, the on-board navigational database, and the base station computer. A third project being undertaken by an undergraduate research student seeks to improve the accuracy and reliability of vehicle navigation.

Once these projects are completed, the next step for the development of the SmartCaddy will be to actually place the vehicle into a manufacturing facility and further evaluate its performance. When all development and testing is complete, the SmartCaddy system will become a commercially available product.

4 Conclusions

This paper describes the design and development of the SmartCaddy, a low-cost, modular, and flexible AGV system. Low cost was achieved by using simple, off-the shelf components and by avoiding large software and hardware development costs. The vehicle navigation system is very flexible in that it is capable of either line-following or free navigation. In addition, the guide path in the line-following mode is a simple reflective tape that can be installed, removed, and changed easily. The modular design of the SmartCaddy enhances its flexibility and cost advantages, since the vehicle can be configured for a specific application by including only those features that are necessary. For example, a functional SmartCaddy could be supplied without a wireless communication link to a base station, since navigation commands could simply be entered into the on-board laptop. Once commercialized, the SmartCaddy should meet the currently unsatisfied demand for low-cost AGV systems in small to medium-sized enterprises.

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