A Material Transfer System using Automated Guided Vehicles

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Abstract

This article describes an implemented solution for the material distribution problem in the machining shop of a typical manufacturing unit using Automated Guided Vehicles (AGV). We briefly describe the AGV and its associated material handling system, and then go on to describe the software components and their underlying algorithms, which, when put together, create an automated material transfer system that assesses demands for materials and accordingly plans, prioritizes and executes deliveries. The system has been tested extensively in a mock environment in our Laboratory, the results for which have also been indicated here.

Introduction

Manufacturing requires continuous movement of materials – starting from the point where vendors deliver semi-finished components, up to the point where the finished products are ready for shipment. In between, the semi-finished components are moved to various machining units, to assembly station, testing and quality control, packaging, and so on until the product is complete in all respects. In the past, these movements were performed manually. The idea of deploying one or more Automated Guided Vehicles (AGV) for this purpose is gaining in popularity these days, because they have the potential of making all movements in the manufacturing unit completely autonomous, safe, and extremely efficient, leading to higher productivity and automatic storage management eventually at a lower cost. All that is required is one or more vehicles that can move and stop precisely along designated trajectories, material transfer mechanisms like powered roller conveyors, and proximity sensors to know the presence and absence of materials on the conveyors. A set of computer programs can then take care of the entire material transfer operations. That adds to its flexibility; the entire plan can be changed at will by editing trajectories and a few other parameters.

Since the requirement for movement of materials is generic, the need for an automated material transfer system is felt by all segments of industries; more so by those whose processes are well structured to take advantage of automation, or those who are keen to avoid manual handling of hazardous (e.g., radioactive or explosive) materials. The available imported solutions turn out to be very expensive, as in each case they need to be customized to meet exact requirements of the industry. The development of Automated Material Transfer System (AMTS) was taken up at DRHR, BARC, to generate an indigenous solution that is affordable to the Indian industries going for modernization of their manufacturing processes, and that can be adapted to the exact requirements of an industry without adding substantially to its cost. The solution can also be readily adapted to automated handling and shipment of radioactive materials in the nuclear establishment.

As a concrete instance around which we can make initial development of the AMTS, we selected the
problem of automation of the transfer of semi-finished components, from a supply point to several machining centres on the shop floor of a typical manufacturing setup. The semi-finished components are packed into bins, which are stacked up for transfer to and from the AGV. The complete stack is handled by the system and delivered at the designated locations. The automation system so developed has the ability to be scaled to use and control multiple AGVs if the situation demands.

Fig. 1 shows the overview of the control architecture of the AMTS [1]. The vehicle is controlled by a Vehicle Control Program (VCP) running on a PLC on the AGV under the guidance of a Plan Executor (PE) program running on an onboard single board computer. PE executes plans for transfer orders prepared and assigned by the Supervisory Control Program to the AGV. The Supervisory Control Program runs on a stationary PC located conveniently in the Control room or Shop Floor. This program displays current status of the AGV and loading/unloading stations. It allows an operator to set transfer orders for materials, or to intervene through Emergency-Stop. A stationary PLC in the shop-floor controls all the conveyors in the loading/unloading stations. These are described in more detail in the following sections.

**Autonomous Guided Vehicle (AGV)**

An AGV is a battery powered mobile platform with the ability to interpret and execute a set of motion commands. This is achieved through appropriate design and control of the vehicle as detailed below.

**Mechanical Design**

In a shop floor, it is desirable for the AGV to move along straight paths, curves, turn in place (around its centre) and crab (shift parallel to itself). In order to cater to these requirements, the quad configuration, having two steer & drive wheels mounted on the AGV on the centre-line along its length and four support castors on four corners, has been selected. In addition to satisfying the motion requirements, this configuration has the advantage of low actuator count for high degrees of freedom, thus making the control relatively simple. The general arrangement of the drive wheels and castors are as shown in Fig. 2. The AGV is about 2m long and 1.4m wide, with three rows of conveyors onboard for loading/unloading bins on either side. Its...
payload capacity is about 700kg, and its maximum speed is about 1.3m/s.

**Vehicle Control**

All the four actuators of the AGV are driven by AC Induction Motors. The control of the motors is achieved using compatible AC Motor Controllers operating on a 48V DC battery supply. The motor controllers provide the velocity loop for the actuators based on the incremental encoders, attached to the motor shaft, as feedback devices. The velocity loop is directly used by the traction actuators for control of wheel speeds. The position control, required for the steer actuators, is achieved by position control PLC module. The position control module takes feedback from the incremental encoders mounted on the motor shaft. The module provides a PI control for maintaining the desired wheel steering angle.

A PLC based Vehicle Control Program (VCP) controls the motion of the AGV. It also controls operation of the onboard material handling system, monitors sensors, compiles AGV status data, and executes operational interlocks. The AGV operations can be controlled either in a program mode, in which it keeps executing commands received from the Plan Executor (PE) module, or in an interactive mode, in which it can be controlled through an operator’s pendant mounted on the AGV. The touch panel based operator’s pendant also serves as a status display unit during program mode operation.

The AGV can move in three different modes – Tangential, Crab, and Differential. The tangential mode allows tangential motion of the AGV along straight lines and curves. The Crab mode allows movement of the AGV in any direction parallel to itself. While doing that, it additionally allows a small specified correction in the orientation of the vehicle. In the differential mode, the AGV wheels are oriented perpendicular to its length, and all motions like straight, turn-in-place and motion along a curve may be executed by appropriate control of magnitude and sense of rotation of the two wheels. In programmed mode of operation of the AGV, we use only tangential and crab motions. Differential motion is used mainly for turn-in-place during interactive control of the AGV.

**Load Handling Mechanisms**

The AGV as well as the loading and delivery stations are provided with motorized roller conveyors for automated transfer of materials to and from the AGV. The AGV conveyors are controlled by the onboard PLC system. The field conveyors have a separate PLC based control system, and the operation of the conveyor sets is coordinated through the Supervisory Control System. Fig. 3 shows the actual AGV with various sub-systems.

**Safety**

The AGV has a set of bump sensors to be able to stop on contact. Apart from physical safety, the integrity of communication channels between various levels of software is monitored continuously. The AGV is stopped if any breach of safety requirement is detected, and the fault is indicated.
to the operator. The AGV so stopped can be put back into the system only with operator intervention after clearing of the faults. A special mode is provided for operation of the AGV under maintenance. The speed of the AGV is limited during such operations.

In order to anticipate and avoid collisions, we are additionally installing a non-contact laser based obstacle detection system, which provides for slowing down or stopping of the AGV depending on the distance of the obstacle much before any contact is established.

**Navigation**

AGV navigation can be either fixed path or free ranging. In fixed path navigation, the AGV paths are rigidly defined on the shop-floor by using path markers such as magnetic tape, photo reflective tape on the floor or burying of wire below the floor. These methods require compatible sensors on the AGV to detect the paths. This method, however, leads to a rigid system. In case of the free ranging technique, the AGV has a map of the navigation area and several fixed reference points which can be detected by onboard sensors of the AGV. The AGV localizes itself on the basis of perceived locations of these reference points.

**Laser Navigator**

The present AGV system uses the free ranging technique. It detects cylindrical reflectors installed within the work area through an onboard laser ranging device. The positions of these reflectors are known in advance in a global coordinate system. The laser navigator system returns the position (x, y) coordinates and orientation θ of the laser ranging device with respect to the same coordinate system to the AGV controller at the rate of 8 Hz [2]. The instantaneous position and orientation of the AGV is easily computed from this data.

The navigator system allows definition of a number of convex-shaped overlapping areas of operation of the AGV, comprising various subsets of reflectors to ensure accurate localization in large or poorly connected areas. Each such area is called a layer. The AGV refers to only the most appropriate layer at any instant for its localization.

**Trajectory Editor**

Systems, which use free ranging techniques, provide high flexibility regarding definition and modification of the work area and AGV trajectories. For this, various entities, such as path segments, branching nodes, loading and unloading stations, reflectors, layers etc., need to be defined. This is done using a system configuration tool called Trajectory Editor (TE). This is a CAD-based software, with the facility to import the layout drawing of the workshop, with outlines of structures, machines and various other entities depicted on it, as a background. TE facilitates creation of routes and loading/unloading stations for the AGV. It runs designated checks on the defined paths, nodes and stations and generates data tables based on the information stored while creating/editing these entities. The trajectory database, so generated by TE, completely describes the system and is loaded on to each AGV in the system. The database is used by Plan Executor (PE) program for navigation of the AGV as per operational attributes over the executing segments. The database is also used by the Supervisory Controller for all its operations including graphical display of system status using workplace drawing.

**Plan Executor**

The Plan Executor (PE) program, running on the Single Board Computer (SBC) of the AGV, carries out execution of the transfer order placed on the AGV by the supervisory control system. A transfer order is assigned to an AGV only when it is free, i.e., it does not have any pending order to attend to. The transfer order specifies sources from which
materials are to be picked and destinations at which they need to be delivered in a single trip of the AGV. In fact, what PE receives is a detailed plan worked out by the supervisory controller for execution of the transfer order in terms of a chain of nodes and associated activities. On the basis of this plan and the trajectory database, PE computes the actual trajectory to be traversed by the AGV. Accordingly, under the control of a trajectory tracking algorithm (e.g., Pure Pursuit Algorithm, as explained below), it keeps issuing motion and activity commands to the Vehicle Control Program (VCP) running on onboard PLC, until the entire plan gets executed.

The AGV is likely to deviate from its desired trajectory due to inaccuracies in motion control. In order to correct for these deviations, the AGV uses a Pure Pursuit Algorithm [3,4]. This algorithm continuously monitors the position error of the AGV with respect to its reference trajectory and adjusts the curvature of its path in such a way as to reduce the error.

PE gets position data from the Laser Navigator. It also receives vehicle odometer data from the PLC, computed on the basis of traction and steer encoder data. PE uses these data for the purpose of trajectory tracking. The navigator data, being more accurate, is normally used to determine tracking error. The odometer data is used in case the Navigator data is not available for a short duration. PE corrects the PLC odometer data periodically, based on the laser navigator data.

PE receives AGV status information packets at a regular interval (every 100ms) from VCP. The regularity of commands and status packets (heart beat) are continuously monitored by VCP and PE respectively to confirm smooth communication between them. In case the communication fails persistently for some time (1 min), command execution on the vehicle is stopped.

Apart from the above tasks, PE also waits for relevant operator level commands like Emergency-Stop, Join etc., coming from supervisor. It also issues commands to supervisor and PLC for coordinating a loading/unloading operation, apart from keeping the supervisor updated periodically about current AGV status.

**Supervisory Controller**

It is a computer program executing on a standard desktop computer, located either in the operation area or the control room as per convenience. Its function is to manage one or more AGVs with active infrastructure supports for pick-up and delivery stations. The supervisory control system carries out a range of tasks, namely monitoring of field devices, AGV traffic control, communications and AGV dispatching, tracking and tracing.

**Traffic Management & Control**

Automatic stopping, starting and routing of AGV is essential to all AGV systems. To ensure against one AGV entering an already occupied zone or intersection of a guide path and to provide for orderly and efficient routing in general, the location of each AGV is monitored and decisions are made based on this knowledge.

In the present system, we have not yet implemented multi-AGV traffic management, as the choice of strategies depend on AGV capacity, transfer load, size and complexity of environment. However, in our developments, wherever possible, we have kept provision for generalizing solutions to multi-AGV case.

**Communications**

The Communication tasks handled by the supervisory controller include messages, such as issue of transfer order to the AGV, insertion of the AGV into the system, and commands to control field devices in the work area. It also includes fault condition
detection and reporting based on the ‘AGV-heartbeat’ monitoring. The supervisory controller also monitors the AGV status and takes necessary action based on the information e.g. commanding the AGV to go to the charging station in case of inadequate battery charge. Considering ease of adaptability, large coverage area and flexibility regarding expansion of the coverage area, the Radio frequency based Ethernet communication between the Supervisory Controller and the AGV has been selected.

Communication between the Supervisory Controller and the field devices (e.g., stationary conveyors) is accomplished by using any standard serial protocol over a wired link, as the systems are largely stationary. The operations of the conveyors in loading/unloading stations have to be controlled and synchronized with that on the AGV. A PLC system with distributed I/O is used for this purpose. The PLC communicates with the Supervisory controller on a RS-232 based Modbus interface. The Supervisory controller issues commands for the operation of the conveyors and also for the compilation of the status data for the conveyors. The commands for the conveyor operations are received from the Plan Executor and the activity of the compilation of the status is periodically carried out by the Supervisory controller.

The status data compiled by the controller is further used by the Supervisory Controller for triggering of transfer plans and the information is also passed over to PE as and when required.

Job Generation & Assignment

Job generation and assignment is an essential and important part of every AGV based system. The operation ensures that all load consuming stations receive timely service from the AGV. It has to be efficient to achieve the maximum benefits from the system.

The generation of transfer requests is application specific. For autonomous operation of the system, the supervisory controller is required to be connected to plant control system. In that case, the supervisory control system monitors the plant status and combines various requirements in the field efficiently to generate the transfer order requests.

In a semi-autonomous mode, the supervisory system is configured to generate a specific, pre-defined transfer order request based on a set of field status conditions. The supervisory controller module for the AMTS currently works in the semi-autonomous mode. A suitable user interface is provided for the operator to define triggering conditions and corresponding transfer plans to be executed in case the trigger gets activated.

The fully autonomous mode of operation has been analyzed and solution worked out with respect to a specific application environment (automotive sector) and transfer load pattern [5,6]. However, it is difficult to generalize such solutions to other environments.

Display and User Interface

The supervisory controller continuously displays the status of various sub-systems on the control console. The display includes update of the locations of the AGVs in the system, the status of operation of AGV load handling equipment, AGV battery charge status, field conveyors status and the indication of any warnings and faults generated on any of the sub-systems. The controller also provides user interface for manual intervention. This includes the facilities for emergency stopping of the AGV, conveyors etc., in case of any fault on the system. The interface also allows generation and transmission of a manual transfer order to an AGV. The system keeps logging in all the status, warning and fault messages which can be used for generating the statistical data for the system as well as for fault debugging. Fig. 4 shows the Supervisory Control software screen.
during operation of the AMTS. The software depicts the status of the various field devices (conveyors etc). It also dynamically updates the AGV positions on the plan (not shown in the current figure).

Test runs

In order to test, debug and eventually establish integrity of the entire hardware software setup going into the AMTS, we have created a mock material transfer environment in the Ground Floor Hall of our Building. The Hall measures approximately 20m x 10m. We have installed one loading station and two unloading stations on a closed trajectory. Fig. 4 shows the arrangement as shown on the display of the Supervisory Controller. Transfer orders are assigned to the lone AGV in this system by the Supervisory Controller in a way such that the AGV keeps looping around the Hall and keeps transferring in and out stacked bins purportedly carrying materials. While the AGV has no problem in completing loops, there are occasionally problems in material transfer because of level difference between the conveyors.
Fig. 5 shows the desired and actual path followed by the AGV during execution of a material transfer plan. There are small deviations of the actual trajectory from the reference trajectory at several points – particularly at turns, or at places where the motion mode undergoes change. However, it is mainly the errors in position and orientation of the AGV, when it stops for a transfer, that counts, as that affects the reliability of material transfer.

While positioning the AGV for a transfer, errors in alignment, orientation, and distance were measured systematically. It was observed that the errors are well within acceptable limits (±10mm for alignment, ±1 degree for orientation, and 100mm for distance) for autonomous operation of the AGV. While we are keen to reduce the errors, we realise that there is a limit to the precision of control because of limitations of the underlying AGV steering mechanisms (e.g., backlash in steering angles of drive wheels). Moreover, the switching of motion modes (tangential to crab and vice-versa) of the AGV, makes it even more difficult to track the reference trajectory consistently.

Conclusion

We have completed development of the first prototype of an automated material transfer system and demonstrated its operation to potential users and manufacturers. Although a specific application in the automotive sector was picked up as a model for design of the AGV and its control software, the solutions so generated are general enough to be used with modifications or enhancements in other application environments as well. Because of the need for customization, the technology is inherently expensive. It will become affordable to the industries in the country once solutions are generated locally based on the presented technology. Since the control architecture is modular, a wide range of sensors, navigation and localization systems can be interchangeably interfaced to the system as per availability and requirement.

References


2. SICK NAV-200 & S-3000 series product documents and manuals.


