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Digital Transformation of Intralogistics: A Framework for AGV Integration in Industry 4.0 Warehouses

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Abstract. The paper offer a framework of how Automated Guided Vehicle (AGV) can be implemented and configured in Industry 4.0 warehouses. It incorporates two hardware platforms: an Arduino Mega 2560 based hardware outfitted with RFID and obstacle-avoidance, and an Arduino UNO based hardware with Bluetooth control and GPS positioning. The architecture provides a unified control platform, which is an infrared line following control, ultrasonic obstacle detection control, RFID-based destination identification, and GPS positioning. Path following Proportional-integral-derivative (PID) control algorithms are used and adjusted to improve the path following, with better track-following results than uncontrolled systems. The navigation technologies are tested with reference to various working parameters. Findings show that the integration of AGV can enhance the throughput of the warehouse by 85%, labour productivity by 145%, safety incidents by 84 % and a payback period of 1.1 years. The paper introduces the methodology and describes the system architecture and Mechanical Design and Electronic Control, and discusses the results analysis, and concludes the paper at the end.

Introduction

The main changes that will take place within warehouses within Industry 4.0 are automation and data integration. AGV installation is a key component that eases optimization of materials handling and logistics. The more common AGV systems are single-control-based systems, which are sensors restricted in nature and thus hinders its use in dynamic warehouse setups. Recent literature has mentioned different contexts of AGV systems [1], [2]; but most of them have been either fully autonomous or manually controlled, which do not cover the hybrid ones. This paper provides that gap by introducing a dual-control system which integrates autonomous navigation and remote control. The main contributions include: (1) a combination of Arduino Mega 2560 and Arduino UNO to offer redundant control; (2) sensor fusion consisting of IR, ultrasonic, RFID and GPS; (3) hybrid control algorithms including autonomous and Bluetooth controlled and mixed operation modes; (4) overall performance analysis in a warehouse environment.

Literature Review

AGVs are another important part of Industry 4.0 automation of a warehouse, the development of the primitive wire-guided systems of the 1950s into modern cyber-physical resources [3]. Modern studies of AGVs give special attention to navigation technologies, control systems and the integration of the systems. Some of the navigation methods include cost-effective line-following [5] and more general LiDAR-based simultaneous localization and mapping (SLAM) systems [6] with different trade-offs in cost, precision, and flexibility. The way of selection of a method of navigation is based on the warehouse layout constraints and work needs. PID controllers have replaced primitive on-off control paradigms and they offer precise path following by rigorously tuning proportional, integral, and derivative parameters [7]. PID algorithms minimise path deviation when tuned well, save energy [5], [8], and can perform complex activities like multi-

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AGV coordination. The combination of AGVs with Warehouse Management Systems (WMS) and Enterprise Resource Planning (ERP) systems allows a two-way communication of data, which can be used to predict maintenance and achieve real-time optimization [2], [9]. This integration enhances such key performance indicators as accuracy of orders and labor productivity [1], [9]. Warehouse Management Systems (WMS) and Enterprise Resource Planning (ERP) integration allows two-way data flow which is the basis of predictive maintenance and real time operational optimization [2], [9]. This kind of integration improves important performance indicators, in particular accuracy of orders and labor productivity [1], [9]. In spite of the prevailing literature researches on single AGV a complete analytical model that encompasses hardware development, control code, and impact evaluation are lacking. This paper fills that gap by providing an extensive implementation process that connects electronic regulation and strategic analysis.

Methodology

1-AGV System Architecture for the Smart Warehouse

The integration of AGVs into a smart warehouse requires a multi-layered technological architecture that connects physical assets to enterprise-level management systems. This Industry 4.0 architecture, Figure.1, ensures seamless data flow, real-time control, and intelligent decision-making.

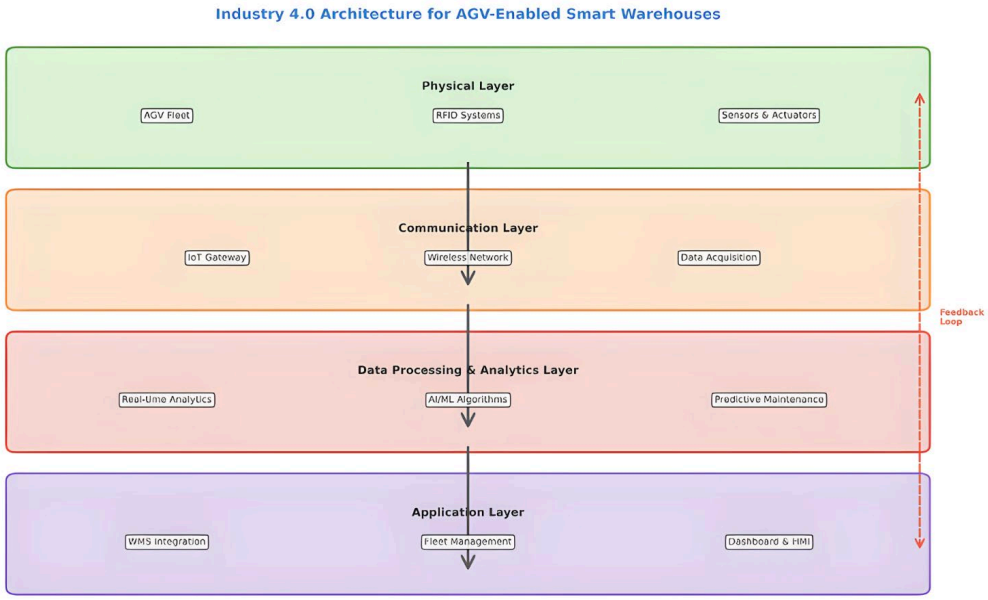


Fig. 1. Multi-layered Industry 4.0 architecture for integrating AGV systems within a smart warehouse.

The architecture comprises four primary layers:

The Physical Layer includes AGV fleet, RFID tags that are used to track the position, sensors, like infrared and ultrasonic sensors, that help the AGV machines to perceive the environment. The Communication Layer provides the connection through IoT gateways and wireless networks, thus, allowing the transmission of data. The Data Processing and Analytics Layer transforms raw data into actionable insights by applying real time analytics and artificial intelligence algorithms to both support predictive maintenance and route optimization. Application Layer links to warehouse management systems to fulfill order, fleet management system and human-machine interface dashboards. An essential one-way back and forth feedback loop makes it possible to be optimized in real-time.

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2-AGV Design and Control Systems

The effectiveness of an AGV system depends on its mechanical design and control electronics sophistication. This section details core components from physical structure to navigation and control logic.

Sensor Integration and Data Processing:

Ultrasonic sensor measurements di for sensors i = 1, ..., 4 are processed through a moving average filter:

$$\overline{d_i}[k] = \frac{1}{N}\sum_{j=0}^{N-1} d_i[k-j]$$

where N = 5 provides noise reduction while maintaining 20 Hz update rate. IR sensor outputs are thresholded for path detection:

$$\text{Path detected} = 1 \quad \text{if } V_{IR} < V_{\text{threshold}}$$
$$\text{Path detected} = 0 \quad \text{otherwise}$$

GPS coordinates (ϕ, λ) are converted to local Cartesian coordinates (xGPS, yGPS):

$$x_{GPS} = R(\lambda - \lambda_0)\cos\phi_0$$
$$y_{GPS} = R(\phi - \phi_0)$$

where R = 6371000 m is Earth's radius.

Kinematic Modeling:

The AGV dynamics are modeled using kinematic equations:

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\cos\theta & 0\\ \sin\theta & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}v\\ \omega\end{bmatrix}$$

where (x, y) is position, θ is orientation, v is linear velocity, and ω is angular velocity. For line-following applications,lateral error ey is defined as:

$$e_y = -\sin\theta_d\,(x - x_d) + \cos\theta_d\,(y - y_d)$$

where (x_d, y_d, θ_d) represents the desired path.

PID Control Implementation:

The Physical Layer includes AGV fleet, RFID tags that are used to track the position, sensors, like infrared and ultrasonic sensors, that help the AGV machines to perceive the environment. The Communication Layer provides the connection through IoT gateways and wireless networks, thus, allowing the transmission of data. The Data Processing and Analytics Layer transforms raw data into actionable insights by applying real time analytics and artificial intelligence algorithms to both support predictive maintenance and route optimization. Application Layer links to warehouse management systems to fulfill order, fleet management system and human-machine interface dashboards. An essential one-way back and forth feedback loop makes it possible to be optimized in real-time.

The PID controller implements the control law:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\,d\tau + K_d \frac{de(t)}{dt}$$

with discrete implementation:

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$$u[k] = K_p e[k] + K_i T_s \sum_{i=0}^{k} e[i] + K_d \frac{e[k] - e[k-1]}{T_s}$$

where T_s = 10 ms is the sampling period.

Controller gains are optimized using the Ziegler-Nichols method with refinement to achieve damping ratio $\zeta = 0.707$ and natural frequency $\omega_n = 15$ rad/s.

The AGV system can be configured in three different modes, such as an autonomous mode with the help of the IR and ultrasonic obstacle sensor to navigate through the pre-drawn paths; Bluetooth mode; the AGV can be controlled via Android application and gives telemetry; and hybrid mode: the AGV is operated autonomously under the control of a person via Bluetooth. Mode transitions are performed with priority-based conflict resolution by using a finite state machine. I2C between Arduino Mega 2560 (id of 0x08) and Arduino UNO (id of 0x09) at 400 kHz is used, whereby the Mega pings the UNO with 100 ms intervals. Wireless communication involves HM-10 BLE 4.0 module based on UART with a 9600 baud rate of communication, structured packets, 1-byte header, 1-byte command, variable length payload, and 1-byte checksum, and CRC-8 error-checking.

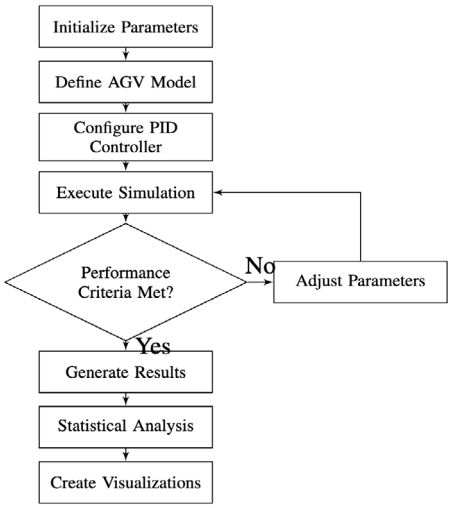


Fig. 2. MATLAB simulation workflow for AGV performance evaluation.

The systematic performance assessment is imposed through the application of MATLAB simulation procedure as shown in Fig.2. The first parameters like: vehicle dimensions, sensor characteristics and control gains are set. On the basis of the kinematic equations, the AGV dynamic model is achieved. The best gains are then coded to the PID controller. Simulations are performed in a performance fashion. quantities that are calculated in time. The parameters are changed and the simulation is repeated in case performance criteria (steady-state error 2%, settling time 3s) have not been met. Result generation, statistical analysis and visualization are the subsequent activities of the most effective simulations.

Operational performance is quantified through key performance indicators:

$$\text{Throughput Increase} = \frac{T_{AGV} - T_{manual}}{T_{manual}} \times 100\%$$

$$\text{Labor Productivity Gain} = \frac{P_{AGV} - P_{manual}}{P_{manual}} \times 100\%$$

$$\text{ROI} = \frac{\text{Annual Savings} - \text{Annual Costs}}{\text{Initial Investment}} \times 100\%$$

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$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Net Savings}}$$

Mechanical Design and Electronic Control

AGVs come in various forms tailored to specific warehouse tasks, including narrow-aisle AGVs for high-density storage and forklift AGVs for pallet transport. The electronic control unit (ECU) brain is typically an Arduino Mega providing sufficient I/O pins for sensors and motors. Figure.3 shows the Proteus simulation integrating key components.

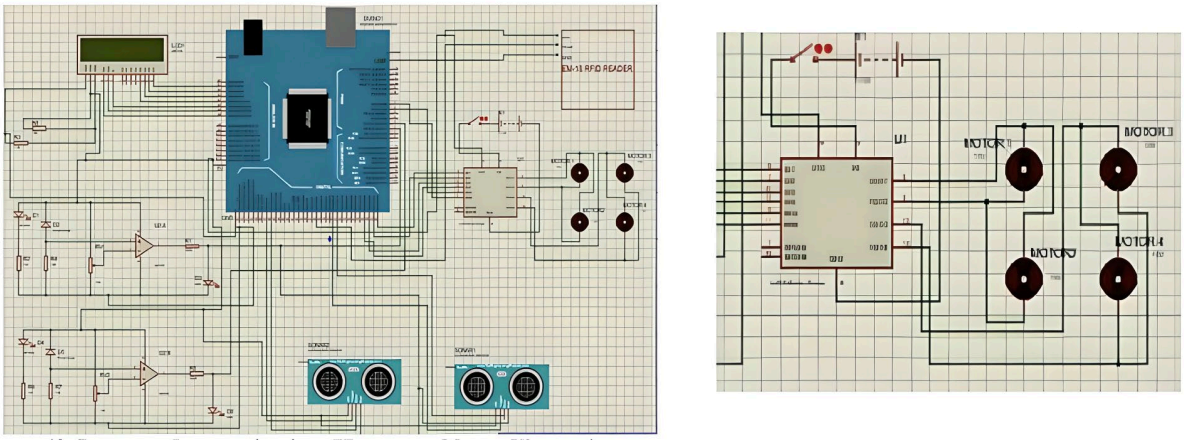


Fig. 3. Proteus simulation of AGV circuitry with microcontroller, IR sensors, ultrasonic sensors, and motor drivers.

The system uses 12-V DC power, regulated to 5V for microcontroller and sensors. The L298N H-bridge module controls motor speed and direction. An RFID reader (EM18) provides tag-based location identification, while ultrasonic sensors enable obstacle detection and collision avoidance.

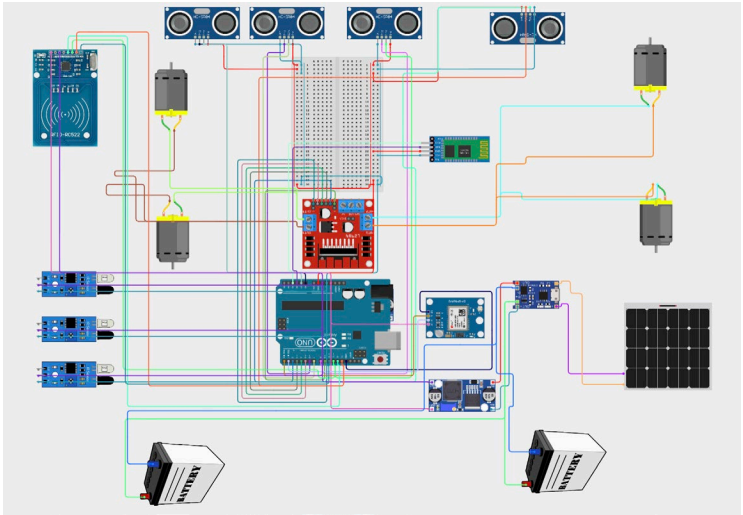


Fig. 4. Prototype Dual-Control AGV System Architecture Combining Autonomous Navigation and Bluetooth Operation Multi-Sensor Integration for Warehouse Navigation.

Fig. 4 depicts that the AGV prototype has a dual-microcontroller and architecture. An Arduino Mega 2560 (54 I/O pins, 256 KB flash) is used to run autonomous navigation, and an Arduino UNO is used to support Bluetooth and auxiliary control to ensure a backup. It has four HC-SR04 ultrasonics (90 360 2 -400 cm) at 90 degrees, five TCRT5000 IRs (line following), a NEO-6M

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GPS (2.5 m), and an RFID-RC522 (13.56 MHz, 10 cm). Two L298N H-bridges drive four planetary gearbox motors (300 RPM, 2.5 kg-cm torque at 12 V) that are driven by planetary gears. A 12 V 7 Ah lead-acid battery that is powered by buck converter, and accompanied by 18650 Li-Ion pack and 5 W solar panel, provide power.

Results and Discussion

This section provides quantitative evaluation of AGV navigation and control systems and their impact on warehouse operations.

1. Navigation System Performance

Figure.5 presents comprehensive AGV navigation performance analysis using MATLAB-style visualizations.



Fig. 5. AGV Navigation Performance: (A) Path following accuracy with/without PID control. (B) Multi-criteria comparison of navigation technologies. (C) PID tuning parameter effects. (D) Energy efficiency comparison.

It has demonstrated that the control of PID in panel A has provided the best control and the path deviation in comparison with the non-controlled systems with high oscillation as well as stabilized under a very short duration. Compared to the rest of the panels B, the comparison of the technologies of navigation, IR Line Follower and Laser Navigation are more expensive and more precise and adaptable, the former is cheaper. The trade-offs of energy are shown in Panel D in which complex systems like SLAM consume more energy and reduce battery life.

2. Warehouse Digitalization Impact

AGV integration catalyzes warehouse digitalization, driving improvements across multiple KPIs Figure.6.

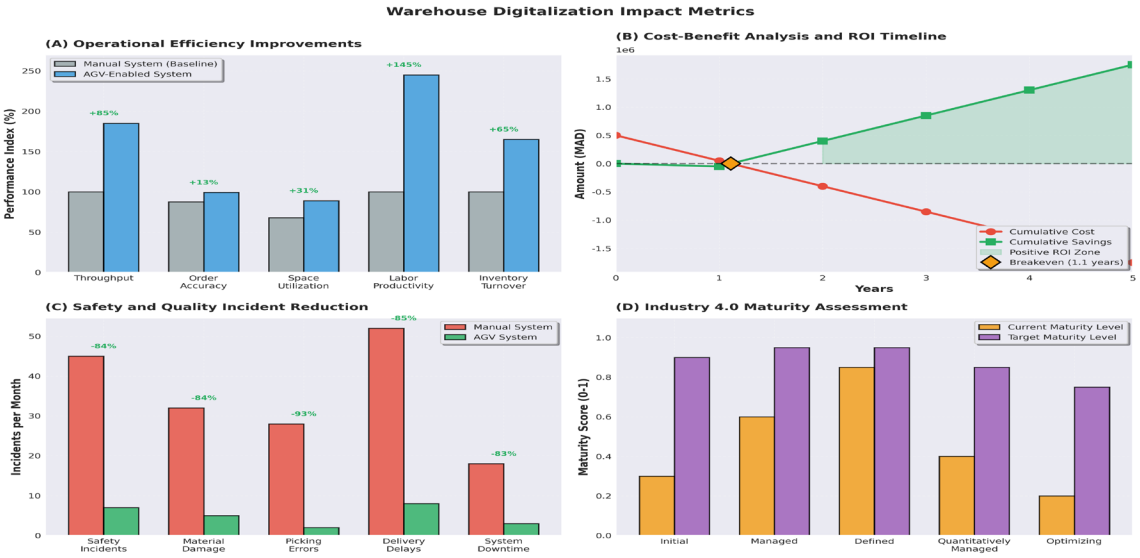


Fig. 6. Digitalization Impact: (A) Operational efficiency improvements. (B) Cost-benefit analysis and ROI. (C) Safety and quality incident reduction. (D) Industry 4.0 maturity assessment.

As seen in Panel A, the effects of operations cannot be underestimated as the throughput level will grow by 85*, level of labor productivity will grow by 145% and level of order accuracy will grow by increasing by 99.2% after the implementation. As can be observed in panel B, it has strong returns on finances with breakeven after 1.1 years with an initial investment of 500,000 MAD, and a savings of 450,000 MAD per year. According to panel C, there were great safety increases because it recorded an 84 minus decline in safety incidences, 84* decline in materials damage and 93% decline in picking errors. Panel D is used to demonstrate the maturity process between an initial/managed stage and a quantitatively managed/optimizing stage.

Conclusion

One of the pillars of the warehouses in Industry 4.0 transformation is the integration of Automated Guided Vehicles. The paper provides an in-depth AGV system, such as low-level electronics and control to PID, as well as the high-level performance and influence in a warehouse. It has been examined that well-designed AGVs on robust Industry 4.0 systems bring significant efficiency, accuracy, safety, and financial outcomes. Large-scale circuitry and control design will provide guidance towards cost effective reliable AGVs. The superiority of PID-controlled systems is measured quantitatively along with the help of the performance analysis with MATLAB, and it provides an opportunity to compare various technologies applied in navigation. The analysis of impacts can be referred to the high ROI and substantial operational profits. The solutions offered herein would be required since warehouses are becoming more automated and data-driven to leverage AGVs to achieve competitive advantage.

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