

Enhancing Warehouse Operational Efficiency Through Vision-Guided Automated Guided Vehicles (AGVs): A Business and Productivity Analysis for SMEs

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Abstract

The increasing pressure for workflow stability, cost efficiency, and labour optimisation in small and medium-sized enterprises (SMEs) has intensified the demand for accessible intralogistics automation. Guided by Industry 4.0 principles and supported by recent research on lightweight, vision-based navigation and integrated material-handling mechanisms, this study presents the design and evaluation of a low-cost, vision-guided Automated Guided Vehicle (AGV) developed specifically for SME environments. The AGV employs PixyCam-based colour navigation and a height-adjustable conveyor module to provide autonomous, reliable material transfer with minimal infrastructural requirements. A mixed-method assessment combining engineering performance tests, operational workflow observations, and financial modelling was conducted. Results show that the AGV reduces takt-time variability from $\pm 18\%$ (manual handling) to approximately $\pm 3\%$, enhances workstation synchronisation, and improves ergonomic safety by reducing walking distance and manual lifting. Annual labour savings range between RM 28,000 and RM 36,000, with a projected payback period of 4 to 6 months. These findings demonstrate that low-cost, vision-guided AGVs offer SMEs a practical pathway to operational stability and digital transformation, delivering measurable technical, ergonomic, and financial benefits without the high cost and complexity of industrial AGV systems.

Keywords: Automated Guided Vehicle (AGV), Intralogistics Automation, SMEs, Vision-Based Navigation, Takt-Time Efficiency, Industry 4.0

Introduction

Intralogistics performance has become a central determinant of manufacturing competitiveness, particularly among small and medium-sized enterprises (SMEs) that continue to depend on manual material-handling routines. Inefficiencies such as inconsistent walking times, fatigue-related delays, and variability in cycle time have been repeatedly identified as major contributors to production bottlenecks and takt-time instability (Soliman, 2020). As SMEs face increasing pressure to stabilise workflow, reduce operational costs, and address workforce shortages, the need for accessible intralogistics automation has intensified (Jie et al., 2023). These challenges provide the contextual motivation for exploring cost-effective automation solutions capable of improving production flow without imposing the high financial and technical burdens typically associated with industrial automation.

Automated Guided Vehicles (AGVs) have long been recognised as effective tools for achieving repeatable, predictable, and safe transport of materials between workstations (Löcklin, 2022). However, their adoption among SMEs remains limited because most commercial AGVs rely on advanced navigation technologies, such as LiDAR, SLAM, or proprietary fleet-management systems, that significantly elevate cost, technical complexity, and maintenance requirements (Hinne & Sangal, 2025). This technological–economic mismatch has resulted in a persistent adoption gap, prompting recent research to focus on “lightweight automation” approaches that emphasise affordability, modularity, and minimal infrastructural disruption (Filip & Leiviskä, 2023).

The theoretical grounding for this study is informed by the convergence of three bodies of literature:

1. **Industry 4.0 adoption in SMEs**, which highlights the need for scalable, low-cost automation aligned with limited resources (Nurlan, 2025).
2. **Vision-based and marker-based navigation**, which demonstrates that colour cues, RGB sensing, and fiducial markers can deliver reliable path-following performance in structured indoor settings at significantly lower cost compared with LiDAR or SLAM (Al Khatib, Jaradat, & Abdel-Hafez, 2020; Pungle, Andhare, & Pungle, 2024).
3. **Integrated material-handling mechanisms**, which show that onboard lifting or conveyor systems can enhance workflow continuity, reduce ergonomics risks, and improve consistency in loading/unloading operations (Kubasakova, 2024).

Positioned within this theoretical context, this study aims to bridge the gap between technical feasibility and practical applicability by developing and evaluating a low-cost, vision-guided AGV tailored specifically for SME intralogistics.

The objective of this study is to design, build, and assess a PixyCam-based colour-guided AGV equipped with a height-adjustable conveyor mechanism, and to evaluate its performance from both engineering and business perspectives. The study specifically examines:

- navigation accuracy, marker detection reliability, and actuator performance;
- takt-time stability relative to manual material handling;
- ergonomic and labour-efficiency impacts; and
- financial feasibility through cost–benefit and ROI analysis.

The scope of the study is therefore twofold:

1. **Technical Scope** – evaluating navigation, mechanical lifting, and overall operational reliability within a structured SME-representative environment.
2. **Managerial/Business Scope** – analysing productivity gains, labour optimisation potential, and financial returns, addressing the practical constraints faced by SMEs.

By integrating these perspectives, the study positions the AGV not merely as a technical artefact but as an accessible Industry 4.0 solution aligned with SME operational realities. This holistic framing contributes to a more comprehensive understanding of how low-cost, vision-guided AGVs can enhance competitiveness, stabilise production flow, and support the gradual digital transformation of resource-constrained manufacturers.

Methodology

The development of the vision-guided Automated Guided Vehicle (AGV) followed a modular engineering design approach aimed at achieving low cost, ease of integration, and technical reliability, requirements that align closely with the operational realities of small and medium-sized enterprises (SMEs). The methodology encompassed mechanical design, electronic integration, navigation development, software architecture, and performance evaluation. Each subsystem was developed iteratively to ensure functional compatibility and operational robustness within a simulated SME production environment.

The system architecture was divided into three major subsystems: the navigation module, the lifting and material-transfer module, and the chassis and mobility module. This modular approach provided design flexibility and allowed each subsystem to be optimised independently before integration. The navigation module employed a PixyCam colour-vision sensor (Figure 1), trained to detect predefined coloured markers placed along the designated pathways. The rationale for selecting colour-based navigation over LiDAR or SLAM approaches was driven by cost considerations and by evidence from recent research that structured indoor pathways, with distinct visual markers, support reliable AGV movement without the need for high-complexity sensors (Pungle, Andhare, & Pungle, 2024; Seki, Kawai, & Hikizu, 2021). The PixyCam continuously scanned its field of view for colour blocks, interpreting these as navigation cues. The corresponding positional information was transmitted to a dedicated microcontroller responsible for steering control, stopping logic, speed regulation, and directional adjustments. The use of marker-based navigation minimised the need for layout modification and reduced implementation cost, making it appropriate for SMEs that prefer minimal infrastructural changes.

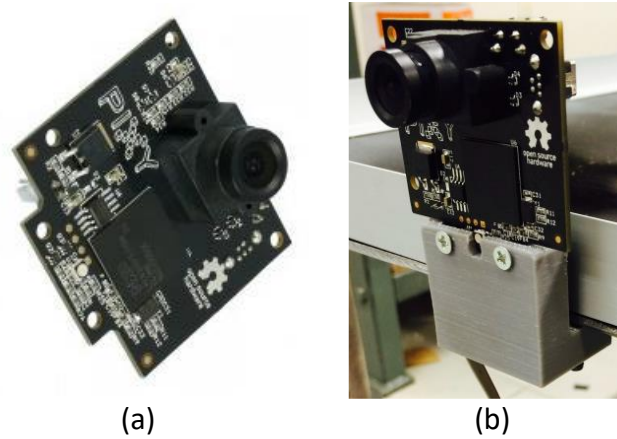


Figure 1: (a) PixyCam module (b) PixyCam mounted on AGV

The lifting mechanism was designed to enhance the AGV's functional capability by enabling autonomous material transfer between the vehicle and workstation platforms. A compact electric linear actuator was integrated beneath a lightweight roller conveyor system mounted on the AGV chassis (Figure 2). This actuator provided the necessary vertical motion for aligning the conveyor height with different workstation levels, facilitating seamless loading and unloading. The roller conveyor enabled passive transfer of materials through linear motion, eliminating the need for additional powered components and thereby lowering system complexity. A separate microcontroller governed the lifting subsystem, enabling it to operate independently of the navigation control architecture. This division of processing responsibilities ensured that lifting operations did not interfere with real-time navigation tasks, which is essential for maintaining stability and responsiveness during AGV operation.

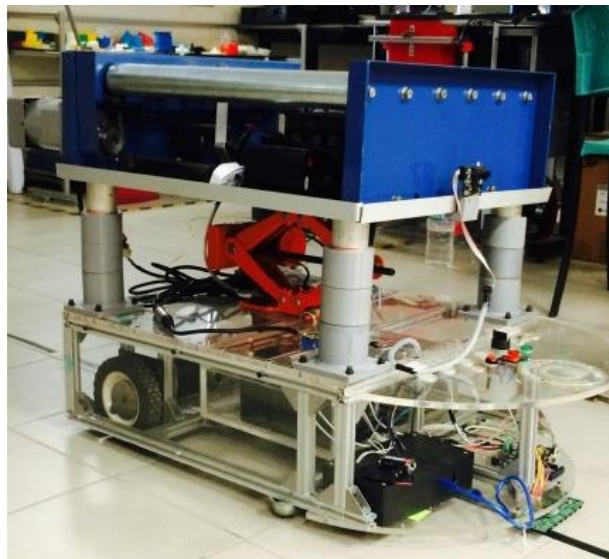


Figure 2: Lifting mechanism with roller conveyor

The chassis and mobility subsystem consisted of a lightweight but rigid platform designed to support all electronic components, mechanical elements, and onboard payloads. The chassis was constructed using low-cost, easily fabricated materials selected based on strength, weight, cost, and manufacturability (Figure 3). Two DC motors provided differential drive mobility, supported by motor drivers and encoders for improved velocity control and positional stability. The power subsystem incorporated separate electrical rails for motors and

sensors to prevent signal noise from affecting the vision system and microcontroller performance. A sealed lead-acid battery was selected due to its cost-effectiveness, reliability, and suitability for multi-hour operation within typical SME production cycles.

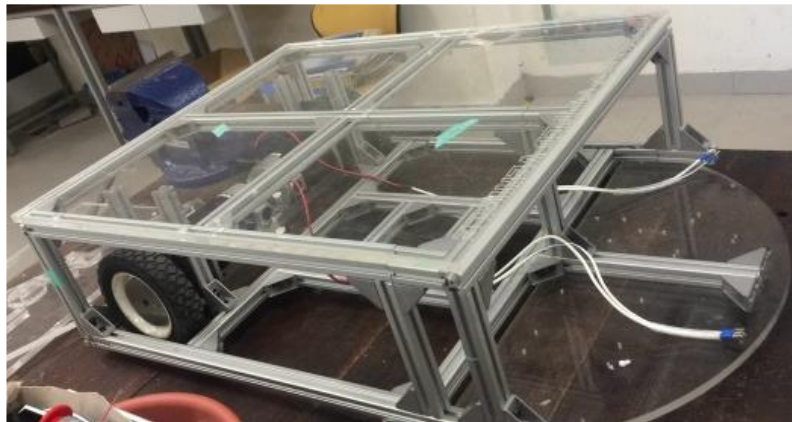


Figure 3: AGV chassis.

The software architecture followed a structured programming approach to ensure predictable and safe AGV behaviour. The navigation microcontroller executed a continuous loop involving image capture, colour-block recognition, interpretation of navigation commands, and motor-control adjustments based on encoder feedback. The lifting microcontroller operated as a state machine activated upon arrival at a designated workstation marker. It executed controlled actuator extension, load-transfer timing, and retraction, with embedded safeguards to prevent unexpected actuator motion. The separation of control responsibilities contributed to reduced computational load and improved system reliability during simultaneous navigation and lifting operations.

To evaluate the AGV's performance, a simulated SME production environment was created featuring two workstations connected by a structured pathway marked with distinct coloured navigation cues as tested in Figure 4. This environment replicated the constrained and predictable layouts commonly found in SMEs, where pathways are narrow, movement patterns are repetitive, and environmental lighting remains relatively stable. Several performance metrics were assessed, including navigation accuracy, marker detection reliability, lateral deviation, turning precision, actuator alignment accuracy, load transfer success rate, and overall takt-time stability. These metrics collectively provided a quantitative and qualitative assessment of the AGV's capability to enhance intralogistics performance.

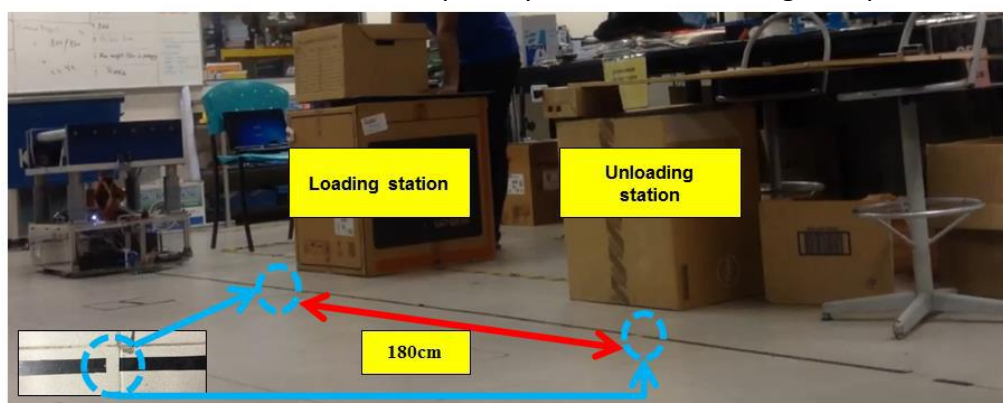


Figure 4: Two workstations (loading and unloading) connected by a structured pathway.

In addition to the engineering evaluation, a financial analysis was conducted to determine the AGV's economic feasibility for SMEs. The analysis followed a cost-benefit framework incorporating equipment cost, labour displacement, productivity gains, and reduced variability in takt time. Annual operational savings were estimated using labour-hour displacement models commonly applied in SME automation studies, and the financial evaluation included calculations of return on investment (ROI), annualised savings, and payback period (Hu et al., 2021; Zenišek et al., 2023; SME, 2018). The financial evaluation included calculations of return on investment (ROI), annualised savings, and payback period, providing decision-makers with tangible economic justification for adopting AGV technology.

Finally, a triangulation strategy was used to enhance the validity of the findings. Engineering performance data were cross-referenced with workflow observations and financial indicators to produce a holistic understanding of the AGV's operational impact. This methodological integration ensured that the AGV was not only technically functional but also organisationally beneficial and economically feasible for real-world SME environments.

Results and Discussion

The evaluation of the vision-guided Automated Guided Vehicle (AGV) demonstrated that a low-cost, modular automation system can deliver performance levels suitable for SME intralogistics while generating measurable operational and financial improvements. Overall, the results confirm that the developed AGV meets the core expectations of navigation reliability, lifting stability, takt-time consistency, ergonomics enhancement, and labour optimisation. These findings support the broader argument that SMEs can adopt structured material-flow automation without the financial burden typically associated with industrial-grade AGV systems.

From a technical standpoint, the AGV exhibited consistently high navigation accuracy throughout the repeated trials performed in the simulated SME environment (Figure 5). The PixyCam sensor achieved an average marker-detection rate exceeding 98%, with only minor deviations occurring in situations involving rapid directional changes or reduced illumination near specific pathway segments. Despite these challenges, lateral deviation was maintained within ± 2 cm, while turning accuracy remained within $\pm 5^\circ$, both of which are well within acceptable tolerances for structured indoor environments. These findings reinforce the viability of colour-coded visual navigation as a dependable alternative to LiDAR or SLAM technologies in SME settings, particularly where floorspace is predictable, paths are stable, and layout changes are infrequent.

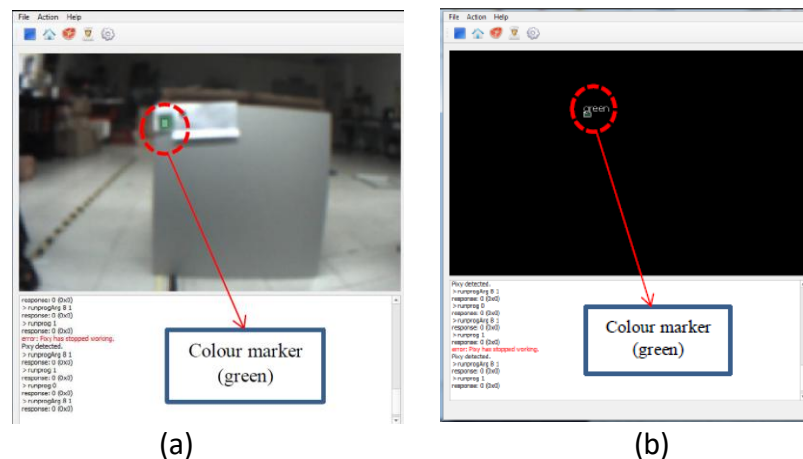


Figure 5: (a) PixyCam raw view (b) Processed image detecting coloured marker

The lifting and material-handling subsystem also demonstrated reliable and repeatable performance. The linear actuator achieved vertical alignment accuracy within ± 5 mm when loaded (Figure 6) and ± 3 mm when unloaded (Figure 7), enabling smooth alignment with workstation conveyor heights. The roller-conveyor transfer mechanism further supported a successful payload-transfer rate of approximately 96%, confirming that simple mechanical solutions can provide practical functionality when carefully integrated. This autonomous lifting capability eliminates the need for operators to manually adjust heights or handle loads during material transfers, reducing ergonomic strain, particularly important for SMEs with ageing workforces or limited labour availability.



Figure 6: Loading operation



Figure 7: Unloading operation

A key operational outcome was the substantial improvement in takt-time stability. During manual transport, cycle-time variability was influenced by operator fatigue, inconsistent walking speed, and occasional delays during loading and unloading. These inconsistencies were significantly reduced when the AGV was introduced. Table 1 summarises the results across ten repeated trials, comparing manual and automated takt times:

Table 1

Takt-Time Comparison Between Manual Handling and AGV Operation

Trial	Manual Takt Time (s)	AGV Takt Time (s)
1	125	118
2	150	123
3	110	119
4	145	122
5	135	121
6	120	120
7	140	124
8	130	119
9	155	121
10	115	122

The results yielded a manual average takt time of 132.5 s with a variability of ± 23.1 s, whereas the AGV achieved a more consistent average of 121.0 s with a variability of only ± 3.8 s. The corresponding comparison is illustrated in Figure 8, which visually depicts the fluctuations across trials under both conditions. The AGV reduced takt-time variability from approximately 18% to 3%, representing an 83% improvement in stability. For SMEs, where throughput consistency directly affects scheduling, work-in-progress (WIP) inventory, and delivery performance, such reductions in variability translate into significantly smoother production synchronisation and improved daily operational reliability.

Beyond takt-time improvements, the AGV contributed meaningfully to labour optimisation. Prior to automation, operators spent a considerable portion of each cycle walking between workstations and performing repetitive transport tasks. With the introduction of the AGV, this non-value-added walking time was effectively eliminated, enabling operators to be reassigned to quality inspection, machine setup, monitoring, or other value-adding activities. This reallocation improves labour productivity and strengthens resource utilisation, a key advantage for SMEs facing rising labour costs and limited staffing. Additionally, the reduction in manual walking and lifting reduces operator fatigue, lowers the likelihood of handling errors, and enhances overall workplace safety.

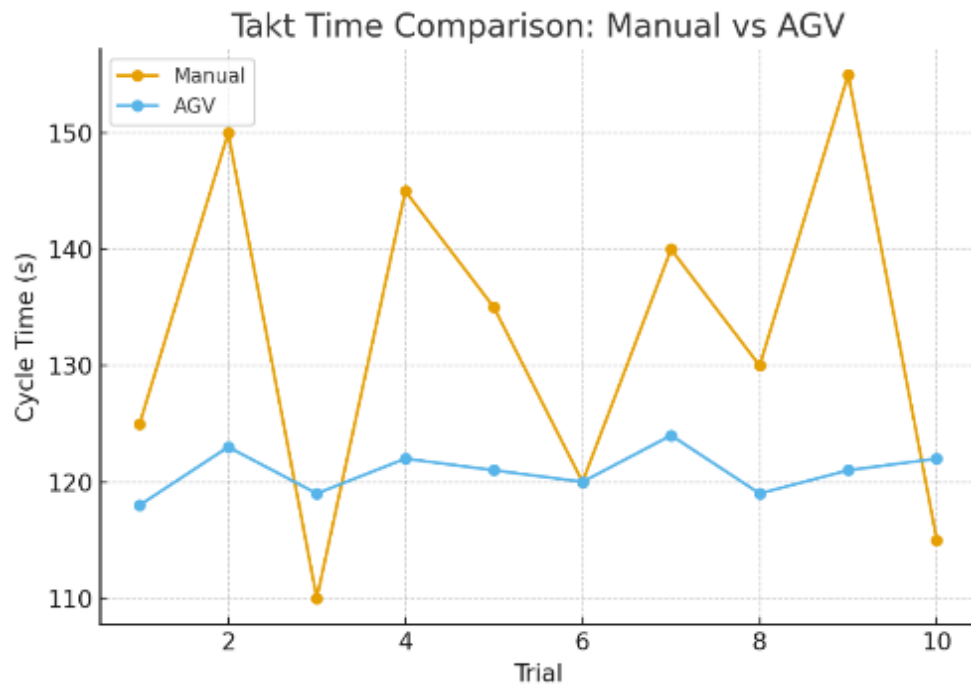


Figure 8: Takt-time comparison between manual handling and AGV operation

The financial evaluation further supports the AGV's feasibility for SMEs. With a total development and deployment cost of approximately RM 8,000 and estimated annual savings ranging from RM 30,000 to RM 46,000, the system demonstrates strong economic performance. Labour-hour displacement (Webtorials, 2025) was calculated using the standard relationship:

$$S_{\text{labour}} = (H_{\text{shift}} \times C_{\text{labour}} \times D_{\text{operating}})$$

where H_{shift} represents the labour hours saved per shift, C_{labour} denotes the hourly labour cost, and $D_{\text{operating}}$ is the number of operating days per year. Total annual savings (Cognexo, 2025) were computed by adding labour savings and productivity gains:

$$S_{\text{total}} = S_{\text{labour}} + S_{\text{productivity}}$$

Return on investment (ROI) (Corporate Finance Institute, 2025) was evaluated using:

$$ROI = \frac{S_{\text{total}} - C_{\text{annual}}}{C_{\text{annual}}}$$

Finally, the payback period (Modula, 2025) was determined using:

$$\text{Payback Period} = \frac{C_{\text{initial}}}{S_{\text{total}}}$$

Applying these equations, the AGV achieves a payback period of approximately 4–6 months, even under conservative assumptions. Such rapid amortisation is highly favourable in SME contexts, where investment decisions often hinge on short-term financial returns and minimal risk exposure.

Safety and organisational benefits add further value to the AGV solution. By automating material transfers, the AGV reduces operator exposure to repetitive lifting and carrying activities and lowers the probability of collisions along shared pathways. Although the

developed AGV does not incorporate advanced dynamic obstacle detection, the use of structured routes ensures predictable movement patterns, supporting a safe operational environment. At the organisational level, integrating the AGV encourages SMEs to adopt more standardised workflow designs, supports gradual digitalisation, and lays the foundation for future enhancements such as IoT-enabled tracking or Manufacturing Execution System (MES) integration.

Taken as a whole, the results confirm that low-cost, vision-guided AGVs hold significant technical and managerial value for SMEs. The combination of strong navigation and lifting performance, substantial takt-time improvements, labour optimisation, workplace safety enhancements, and rapid ROI positions AGVs as a practical and high-impact automation strategy for resource-constrained manufacturing environments. These advantages make the system especially suitable for SMEs seeking to enhance operational stability and progress toward Industry 4.0 readiness without substantial capital expenditure.

Conclusion

The results of this study confirm that a low-cost, vision-guided Automated Guided Vehicle (AGV) can meaningfully enhance intralogistics performance within small and medium-sized enterprises (SMEs). By integrating PixyCam-based colour navigation with a compact lifting and roller-conveyor mechanism, the system demonstrated reliable navigation accuracy, stable material handling, and substantially improved takt-time consistency. These engineering outcomes translated into operational benefits by stabilising workflow, reducing cycle-time variability, and enhancing material-flow predictability—key requirements for SMEs operating under resource and labour constraints.

From a business and organisational perspective, the AGV enabled significant labour optimisation by eliminating non-value-adding walking and repetitive manual transport, allowing operators to be reassigned to higher-value tasks. The estimated annual savings of RM 30,000 to RM 46,000, combined with a payback period of approximately 4–6 months, demonstrate that a cost-effective AGV can deliver strong financial justification even for SMEs with limited capital capacity. In addition, the reduction in manual lifting and fatigue-related activities offers clear ergonomic and safety benefits, supporting long-term workforce sustainability.

However, the system presents several limitations. Dependence on colour-based markers introduces sensitivity to lighting variations, constraining applicability in environments with inconsistent illumination. The lightweight chassis and actuator design limit payload capacity, and the absence of dynamic obstacle detection restricts use to structured and low-traffic pathways. These limitations highlight the need for additional sensing, structural reinforcement, and advanced navigation algorithms to extend the system's operational robustness.

Overall, this study demonstrates that appropriately scaled, low-cost automation can provide SMEs with a feasible and impactful step toward improved operational efficiency and Industry 4.0 readiness. By delivering measurable technical, ergonomic, and financial benefits through an accessible design, the developed AGV offers a practical model for SMEs seeking to modernise intralogistics processes without substantial investment or technical complexity.

Future Research

Future developments of the AGV should focus on enhancing robustness, adaptability, and integration with broader digital manufacturing ecosystems. One key direction is the incorporation of additional sensing technologies, such as ultrasonic, infrared, or low-cost LiDAR modules, to enable obstacle avoidance and safer operation in dynamic production environments. Improving the reliability of the navigation system through hybrid approaches that combine colour vision with odometry, fiducial markers, or low-level SLAM algorithms would mitigate sensitivity to lighting variations and expand applicability to more complex layouts. Mechanically, the lifting mechanism and chassis can be reinforced using stronger actuators and lightweight structural materials to increase payload capacity and operational durability. Integrating Internet of Things (IoT) connectivity and cloud-based monitoring would enable real-time tracking, predictive maintenance, and data-driven optimisation of intralogistics workflows. Finally, scaling the system into a coordinated multi-AGV fleet, supported by simple traffic management algorithms, would enable SMEs to automate larger portions of their material flow, further enhancing throughput and supporting a gradual transition toward full intralogistics automation.

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