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Toward energy-efficient AGVs: A review of mechanical design contributions and optimization framework

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ABSTRACT

Energy optimization in automated guided vehicles (AGVs) is critical for improving efficiency and sustainability in intralogistics systems, particularly in path planning and scheduling applications. Various optimization approaches have been proposed from operational, computational, and energy supply perspectives. Although energy supply technologies offer advantages in energy storage and recovery, their integration into AGV systems remains limited due to technological maturity and implementation challenges. Consequently, control-based approaches, including artificial intelligence, have become dominant optimization strategies. While these methods improve operational performance, they also increase computational energy demand, highlighting the need for alternative approaches to reduce baseline power consumption. This paper reviews AGV energy optimization studies while emphasizing the potential of mechanical design as an alternative optimization scope. The review reveals that mobility inefficiencies such as slip, skid, and instability are commonly mitigated through control strategies rather than resolved at their mechanical source. To address this gap, a Taguchi-based mechanical optimization framework is proposed for evaluating multiple mechanical factors and parameter levels. The framework aims to reduce baseline power demand and minimize reliance on computationally intensive control strategies, contributing toward more energy-efficient AGV systems.

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1. INTRODUCTION

Automated guided vehicles (AGVs) are widely deployed in modern manufacturing and logistics environments for reliable and flexible material handling. With the increasing level of industrial automation, efficient energy utilization has become a critical concern due to limited onboard energy capacity and growing operational demands. These demands arise from higher payload requirements [1], [2], enhanced wireless communication [3], [4], more complex drive systems [5], [6], advanced sensing technologies [7], [8], and AI-driven data processing [9], [10]. Although energy-related research has focused on new energy sources and auxiliary backup systems to increase onboard capacity, growing attention has also been directed toward minimizing operational energy consumption through controller-based technologies. These approaches integrate advanced controllers with complex algorithms [10]-[13] that continuously process signals from sensors and electrical components to maintain energy-efficient operation within defined system constraints. However, increased computational demand associated with continuous monitoring and signal processing may introduce additional energy overhead.

To overcome the aforementioned limitations, this study conducts a systematic literature review referring to sources such as Google Scholar and major databases including IEEE, Scopus, and ScienceDirect, with a primary focus on publications from 2018 onwards. The main objective is to explore alternative approaches that reduce computational dependency while promoting the integration of mechanical design considerations into energy optimization. In addition, comparatively less attention has been given to the performance of mechanical elements, including drivetrain configuration, wheel characteristics, and chassis structure, despite their direct influence on traction behavior, motion stability, and overall energy consumption. In most studies, these mechanical elements are treated as fixed parameters, with limited consideration given to how interactions among mechanical design parameters affect system energy efficiency

Hence, this review is structured into three main parts. First, it examines existing optimization strategies from control-based and computational approaches to identify underlying mechanical implications within these methods, as discussed in sections 2 and 3. Second, it synthesizes key factors affecting AGV energy consumption, particularly physical parameters related to mobility inefficiencies and their potential for design improvement. These findings contribute to the study by showing that mechanical elements can address concerns commonly handled through control-based approaches, as reviewed in sections 4 and 5. Section 6 provides a structured framework to optimize mechanical design factors across multiple parameter levels, representing a major contribution of this study toward energy-efficient AGV design and mechanical optimization. Finally, section 7 concludes the overall findings regarding the contribution of mechanical design to AGV energy optimization.

2. AGV SYSTEM ARCHITECTURE AND ENERGY INTERACTION

The AGV system architecture is designed to integrate different subsystems, including mechanical, electronic, and electrical components. Understanding their interactions provides the foundation for analyzing energy flow, computational modelling, and optimization approaches aimed at improving overall system efficiency.

2.1. AGV subsystem and integrated system

A typical AGV consists of interdependent subsystems connected through electrical power flow, signal communication, and mechanical transmission mechanisms, as illustrated in Figure 1. In Figure 1, power distribution, represented by the red dotted lines, is supplied from a DC energy source, typically a 24-48 V battery, and distributed to electrical and electronic components through power converters. Motor controllers regulate power delivery using pulse-width modulation (PWM), enabling efficient motion and torque generation. The generated motor torque is transmitted through the drivetrain, driving the wheels to produce vehicle motion. Another crucial flow in the AGV architecture is the communication and feedback system. The blue dotted lines represent signal interactions within a closed-loop control system, where feedback signals are transmitted through sensors and communication devices, including encoders, current sensors, distance sensors, obstacle detectors, IMUs, and the communication network. The motions and control feedback are regulated through a controller processed using control algorithms like proportional-integral-derivative (PID) and field-oriented control (FOC) [14]. All subsystems are embedded within the chassis, as indicated by the green dotted lines, and interact with the payload and surrounding conditions, while caster wheels provide stability and maneuverability. This multi-domain interaction highlights the tightly coupled nature of AGV operation, where overall efficiency depends on coordinated behavior across electrical, control, and mechanical subsystems rather than isolated optimization.

2.2. Energy modelling and calculation

Continuous operation leads to power consumption and gradual battery energy depletion. In analyzing AGV energy consumption, studies commonly consider electrical aspects, mechanical aspects, or a combination of both. From the electrical perspective, total energy consumption is measured at the power source using battery voltage and current. Motor current, in particular, reflects traction and mobility-related load demands [15]. The electrical energy consumption can be expressed as (1).

$$E_{electrical} = \int V_{battery}\, I_{motor}\, dt \tag{1}$$

Where $E_{lectrical}$ is the total energy supplied to the system, $V_{battery}$ represents the battery voltage, I_{motor} denotes the current drawn by the motor, and dt is the running time duration. This measurement method enables accurate estimation of total electrical energy consumption without requiring detailed energy data from individual components.

From the mechanical perspective, energy represents the useful work required to overcome resistive forces during motion. Based on Newton's second law, the total traction force can be expressed as [16].

$$F_{total} = ma + F_{rolling} + F_{gradient} + F_{drag} \quad (2)$$

Where: F_{total}: total traction force (N), ma: inertial force to move the robot for m is mass (kg) and a is acceleration (m/s^2), $F_{rolling}$: rolling force = $C_r mg$ for C_r is the rolling resistance coefficient and g is gravitational force (m/s^2), $F_{gradient}$: gradient force = mgsin(θ), for θ is the incline slope, F_{drag}: drag force = $\frac{1}{2}\rho C_d A v^2$, ρ is air density (km/m^2), C_d drag coefficient, A is the frontal surface area (m^2), and v is robot speed (m/s).

The mechanical energy required for motion is then given by (3),

$$E_{mechanical} = \int F_{total} \,.\, ds \quad (3)$$

where ds is the differential displacement. This formulation represents the work required to overcome resistive forces during AGV operation. Unlike the electrical model, this mechanical model enables the estimation of energy contributions from different effects within the system. The relationship between electrical input and useful mechanical output can be expressed through system efficiency,

$$\eta = \frac{E_{mechanical}}{E_{electrical}} \quad (4)$$

where η represents the overall energy conversion efficiency. A lower efficiency indicates greater energy losses occurring during energy conversion, transmission, and drivetrain operation.

These energy relationships enable the quantification of total energy flow from input to output, providing a basis for understanding system performance and identifying potential areas for improvement through the approaches discussed in the following sections.

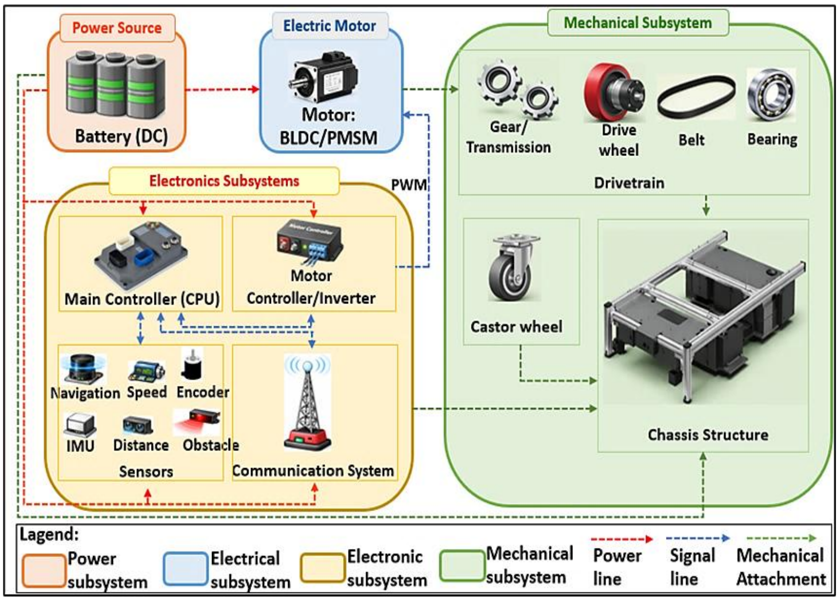

Figure 1. AGV system architecture and subsystem integration

3. REVIEW OF CURRENT ENERGY OPTIMIZATION STRATEGY

Building upon the energy relationships, numerous optimization strategies have been proposed to improve AGV energy efficiency and overall system performance. In this study, the existing approaches are categorized into three main groups, namely optimization through control-based operational approaches, which focus on operational strategies and control methods; optimization through computational approaches, which involve intelligent algorithms and computational techniques; and optimization through energy system approaches, focusing on energy supply, storage, and recovery systems. These categories provide a closer overview of current directions in AGV energy optimization.

3.1. Optimization through control-based operational approaches

During operation, AGV motion is continuously affected by various operational factors that may cause deviations from the planned trajectory, resulting in operational inefficiencies and increased energy consumption. These disturbances influence the total traction force described in (2), leading to increased energy demands during motion. Consequently, controllers are employed to improve trajectory tracking, obstacle avoidance, and motion stability during motion planning and execution while also supporting energy-conscious operation through efficient path planning, speed regulation, acceleration control, and power management [12], [17].

Load conditions and path geometry are two major factors influencing AGV operational performance and energy consumption. As payload increases, higher driving torque is required, resulting in greater energy consumption, as shown by [18]. Excessive loading may also increase energy losses due to wheel deformation [19] and increase torsional force during cornering [20]. Inclined surfaces increase power demand due to gravitational effects [21]-[23], and curved paths require additional steering effort [24], [25].

Various control-based strategies have been developed to improve AGV motion efficiency under load and path variations. One important approach involves speed profiling and motion management. For example, [26] proposed a speed control strategy based on steering angle, where smaller wheel turning angles allow higher travelling speeds, thereby reducing travel time and overall energy consumption. Other studies introduce control for maintaining motion stability [27]-[29] by using adaptive speed control strategies to minimize unnecessary energy dissipation during operation. Speed profiling also incorporates acceleration management strategies to reduce abrupt motion changes and improve overall energy efficiency [24]. These speed and acceleration control profiles help prevent sudden power surges while promoting smoother and more coordinated operation.

In broader operational applications, similar control strategies are implemented in global path planning, where AGVs adjust speed profiles according to varying path conditions during continuous task executions. To address the complexity of decision-making, intelligent path-planning algorithms are developed with priority on energy saving by identifying routes with minimal geometric disturbances and obstacle interference. Such paths enable smoother motion, reduced obstacle-avoidance maneuvers, and more stable high-speed travel, thereby lowering overall energy consumption [30]-[32]. In multi-AGV systems, these strategies are further integrated with scheduling and coordination mechanisms to reduce overall energy consumption while improving system efficiency and operational performance [22], [33]-[35]. To summarize, operational energy optimization mainly focuses on minimizing factors that increase energy consumption, such as unfavorable path conditions and load variations, while maintaining stable high-speed operation to reduce travelling time in accordance with (1), as depicted in Figure 2.

Figure 2 suggests the qualitative relationship between energy consumption, operational noise factors, and AGV speed. Increased disturbances such as load and path conditions tend to increase energy consumption, while efficient speed regulation can help improve operational efficiency. Therefore, controllers are designed to intelligently balance these factors during AGV operation. This discussion highlights how mechanical factors such as slipping, skidding, and stability affect trajectory deviation and energy consumption, while controllers intervene to maintain stable and energy-efficient operation. The highly successful and close interaction between controllers and mechanical disturbances has led to a significant increase in studies on control-based approaches.

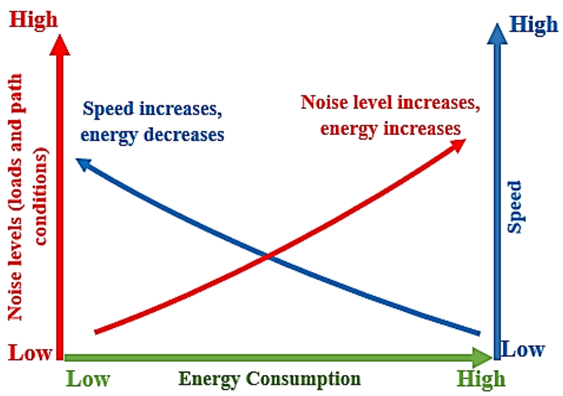

Figure 2. Illustration of the relationship between AGV energy consumption, noise factors, and speed

3.2. Optimization through computational approaches

As described by [36], the levels of control complexity can generally be categorized into classical, metaheuristic, and artificial intelligence-based methods. Classical algorithms, such as A* and Dijkstra, provide reliable solutions with relatively low computational complexity but exhibit limited adaptability in dynamic environments. In contrast, metaheuristic approaches offer greater capability in handling multi-constraint optimization problems, although they typically require higher computational effort, which may limit real-time performance.

As AGV operating environments become increasingly complex, these optimization techniques must accommodate multiple layers of decision-making and dynamic operational constraints. Consequently, control-based AGV systems have evolved toward more intelligent and computationally intensive approaches to achieve accurate and reliable operation. However, no single algorithm can achieve optimal performance under all operating conditions, leading to the adoption of hybrid control approaches [14], [37]-[39].

In recent years, hybrid control systems have increasingly integrated artificial intelligence (AI)-based techniques to achieve higher levels of adaptive optimization. These approaches enable AGVs to learn from and respond to dynamic operational conditions. Among AI-based methods, multi-agent reinforcement learning (MARL) has emerged as a promising approach for coordinating multiple AGVs through collaborative learning, real-time decision-making, and distributed control [40], [41]. Owing to these capabilities, AI-based approaches are increasingly applied in path planning, scheduling, obstacle avoidance, fleet coordination, and energy management within smart warehouse and manufacturing environments [42], [43].

However, it is notable that AI-MARL requires substantial computational resources due to high-dimensional state representations, continuous learning processes, and coordination among multiple agents. To mitigate these limitations, studies have explored techniques such as state abstraction and parameter sharing to improve scalability and reduce computational burden [44], [45]. Efforts to simplify computational processes for faster execution and lower processing energy consumption have been reported, with significant energy savings ranging from 10% to 75% by [46], [47]. Nevertheless, real-time implementation remains challenging due to continuous learning requirements and large-scale multi-agent coordination, which are still primarily simulation-based. In addition, the trade-off between achieved energy savings and the computational energy consumption required by these approaches remains insufficiently disclosed, motivating ongoing efforts to reduce computational power demand. The discussion indicates that future AGV systems will increasingly rely on advanced computational approaches, calling for the exploration of multiple energy optimization scopes rather than relying solely on controller-based methods.

3.3. Optimization through energy system approaches

Besides understanding control-based strategies and their optimization strategies, it is also important to examine studies related to energy sourcing, storage, and recovery technologies. This discussion provides a more comprehensive understanding of energy management in AGVs and helps establish the relationship between control-based approaches, energy supply characteristics, and areas of controller intervention for further energy optimization.

Research on increasing onboard energy supply and storage has predominantly focused on lithium battery technologies [48], [49]. These studies investigate alternative materials and electrochemical compositions to improve energy generation, transfer efficiency, and storage capacity. More advanced approaches have also explored alternative energy sources, such as fuel cells [50], [51], which offer faster refueling capability and significantly longer operating duration compared to conventional battery systems. In addition, supercapacitors have been introduced as hybrid energy support for fuel cell power systems [52]. With the advantage of fast charging capability, supercapacitors have also been widely studied in hybrid battery and regenerative energy systems [53], [54] for transient power delivery, energy recovery, and improved overall system efficiency. The significant achievements demonstrated in EV applications, where supercapacitor-based energy recovery improves operational efficiency by approximately 30% to 90% [55], have become a strong motivation for further implementation in AGV studies.

For energy recovery and replenishment, innovations in charging methods, including fast charging and opportunity charging, have been widely studied to reduce operational downtime. Major efforts are focused on overcoming limitations related to ion transport, charge transfer, and thermal management [56]. The charging process requires management of sophisticated battery management systems (BMS), focusing on maintaining efficient state-of-charge (SOC) control and preserving battery state-of-health (SOH) to ensure long-term performance and operational lifespan [57], [58]. Energy replenishment technologies are commonly integrated with charging infrastructure systems based on charging frequency, charging duration, and docking method. To improve automatic docking performance, studies have proposed self-guidance and mechanical alignment approaches to achieve faster and more accurate docking processes [59], [60]. Based on the energy-related studies discussed above, the readiness of onboard energy systems is summarized in Table 1.

Table 1 compares various onboard energy technologies used to enhance AGV energy capacity, together with their storage capabilities and major implementation challenges. The comparison indicates that advancements in energy sourcing, storage, and recovery technologies have strong potential to improve onboard energy availability in AGVs. However, from a technological implementation perspective, most technologies still lack readiness for large-scale deployment due to limitations in technological maturity and cost. Therefore, these limitations highlight the importance of broader energy-saving studies for AGV systems.

Table 1. Comparison of onboard energy storage technologies and associated challenges in AGVs

Types of power supply	Onboard energy storage capacity	Major challenges
Battery	High	Material compatibility Implementation cost: Moderate
Supercapacitor	Moderate to very high	Material compatibility Integration and control system Implementation cost: Moderate to high.
Fuel cell (alternative power source)	Very high	Space requirement Integration and control system Implementation cost: High to very high.
Regenerative system	Moderate to high	Integration and control system Implementation cost: High
Power replenishment system	High	Infrastructure preparation Integration and control system (BMS) Implementation cost: Moderate to high.

4. CHALLENGES IN EXISTING ENERGY EFFICIENCY APPROACHES

The review of the optimization approaches presented in section 3 provides a broader understanding of current AGV energy research trends and associated challenges. Overall, existing studies still exhibit several limitations, which can be summarized into five major challenge areas.

i) Over-reliance on control-based methods

Current research on control-based methods adopts widely popular frameworks such as the Robot Operating System (ROS) [61], [62]. However, these approaches commonly treat mechanical characteristics as fixed parameters, with limited consideration of their influence on energy consumption and system performance.

ii) Computational complexity and energy overhead

The increasing use of artificial intelligence, advanced sensing technologies, and extensive sensor integration has improved AGV intelligence and adaptability, but also increased energy consumption due to higher computational demand. Therefore, the trade-off between system performance and energy efficiency must be carefully addressed, although the additional energy demand associated with increasing computational complexity has yet to be quantitatively investigated and remains a recognized challenge in intelligent AGV systems [3], [63].

iii) Fragmented and Isolated Studies

Current AGV energy optimization studies often address complex system parameters in isolation. Therefore, more integrated optimization approaches are needed to achieve broader and more effective parameter optimization, as suggested by [64].

iv) Dependence on simulation-based validation

Many studies rely on simulation environments, as the availability of open-source platforms such as ROS integrated with Gazebo [65], [66] facilitates widespread and active use of simulation due to their low cost, flexibility, and high repeatability. However, validation under real-world operating conditions remains limited.

v) Immature development of new energy sourcing technologies

Emerging energy technologies, including advanced batteries, supercapacitors, fuel cells, and regenerative systems, offer promising performance improvements. However, their adoption in industrial AGV systems remains constrained by cost, integration complexity, and implementation challenges [67], [68]. However, observations of their progress remain relatively slow compared to the growing demand for advanced AGV applications as reported by [69].

vi) Underrepresentation of mechanical design optimization

Mechanical design remains relatively underexplored despite its direct influence on mobility behavior and power demand, as mainly discussed in 3.1. Although some works acknowledge drivetrain and traction systems, their role in energy optimization is rarely investigated systematically compared to electrical and control-based approaches [70].

5. MECHANICAL DESIGN CONTRIBUTION TO ENERGY OPTIMIZATION

Section 3.1 already discussed how mechanical design aspects influence AGV energy performance through their effects on traction behavior, motion stability, and drivetrain efficiency. Although these mechanical factors have been widely studied, they are often investigated separately and are rarely directly associated with energy performance. Therefore, this section reviews mechanical design strategies that are commonly studied independently of energy awareness but have potential for future integration into energy-aware systems.

5.1. Drivetrain configuration

Drivetrain configuration refers to the motor characteristics, gearbox ratio, and wheel size, which together influence torque delivery and overall AGV energy efficiency. One important aspect of drivetrain design is motor sizing, in which the motor is selected to satisfy the required traction torque and operating speed while considering the wheel diameter, gear ratio, and drivetrain efficiency [71]. Common motor choices for AGV applications include PMSM and BLDC motors. Compared with BLDC motors, PMSM motors exhibit approximately 29.90% greater power and torque density [72]. However, BLDC motors remain attractive for AGV applications because of their simpler control structure, lower implementation cost, and easier integration into compact and low-cost robotic systems.

Transmission design also directly affects AGV energy efficiency because gearbox performance varies with operating load and rotational speed, leading to mechanical losses such as friction, gear meshing losses, and bearing resistance [73], [74]. In particular, gear ratio selection significantly influences torque transmission and motor operating conditions [70], [75], [76]. further demonstrated that selecting a higher gear ratio can shift the motor operating point into a high-efficiency region, where motor efficiency may exceed 85%. Efforts to improve drivetrain efficiency have led to the introduction of hub-integrated and planetary gear configurations, as shown in Figure 3, to better appreciate the hub-planetary motor.

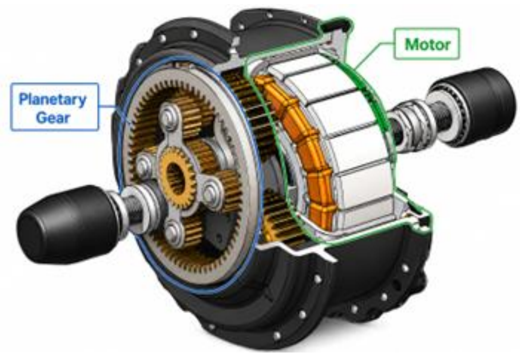

Figure 3. Cross-sectional diagram of a hub motor with a planetary gear system

Figure 3 shows how the hub motor-integrated drives simplify drivetrain architecture by eliminating intermediate transmission components, while planetary gear mechanisms provide compactness, high torque density, and high transmission efficiency, typically ranging from 95-98%, compared with approximately 85-95% for conventional multi-stage gearbox systems [77]. These advantages have contributed to the widespread adoption of hub-integrated planetary drivetrains in AGV applications. Furthermore, recognizing that gearbox performance varies with load and speed under different operating conditions, adaptive transmission mechanisms have also been introduced, with reported reductions in power consumption of approximately 5-15% through improved motor–drivetrain matching [78], [79].

Wheel diameter also affects drivetrain efficiency by influencing the motor speed and gearbox reduction required to achieve the desired wheel torque and AGV travelling speed. The motor power requirement can be expressed as (5):

$$P_m = F.r.\omega \tag{5}$$

where P_m is motor power and can be related to (1), F is the driving force mentioned in (2), r is wheel radius, and ω is angular velocity. Overall, effective drivetrain configuration for energy optimization requires integrated consideration of the motor, gearbox, and wheel system to enhance motor performance and improve overall energy efficiency.

5.2. Contribution of wheel designs

Wheel design influences AGV energy efficiency through its effects on rolling resistance, traction behavior, as well as wheel-ground contact characteristics [80]. Therefore, optimization of material properties, wheel geometry, and contact conditions is important for reducing mechanical losses and improving energy performance during AGV operation. With regard to wheel material considerations [19], demonstrated that wheel deformation behavior associated with material characteristics can influence traction performance and trajectory stability. In addition, [20] further highlighted the influence of wheel material on motion performance by demonstrating its effect on torsional resistance during cornering maneuvers.

Besides material selection, the structural design of wheel-related components can also be improved. For example, [81] improved a slanted caster wheel design by optimizing the interaction between the wheel and its supporting structure, thereby reducing lateral resistance and internal friction, which lowered the force required for wheel alignment. Similarly, studies on omnidirectional wheel systems have focused on wheel arrangement, structural configuration, and system-level integration to enhance overall AGV motion efficiency [82], [83]. These improvements contribute to lower energy consumption through smoother motion, reduced slippage, minimized actuator overload, and enhanced maneuverability.

5.3. Chassis structure and weight effect

The chassis serves as the primary structural platform integrating all system components, while its overall mass significantly influences the power demand of the AGV. Therefore, the chassis mass should be minimized to reduce load burden and energy consumption without compromising structural safety and load-carrying capacity.

In this context, a study by [1], [84] applied a systematic engineering optimization approach to develop a structure capable of supporting a 20ton load capacity. Similarly, [85] conducted a topology optimization study that not only reduced structural mass but also identified optimal wheel placement locations based on load distribution requirements. In another study, [86] improved the structural strength of AGV systems while simultaneously reducing structural load to enable operation under highly robust and extreme vibration conditions. Collectively, these studies achieved load reductions of approximately 10-20%, which can directly contribute to lower energy demand and improved overall AGV efficiency.

5.4. Mechanical guidance system for trajectory control

Although AGV navigation is primarily achieved through sensor-based systems and intelligent programming for predefined path following [87], [88] proposed alternative mechanical guidance approaches. While these methods may not be suitable for all operating conditions, they reduce dependence on continuous sensing, data processing, and computational control requirements, and therefore should be considered as practical alternatives for selected AGV applications.

In a related study, [89] proposed instrumented passive wheels for localization purposes. The passive castor wheels exhibit low-slip and stable motion characteristics, while reducing reliance on continuously powered sensing systems and lowering energy consumption. These studies suggest that mechanical design can reduce reliance on sensing and navigation systems, thereby lowering computational and sensor energy consumption. Although such implementations may be limited to specific operating conditions, they can be considered as hybrid operational concepts, similar to tram-train systems used in several cities worldwide.

5.5. Dynamic counterbalance

Vehicle stability can also be enhanced through mechanical design approaches [90]. Highlighted structural parameters affecting center-of-gravity variation in AGV forklifts, demonstrating the potential of mechanical design to improve stability under varying load conditions. In a related study, [91] reviewed mechanical approaches for managing dynamic center-of-gravity variations, including adjustable wheelbase systems, movable counterweights, adaptive balancing mechanisms, and variable-geometry chassis designs to improve vehicle stability during lifting and transportation operations.

This concept can be further extended through chassis design integration to improve adaptability across varying surface conditions, such as smooth industrial floors, asphalt roads, and soft soil terrain. Although the presented examples do not explicitly quantify energy savings, such mechanical adaptability can reduce dependency on continuous monitoring power required in control-based systems.

5.6. Wheel drive configuration

Various wheel drive configurations are used in mobile robotic systems depending on factors such as steering angle requirements, maneuverability, stability, controllability, and operating environment. Common configurations include differential drive, omnidirectional drive, tricycle drive, and multi-steer systems [70]. Energy consumption-wise.

The differential drive is the simplest configuration, while omnidirectional systems are more complex because they can move in multiple directions without changing orientation. Differential drives generally consume less energy due to their simpler control system and fewer actuators. It was reported omni directional and Mecanum wheeled robots consumed 15- 35% more energy compared to differential drive [92] for systems that require multiple motors, continuous wheel coordination, and more advanced control algorithms. To balance mobility performance with energy efficiency, studies by [84] and [93] proposed improved wheel configuration designs that achieve omnidirectional mobility without relying on Mecanum wheels. Their optimization approaches reduced the number of motors required, improved wheel arrangement, minimized drivetrain complexity, and reduced lateral wheel slip, thereby potentially enhancing overall energy efficiency.

5.7. Energy factors and mitigation strategies in AGVs

The discussions in Sections 5.1 to 5.6 highlight several mechanical design aspects that may influence not only system performance but also energy efficiency under specific operating conditions. The next step is to establish closer integration between these designs and energy-saving studies. To relate the potential energy benefits of mechanical design improvements to conventional control-based solutions, Table 2 summarizes alternative mechanical approaches corresponding to existing control strategies.

Table 2. Energy improvement areas: Control-based vs. mechanical approaches

Types of energy improvement	Source of problems	Issues	Controller-based mitigation	Potential mechanical design mitigation strategies
Operational and control-based approach	Load issues	Increase in traction demand	Feedback control	– Lightweight chassis structure to reduce base load – Optimized wheel geometry and material selection to improve traction – Appropriate wheel configuration to improve traction and stability – Adaptive gearbox configuration for variable operating conditions
		Stability instability	Feedback control	– Mechanical adaptive structure to improve stability.
	Path geometry	Wheel slip and frequent speed variation	Feedback control	– Smooth cornering geometry to reduce speed and acceleration adjustment. – Chassis optimization for stable cornering. – Optimized drivetrain configuration for adaptive speed control
		High uphill torque demand	Adaptive torque and braking control	– Optimized gear ratio for gradient climbing efficiency. – High-traction wheel materials for slope stability
		Frequent speed variation and power surges	Implement speed profiling.	– Optimized drivetrain system for adaptive speed.
		High computational demand for complex paths		– Mechanical trajectory guidance
		Varying path conditions	High-speed operation	– Consider smooth cornering to reduce speed and acceleration adjustment – Design chassis structure for stable cornering
Computational and intelligent approaches	Aggressive control behavior and unstable dynamics	Increased computational, sensing, and control energy demand	Optimized algorithms with AI-based.	– Mechanically stabilized sensor mounting to reduce computational calibration demand
Energy sourcing, storage, and recovery technologies	Material reliability and system integration	Technology maturity, cost, and adaptability	Advanced control integration	– Docking infrastructure with self-docking alignment

Table 2 categorizes common energy improvement areas and breakdown into corresponding primary sources of problems and their associated issues. The final two columns compare conventional control-based solutions with alternative mechanical approaches that may reduce reliance on complex controllers, minimize battery stress, improve motion stability, and enhance overall AGV energy efficiency. Mechanical approaches have demonstrated considerable potential in improving AGV operation through various design alternatives. However, their contribution toward simplifying computational demand and reducing dependence on advanced energy sourcing technologies remains comparatively limited. One suggested solution is to combine sensor positions at the best mechanical position, so as to provide more accurate reading for less calibrations. In energy storage, sourcing, and recovery technologies, although research involves extensive research and development, mechanically oriented solutions should also be extended for practical and cost-effective innovation. As observed in the mechanical mitigation suggestion, introducing mechanical intervention helps identify an accurate charging point. This simplifies computation for finding the right charging point and charging infrastructure.

6. MECHANICAL PARAMETER OPTIMIZATION

Various mechanical aspects were presented in section 5, highlighting their potential contributions to AGV energy efficiency. Besides highlighting that mechanical factors can reduce energy consumption, the simultaneous interaction among these parameters must also be considered in the overall energy performance. Thus, a systematic optimization approach is required to determine the most effective parameter combinations for sustainable AGV operation.

6.1. Mechanical energy optimization framework

Several optimization methods, including full factorial design and response surface methodology, have been widely applied in engineering optimization. However, these approaches may require extensive experimentation and high computational effort when involving multiple design parameters. Therefore, a more efficient and systematic optimization method is needed for AGV mechanical parameter analysis.

The Taguchi method is considered suitable for this optimization purpose. It is a robust design technique that employs orthogonal arrays and signal-to-noise (S/N) ratio analysis to efficiently evaluate multiple parameters and identify optimal and stable configurations. Compared with full factorial designs, which require a large number of experimental runs, the Taguchi method significantly reduces experimental effort while maintaining effective parameter evaluation. In addition, compared with simulation-based approaches, it offers practical advantages such as lower cost, shorter implementation time, and suitability for early-stage design optimization [94]-[96]. Many studies have adopted the Taguchi method across various engineering and optimization applications, including energy-related contexts [97]-[99]. In addition, to the best of the authors' knowledge, no study has specifically applied the Taguchi method to mechanical energy optimization in AGV systems

6.2. Taguchi optimization framework

The Taguchi method is implemented through several systematic steps, including problem definition, selection of control and noise factors, determination of suitable orthogonal arrays, experimental data collection, computation of robustness using signal-to-noise (S/N) ratio analysis, and evaluation of the results to identify the optimal parameter settings. Finally, validation is conducted to verify the robustness and effectiveness of the optimized parameters. To illustrate the proposed implementation more clearly, selected mechanical factors from Section 5 are organized into a P-diagram, where relevant parameters are grouped for the optimization process, as shown in Figure 4.

Figure 4 illustrates the proposed P-diagram for the AGV mechanical energy optimization framework based on the Taguchi method. The framework organizes the optimization process into input, control, noise, and output factors. The input factor represents operating conditions such as speed variation, while the control factors include adjustable mechanical parameters such as gear configuration, wheel characteristics, drivetrain arrangement, and chassis properties. Meanwhile, noise factors represent uncontrollable operational variations, including payload, path, and floor conditions, which may influence AGV energy performance. The output factor corresponds to energy-related responses such as energy consumption and power losses.

In this context, the Taguchi Method framework enables efficient evaluation of multiple parameters and levels through a structured experimental approach. By employing signal-to-noise (S/N) ratio analysis, the framework supports robustness evaluation and systematic decision-making while providing a low-cost and scalable approach for improving AGV energy efficiency and mechanical reliability. In addition, the framework is well suited for industrial participation in the energy optimization process due to its systematic procedures, straightforward implementation, and practical validation methods.

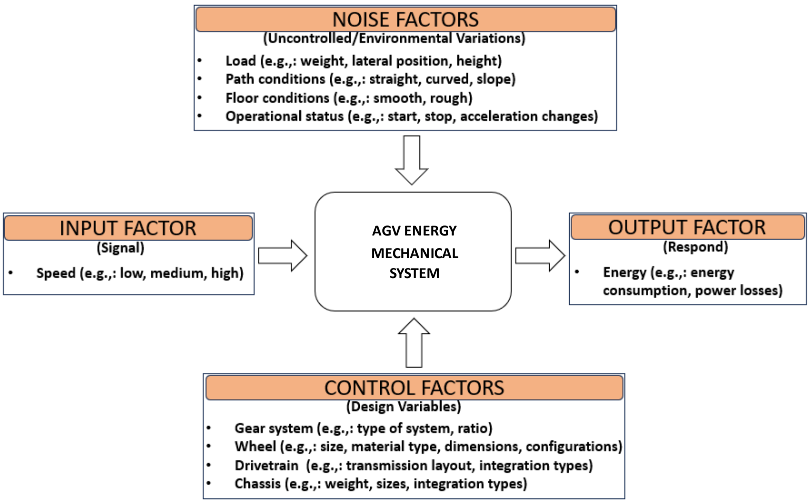

Figure 4. P-Diagram for mechanical energy influencing factors in AGV systems

7. CONCLUSION

This paper reviews the current landscape of energy optimization in AGVs, highlighting the dominant reliance on control-based and computational approaches. The findings indicate that many mobility inefficiencies, including slip, skid, and instability, originate from mechanical limitations, yet are predominantly addressed through reactive control strategies rather than resolved at the source. The study also highlights key contributors to energy consumption at the system level, particularly mechanical components within the drivetrain.

While several studies have explored mechanical aspects, their contributions are often indirect, focusing primarily on mobility improvement rather than explicitly targeting energy reduction. To address this gap, a systematic mechanical optimization framework is proposed by considering key mechanical factors and parameter levels influencing AGV energy performance. The reviewed mechanical design studies indicate that several mobility-efficiency approaches correspond to issues currently addressed through control-based methods. Among the identified areas, the drivetrain shows the highest potential for energy reduction, with several studies reporting significant energy-saving improvements. Chassis weight reduction also contributes directly to lowering energy consumption, although its impact is comparatively moderate. Other mechanical aspects, including wheel design, mechanical guidance, wheel configuration, and dynamic counterbalance systems, demonstrate promising potential for energy savings but still present implementation limitations and opportunities for further development.

This paper also contributes by proposing a Taguchi robust design approach using signal-to-noise (S/N) ratio analysis under the “smaller-the-better” criterion to minimize energy consumption. The proposed optimization framework provides a practical and systematic approach for AGV studies by considering controllable factors, parameter variations, and environmental noise conditions to improve energy efficiency across diverse AGV configurations. Although the framework has not yet been validated through a complete case study, it highlights an important and underexplored dimension of AGV energy optimization. In addition, the framework emphasizes experimental validation, offering a more realistic evaluation approach compared to the predominantly simulation-based methods commonly reported in existing studies.

Future research should focus on integrated optimization frameworks that position mechanical design as a foundational layer, supported by control strategies. Systematic and experimental validation is needed to quantify mechanical contributions, reduce baseline energy demand, and minimize reliance on computationally intensive methods, ultimately enabling more energy-efficient, scalable, and sustainable AGV systems.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known conflicting financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data availability is not applicable to this article as no new data were created or analyzed in this study. All information presented is derived from previously published sources, which are cited within the manuscript.

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