ภาคผนวก

บทความทางวิชาการที่ได้รับการตีพิมพ์เผยแพร่ในระหว่างการศึกษา

รายชื่อบทความที่ได้รับการตีพิมพ์เผยแพร่ในระหว่างศึกษา

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Estimated Mathematical Model for Controlling Distance of AGVs with Differential Drive Systems

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Abstract. This paper investigates the estimation of a straightforward mathematical model tailored for overseeing and regulating the motion of an AGV (Automated Guided Vehicle) equipped with differential drive systems. The mathematical model delineates the correlation between the input voltage signal of the DC motor and the resultant distance output, empirically tested within an open-loop system. This methodology facilitates the development of precise mathematical models aimed at mitigating errors in powertrains and mechanical motion components, including gears, chains, and ground-contacting tires, along with system friction. Moreover, a P controller system is devised to oversee the AGV motion. The stability and control efficacy are assessed through practical experimentation on the AGV's ability to attain predefined distances. Tests were conducted under two distinct conditions: case 1) AGV operation without any payload and case 2) AGV operation while bearing a 14 kg payload. The system's response to the input distance was meticulously observed. The average distance error is calculated at 1.74% of the designated control distance (2m, 3m, and 4m) across all cases. In the absence of a load (case 1), the average distance error remains consistent at 1.74% of the control distance, showcasing a motor speed response of 23.76 RPM (with a rise time of 2.1 s). Conversely, when subjected to a 14 kg payload (case 2), the average distance error marginally increases to 1.76% of the control distance, with a corresponding motor speed response of 23.71 RPM (and a rise time of 2.2 s). These results show the effectiveness of the control system, facilitated by the estimation of a simplistic mathematical model tailored specifically for AGV operations.

Keywords. Mathematical model of AGV, differential drive, control system design

1. Introduction

AGVs have emerged as integral assets in modern industries, revolutionizing the transportation of goods and enhancing production efficiency. Their applications extend beyond industrial domains, finding utility in healthcare settings for tasks such as delivering food, medication, and medical supplies to patients [1]. This widespread adoption of AGVs not only streamlines operations reduces labor requirements, and optimizes time management but also fosters automation, thereby bolstering overall operational efficiency. The past decade has witnessed significant strides in AGV research

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and development, resulting in substantial enhancements in their performance and capabilities. Among the myriad challenges confronting AGVs, trajectory tracking stands out prominently, particularly in industrial environments where precise adherence to planned paths is paramount. Research endeavors in control methodologies have explored various avenues, including the utilization of PID controllers in tandem with optimization techniques, adaptive control strategies, and integration of AI and machine learning algorithms [2]. These endeavors aim to address diverse facets of AGV motion, such as predictive maintenance scheduling, adaptation to dynamic environments, and decision-making in complex operational landscapes. Specifically concerning AGVs equipped with kinematic models of differential drive systems, studies have delved into differential steering control strategies aimed at mitigating risks of sideslip and rollover on sloped terrains, stemming from load asymmetry and ground concavity [3, 4, 5]. The realm of Localization and Mapping has also witnessed notable advancements, with techniques leveraging sensors such as LIDAR, cameras, and odometry to accurately ascertain AGV positions within their operational environments [6]. Furthermore, research endeavors in Human-Robot Interaction and Safety and Regulations have sought to enhance collaborative dynamics between AGVs, humans, and other robots. This encompasses the development of user-friendly interfaces, formulation of safety protocols, and adherence to regulatory standards to facilitate seamless collaboration and ensure operational safety [7, 8]. Efforts to optimize energy consumption in AGV operations have also garnered attention, encompassing route planning, speed control, and utilization of regenerative braking mechanisms [9, 10].

Collectively, these research endeavors underscore the multifaceted efforts aimed at advancing AGV technologies, addressing diverse operational challenges, and enhancing their efficacy across industrial and healthcare sectors while ensuring safety, regulatory compliance, and environmental sustainability. To ensure that AGV can operate in various conditions or complex environments suitable for real-world use, ongoing research and development are necessary. Therefore, this study investigates the mathematical modeling, system validation, and motion control of AGV in the form of a differential drive system. This system has the simplest control structure and requires minimal energy for control. The mathematical model of the system is derived from testing control signals (input voltage) and output responses as distance of AGV of the actual system, designed and tested in an open-loop configuration. Additionally, a feedback control system is designed to regulate the motion of the AGV and to assess the stability and performance of the control system under different payload conditions and varying motion distances toward target positions.

2. System modeling and validation

First paragraph. This study evaluated the control signals and response results of an AGV system with differential drive to create a mathematical model. This model was created by evaluating the connection between the input voltage signal and the system's position output response. Figure 1 depicts the open-loop setup used for designing and testing these signals.

Table 1 presents the results of the signal tests, which show how the system responds to control signals.

An accurate calculation of the settling time of a linear system using new expressions and iterative algorithms [11]. In a critically damped system at a 5% error of final response value, the equation of settling time is related to natural frequency (ω_n) as given by

$$t_s = \frac{4.74}{\omega_n} \tag{1}$$

Figure 1. System open loop block diagram of AGV system.

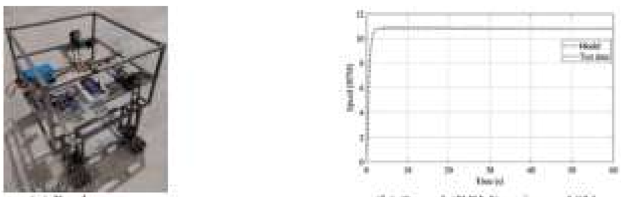
Table 1. Experimental results of the open-loop control system of AGV.

Voltage; V_a (v)	Time (s)	Motor speed; ω_{motor} (RPM)	Open loop Gain (K)	Distance; d_{avg} (m)
6	60	6.1	1.02	1.45
10	60	10.5	1.06	2.50
14	60	14.9	1.07	3.52
18	60	19.4	1.08	4.56
22	60	23.8	1.08	5.45
			Avg = 1.06	

From the experimental data, average of settling time at 5% error of final response value is 1.58 s. Substitute t_s = 1.58 s in Equation (1), then natural frequency (ω_n) is 3 rad/s. Based on the system response obtained from testing, it is possible to estimate the system's parameters using Equation (2), which is presented in the standard form of a second-order system.

$$\text{System modeling} = \frac{K\omega_n^2}{s^2 + 2\omega_n \varsigma s + \omega_n^2} = \frac{(1.06)3.06^2}{s^2 + 2(3.06)(1)s + 3.06^2} \tag{2}$$

The system was then validated (System Validation) by comparing the actual system's response results with those predicted by the mathematical model. This comparison showed consistent results, as illustrated in Figure 2.



(a) Real system (b) Speed (RPM) at input 10V

Figure 2. Response of System modeling and validation.

3. Controller design and system performance

In designing the controller for the AGV (Automated Guided Vehicle) robot system, this study implemented a feedback controller configured as a Proportional (P) Controller. This setup is depicted in the control system's block diagram shown in Figure 3. The objective was to manage the AGV's movement so that its actual moving distance, or Output Response (distance), matches a predetermined reference distance (Ref. distance). This reference distance represents the specific distance the robot is required to travel.

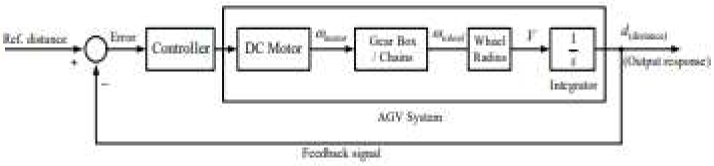
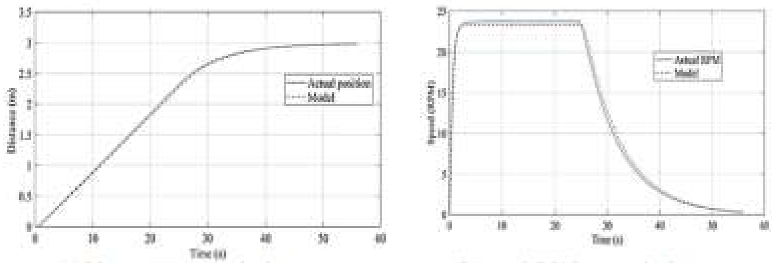


Figure 3. Block diagram of close loop feedback control for AGV system.

The controller designed for this study can illustrate the system's response to a step input signal (Ref. distance = 3 m), showcasing the system's control performance through simulation results as depicted in Figure 4. These results indicate the system's ability to achieve the desired moving distance with a rise time of 45 s, without any overshoot. Additionally, the system exhibits a steady-state error of 0.045 m and maintains a steady-state motor speed of 23.7 RPM.



(a) Distance (m) at setpoint 3 m (b) Speed (RPM) at setpoint 3 m

Figure 4. Step response and system performance with P-Controller (Simulation vs real system).

4. System modeling and validation

After designing the controller to interface with the AGV System, this study employed MATLAB & Simulink software, alongside an Arduino Board (Mega 2560), to manage the operation of a 24 Vdc Permanent Magnet DC Motor actuator. This motor, characterized by a gear ratio of 1:336 and paired with an Absolute Encoder of 17 PPR resolution, along with a mechanical power transmission system, facilitates the movement of the AGV robot over a specified distance. The interfacing setup between the controller and the AGV System is depicted in the block diagram in Figure 5.

To evaluate the performance of the control system and examine the system's response, this study conducted tests under two scenarios: Case 1 involved operating the

AGV robot without any load (No Load) and Case 2 involved operating it with a payload (equipped with a 14 kg mass). The tests measured the system's response to input distances (reference control distances) set at three different lengths: 2m, 3m and 4m. These tests were designed to assess both the Motor Speed and the moving distance of the AGV robot, yielding the following results.

The results of the system's response when the AGV operates without any load (No Load) are presented in Table 2 and visually illustrated in Figure 6.

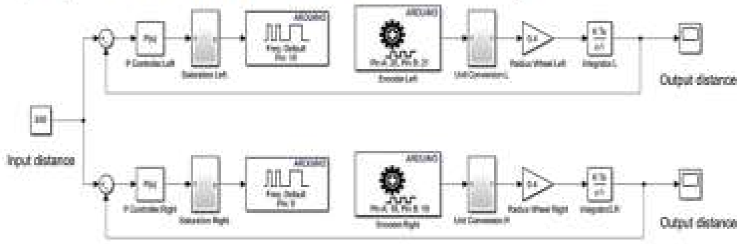


Figure 5. Interfacing block diagram with AGV system integration (differential drive).

Table 2. Experimental results of closed-loop control with P-controller of AGV (No Load).

Input distance; $d_{ref.}$ (m)	Output distance; d_{avg} (m)	%Error
2.00	1.962	1.90
3.00	2.951	1.63
4.00	3.932	1.70

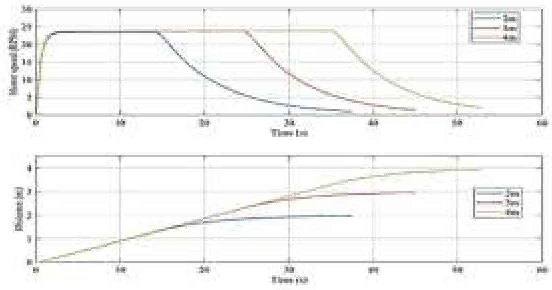


Figure 6. Top: Motor speed (No Load), Bottom: Distance of AGV (No Load).

The response results of the system, when the AGV robot carries a payload (with a mass of 14 kg), are displayed in Table 3, and further illustrated in Figure 7.

Table 3. Experimental results of closed-loop control with P-controller of AGV payload with a mass of 14 kg.

Input distance; d_r (m)	Output distance; d_{avg} (m)	%Error
2.00	1.964	1.80
3.00	2.946	1.80
4.00	3.932	1.70

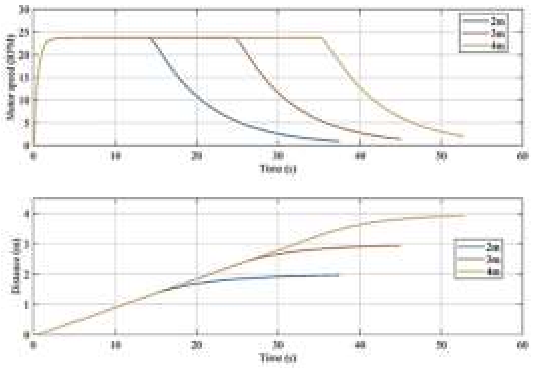


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Figure 7. Top: Motor speed with payload, Bottom: Distance of AGV with payload.#

5. Conclusions

This research explores the development of mathematical models by examining the motion control signals of actual systems through open-loop testing. This approach enables the estimation of a mathematical model that minimizes prediction errors in the power transmission unit and mechanical system stiffness. Additionally, the accuracy of the mathematical model is validated by comparing its response results with those of the actual system (System Validation). This validation process includes designing controller for the AGV robot's movement distance, utilizing a differential drive and a Proportional (P) controller for system regulation. The study assesses the system's stability and control performance by conducting tests on the AGV movement over specified distances. These tests are categorized into two scenarios: case 1) the AGV robot operating without any load (No Load) and case 2) the AGV robot operating with a payload (having a mass of 14 kg). The investigation includes analyzing the system's response to three predefined control distances (2m, 3m and 4m) to evaluate the Motor Speed and the actual moving distance of the AGV robot.

The test results indicated that the designed controller is capable of directing the AGV to move to a controlled distance with stability and high performance. When the AGV operates without any load (No Load), the average distance error was found to be 1.74% of the target distance that the robot was set to cover. Additionally, the motor speed response was recorded at 23.76 RPM, with a rise time of 2.1 s.

In scenarios where the AGV robot was loaded with a 14 kg payload, the average distance error slightly increased to 1.76% of the intended distance, and the motor speed response slightly decreased to 23.71 RPM, with a rise time of 2.2 s. These findings underscore the load's impact on the control system's performance. Therefore, to enhance efficiency and minimize control position errors, particularly considering the load's effect, future work may involve developing a more suitable controller or designing a robust control system for the AGV.

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