

Velocity Analysis of a DC Brushed Encoder Motor using Ziegler-Nichols Algorithm: A Case of an Automated Guided Vehicle

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Abstract

Objectives: The use of “Automated Guided Vehicles” (AGV) has emerged for automation in material handling applications. These AGVs are equipped with DC brushed/ brushless motors with encoders. The encoders feed the actual shaft position of a DC motor to the microcontroller, which converts the shaft position into the angular velocity. This is called as velocity analysis of DC encoder motor. **Methods/Statistical Analysis:** The first phase of paper focuses on the hardware of AGV and interfacing a controller with MATLAB. In the second phase, the transfer function of the system, type of the system, order of the system, steady state and transient analysis are shown. In the final phase of the paper, system’s response with P, PI and PID controllers are shown with the help of Ziegler-Nicholas (Z-N algorithm) algorithm (Real time and simulation both) with respect to step input. **Findings:** Industries have different types of layout for production. Some has process layout whereas some has plant layout. According to the production capacity and type of the layout, industries design the path for AGVs (for material handling). Generally AGVs do loading and unloading stuff, which is very much useful as far as smooth production is concerned. Some companies and researchers have designed AGVs with different specifications. If AGV comes out of the track due to irregular velocity, leads the plant to higher lead time and it may damage the productivity chain. To overcome this problem a metrology for doing velocity analysis for different controllers and algorithms are shown. **Application/Improvements:** This algorithm and control strategy helps AGV to move with constant velocity. It also protects AGV from accident or collision, which directly affects the productivity and better material handling process.

Keywords: Arduino Controller, DC Brushed Encoder Motor, MATLAB, P, PI and PID Controller, Real Time Data Acquisition, Z-N Algorithm

Nomenclatures: s = Laplace operator, ω_n = Natural frequency of oscillations, K = gain of the system, K_m = Motor size constant, K_b = Back emf constant, J = Inertia of the motor, ζ = damping ratio, ω_d = damped angular velocity, K_p = positional error constant, K_v = velocity error constant, K_a = acceleration error constant, e_{ss} = steady state error, $G(s)$ = Transfer function, Z-N method = Ziegler Nichols method, T-L = Tyreus-Luyben method, $C(t)$ = time domain output response, T_d = delay time, T_r = Rising time, T_p = pick time, M_p = overshoot in %, T_s = settling time.

1. Introduction

The present research work demonstrates the methodology of doing a real time velocity analysis of a DC motor with Encoder. The Errors in control systems may be attributed to many factors^{1,2}. Changes in the reference input will cause unavoidable errors during transient periods, and also cause steady state errors³. Any physical control system inherently suffers from steady state error in response to certain types of inputs. Whether a given system will

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exhibit steady state error for a given input depends on the type of the open loop transfer function of the system. Various applications are there where controlling of DC motors are required^{3,4}. The present work is focused on AGV, which is required to move at constant velocity. AGV has to stop for loading/ unloading / detecting any product in context of material handling⁴. The velocity analysis of a DC brushed encoder motor becomes essential to increase the productivity and decrease the lead time⁵. The AGV, as shown in Figure 1 detects RFID number of the product and sends it to the server. The AGV travels on a straight black track as shown in Figure 2. A Line sensor array is used to detect and to follow the black track. AGV follows only black track, which is detected by IR sensor array. The analysis is carried out just by considering the self-weight of AGV and accordingly the control system is designed. The present system is having 5 different products with different RFID numbers. According to the given application, AGV has to travel with a constant velocity accept loading or unloading. The focus of this work is on constant velocity of AGV. There is nothing to mention about RFID and IR sensor array. Encoder values are to be calculated according to the diameter of the wheel. Encoder keeps on calculating the shaft position. Encoder feeds the shaft position

to the Arduino board. Arduino converts it to the angular velocity^{5,6}. Then Arduino tries to solve the error, which is based on the algorithm as well as type of the controller. Then the solved error (manipulated signal) is given to the motor via motor driver⁶. That manipulated signal is a pulse width modulated signal. As far as error solving is concerned, P, PI and PID controllers are used. K_p , K_i and K_d parameters are chosen according to Ziegler-Nichols algorithm. The specifications of the AGV are shown in Table 1.

2. Block Diagram of the System with Problem Description

The block diagram of the overall system is shown in Figure 1. Step input is given to the system as 6 volts DC. Encoder's highest count values are 65535. Any set point can be fed into the system (depends upon the application)^{7,8}. Error signal generated from the summation of the set point and feedback signal is given to the Arduino micro-controller⁸. Arduino manipulates the signal and gives to the motor via motor driver, because motor driver gives PWM signals⁸. The connections for experimental velocity analysis technique are shown in Figure 3^{8,9}. The Prototype of the AGV is shown in Figure 2. The complete setup for velocity analysis is shown in Figure 4.

The feedback signal, which is produced by encoder, is compared with the set point. Error signal is solved by Arduino using various controllers (P, PI or PID) and control algorithm (Z-N algorithm). Finally the signal solved by Arduino, is given to DC motor of AGV.

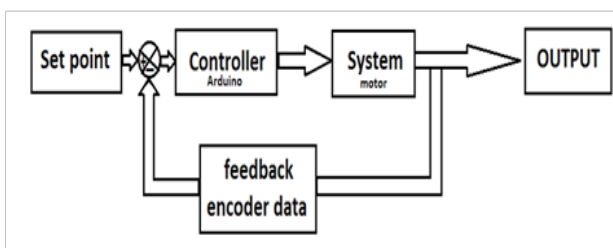


Figure 1. Block diagram of the system.

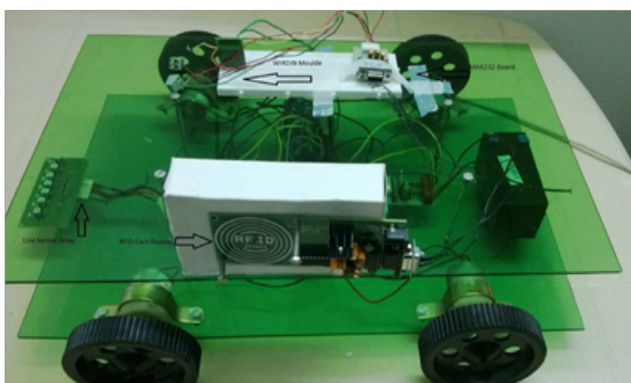


Figure 2. AGV Prototype.

Table 1. AGV Specifications

Sr No	Parameters	Values
1	L × B × H	35cm × 25cm × 15cm
2	Mass of AGV	3.2 Kg
3	No of Motors	4
4	Types of Motors	DC brushed Encoder
5	Motor Specification	6 volts, 120 PRM, 3.6 Kg.cm at 2.2 Amp
6	Wheel Diameter	10 cm
7	Path to be followed	Straight Dark line
8	Path Followed by	IR sensor Array
9	Motor Gear Ratio	47:1

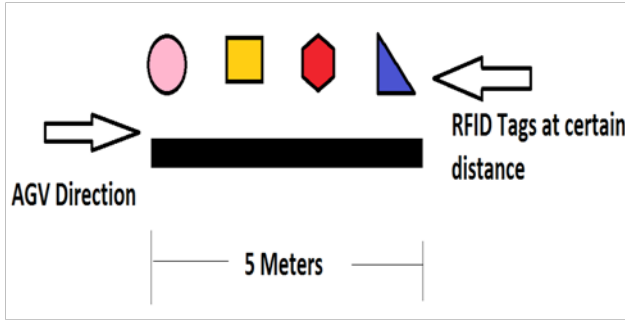


Figure 3. Path of AGV.

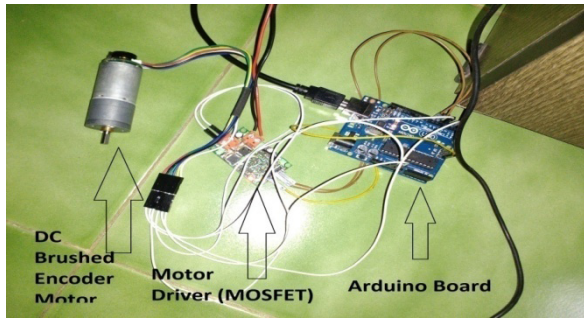


Figure 4. Setup for velocity Analysis.

3. Hardware Description and Methodology

3.1 Hardware Description of the System

The hardware is developed using Arduino board, as it is an open source physical computing platform. It can be used to develop interactive objects^{8,9}. Taking inputs from a variety of switches or sensors, controlling of variety of lights, motors, and other physical outputs can be achieved. It has 14 digital I/O and 6 Analog I/O. It works on +5volts DC, 10 bit analog to digital converter and 14kb ROM^{8,9}. The DC motor used in this application is a brushed DC motor with 47:1 metal gear box^{9,10}. It is equipped with 48 CPR quadrature encoders on the motor shaft. It provides 2249 counts per revolution of the gear box’s output shaft. These motors are intended for use at 6 V. Key specifications of motor at 6 V: 120 RPM and 80 mA free-run, 50 oz-in (3.6 kg-cm) and 2.2 Amp stall current. A two-channel Hall Effect encoder is used to sense the rotation of a magnetic disk on a rear protrusion of the motor shaft. The quadrature encoder provides a resolution of 48 counts per revolution of the motor shaft when counting both edges of both channels¹¹⁻¹³. Table 2 gives the complete idea about the motor parameters and system parameters.

3.2 Methodology to Acquire the Data

To acquire the real time data of velocity, Arduino controller and MATLAB real time data acquisition tool is used. Table 3 shows the all final results of simulated as well as practical values. Simulated results are carried out by MATLAB simulink^{13,14}. The methodology to acquire real time data is demonstrated in the current topic. It becomes essential to acquire real time data to compare simulated and actual data (refer Table 3). This topic will describe some of the general usage of MATLAB’s Data Acquisition Toolbox (DAT). The software in the tool-box allows MATLAB to acquire data from sensors and to send out electrical signals that can be used to control or drive external devices. Here encoders are giving the data to microcontroller. Microcontroller is connected to MATLAB data acquisition tool box using serial communication technique¹⁵. Figure 5 and Figure 6 shows block diagram for real time data acquisition and time data acquired from AGV using simulink respectively.

Table 2. Physical parameters of the motor¹²

Sr. No.	Motor Parameters	Symbol	Information
1	Motor Inductance	La	0.5 Henry
2	Armature Resistance	Ra	2Ω
3	Motor Inertia	J	0.03 Kg.m2
4	Torque Constanta	Ka	0.01 N.m/Amp
5	Type of the system	See Eq 2	Type Zero
6	Order of the system	See Eq 1	Second Order
7	Type of feedback	-	Unity

Table 3. Routh’s Criteria⁸

Laplace Operator	First Coefficient	Second Coefficient
S2	0.015	0.2 + K _p
S1	0.11	0
S0	0.2 + K _p	-

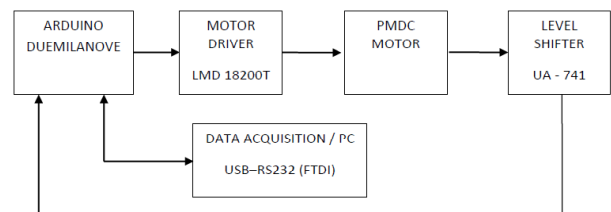


Figure 5 Block Diagram for real time data Acquisition

Here the whole system is controlled by the combination of Arduino, MATLAB simulink, Serial communication, motor driver, DC encoder motor and data acquisition tool box^{15,16}. Arduino will send the encoder data to MATLAB serially and MATLAB plots it. These readings are provided in chapter 4. They are calibrated in the form of RPM.

4. Simulation of the System

Figure 7 shows the simulated block diagram of the system and Table 4 gives the information about all physical parameter of the DC brushed encoder motor^{15,16}. Equation 1 shows the type of the system and equation 2 shows the order of the system. From below two equations, it could be observed that, the present system is a second order system and type of the system is zero (as $j = 0$ in equation 2). K_a (motor torque constant can be found from Routh's criteria and Equation 4, which is a characteristic equation for stability)

$$G(s)H(s) = K \frac{(1 + T_1(s))(1 + T_2(s)) \dots (1 + T_n(s))}{(1 + T_a(s))(1 + T_b(s)) \dots (1 + T_m(s))} \quad (1)$$

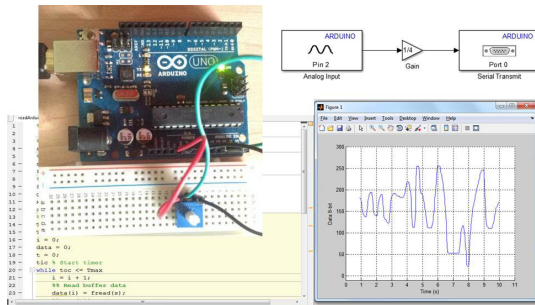


Figure 6. Real time data acquired from AGV using simulink¹⁸.

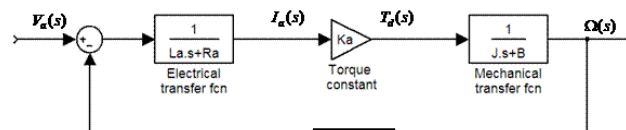


Figure 7. Block Diagram for simulation¹⁵

Table 4. Result of Routh's Criterion²

Parameter	Value
Kp	>-0.2
Ku (Ultimate Gain)	0.2
S	$j\omega$
$\omega = 2\pi/P_u$	5.16 rad/sec
Pu (Ultimate Time)	1.21 sec

$$G(s)H(s) = K \frac{(1 + T_1(s))(1 + T_2(s)) \dots (1 + T_n(s))}{s^j (1 + T_a(s))(1 + T_b(s)) \dots (1 + T_m(s))} \quad (2)$$

$$G(s)H(s) = \frac{(K_a)}{(0.5s + 13)(0.003s + 0.1)} \quad (3)$$

$$1 + K_a G(s)H(s) = 0 \quad (4)$$

4.1 Steady state Analysis of the System

Equation 5 is applicable for under damped system. The time domain response is calculated based on Eq. 5. Now it is important to know the steady state parameters (K_p , K_v , K_a and e_{ss}) of the system¹⁵.

$$C(t) = \left(\frac{\omega_n}{\sqrt{1 - \zeta^2}} \right) e^{-\zeta \omega_n t} \sin \omega_d t \quad (5)$$

$$K_p = \lim_{s \rightarrow 0} (G(s)H(s)) \quad (6)$$

$$K_v = \lim_{s \rightarrow 0} (sG(s)H(s)) \quad (7)$$

$$K_p = \lim_{s \rightarrow 0} s^2 (G(s)H(s)) \quad (8)$$

$$E_{ss} = \frac{6}{K_v} \quad (9)$$

4.2 Transient Analysis of the System

It becomes essential to find transient parameters of the system. Every system opposes an oscillatory behavior (damping). This tendency controls the closed loop poles of the system. The closed loop poles decide the response of the system. Eqn. 10 to 14 belongs to the transient parameters of the system. Table 2 shows all motor parameters.

$$T_d = \frac{(1 + 0.7\zeta)}{\omega_d} \quad (10)$$

$$T_r = \frac{(\pi - \beta)}{\omega_d} \quad (11)$$

$$T_p = \frac{\pi}{\omega_d} \quad (12)$$

$$M_p \text{ in \%} = 100 \left(e^{\frac{-\zeta \pi}{\sqrt{1 - \zeta^2}}} \right) \quad (13)$$

$$T_d = \frac{(4\zeta)}{\omega_n} \quad (14)$$

4.3 MATLAB Simulation

Figures 8 and Figure 9 shows the simulated block diagram and simulated response respectively.

Figure 10 shows the combined simulation for P, PI and PID controller. However a system without controller is also simulated in the Figure 11. Figure 12 shows the combined simulated response of the system. Above two figures are related with simulation only. In the upcoming topic, Figures 13 show the actual response of the system.

4.4 Ziegler Nichols Algorithm for P,PI and PID Controller

It can be observed from Figures 10 and 11, that system without any controller is oscillatory and bit slow. It is necessary to design a compensator to make system stable and fast. Ziegler and Nichols published in 1942 a paper where they described two methods for tuning the parameters of P, PI and PID controllers¹⁶. These two methods are the Ziegler-Nichols' closed loop method, and the Ziegler-Nichols' open loop method. Among these two methods, the closed-loop method is the most useful, and it is applied in the present work. Table 5 shows the Z-N tuning chart for Kp, ki and kd. Equation 16

shows the transfer function of the plant. Equation 17 shows the overall transfer function of the system. Equation 18 shows the characteristic equation of the system^{17,18}.

$$C(s) = K_p + \left(\frac{1}{T_i}\right)\left(\frac{1}{s}\right) + T_d s \quad (15)$$

$$G(s) = \frac{K_p}{(0.015s^2 + 0.11s + 0.2)} \quad (16)$$

$$T.F = \frac{K_p}{(0.015s^2 + 0.11s + 0.2 + K_p)} \quad (17)$$

$$C.C.Eq. = (0.015s^2 + 0.11s + 0.2 + K_p) \quad (18)$$

$$0.015s^2 + K_p + 0.2 = 0 \quad (19)$$

Table 3 shows the Routh criterion technique applied on the current system to find the stability of the system. Routh's criterion is useful for finding stability and gain of the system. Table 4 shows the results of Routh's criterion.

Main aim of this work is to reduce steady state error, less settling time, less overshoot and less velocity gain. A proportional-integral-derivative controller (PID

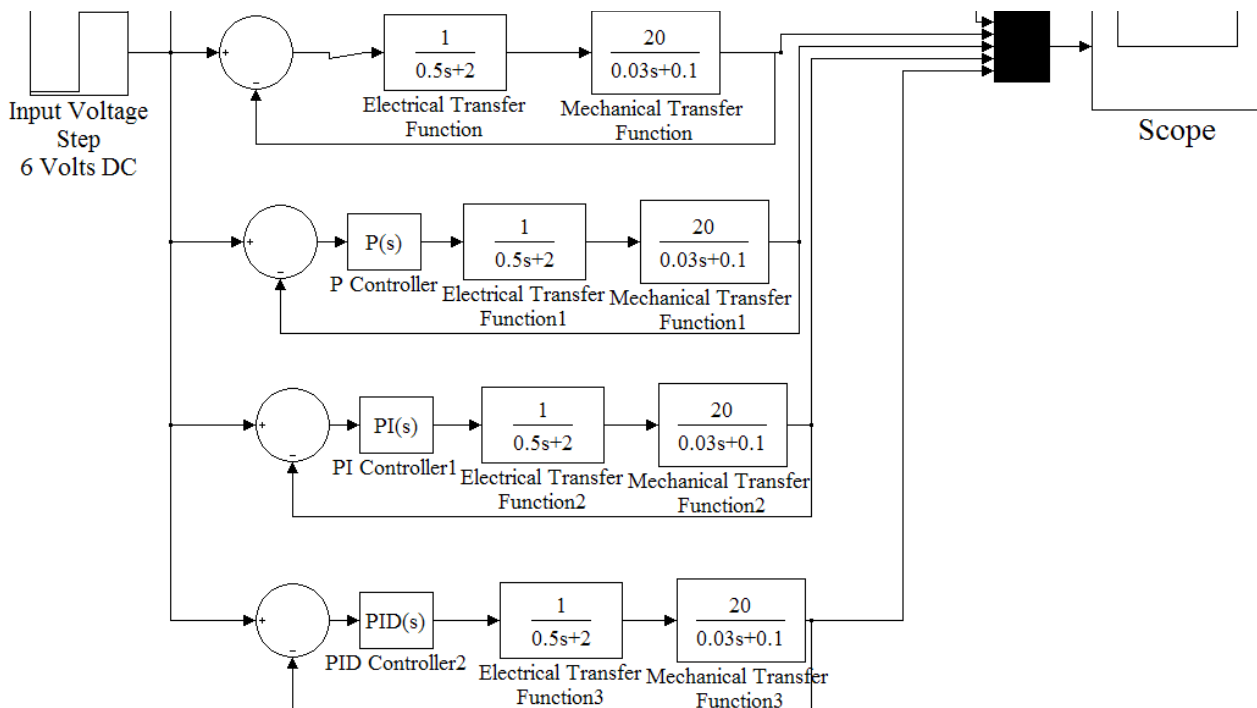


Figure 8. Matlab Simulation.

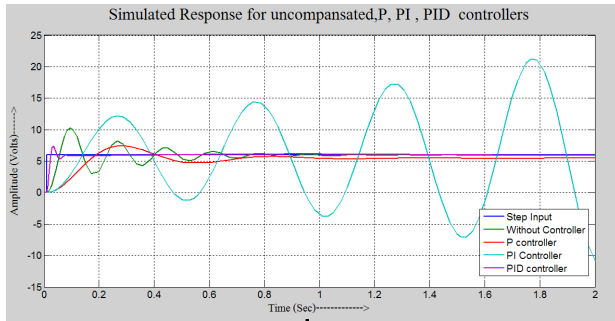


Figure 9. MATLAB Simulated response of uncompensated system, P, PI and PID controller.

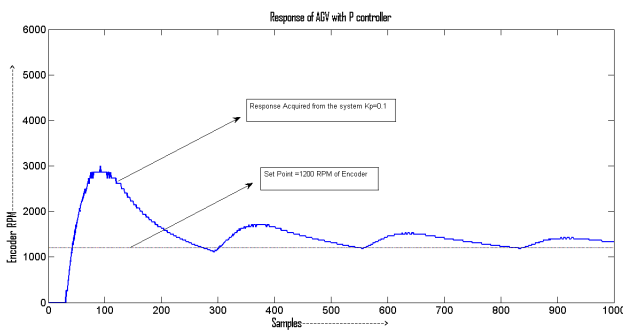


Figure 10. Response of AGV with P controller.

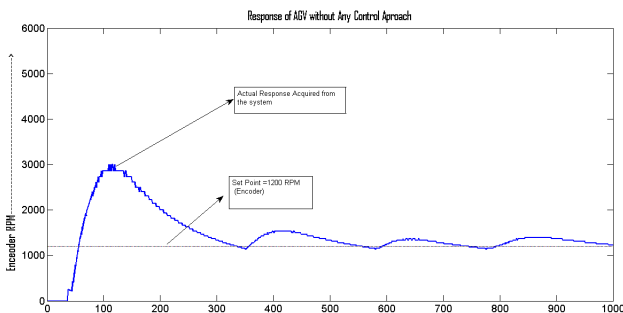


Figure 11. Response of AGV without any controller.

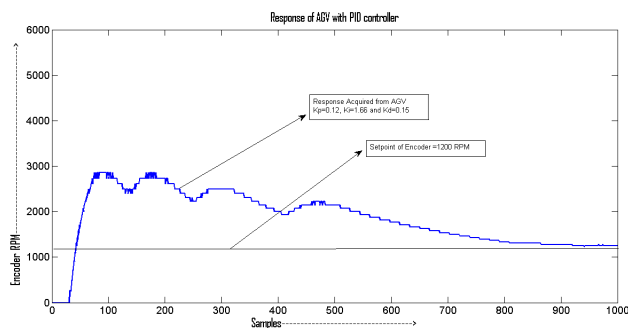


Figure 12. Response of AGV with PID controller.

Table 5. Ziegler Nichols Tuning Chart

Controller	K_p	K_i	k_d
P	$K_u/2$	-	-
PI	$K_u/2.2$	$P_u/1.2$	-
PID	$K_u/1.7$	$P_u/2$	$P_u/8$

controller) is a generic feedback controller¹⁹. It can be used whenever a mean position has to be achieved but the controls of the system do not react instantaneously and accurately. The PID algorithm, takes in account the following three things are to be taken in account- the existing error, the time the system has stayed away from the mean position and the possibility of overshooting the mean position. Using these three quantities, the system is controlled better, allowing it to reach the mean position faster and without over shooting it. Table 6 shows values of K_p , K_i and K_d according to the Z-N algorithm.

4.5 Applying Ziegler Nichols Algorithm to AGV (Actual Obtained Results)

The actual response of the system with all the controllers (P, PI, PID and no controller) are shown in Figure 13. respectively. The set point is 1200 RPM of encoder. Arduino is connected serially with MATLAB and acquired the real time data according to the values of K_p , K_i and K_d . Observing the above figures, it could be concluded that, PID settles down the system quickly but gives higher overshooting.

5. Results and Analysis

The present research paper elaborates the interfacing technique between Arduino and DC encoder motor, simulation of the system in SIMULINK, real time data Acquisition in MATLAB. Moreover it demonstrates the use of Ziegler-Nicholas algorithm for P, PI and PID controller for real time applications¹⁶. It can be concluded that:

- Overshoot in P controller is lesser but system becomes slower with higher steady state error. It clearly shows that AGV with P controller consumes more time to get settled.
- AGV with PI controller becomes unstable. It will not be able to stop itself at the exact location. PI controller is not suitable according to the simulated results.

- AGV with PID controller works well in all criteria. System becomes fast with less steady state error and negligible overshoot for PID controller. Z-N Algorithm & PID controller suits well as far as simulated results are concerned.

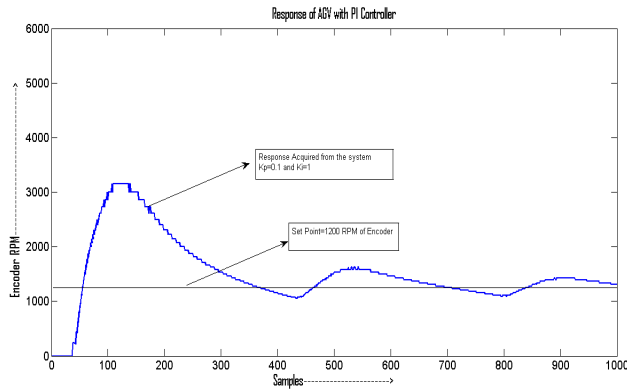


Figure 13. Response of AGV with PI controller.

Table 6. Values of K_p , K_i and K_d based on Z-N Algorithm

Controller	K_p	K_i	k_d
P	0.1	-	-
PI	0.1	1	-
PID	0.12	1.66	0.15

- Referring actual results as per Table 7, AGV works well for PID and PI controller, but becomes oscillatory for P controller.
- The error between simulated and actual response is due to misalignments of motors and wheels, voltage fluctuations in step input, viscous friction, wheel mounting, motors inductance and internal resistance.
- Delay time is almost same for all controllers.
- Positional gain is 100 for all the controllers since this system is a type zero system.
- Velocity and acceleration gain are zero since this system is a type zero system.
- It is a under damped system
- Steady state error is higher for P and PI controller.
- Steady state error is lesser for PID controller.
- PID and PI controller have given lesser overshooting compared to P controller.

In future the same approach may be adopted for acceleration analysis of AGV. The approach may be evaluated in context of constant acceleration of AGV, achieving constant RPM of a servo Motor in CNC machines and automatic stir up bending mechanism^{13,14}, color based sorting system automation¹⁹, motor of a conveyor belt, back plug press fitting assembly^{4,5}, checking parallelism of a railway track¹³. The methodology will be very useful in electro hydraulic circuits used for retrofitting of machine tools¹⁰.

Table 7. Actual and simulated control parameters

Sr No	Parameters	Without Controller Theoretical	Without Controller Practical	Theoretical Values P	Practical Value P	Theoretical PI	Practical Value PI	Theoretical PID	Practical Value PID
1	K_p	100	100	100	100	100	100	100	100
2	K_v	0	0	0	0	0	0	0	0
3	K_a	0	0	0	0	0	0	0	0
4	Ess	0.8 volt	80 RPM	0.65 volts	60 RPM	0.47 Volts	50 RPM	0.2 volts	30 RPM
5	Mp	73 %	61%	36.6 %	30.2 %	26 %	25.3 %	24.6 %	19%
6	T_s	1.05 sec	1.12 sec	0.95 sec	1 sec	0.3 sec	0.25 sec	0.22 sec	0.22 sec
7	T_p	0.09 sec	0.09 sec	0.06 sec	0.06 sec	0.03 sec	0.04 sec	0.0257 sec	0.03 sec
8	T_r	0.03 sec	0.03 sec	0.111 sec	0.12 sec	0.018 sec	0.014 Sec	0.010sec	0.010 sec
9	T_d	0.01	0.01 sec	0.01 sec	0.01 sec	0.01 sec	0.01 sec	0.005 sec	0.01 sec

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