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Modeling, Simulation and Implementation of DC Motor Position Servo Control Using PID Controller and Incremental Encoder

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In this paper, a small geared DC motor together with a simple rotary encoder switch, module KY-040, as an angular position sensor, were modeled. A servo control system with angular position feedback is then constructed and tested both in simulation and in real-time control hardware by using MATLAB-Simulink with Arduino Mega as rapid prototyping test plat-form. To confirm the ability of the simulation to conceptualize the system's behavior and analyze its response theoretically before practical implementation, the results of the servo control system implementation in both simulation and hardware were compared, and very similar results were obtained, as expected.

I. INTRODUCTION

DC motors are extensively implemented in both industrial and household applications, where precise position control is essential. Achieving this level of accuracy demands advanced dynamic control strategies that specifically enhance both the transient and steady-state responses of the motor [1, 2].

The Proportional-Integral-Derivative (PID) controller is the most commonly employed control strategy in servo systems. In this study, the trial-and-error tuning method was adopted, as it is widely used in industrial applications due to its simplicity and straightforward implementation both in simulation as well as in physical hardware environments [3].

Recently, system modeling and computer simulation have become essential tools in industry. They enable engineers to study complex systems using mathematical models and computational techniques. A model of a system is either a physical or mathematical representation that captures the key properties, behaviors, and functions of the actual system. Simulation, on the other hand, is the process which virtualizes on the computer the actual scenario as close to the real system as possible [4].

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In recent years, the amount of resources invested in testing embedded proto-typing applications has decreased significantly due to the widespread use of various advanced simulation techniques. The goal of systems simulation is to test and improve the efficiency and effectiveness of systems, their implementations, and their developments. In simulation, the challenge is not necessarily the cost of the hardware itself, but rather access to the information needed to simulate it accurately [5].

The main objective of this study is to compare the performance of a position servo control system both in simulation and real-time control implementation. In this work, a no-load geared DC motor, known as a yellow DC motor, was used in the real-time hardware application, and its parameters were used in both the modeling and simulation. The sensor used in this work is rotary encoder switch, module KY-040, with a resolution 20 pulses per revolution (ppr). For this comparison, the parameter values of the PID controllers used in both the simulation and real-time hardware applications were set equal.

The significance of this research lies in the implementation of Arduino Mega as a digital signal processor and its application as a hardware controller utilizing MATLAB-Simulink real-time control algorithms. This rapid prototyping technology was previously unavailable and prohibitively expensive for under developed countries, but now, it is available and inexpensive. This opens the door for new researchers and students with limited budgets to conduct comprehensive studies, starting from simulation to experimentation and practical application on real systems.

Since DC servo motors have a wide area of use, DC motor's servo control studies have been actively researched, e.g., in [6], the research used microprocessor-controlled DC motor control for non-load sensitive position servo system. In [7], the research introduces modelling and controlling of a permanent magnet brushless DC motor drive using a fractional proportional-integral-derivative controller. In [8], the research carried out the experimental setup and verification of servo DC motor position control based on the integral sliding mode control approach. In [9], position control of the DC motor was carried out by using Thomas and Poongodi genetic algorithm based PID controller. In [10], the research realized the speed and position control of real-time DC motor by using a PID control method with TMS320C31 digital signal processing starter kit with on-line parameter setting. In [11], the research implemented the adaptive neuro-fuzzy inference systems based speed control of DC motor. In [13], modeling of DC motor and position control under different loads were performed using sliding mode control and proportional integral-derivative control method. In [14], the research studies the potential application of PID control systems to regulate DC servo motors, using tools such as Inkercad, Falstad, and MATLAB-Simulink for simulation and implementation.

The structure of this work is as follows, section II presents first the mathematical modelling of DC motor; Second, parametric modeling of a real geared DC motor; third, the modeling of the incremental encoder and decoder; fourth, the modeling of the PID controller and fifth, the construction of the block diagram for the DC motor position servo control model. Moreover, section III presents first the simulation results and second the hardware results. Furthermore, in section IV, a conclusion is presented. Finally, the references are given at end.

II. MODELLING OF DC SERVO MOTOR

In this section, the servo control modelling of DC motor position is presented. Where, in the following, the mathematical modelling of DC motor is presented at first subsection. Then at the second subsection, the parametric modelling of the used DC motor is presented. At the third subsection, mathematical modelling of the used sensor (incremental encoder & decoder) is presented. Moreover, at the forth subsection the Mathematical model of PID controller will be presented. Finally, at the fifth subsection, the building of the block diagram of DC motor position servo control model will be presented.

Fig.1 below shows the block diagram of the real servo control system loop that will be modeled in this section.

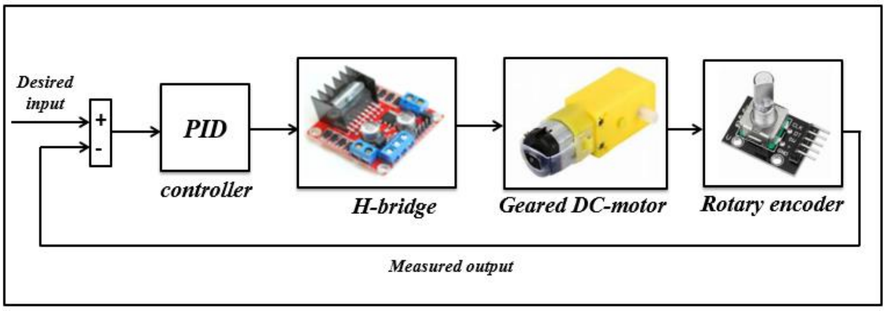

Figure 1. Block diagram of the real servo control system loop

A. Mathematical Modelling of DC motor

In this subsection a linear DC motor will be modeled. The electric circuit of the motor's armature and the free body diagram of the rotor are shown in the next Fig.2.

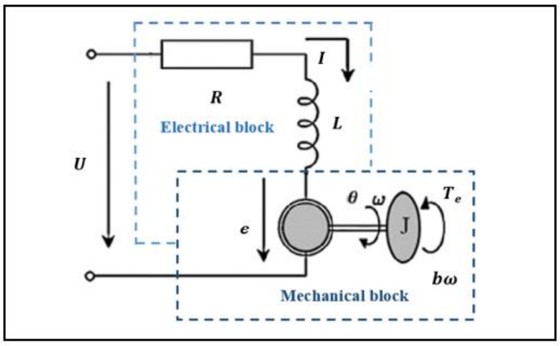

Figure 2. The electrical circuit of the armature and the free body diagram of the rotor

With reference to Fig.2 above, the voltage source (U) applied to the motor's armature is considered as the control input that drives the motor; while the angular position of the shaft θ is the measurable output. The DC motor's rotor and shaft are assumed to be rigid. It is further assumed that the system follows viscous friction model, that is, the friction torque is proportional to shaft angular velocity. In general, the torque generated by the DC motor is proportional to the armature current and the strength of the magnetic field.

It is assumed that the magnetic field is constant and, therefore, that motor torque T_e is proportional to the armature current I by a constant factor torque constant, K_t as:

$$T_e = K_t . I \,, \tag{1}$$

this is referred to as an armature-controlled motor. [16]

Back emf is the generator output of a motor, and so it is proportional to the angular velocity ω of the motor's shaft by a constant factor, back emf constant, K_e,

$$e = K_e . \omega \,. \tag{2}$$

In *SI* units, motor's torque constant and motor's back emf constant are almost equal, that is

$$K_t \approx K_e . \tag{3}$$

From Fig.2 above, we can derive the following governing equations based on Newton's 2 d law and Kirchhoff's voltage law,

$$J\ddot{\theta} + b\,\dot{\theta} = K_t . I \,, \tag{4}$$

where *J* is the motor's moment of inertia, *b* is the viscous friction coefficient.

When the voltage *U* is applied to the motor, it produces the current, *I*, which depends on the motor's angular velocity , ω, the circuit equation of the motor is

$$L\frac{\partial I}{\partial t} + R.I = U - K_e . \omega \,\,. \tag{5}$$

Applying the Laplace transform, the above modeling equations can be expressed in terms of the Laplace variable s as:

$$(Js + b)s\theta(s) = K_t . I(s) \tag{6}$$

$$(Ls + R)I(s) = U(s) - K_e . s\theta(s) \,. \tag{7}$$

The transfer function of the DC motor's coil is,

$$\frac{I(s)}{U(s) - K_e .\, s\theta(s)} = \frac{1/_R}{(L/_R)s + 1} \,. \tag{8}$$

The next Fig.3 , shows a general block diagram of the mathematical model of no-loaded DC motor in open loop configuration, which is built based on the equations (1), (6) and (8).

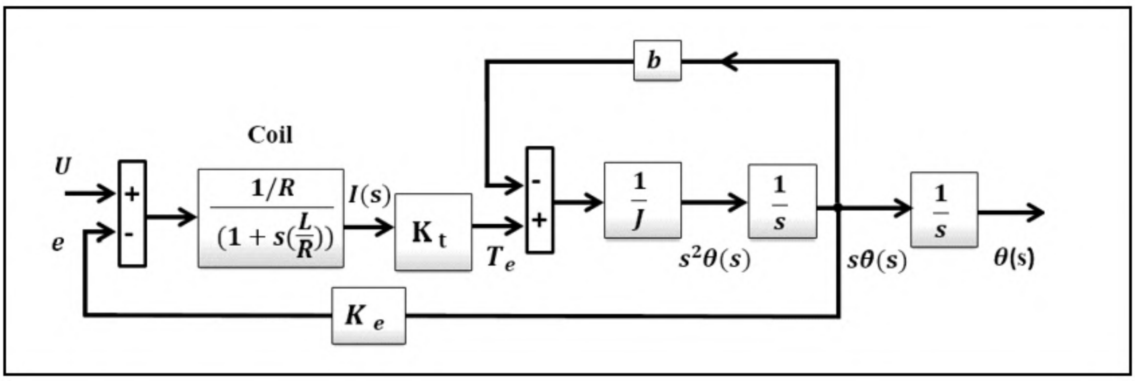

Figure 3. Block diagram of no-load DC motor electromichanichal model

B. Parametric Modelling of DC motor

Classic analytical parametric modelling is largely based on complete knowledge of measurement technology and the measurement process [17]. In this subsection, a model of a real no-loaded geared DC motor, known as a yellow DC motor is presented. The motor parameters shown in the tables below were measured /calculated at an operating voltage of 6 volts. The TABLE I. below lists the measured stall current, and the stall torque from the datasheet.

TABLE I. MOTOR'S STALL CURRENT AND STALL TOURQE

Parameter	Symbols	Values	Unit
Stall torque	T_{stall}	0.07845	N.m
Stall current	I_{stall}	0.3	[A]

With (1) and the given parameters, the motor's torque constant is calculated to be:

$$K_t = \frac{T_{stall}}{I_{stall}} \tag{9}$$

Using (2), the back-emf constant can be calculated as:

$$K_e = \frac{e}{\omega} \tag{10}$$

In order to calculate electromotive force constant, K_e, the back emf, e, must be identified using (5) as:

$$e = U - I * R \tag{11}$$

The following TABLE II. lists, the no-load motor's speed ω and the nominal voltage *U* from the motor's datasheet, as well as the measured armature current *I*, at no-load.

TABLE II. MOTOR'S SPEED, NOMINAL VOLTAGE AND ARMATURE CURRENT

Symbols	Value (no-load)	unit
ω	20.9439	Rad/sec
I	0.148	[A]
U	6	[V]

The motor's viscous friction constant is calculated as:

$$b = \frac{T_{stall}}{\omega}\,. \tag{12}$$

The moment of inertia is calculated from the measured rotor's radius and the measured rotor's mass using the next equation:

$$J = \frac{1}{2} m.r^2 \tag{13}$$

Due to fact the maximum motor's angular velocity and motor's stall torque at no-load are in the datasheet, the DC motor model is a grey box model [17]. The following TABLE III. lists the measured and calculated parameters of the DC motor model.

TABLE III. DC MOTOR'S MODEL PARAMETER VALUES

Parameters	Symbols	Values	Units
Armature resistance	*R*	7	Ohm
Armature inductance	*L*	1.2 e^{-3}	H

Rotor radius	r	3	mm
Rotor mass	m	26	gm
Viscous friction coefficient of the motor	b	0.003745	N.m.s
Moment of inertia	J	$9.36\ e^{-7}$	$kg.m^2$
Motor torque constant	K_t	0.2615	N.m/A
Back electromotive force (emf) constant	K_e	0.237	v.s/rad
Gear ratio	GR	1:48	-

C. Mathematical Modelling of the Sensor (Incremental Encoder & Decoder)

Incremental encoders and their decoders are among the most commonly used sensors in servo control systems for measuring position, velocity, and acceleration. They provide control systems with essential feedback, enabling them to achieve the desired performance.
Mathematical modeling of sensors and encoders is crucial to the application of control theories, as it allows engineers to test and refine control systems into more accurate and reliable ones. [18]
An incremental encoder is an electromechanical device that generates a series of electrical pulses at outputs A and B to measure the rotational position, speed, and direction of the shaft in response to incremental rotary mechanical movements of a rotating axis. [19]

In this subsection, the rotary encoder and 1x-logic decoder will be modeled to be used in the servo motor model later.

- **Rotary Incremental Quadrature Encoder**

  The rotary incremental quadratic encoder model is based on the sine function, because the phase signals A and B of encoders are generated from the sine function. For the block diagram of the angular displacement rotary encoder model and further details, please refer to reference [18]. It should be noted that the real rotary encoder model will be built in MATLAB-Simulink environment to use later in the simulation of the yellow dc motor servo control system loop.

- **Logic 1X Decoder**

  The decoder, a logic circuit designed to detect the (A, B) signal transition from old state to new state, triggering the count up action, and the state transition from old state to new state triggering, the count-down action in the opposite direction. For further details and to view the 1x logic decoder model in the MATLAB-Simulink environment, which will be used for both simulation and practical implementation, please refer to reference [18].

D. Mathematical Model of Proportional–Integral–Derivative (PID) Controller

The PID controller is implemented to control the position of the geared DC motor in both simulation and hardware. The control error is defined by the difference between the desired and the respective measured angles as following:

$$\mathrm{E}\ (t) = \theta_d(t) - \theta_m(t) \tag{14}$$

In a typical PID method, the controller corrects the error between the desired input value θ_d and the measured value θ_m. PID tuning consists of three parameters: P (proportional), I (integral), and D (derivative), whose correct values maintain the stability of the entire system. The weighted sum of these three parameters is used to control the process. Fig.4 below shows the general block diagram of a control system loop with PID Controller. [20]

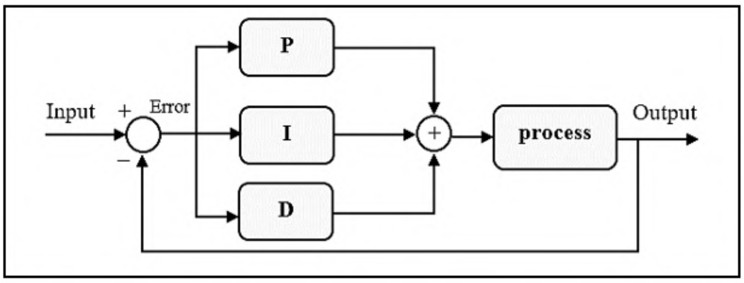

Figure 4. Control loop with PID Controller

The Mathematical model of PID controller is,

$$u(t) = K_p E(t) + K_I \int_0^t E(\tau)d\tau + K_D \frac{d}{dt}\,\mathrm{E(t)}, \tag{15}$$

while the digital model of PID controller is,

$$u(n) = K_p E(n) + K_I T_s \sum_0^N E(n) + K_D \frac{E(n) - E(n-1)}{T_s}. \tag{16}$$

Where T_s is the sampling period, u is the manipulated variable and E is the error.

E. Building the Block Diagram of DC motor Position Servo Control Model

As shown in Fig.1 in general the servo control system consists of the motor, the gears, driver, controller and sensor. To build the DC motor position servo control system model, we need the model of no-load DC motor shown in Fig.3, Encoder and decoder models and PID controller. From (9) and (11) we derive:

$$U - e = \frac{R}{K_t}\,T_{max} \tag{17}$$

Fig.5 below presents the block diagram of geared DC motor position servo control model:

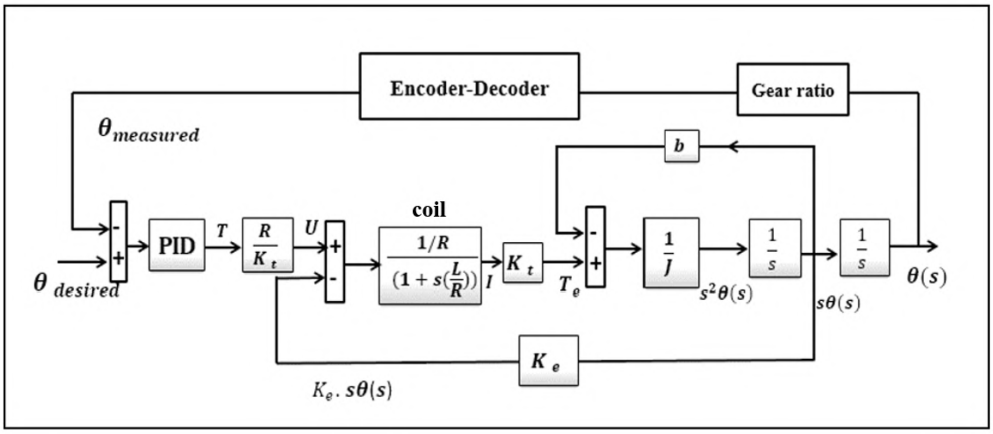

Figure 5. Block diagram for geared DC motor position servo control model

III. APPLICATIONS AND RESULTS

A. Simulation of DC motor Position Servo Control

In this subsection, based on Fig.5 above the DC motor position servo control model using a PID controller in the MATLAB-Simulink environment is built. The Simulink model consists of a DC motor model, as well as a sensor model (1x incremental logic encoder-decoder) as shown in Fig.6 below and a PID controller model. Fig.7 below shows the simulation model of the geared yellow DC motor position servo-control loop, that was modelled and will be later implemented in real hardware system.

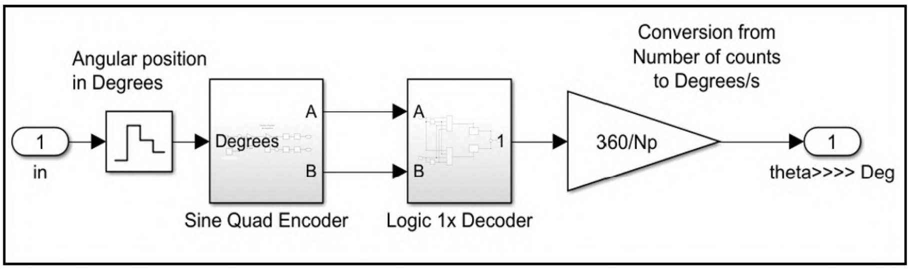

Figure. 6 Simulink block diagram of encoder-logic-1x decoder model

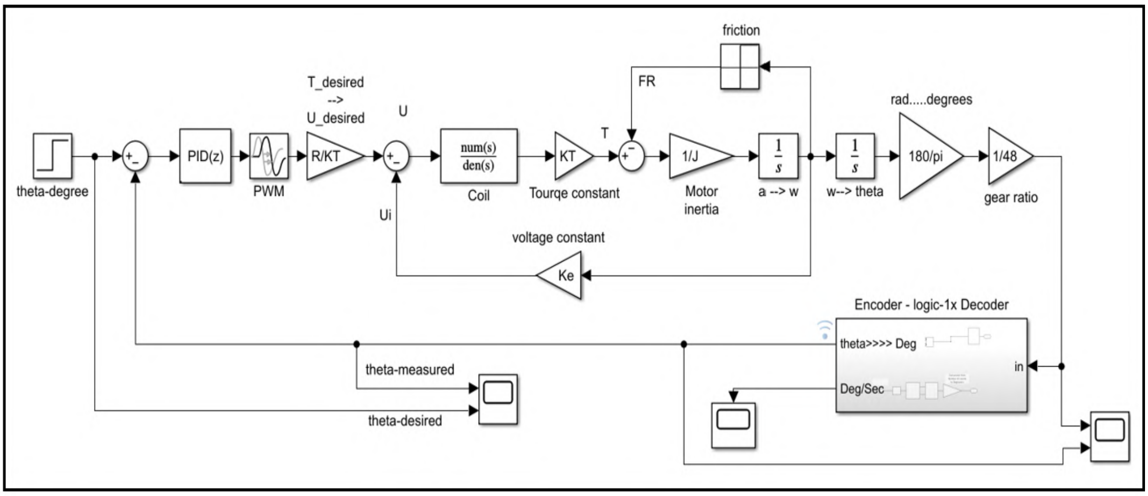

Figure. 7 Simulation model of no-load DC motor position servo control loop

TABLE IV. Below present the used PID controller parameters:

TABLE IV. PID CONTROLLER PARAMETERS

Controller parameter	Val ue
K_P	1
K_I	0
K_D	0

By running the angular position servo control simulation model shown above in Fig.7 and using the yellow DC-motor parameters in TABLE III, with a rotary encoder model at resolution of 20 pulses per revolution, and using the control parameters shown in TABLE IV. above, Fig.8 below shows the measured output response to a 0-90° input step of the servo system. The 1x decoder counted five pulses from the encoder signals, stages A and B, indicating a 90° step increment. Thus, the DC motor accurately achieved the desired angular position within 0.013 seconds.

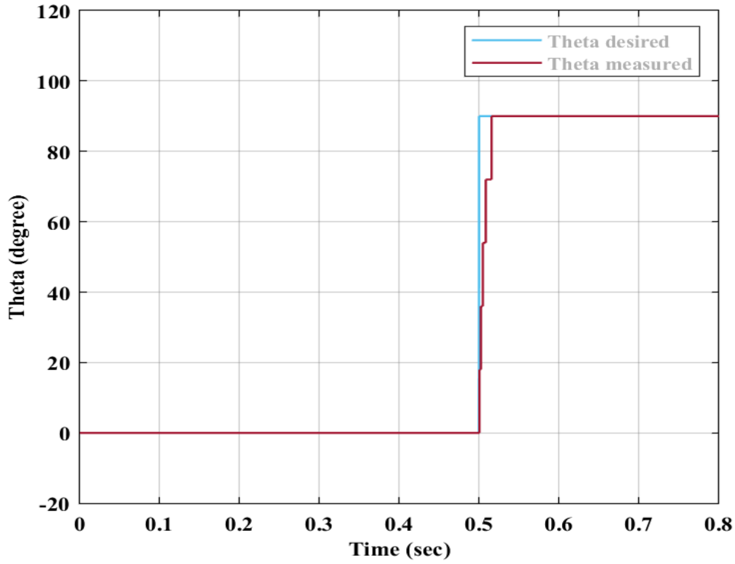

Figure. 8 measured output step response by using the Simulink model of position servo control loop

B. Hard ware Implementation of DC motor Position Servo Control

In this subsection, the rotational position servo control system is realized by controlling the angular position of DC motor known as geared yellow DC motor through the dual H-bridge L298N unit, and the output shaft rotational position is detected by a rotary quadrature encoder switch KY-040 unit with a resolution of 20 ppr. The control algorithms were tested in MATLAB-Simulink graphical programming environment and then the hardware compiled and run in real time using Arduino Mega 2560 board; the mechanical and electrical interconnections of the test platform hardware details are shown in section V of reference [18]. Fig.9 below shows the block diagram of the real-time interfacing in the servo control system.

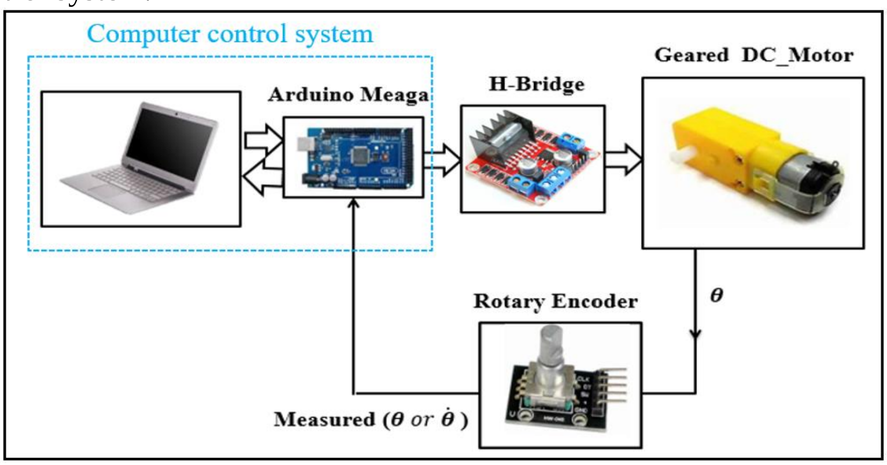

Figure. 9 Block diagram of the real-time interfacing in the servo control system

Fig.10 below shows the Simulink block diagram of the real-time DC motor angular position servo control loop, where a digital PID controller is used to control the angular position of the geared motor's output shaft, by selecting the measured angular position to close the feedback loop.

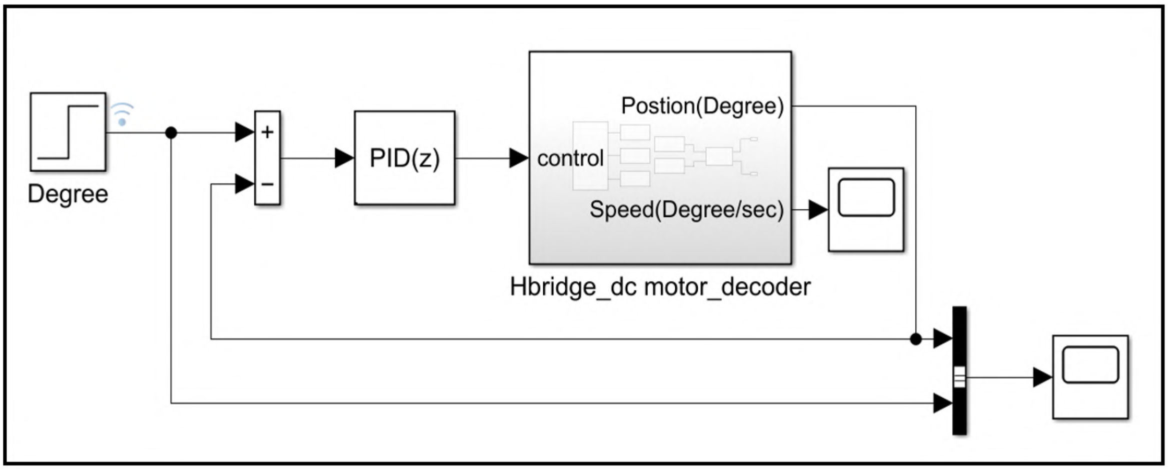

Figure. 10 Simulink block diagram of the real-time DC motor position servo control

The block diagram (Hbridge_DC motor_decoder) Hbridge control as well as the encoder decoder subsystem is shown in the next Fig.11. The subsystem of Hbridge control details are in section V of reference [18].

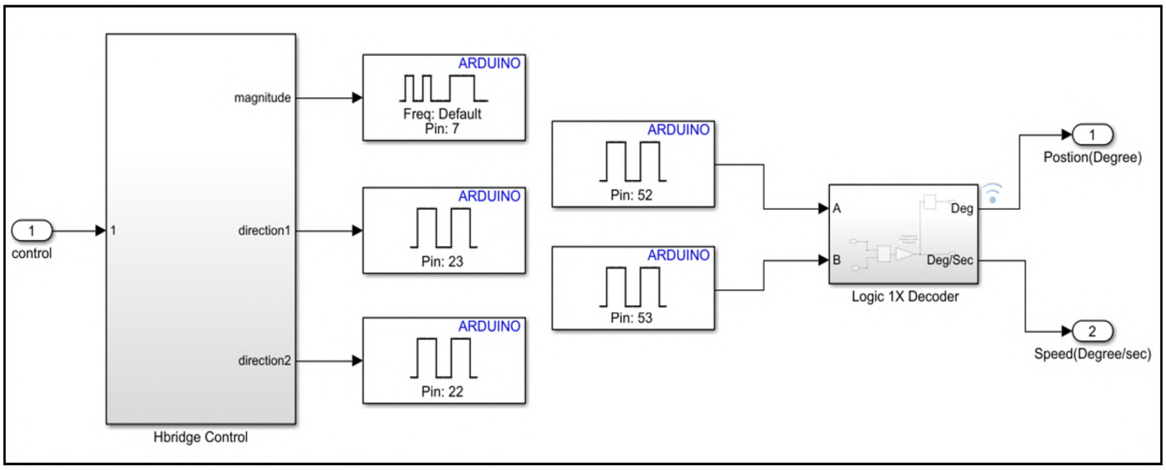

Figure.11 Block diagram of H-bridge, DC motor and encoder-decoder subsystem

After the successful hardware and software operation, the next Fig.12 shows the measured output response to a step input from 0 to 90 degrees for servo system, where the 1x-logic decoder has counted 5 pulses from the encoder signals, phase A and B, indicating 90 degrees, increase. Thus, the DC motor accurately achieved the desired angular position within 0.14 seconds.

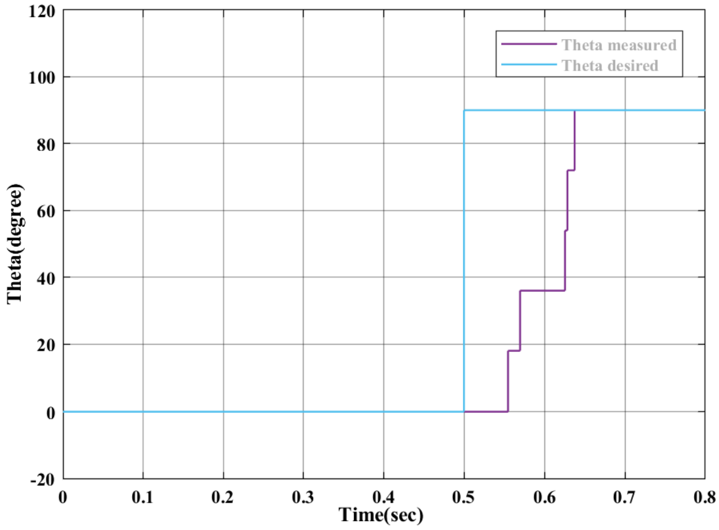

Figure.12 Real-time measured output step response using 20 ppr encoder & 1x logic-decoder

IV. CONCLUSIONS

In this work, a DC motor known as the geared yellow DC motor and rotary incremental encoder switch; both are modelled, simulated and hardware implemented in a servo control loop. To model and simulate the yellow DC motor, first, the motor parameters not listed in the data sheet were first measured and calculated. The simulation model of position servo control loop, is also built using MATLAB-Simulink. To control the position of the geared DC motor, the PID controller is proposed based on a feedback mechanism with rotary incremental encoder with resolution of 20 pulses per revolution to use as angular position measurement sensor.

The encoder's incremental feedback mechanism relies on decoding the quadratic phase of encoder pulses A and B. Samples of the decoded position data are done to measure the DC motor angular position. the PID controller algorithm is applied to compute control variable in the form of PWM. The resulting PWM signal is then applied to the H-bridge.

This work aims to model a yellow DC motor, a rotary incremental encoder, and compare position servo control of an unloaded geared DC motor in both simulation and hardware applications. Simulation and hardware results demonstrated good dynamic behavior of the servo motor, with fast rise and settling times and accurate angular positioning of the DC motor. The results demonstrated the positioning accuracy of the DC servo motor in both simulation and hardware implementation. This confirms the effectiveness of simulation before practical applications in improving the efficiency of DC motors and reducing energy loss.

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