# ELECTRONIC CONTROL DESIGN FOR A DC MOTOR BASED ON THE 1-BIT ANALOG-TO-DIGITAL CONVERTER STRUCTURE

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**Abstract**

A 1-bit Analog-to-Digital converter (also called a Delta-Sigma modulator) is a widely used system that converts a continuous signal into a digital one. The Delta-Sigma modulator is essentially a stable, closed-loop system built around a first-order plant. This fact is demonstrated here using Lyapunov theory, along with some remarks on its robustness. Since the Delta-Sigma system architecture is a stable closed-loop system, it is a straightforward tool for controlling first-order dynamical systems, like a DC motor. Based on previous findings, a new electronic system was designed to specially manipulate the shaft speed of a dual-shaft worm-gear DC motor. To enhance the performance of our electronic design, we also used a low-cost microcontroller. Additionally, our electronic system does not utilize Analog-to-Digital (ADC) or Digital-to-Analog (DAC) converters. This is because the 1-bit analog-to-digital conversion is accomplished by a comparator signal within the closed-loop system. To support our approach, experimental results are shown.

**Key words**

Delta-Sigma modulator, DC Motor, Electronic circuit control design, Microcontroller, Experimental platform.

## 1 Introduction

The Delta-Sigma modulator, also known as a 1-bit Analog-to-Digital Converter (ADC), is a well-established system to convert analog signals to digital ones using only a single bit [Zapateiro De la Hoz et al., 2015; Zapateiro et al., 2014; Acho, 2014]. Its architecture is too simple, as shown in Figure 1.

Therefore, $V_{in}$ is the analog input signal and $y(t)$ is its 1-bit digital version. The Low Pass Filter (LPF) actually acts as a digital-to-analog converter [Zapateiro De la Hoz et al., 2015; Zapateiro et al., 2014; Acho, 2014]. From a control systems perspective, this modulator can be seen as a closed-loop system where the low-pass filter (LPF) acts as the plant model. The LPF block can be an integrator or other options [Ren et al., 2014; Pavan et al., 2008]. The Delta-Sigma modulator has already been used in some engineering applications. For example, reference [Li et al., 2022] presents a high-resolution sensor design for electrical motors that uses a Delta Modulator. In a network communication environment, a Delta-Sigma modulator was used in a closed-loop PID controller for wind energy conversion [Wanigasekara et al., 2021]. An efficient controller for manipulating the speed of a DC motor, based on a Delta-Sigma modulator, is detailed in [Al-Makhles et al., 2012]. The controller was implemented using an FPGA (Field Programmable Gate Array) digital board. However, this control method requires an FPGA board, optical encoders, an H-bridge connection to the DC motor, and a third-order digital controller programmed into the FPGA device. Our approach, which we will discuss later, is simpler. Furthermore, because the Delta-Sigma modulator produces a form of PWM signal (Pulse-Width Modulation), the Delta-Sigma mechanism has also been ap-

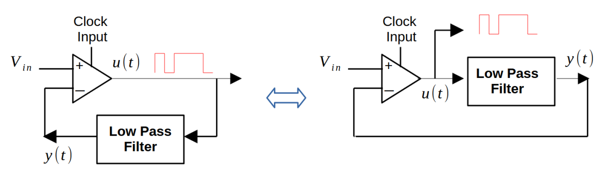



Figure 1. Block diagram of a Delta-Modulator. The operational amplifier functions as a comparator within its digital framework. It receives a clock signal. The red signal is the digital response.

plied in power electronics applications that require PWM [Keskar and Rincón-Mora, 2008; Chen et al., 2010], and in certain propulsion systems where a control switching signal improves controller performance [Zappulla et al., 2017]. Naturally, the Delta-Sigma modulator, originally designed for the discrete time domain, has been extended to the continuous time domain [Sira-Ramírez and Villeda, 2004; Linares-Flores and Sira-Ramírez, 2004].

Because the Delta-Sigma modulator incorporates a low-pass filter (LPF) system, this modulator block can be substituted with a dynamical system that has a similar LPF state-space dynamical behavior. Therefore, the main contributions of this paper are to present a new electronic controller design for manipulating the shaft speed of a dual-shaft worm gear DC motor using a Delta-Sigma modulator and a mathematical proof of the closed-loop system using Lyapunov theory. A microcontroller unit is used to implement the discrete version of the comparator stage for this modulation scheme. We have specifically chosen the PIC12F508 from Microchip. The resulting electronic controller is low-cost to build.

Controlling a DC motor is challenging due to its inherent nonlinearities such as hysteresis and friction [Padthe et al., 2008; Aboelhassan, 2008; Tomchina, 2023]. We also present experimental results to support our electronic control approach. We use a dual-shaft worm gear DC motor extracted from a massage chair. Our control scheme is configured for velocity control. In addition, a link to a video on experimentation is also provided in the experimental section.

While modern digital networks offer benefits in various communication fields, the control and sensor signals operating within them face limitations imposed by the technology itself, such as quantization effects [Andrievsky, 2013; Fradkov et al., 2006]. To address these limitations, [Andrievsky, 2013] proposed a modulator/demodulator scheme and applied it to the synchronization of chaotic Lorenz systems. In its implementation, the author utilized uniform sampling within the closed-loop system through digital networks. Selecting an appropriate sampling rate for chaotic signals can be challenging in real applications due to the external limitations imposed by digital electronics. In our approach, this issue is obviated because the digital signal is directly modulated using a microcontroller unit (MCU). Our microcontroller-controlled system operates without the need for A/D or D/A conversion. This occurs because the 1-bit ADC functionality is realized by a comparator signal integrated into the closed loop.

The remainder of this paper is organized as follows. Section 2 presents the closed-loop stability and robustness analysis for the Sigma-Delta modulator by invoking Lyapunov theory. We also present a control scheme to achieve DC motor velocity control. Section 3 details our electronic control design, including experimental results and a video link. Finally, Section **??** provides concluding remarks.

## 2 Stability and robustness of the Delta-Sigma modulator

Using Figure 1 as a guide, here is the general mathematical model for a Low Pass Filter (LPF):

$$\dot{y}(t) = a\left[u(t) - y(t)\right], \tag{1}$$

where $u(t)$ is the output signal from the comparator. $a = \frac{1}{\tau}$, where $\tau$ the time constant of the LPF system and $\dot{y}(t) = \frac{dy(t)}{dt}$. To prove the stability of the closed-loop system, let us use a continuous-time representation of the comparator with the sign function, as shown in [Linares-Flores and Sira-Ramírez, 2004]:

$$u(t) = \frac{1 + \mathrm{sgn}\left(V_{in} - y(t)\right)}{2}, \tag{2}$$

where sgn$(\cdot)$ is the signum function defined as:

$$\mathrm{sgn}(x) = \begin{cases} 1 & \text{if } x \geq 0 \\ -1 & \text{if } x < 0 \end{cases}.$$

Equation (2) can be rewritten as follows:

$$u(t) = \begin{cases} 1 & \text{if } V_{in} \geq y(t) \\ 0 & \text{if } V_{in} < y(t) \end{cases}. \tag{3}$$

The mathematical model in Equation (2), or Equation (3), is fit to be used as a digital Transistor-Transistor Logic (TTL) signal, where a binary 1 is represented by 5 V and a binary 0 by 0 V. Additionally, we can define the error signal, $e(t)$, as:

$$e(t) = V_{in} - y(t), \tag{4}$$

where the reference signal, $V_{in}$, is a continuous signal with slow time variation. For simplicity, we will assume $V_{in}$ to be a constant value. Substituting equation (2) into (1) gives us the closed-loop mathematical model:

$$\dot{y}(t) = a\left[\frac{1 + \mathrm{sng}\left(e(t)\right)}{2} - y(t)\right]. \tag{5}$$

The time derivative of equation (4) produces:

$$\dot{e}(t) = -\dot{y}(t) = -\frac{a}{2}\left[1 + \mathrm{sgn}\left(e(t)\right) - 2y(t)\right], \tag{6}$$

where $\dot{e}(t) = \frac{dy(t)}{dt}$. After some algebra, Equation (6) becomes:

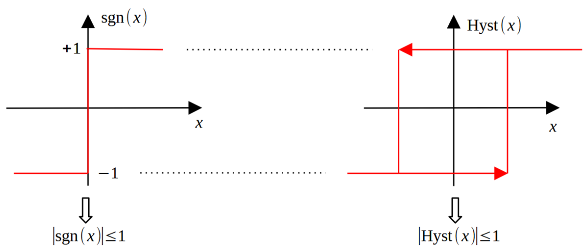



Figure 2. Plots of the signum (SGN) and hysteresis (Hyst) functions.

$$\dot{e}(t) = -ae(t) - \frac{a}{2}\text{sgn}\left(e(t)\right) + a\left(V_{in} - \frac{1}{2}\right). \quad (7)$$

To conclude stability of the closed-loop system in Equation (7), let us introduce the following Lyapunov function:

$$V_L(t) = \frac{1}{2}e^2(t). \quad (8)$$

The time derivative of the Lyapunov function (8) is:

$$\begin{aligned}\dot{V}_L(t) &= e(t)\left[-ae(t) - \frac{a}{2}\text{sgn}(e(t)) + a\left(V_{in} - \frac{1}{2}\right)\right] \\ &= -ae^2(t) - \frac{a}{2}|e(t)| + a\left(V_{in} - \frac{1}{2}\right)e(t) \\ &\leq -a|e(t)|\left[\frac{1}{2} - |V_{in} - \frac{1}{2}|\right] \quad (9)\end{aligned}$$

There, from (9), we have:

$$\dot{V}_L(t) \leq -a|e(t)|\left[\frac{1}{2} - |V_{in} - \frac{1}{2}|\right],$$

meaning that this time derivative will be non-positive definite if:

$$|V_{in} - \frac{1}{2}| < \frac{1}{2}. \quad (10)$$

Hence, the closed-loop system of the Delta-Sigma modulator is stable if $0 \leq V_{in} \leq 1$. This implies that $e(t)$ will be bounded if $0 \leq V_{in} \leq 1$. For an electronic digital implementation, this condition shows that 0 V $\leq V_{in} \leq$ 5 V. Because we use a signum function in our modeling, the closed-loop system will exhibit chattering behavior [Sira-Ramírez and Villeda, 2004; Linares-Flores and Sira-Ramírez, 2004]. This is only true if our system exists in the continuous-time domain. In the digital realization, the chattering effect will not be produced by the electronic comparator, which functions as the equivalent of a signum function (see Figure 1).

To demonstrate the robustness of the Delta-Sigma modulator against the inability to perfectly reproduce the signum function in digital form, we assume that the signum function can be approximated as a hysteresis function [Padthe et al., 2008]. See Figure 2.

Then, from Equation (5), we have the following closed-loop system using the hysteresis function instead of the signum model:

$$\dot{y}(t) = a\left[\frac{1 + \text{Hyst}\left(e(t)\right)}{2} - y(t)\right]. \quad (11)$$

Using the same Lyapunov function in Equation (8) and the same mathematical procedure to conclude (9) along with the fact $|\text{Hyst}(x)| \leq 1$, we will find the same fact:

$$\dot{V}_L(t) \leq -a|e(t)|\left[\frac{1}{2} - |V_{in} - \frac{1}{2}|\right].$$

This maintains the same stability assertion for the closed-loop system as for the signum function.

## 3 Electronic control design and experimental results

This section describes the electronic realization of our Delta-Sigma modulator. First, we use a passive RC (Resistance-Capacitance) low-pass filter as the plant. Then we replace it with a dual-shaft worm gear DC motor. Our experimental platform allows for a performance comparison between the RC system and the motor device, as the choice of plant is selectable. In addition, our digital comparator was implemented using a Microchip PIC12F508 microcontroller. This microcontroller is one of the lowest-cost options on the market. More technical details on this microcontroller can be found in its technical data sheet. We configured this microcontroller's clock with an RC circuit, allowing us to manually tune its frequency by varying the resistance and/or capacitance. This is because the electronic control's performance also depends on this clock behavior. Figure 3 shows our complete experimental platform. Figure 4 shows a screenshot of the code in the PIC12F508 program memory. In Figure 3, the voltage probe points labeled $O_1$, $O_2$, $O_3$ and $O_4$. These correspond to the reference signal, the digital comparator response, the RC plant output, and the motor current measurement, respectively. The DC motor is connected to the electronics via a power interface that includes:

- A power transistor;
- A motor current sensor;
- An active RC filter for the sensor's signal.

Consequently, the electronic controller will regulate the current of the DC motor by emulating the RC system required for the Delta-Sigma control scheme. Figures 5 and 6 show the experimental results using the RC plant,

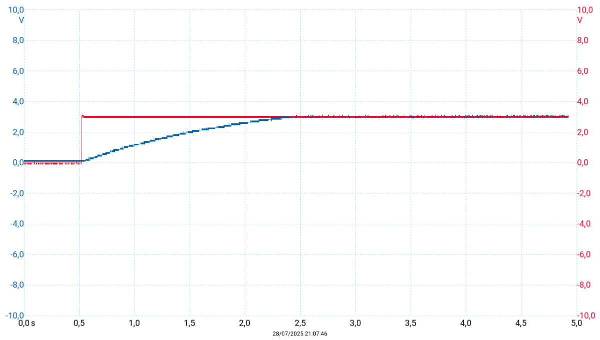


Figure 5. Experimental results: The experimental platform was turned on for about 0.5 s. The red line shows the reference signal $V_in$, and the blue line shows the RC-plant response.

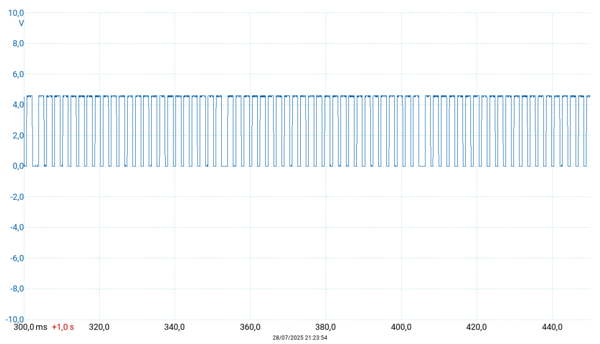


Figure 6. Experimental results for the RC plant: The digital comparator Response.

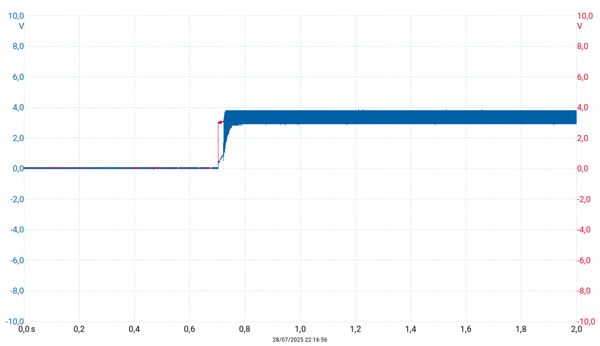


Figure 7. Experimental results: The experimental platform was turned on for about 0.65 s. The red line shows the reference signal $V_in$, and the blue line shows the DC Motor's current response.

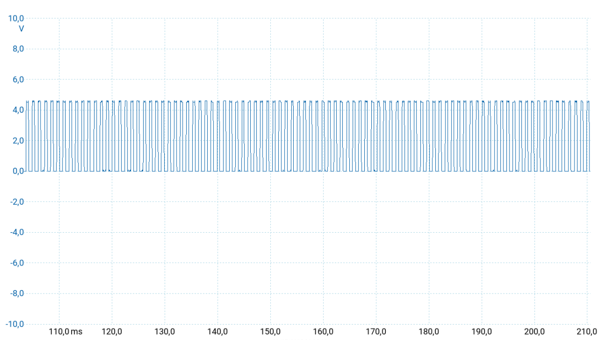
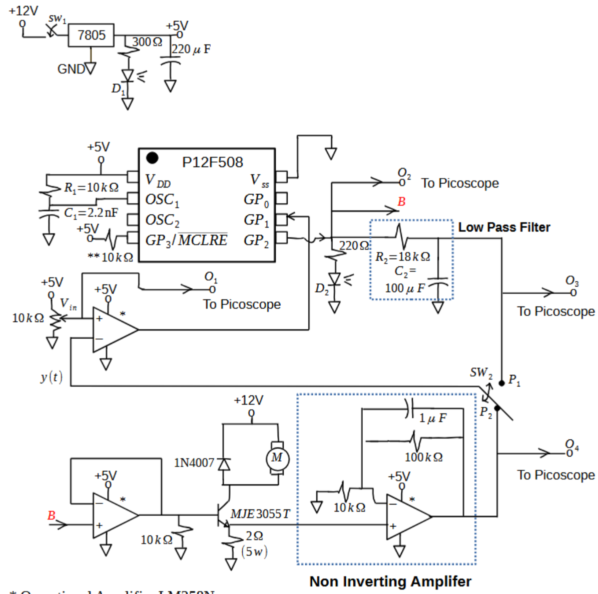
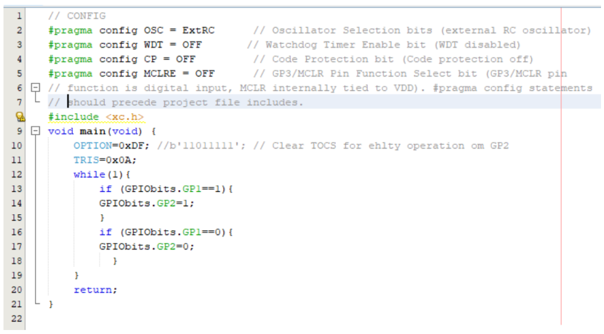


Figure 8. Experimental results for the DC-Motor device: The digital comparator Response.




* Operational Amplifier LM358N.
** A pull-up resistor to programming the microcontroller unit.

Figure 3. Experimental platform. Switch $SW_2$ allows to choice between the RC system and the DC motor. Voltage probe lectures are labeled with $O_1$, $O_2$, $O_3$, and $O_4$.



```c
// CONFIG
#pragma config OSC = ExtRC      // Oscillator Selection bits (external RC oscillator)
#pragma config WDT = OFF       // Watchdog Timer Enable bit (WDT disabled)
#pragma config CP = OFF         // Code Protection bit (Code protection off)
#pragma config MCLRE = OFF      // GP3/MCLR Pin Function Select bit (GP3/MCLR pin
// function is digital input, MCLR internally tied to VDD). #pragma config statements
// should precede project file includes.
#include <xc.h>
void main(void) {
    OPTION=0xDF; //b'11011111'; // Clear TOCS for ehlty operation om GP2
    TRIS=0x0A;
    while(1){
        if (GPIObits.GP1==1){
        GPIObits.GP2=1;
        }
        if (GPIObits.GP1==0){
        GPIObits.GP2=0;
          }
    }
    return;
}
```

Figure 4. Screenshot of the PIC12508 internal code. The code was developed in the microcontroller C language.

while Figures 7 and 8 show the results for the DC motor. A video of the experiment is provided in the link youtu.be/Xn7UlByXIqw. In this video, a potentiometer is used to manipulate the reference command ($V_{in}$). The results were captured using a Pico Technology PicoScope 2000 digital oscilloscope. Therefore, the images are shown exactly as they were produced by the low-cost digital oscilloscope.

By comparing the experimental results of the RC circuit with the DC motor outcomes, we observe that the DC motor response exhibits some switching behavior. This behavior could be caused by factors such as the motor's friction and cogging effects, in addition to its other nonlinearities. Our controller performance is notable because the motor response is below and above the reference signal ($V_{in}$). Finally, we would like to highlight the low-cost realization of our experimental platform.

## 4 Conclusion

We have developed a new, low-cost electronic controller that controls the speed of a dual-shaft worm-gear DC motor. This control architecture may also be applied to any dynamical system with a stable first-order mathematical model. Our low-cost electronic controller design can introduce an affordable experimental platform for teaching engineering mechatronics. As a future project, we plan to apply our control scheme to piezoelectric systems for detecting faults in intelligent composite structures. The stable dynamics provided by this control scheme, among other factors, tailors it for this application. Finally, from a technological standpoint, our electronic system does not employ any analog-to-digital (ADC) or digital-to-analog (DAC) converters. Our 1-bit analog-to-digital converter (ADC) utilizes a single comparator.

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