WIRELESS CONTROL DESIGN FOR DRIVE SYSTEMS USING A PID CONTROLLER COMBINED WITH GENETIC ALGORITHM AND DISTURBANCE OBSERVER

THIẾT KẾ GIẢI PHÁP ĐIỀU KHIỂN KHÔNG DÂY CHO HỆ TRUYỀN ĐỘNG ỨNG DỤNG BỘ ĐIỀU KHIỂN PID KẾT HỢP THUẬT TOÁN DI TRUYỀN VÀ BỘ QUAN SÁT NHIỄU

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Abstract - This paper proposes a secure bidirectional control system for a separately excited DC motor via wireless communication. In this system, the Pulse Width Modulation (PWM) control signal and the speed feedback signal are encoded using two Liu chaotic systems - a master system located at the control station and a slave system at the remote-control area. This encoding enhances security, preventing potential eavesdropping or attacks during data transmission. To enable encoding and decoding using chaotic systems, synchronization between the two chaotic systems with different initial conditions is required; therefore, a Proportional-Integral-Derivative (PID) controller is integrated, combined with a disturbance observer. The optimal PID parameters are obtained using a Genetic Algorithm. The viability and effectiveness of the proposed method are validated through real-world experiments using two ESP32 microcontrollers.

Key words - PID Controller; Genetic Algorithm; Disturbance Observer; Liu Chaotic System; Takagi-Sugeno fuzzy.

Tóm tắt - Bài báo đề xuất một hệ thống điều khiển song phương an toàn thông tin cho động cơ một chiều kích từ độc lập thông qua truyền thông không dây. Trong hệ thống này, tín hiệu điều khiển xung PWM và tín hiệu phản hồi tốc độ được mã hóa bằng hai hệ hỗn loạn Liu - hệ chủ đặt tại trạm điều khiển và hệ tớ đặt tại khu vực điều khiển từ xa. Việc mã hóa giúp tăng tính bảo mật, ngăn chặn các nguy cơ nghe lén hoặc tấn công trong quá trình truyền dữ liệu. Để có thể thực hiện mã hóa và giải mã bằng hệ hỗn loạn, ta cần đạt được tính đồng bộ giữa hai hệ hỗn loạn với các điều kiện khởi đầu khác nhau. Do đó, bộ điều khiển PID được tích hợp, kết hợp với bộ kháng nhiễu. Quá trình tối ưu tham số PID được thực hiện bằng thuật toán di truyền (Genetic Algorithm). Tính khả thi và hiệu quả của phương pháp được xác thực thông qua thí nghiệm thực tế với hai vi điều khiển ESP32.

Từ khóa - Bộ điều khiển PID; Thuật toán di truyền; Bộ quan sát nhiễu; Hệ hỗn loạn Liu; Mô hình mờ Takagi-Sugeno.

1. Introduction

In the era of the Fourth Industrial Revolution, characterized by information and connectivity, an increasing amount of sensitive signals and data are being transmitted and received. The demand for wireless control signal transmission is becoming urgent and finds applications in various fields. It can be utilized for industrial production control, building automation, security systems, and more. Wireless control systems are also applicable in the design of secure wireless control systems for intelligent transportation systems, as presented in [1]. Another application is power control, which can be found in [2] - [4]. One of the most common and versatile techniques for generating control signals is Pulse Width Modulation (PWM). With the development of wireless technology and industrial devices, as control systems continue to evolve, security considerations for these systems are becoming increasingly important. The security issues of control systems are discussed in [5], where a real-time secure communication system between two wireless devices is implemented through the application of secure communication control. The implementation of chaotic systems in secure wireless communication is presented in [6], in which the Takagi-Sugeno fuzzy (TSF) model is used to transform a chaotic system in the discrete-time domain into a fuzzy model. The foundation of the nonlinear approach, used in this paper to convert the original system into a fuzzy format, can be found in [7]. The use of the TSF model in secure communication systems can be found in [8] - [12], and its applications in control system design can be found in [13] - [15]. The purpose of using the TSF model is to simplify the computation and controller design process. After collecting and transforming the states of the master and slave systems into the fuzzy format, an optimal PID controller using a Genetic Algorithm (GA) and a Disturbance Observer (DOB) are designed to synchronize the master and slave systems, while minimizing the impact of disturbances affecting the system.

The Proportional-Integral-Derivative (PID) controller is employed due to its simplicity and flexibility. The basic model of the PID controller is presented in [16]. The main drawback of the PID controller lies in the difficulty of selecting the PID parameters, which can be overcome by implementing a Genetic Algorithm. The GA is an ideal solution for PID controllers and is inspired by the work in [17], with the fundamental theory of this method detailed in [18]. The GA optimizes the PID controller based on the selection process over multiple generations according to a fitness value. The PID controller with GA can now be reliably used to achieve high performance in controlling the master and slave systems.

Here, disturbances caused by channel attacks and interpolation changes are considered as being embedded in the slave side. The DOB in this study aims to compensate for disturbances and their first derivatives, as investigated in previous studies [19] - [22]. The DOB in this research is designed to effectively handle a wide range of disturbance complexities. Therefore, the proposed system aims to achieve optimal performance in synchronization and decoding.

This paper is inspired by previous studies on secure communication systems in wireless devices, which did not consider disturbances. To the best of the authors' knowledge, research related to the optimization of PID controllers using Genetic Algorithms (GA) for the synchronization of chaotic systems, as well as the analysis of disturbance effects and the design of disturbance observers, remains limited and has not been comprehensively or systematically presented. Therefore, the design of secure control in wireless communication proposed in this paper is both necessary and novel.

2. Mathematical foundations and modeling

In this section, the models of the master and slave systems are transformed into the Takagi-Sugeno fuzzy (TSF) form, and the fundamental basis of the proposed disturbance observer is presented.

First, the TSF fuzzy model used in this paper is adopted from [7].

Next, using the discrete-time calculation method from [23], the first-order differential equation of a system in the continuous-time domain:

$$\dot{y}(t) = f(t) \tag{1}$$

Can be transformed into the discrete-time domain as follows:

$$y(t_{k+1}) = y(t_k) + hf(t_k) \tag{2}$$

where h is the discrete time step of the system.

2.1. Model of the master and slave systems

The Liu chaotic system used in this paper is taken from [24] and is represented in the continuous-time domain as follows:

$$\begin{cases} \dfrac{dx}{dt} = -ax(t) + by(t) \\ \dfrac{dy}{dt} = -ex(t)z(t) \\ \dfrac{dz}{dt} = cex(t)^2 + ex(t)y(t) - \dfrac{d}{e} \end{cases} \tag{3}$$

With $a = 1, b = 2, c = 1, d = 3, e = 2$, system (3) can be expressed in the discrete-time domain using transformation (2):

$$\begin{aligned} x(t_{k+1}) &= x(t_k) + h \times \left[-ax(t_k) + by(t_k)\right] \\ y(t_{k+1}) &= y(t_k) + h \times \left[-ex(t_k)z(t_k)\right] \\ z(t_{k+1}) &= z(t_k) + h \times \left[cex(t_k)^2 + ex(t_k)y(t_k) - \frac{d}{e}\right] \end{aligned} \tag{4}$$

The Lyapunov exponent method is used to prove the chaotic property of the system after transformation from the continuous-time domain to the discrete-time domain, following the approach in [25]. Equation (4) is rewritten as equation (5) as follows:

$$\chi(t_{k+1}) = \sum_{i=1}^{2} \omega_i \left\{\chi(t_k)\right\} hA_i \chi(t_k) + H(t_k) \tag{5}$$

where $\chi(t_{k+1}) = \left[x(t_{k+1}) \quad y(t_{k+1}) \quad z(t_{k+1})\right]^T$ is the state vector of the system.

The weighting function $\omega_i \left\{\chi(t_k)\right\}$ in equation (5) is calculated as follows:

For the x-axis:

$$\begin{cases} \omega_1 \left\{\chi(t_k)\right\}_x = \dfrac{x_{\max} - x(t_k)}{x_{\max} - x_{\min}} \\ \omega_2 \left\{\chi(t_k)\right\}_x = 1 - \omega_1 \left\{\chi(t_k)\right\}_x = \dfrac{x(t_k) - x_{\min}}{x_{\max} - x_{\min}} \end{cases} \tag{6}$$

Similarly, for the y and z axes, with $x(t_k), y(t_k), z(t_k)$ satisfying: $x(t_k) \in \left[x_{\min}, x_{\max}\right]$, $y(t_k) \in \left[y_{\min}, y_{\max}\right]$, $z(t_k) \in \left[z_{\min}, z_{\max}\right]$.

The fuzzy input matrix $A_i \in R^{3\times3}$ for the x-axis is calculated as:

$$\begin{aligned} A_1 &= \begin{bmatrix} -a & b & 0 \\ 0 & 0 & -ex_{\min} \\ cex_{\min} & ex_{\min} & 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -d/(z \times e) \end{bmatrix}; \\ A_2 &= \begin{bmatrix} -a & b & 0 \\ 0 & 0 & -ex_{\max} \\ cex_{\max} & ex_{\max} & 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -d/(z \times e) \end{bmatrix} \end{aligned} \tag{7}$$

The matrices $A_i \in R^{3\times3}$ for the y and Z axes are defined similarly.

The matrix $H(t_k) \in R^{3\times1}$ is the previous state vector of the system, with: $H(t_k) = \begin{bmatrix} x(t_k) \\ y(t_k) \\ z(t_k) \end{bmatrix}$.

With the values a, b, c, d, e, $x_{\min} = -100$, $x_{\max} = 100$, and similarly for the y and z axes, using the transformation from equations (4) and (5), the state of the master system can be calculated as follows:

$$\chi_m(t_{k+1}) = \sum_{i=1}^{2} \begin{bmatrix} \omega_{mi} \left\{\chi_m(t_k)\right\} hA_i \chi_m(t_k) \\ + H_m(t_k) + Dd_m(t_k) \end{bmatrix} \tag{8}$$

where $d_m(t_k) = \left[d_{mx}(t_k) \quad d_{my}(t_k) \quad d_{mz}(t_k)\right]^T$ is the disturbance variable of the master system, and D is the identity matrix 3×3.

Assumption 1 must be satisfied for the system to operate stably.

Assumption 1: The disturbance variable for each axis of the master system must satisfy $|d_{m\text{x}}(t_k)| \le \tau_{\text{x}}, |d_{my}(t_k)| \le \tau_y$, and $|d_{mz}(t_k)| \le \tau_z$. Where τ_x, τ_y, and τ_z are given positive constants.

Similarly, for system (4) with full consideration of disturbances and uncertainties in the state parameters of the slave system, using the transformation from equation (5), the state of the slave system can be written as:

$$\chi_s(t_{k+1}) = \sum_{i=1}^{2} \begin{matrix} [\omega_{si}\{\chi_s(t_k)\} hA_i \chi_s(t_k) \\ +H_s(t_k) + Dd_s(t_k) + Bu(t_k)] \end{matrix} \quad (9)$$

where $d_s(t_k) = \begin{bmatrix} d_{sx}(t_k) & d_{sy}(t_k) & d_{sz}(t_k) \end{bmatrix}^T$ is the disturbance variable, $u(t_k) = \begin{bmatrix} u_x(t_k) & u_y(t_k) & u_z(t_k) \end{bmatrix}^T$ is the control signal for each axis of the slave system, and D, B is the identity matrix 3×3.

Assumption 2 must also be satisfied for the system to operate stably.

Assumption 2: The disturbance variable for each axis of the slave system must satisfy:

$$|d_{\text{sx}}(t_k)| \le \gamma_{\text{x}}, |d_{sy}(t_k)| \le \gamma_y \text{ and } |d_{sz}(t_k)| \le \gamma_z.$$

where γ_x, γ_y and γ_z are given positive constants.

2.2. Controller design and Genetic Algorithm (GA)

To achieve the objective of designing an optimal PID controller using the GA algorithm and implementing the DOB, the error on each axis and certain disturbance concepts are defined as follows:

$$\begin{cases} e_x(t_{k+1}) = x_m(t_{k+1}) - x_s(t_{k+1}) \\ e_y(t_{k+1}) = y_m(t_{k+1}) - y_s(t_{k+1}) \\ e_z(t_{k+1}) = z_m(t_{k+1}) - z_s(t_{k+1}) \end{cases} \quad (10)$$

This can be rewritten using equations (7), (9), and assigning $Dd_m(t_k) - Dd_s(t_k) = D\bar{d}(t_k)$ as follows:

$$\begin{aligned} e(t_{k+1}) &= \chi_m(t_{k+1}) - \chi_s(t_{k+1}) \\ &= \left[\begin{matrix} \sum_{i=1}^{2} [\omega_{mi}\{\chi_m(t_k)\} hA_i \chi_m(t_k) \\ +H_m(t_k)] \end{matrix} \right] \\ &\quad - \left[\begin{matrix} \sum_{i=1}^{2} [\omega_{si}\{\chi_s(t_k)\} hA_i \chi_s(t_k) \\ +H_s(t_k) + Bu(t_k)] \end{matrix} \right] + D\bar{d}(t_k) \end{aligned} \quad (11)$$

2.2.1. PID Controller Design

With the basic design of the PID controller, the control signal can be written in the continuous-time domain as follows:

$$\begin{aligned} u(t) &= u_P(t) + u_I(t) + u_D(t) \\ &= K_P e(t) + K_I \int_0^t e(\Gamma) d\Gamma + K_D \frac{de(t)}{dt} \end{aligned} \quad (12)$$

where $u_P(t), u_I(t)$ and $u_D(t)$ are the component control functions of the PID controller, and K_P, K_I, K_D are the proportional, integral, and derivative gains of the PID controller, respectively.

Using the backward difference method for the discrete transformation of equation (12), the control signal in the discrete-time domain can be calculated as follows:

$$\begin{aligned} u(t_k) &= u_P(t_k) + u_I(t_k) + u_D(t_k) \\ &= K_p e(t_k) + K_I \sum_{j=0}^{k} e(t_j) h + K_D \frac{e(t_k) - e(t_{k-1})}{h} \end{aligned} \quad (13)$$

In the calculation of the PID controller, we need to approach the system at a steady state. This means that we must eliminate the impact of disturbances, i.e. $D\bar{d}(t_{k-1}) = 0$.

Considering (11) with $D\bar{d}(t_{k-1}) = 0$, $H_m(t_k)$ and $H_s(t_k)$ as the previous states of the master and slave systems, the integral component function $u_D(t_k)$ can be rewritten as:

$$\begin{aligned} u_D(t_k) &= K_D \left[\sum_{i=1}^{2} \omega_{mi}\{\chi_m(t_{k-1})\} A_i \chi_m(t_{k-1}) \right] \\ &\quad - K_D \left[\begin{matrix} \sum_{i=1}^{2} [\omega_{si}\{\chi_s(t_{k-1})\} A_i \chi_s(t_{k-1}) \\ +Bu(t_{k-1})] \end{matrix} \right] \end{aligned} \quad (14)$$

Note that the integral component function can be rewritten as $u_I(t_k) = u_I(t_{k-1}) + K_I e(t_k) h$, so equation (13) can be recalculated as follows:

$$\begin{aligned} u(t_k) &= K_p e(t_k) + u_I(t_{k-1}) + K_I e(t_k) h \\ &\quad + K_D [\dot{\chi}_m(t_k) - \dot{\chi}_s(t_k)] \end{aligned} \quad (15)$$

From this, the calculation of the control signal can be achieved based on the error and the control signal at the previous time step.

2.2.2. Genetic Algorithm for PID controller

In this section, the GA is integrated into the slave system controller to optimize the PID control method by finding suitable PID component parameters to accurately synchronize the system. The general GA algorithm can be found in [18].

In this paper, the genetic algorithm (GA) is designed to optimize the control method while being suitable for lightweight microcontrollers with limited computational capacity. Therefore, the GA is constructed with moderate accuracy and complexity, sufficient to ensure effectiveness and compatible with the feedback control method in motor control applications.

The following GA will iterate for a certain number of generations, with each iteration the slave system receives the encoded master signal. This algorithm will evaluate and find the most suitable PID parameter set for accurate synchronization control, after which the slave system can decode and receive the original signal. An overview of this algorithm is illustrated in Figure 1.

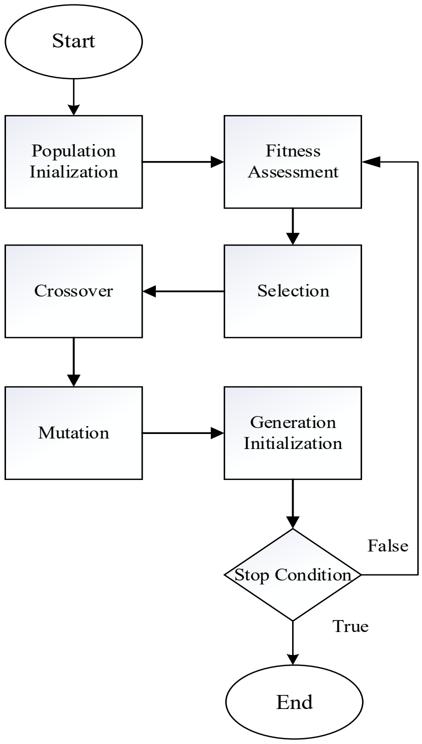


Figure 1. *General block diagram overview of the algorithm*

a. Initialization of the Population

The main purpose of this step is to encode the PID component parameters into a chromosome string, thereby generating a population of potential solutions for the GA to process. The role of the chromosome is to serve as a data structure representing a feasible solution to the problem.

In this paper, binary encoding is used to encode the individuals in the population. Three populations are created with 100 individuals each, for each PID parameter, where each individual of the three populations is represented as a potential parameter in binary form.

The number of chromosome segments per individual is calculated based on the requirements of the problem, and in this paper, the authors choose 20 as the number of segments per chromosome, corresponding to 20 binary bits in the encoding.

b. Fitness evaluation function

The binary populations are then converted to decimal populations to calculate the fitness evaluation using the following conversion formula:

$$K = \frac{(a_1 a_2 \dots a_{20})_{10}}{10000} \tag{16}$$

Where K is the decimal result of an individual, $(a_1 a_2 \dots a_{20})_{10}$ is the decimal form of the original 20-bit binary number $a_1 a_2 \dots a_{20}$.

A new population is then created using the previous three populations, corresponding to indices from 1 to 100, where each individual with a certain index from the three populations together forms a group of three individuals, representing a complete parameter set for the PID controller.

Each individual in the new population is then evaluated by calculating the fitness value based on the error between the master and slave systems when using this parameter set. The fitness value represents the suitability of the individual. The error between the two state vectors of the master and slave systems is calculated using the L_1 norm (Manhattan norm) as follows:

$$\begin{cases} \|e_{fit}\|_1 = |x_m - x_{s\_GA}| + |y_m - y_{s\_GA}| + |z_m - z_{s\_GA}| \\ f = \dfrac{1}{\|e_{fit}\|_1} \end{cases} \tag{17}$$

Where e_{fit} is the error between the master and slave systems, calculated based on (11). x_m, y_m and z_m are the states of the master system. x_{s_GA}, y_{s_GA} and z_{s_GA} are the states of the slave system when using the controller with the parameter set under consideration for an individual. f is the fitness value of the individual.

It is evident that the higher the value of f the better the fitness of the individual.

c. Selection

After each individual in the current generation has its own fitness value, the selection and crossover steps are performed to create the new generation of the population. There are many selection methods, but in this paper, we use the roulette wheel selection method, as the fitness values are not significantly different and there is still a chance for individuals with lower fitness values.

This step selects two individuals for the crossover step using the following mechanism. First, the total fitness value of the population is assigned in the form of a roulette wheel. Each individual occupies a segment of the population wheel, and its area on the wheel is proportional to its fitness value. The probability of an individual being selected is calculated as follows:

$$P_i = \frac{f_i}{\sum_{j=1}^{100} f_j} \tag{18}$$

where P_i is the selection probability of an individual with fitness f_i.

Next, spinning the wheel to select a value can be simulated as follows. Initially, a random number is chosen within the range $[0,1]$, representing a certain point on the wheel. Then, the population is traversed by adding the probability of the current individual to the total fitness value, and as soon as the total equals or exceeds the value P_i, the latest individual is selected as the subject for the crossover process.

Each time crossover is performed, this step is repeated twice to select a pair of individuals, which are then converted back to binary chromosome form for the crossover step.

d. Crossover

After obtaining a pair of chromosomes, the crossover process is performed. There are many methods for crossover, but in this paper, one-point crossover is selected due to its simplicity and the requirements of the problem. The new pair of chromosomes in the new population is created by swapping two parts of the two individuals in binary chromosome form, generated by splitting the chromosome at a randomly selected point along its length.

The selection and crossover steps continue until a specific number of individuals in the new generation is created, in this case, 50. The 50 individuals with the lowest fitness values in the previous generation will be replaced by the newly created individuals in this process, while the remainder remain unchanged from the previous generation.

e. Mutation

When a new generation is created, mutation is performed to maintain the diversity of the population and avoid local extrema in the search space. In other words, this operation is essential to prevent the entire population from converging to a single individual's chromosome, as crossover becomes ineffective in such situations.

In this algorithm, we use one-point mutation, flipping the value of one bit and introducing new genetic material into the chromosome pool, with a so-called 'Mutation Rate' of 0.03.

After a certain number of generations are created, the individual with the highest fitness value in the final generation will be selected for the actual PID controller.

2.3. Disturbance Observer (DOB)

The general overview of the adaptive DOB used in this paper is based on [25]. Using equations (9) and (11), the disturbances in the master and slave systems caused by signal attacks on public channels can be calculated as follows:

$$\begin{aligned} Dd_m(t_k) &= \chi_m(t_{k+1}) - \begin{bmatrix} \sum_{i=1}^{2} \omega_{mi}\{\chi_m(t_k)\} hA_i \chi_m(t_k) \\ +H_m(t_k) \end{bmatrix} \\ Dd_s(t_k) &= \chi_s(t_{k+1}) - \begin{bmatrix} \sum_{i=1}^{2} \omega_{si}\{\chi_s(t_k)\} hA_i \chi_s(t_k) \\ +H_s(t_k) + D\tilde{d}_s(t_k) + Bu(t_k) \end{bmatrix} \end{aligned} \tag{19}$$

where $\tilde{d}_s(t_k)$ is the value estimated by the DOB observer.

To estimate the disturbances and uncertainties of the system, we consider the system in a synchronized state, i.e. $\chi_m(t_{k+1}) = \chi_s(t_{k+1})$.

Together with the assignment $D\bar{d}(t_k) = Dd_m(t_k) - Dd_s(t_k)$, equation (19) can be rewritten as:

$$\begin{aligned} D\bar{d}(t_k) &= \begin{bmatrix} \sum_{i=1}^{2} \omega_{si}\{\chi_s(t_k)\} hA_i \chi_s(t_k) \\ +H_s(t_k) + D\tilde{d}_s(t_k) + Bu(t_k) \end{bmatrix} \\ &- \begin{bmatrix} \sum_{i=1}^{2} \omega_{mi}\{\chi_m(t_k)\} hA_i \chi_m(t_k) \\ +H_m(t_k) \end{bmatrix} \end{aligned} \tag{20}$$

Also, by assigning $D\hat{d}(t_k) = D\bar{d}(t_k) - D\tilde{d}_s(t_k)$ as the error between the actual disturbance and the value estimated by the adaptive disturbance observer, equation (20) can be written as:

$$\begin{aligned} D\hat{d}(t_k) &= \begin{bmatrix} \sum_{i=1}^{2} \omega_{si}\{\chi_s(t_k)\} hA_i \chi_s(t_k) \\ +H_s(t_k) + Bu(t_k) \end{bmatrix} \\ &- \begin{bmatrix} \sum_{i=1}^{2} \omega_{mi}\{\chi_m(t_k)\} hA_i \chi_m(t_k) \\ +H_m(t_k) \end{bmatrix} \end{aligned} \tag{21}$$

Then, the adaptive DOB in this paper is estimated by the following formula:

$$\begin{aligned} &\tilde{d}(t_k) = \bar{d}(t_k) + \hat{k}_D \hat{d}(t_{k-1}) \\ &\Leftrightarrow \hat{d}(t_k) = -\hat{k}_D \hat{d}(t_{k-1}) \end{aligned} \tag{22}$$

where, $\hat{k}_D$ is the compensation gain of the disturbance observer, calculated for each axis by the following formula:

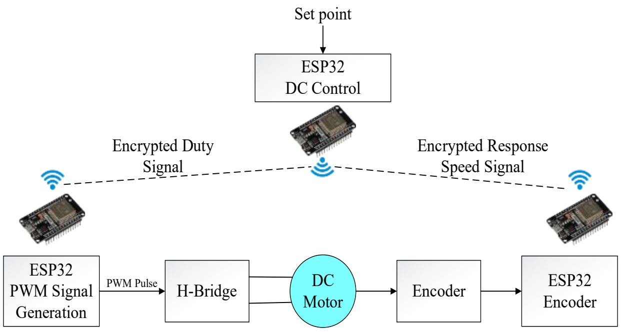
$$\begin{cases} \hat{k}_{Dx} = k_{Dx} \left| \hat{d}_x(t_{k-1}) \right| \\ \hat{k}_{Dy} = k_{Dy} \left| \hat{d}_y(t_{k-1}) \right| \\ \hat{k}_{Dz} = k_{Dz} \left| \hat{d}_z(t_{k-1}) \right| \end{cases} \tag{23}$$

with k_{Dx}, k_{Dy} and k_{Dz} being the compensation gains of the DOB for each axis.

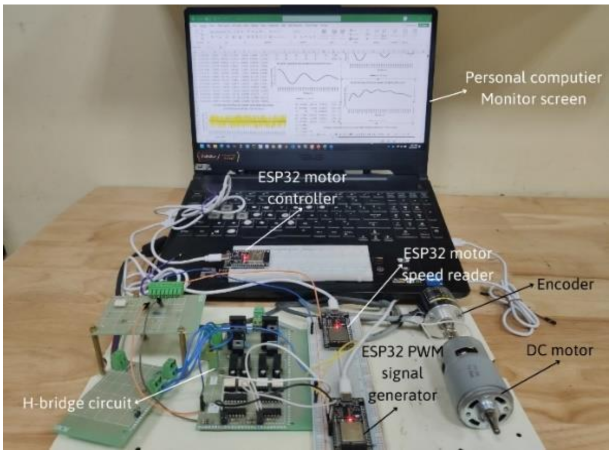
3. Experiment and results

In this section, a practical experiment is conducted to demonstrate the effectiveness of the proposed method in securing signals.

The experimental study utilized a DC motor and three ESP32 WIFI microcontrollers to conduct an experiment demonstrating the strength of this method. The detailed specifications of the DC motor in the experiment are: $U_{dm} = 24V, I_0 \approx 1.5V, P_{\max} = 200W$ and $\omega_0 = 12000\text{r}pm$. The detailed specifications of the encoder are: $V_s = 5 - 24V$, $N = 1000(p/r)$ and $\omega_{\max} = 5000\text{r}pm$. The block diagram of the algorithm is shown in Figure 2a, describing the designed communication system used in the experiment. The actual setup of the experiment is shown in Figure 2b.

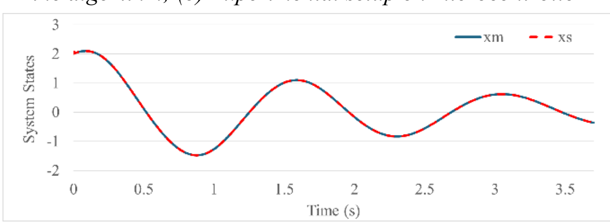


(a) Block diagram of the algorithm

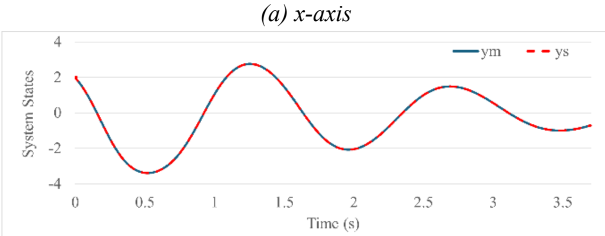


(b) Experimental setup

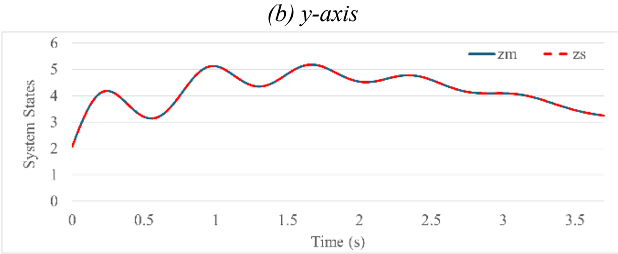
Figure 2. *Motor control system: (a) Block diagram of the algorithm; (b) Experimental setup on microcontroller*



(a) x-axis

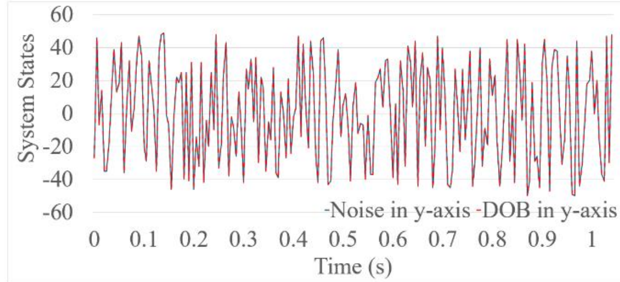


(b) y-axis

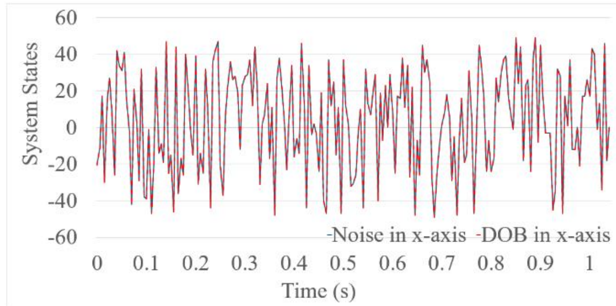


(c) z-axis

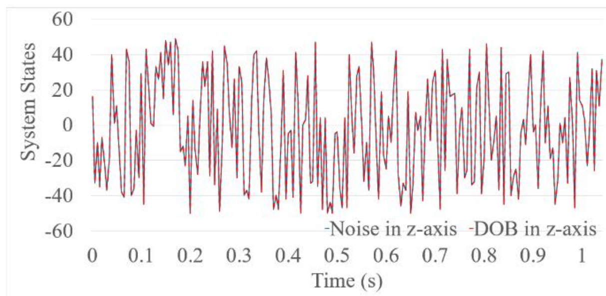
Figure 3. *Comparison of the master and slave states after synchronization and decryption*



(a) x-axis



(b) y-axis



(c) z-axis

Figure 4. *Comparison of disturbance and disturbance compensation in the first 1 second of the system*

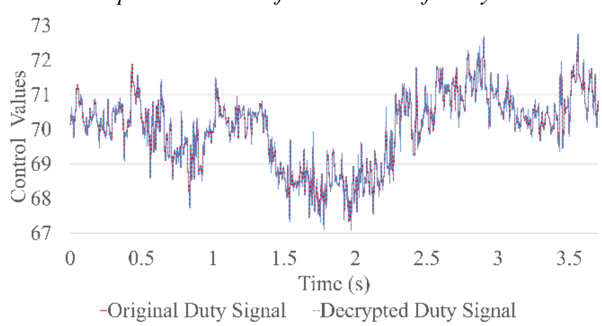


Figure 5. *Comparison between the original duty signal and the decrypted duty signal*

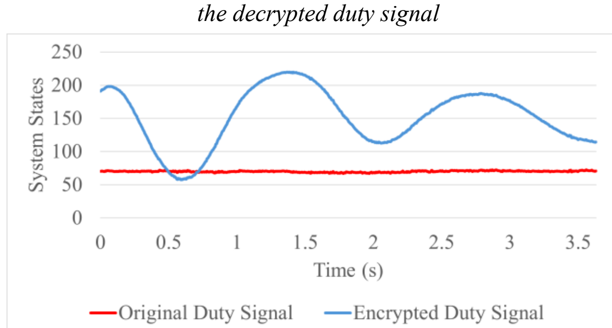


Figure 6. *Comparison between the original duty signal and the encrypted duty signal*

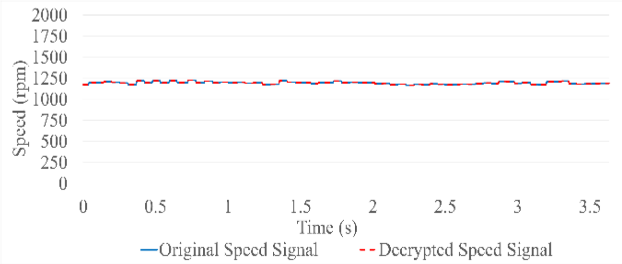


Figure 7. *Comparison between the original speed signal and the decrypted speed signal on the slave side*

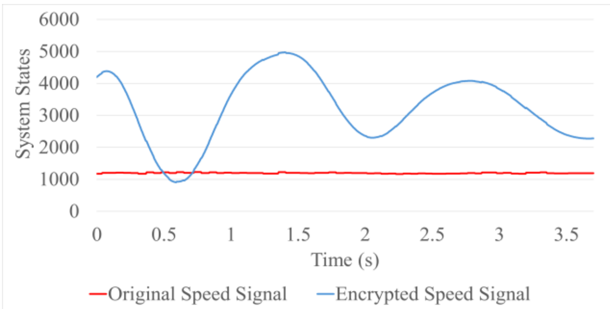


Figure 8. *Comparison between the original speed signal and the encrypted speed signal*

In this experiment, the communication system uses two master and slave chaotic system models, with different initial conditions, to encode bidirectional data, including the speed feedback signal to the motor controller and the duty control signal sent to the motor. The ESP32 measuring speed (Encoder) (A) reads the measured motor speed, uses master chaotic system 1 to encode and send via ESP-Now wireless protocol to the motor control ESP32 (B). At ESP32 B, the speed feedback signal is decoded based on synchronization between master and slave system 1, and an appropriate duty control signal is generated. This duty signal is then encoded with master chaotic system 2 and sent to ESP32 PWM pulse generator (C). ESP32 C receives the encoded signal, decodes it by synchronizing slave and master system 2, and removes disturbances using the proposed DOB in slave system 2. The decoded duty signal is then used to generate PWM pulses to control the DC motor.

The communication runtime of the experiment is $3.65s$ with a discrete time step of $h = 0.005s$. The initial values of the two systems are $(x_m, y_m, z_m) = (2;2;2)$ and $(x_s, y_s, z_s) = (0;0;0)$. The two pairs of master and slave chaotic systems synchronize after 0.02s, immediately after which the control and speed signals are added to the three state axes of the master chaotic system. On the slave side, the received signal is decoded based on synchronization with the master system using a PID controller combined with the GA algorithm. The crossover rate and mutation rate of the GA are set at 0.5 and 0.03, respectively. The DOB in the slave system also simultaneously compensates for disturbances. The initial compensation gain of the DOB is $(k_{dx}, k_{dy}, k_{dz}) = (0.1;0.1;0.1)$. With the above parameters, the experimental results were recorded via the Data Streamer extension in Microsoft Excel and illustrated from Figure 3 to Figure 8.

In Figure 3, the states of the master and slave systems are described, where the state of the slave system synchronizes with the master system in less than 0.003 seconds. The error between the master and slave systems quickly decreases to approximately zero and remains below 1×10^{-6}. In Figures 5 and 7, a comparison between the transmitted duty and speed data signals and the corresponding decoded signals received at the slave side can be seen. The error of the received signals fluctuates within the range $[-0.001, 0.001]$. In Figures 6 and 8, a comparison between the original duty and speed signals and those after being encoded with the chaotic system is also shown.

Disturbances on each axis were added within the range $[-50, 50]$. When the slave receives a disturbed signal, the adaptive DOB performs its role by eliminating disturbances on each axis. Figure 4 shows the comparison between the disturbance and the adaptive compensation in the first second. As can be seen in the two figures, the adaptive DOB quickly captures and synchronizes with the disturbance in less than 0.005 seconds. The attacks tested on all three axes were mostly eliminated by the proposed DOB.

4. Conclusion

This paper presents a novel approach for securing bidirectional signals in wireless control communication systems. The security of communication signals between microcontrollers is based on the synchronization control of two chaotic systems with different initial values. Specifically, the paper utilizes two master and slave chaotic systems to transmit control signals securely. The PID controller used to synchronize the two master and slave chaotic systems is optimized using a genetic algorithm (GA), which is implemented to minimize the synchronization error between the two chaotic systems. Once the two systems are synchronized, the data is encoded and can be easily and accurately decoded by the slave system. Due to their unpredictability and complexity, chaotic systems can generate dynamic keys, making security stable and robust. Furthermore, an adaptive disturbance observer (DOB) is integrated to compensate for disturbances and parameter uncertainties, thereby significantly improving the security and wireless decoding performance. This experimental study provides valuable insights into the method of securing two-way signals for wireless communication systems in remote machinery and equipment control. Future research may explore new signal security applications with secure communication on microcontrollers.

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