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Design and Implementation of a Chaotic Acoustic Generator for Agricultural Field Protection

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Abstract: Crop production plays a vital role in human survival and is a key driver of the economies of many developing countries. It ensures the supply of staple foods worldwide and represents a major source of income and livelihood for a large portion of the global population. However, this sector remains highly vulnerable to pest attacks, which lead to yield losses and significant economic impacts. Despite the use of various sound-based deterrent systems, their effectiveness remains limited. This limitation is largely due to the periodic nature of the emitted signals. Moreover, animals gradually adapt to repetitive sounds and eventually stop responding to them. In this context, the present study introduces the design of an aperiodic sound generator intended to repel pests from cultivated fields. The proposed system is based on a microcontroller equipped with an analog output, capable of generating a non-periodic electrical signal derived from the implementation of a chaotic dynamical system using the Runge-Kutta numerical method. The generated signal is then amplified and converted into sound waves through a loudspeaker. The analysis of its temporal evolution highlights its non-repetitive nature, thereby confirming its unpredictability. Experimental results show that the device has a deterrent effect on certain pests, particularly weevils as well as poultry

Keywords: Chaotic sounds, deterrent device, microcontroller, Runge-Kutta.

INTRODUCTION

Agricultural production plays a fundamental role in global food security and represents a vital source of income for millions of people. It is also a key pillar of economic development in many countries, particularly those with a high dependence on agriculture. Therefore, crop protection remains a major challenge to ensure the stability of food systems. However, agricultural crops are constantly exposed to pest attacks, which have been a major constraint since the beginning of farming. These harmful organisms cause significant yield losses and affect the quality of agricultural products. According to estimates from the Food and Agriculture Organization of the United Nations (FAO), pest-related losses can reach 20 to 40% of global agricultural production each year, representing a considerable economic burden for farmers [1]. To combat these threats, various protection methods have been developed, including physical and behavioral devices such as bird nets and visual scare devices. However, these techniques present important limitations, particularly their dependence on environmental conditions and the gradual habituation of animals to repeated stimuli, which reduces their long-term [2]. Furthermore, the use of pesticides remains one of the main approaches for pest control. Although these products can effectively reduce infestations, their prolonged use may negatively affect food quality and human health, reinforcing the need to develop more sustainable and environmentally friendly alternatives [3].

Sound-generating devices are currently used as technological tools in certain agricultural applications, particularly for crop protection. Their relevance lies in their ability to reduce losses caused by pests while minimizing the impact on agricultural product quality. Owing to their relatively simple design and adaptability, these systems represent a potentially accessible solution for farmers. In recent years, non-lethal deterrent technologies based on acoustic stimuli have attracted increasing interest in crop protection. Acoustic systems are considered more environmentally friendly alternatives compared to conventional chemical methods. Several studies have shown that sound signals can influence animal behavior and reduce crop damage, although their effectiveness strongly depends on the targeted species and operating conditions [4-5]. In this context, acoustic devices appear as a complementary approach to conventional pest control methods, particularly in the context of reducing pesticide use and promoting more sustainable agricultural practices [1,6]. Sound emitters based on the NE555 circuit are widely used in various deterrent systems aimed at repelling crop pests [7-9]. In addition, other acoustic devices, typically powered by a direct current source and operating as sirens, are also employed in agricultural environments to reduce damage caused by pests [10-13]. Other approaches make use of audio players broadcasting pre-recorded sounds directly in the fields to repel animals [14-16].

It has been observed that animals quickly become accustomed to periodic or repetitive sounds, eventually ceasing to respond to them [17]. In most deterrent systems, the generated acoustic signals are inherently periodic. Other systems, particularly those based on audio players, continuously broadcast the same audio sequence. The objective of this study is to propose a deterrent device characterized by temporal acoustic unpredictability based on microprocessor technology. Section 2 describes the materials and methodology adopted in this study. Section 3 presents the obtained results, while the final section is devoted to discussion and conclusions.

MATERIALS AND METHODS

In this section, we present the components and methods used to develop the prototype. Section 2.1 describes the dynamical system of equations used to generate unpredictable signals. Section 2.2 outlines the hardware architecture of the proposed deterrent device. Section 2.3 focuses on the design of the software architecture embedded in the microcontroller. Finally, Section 2.4 details the oscilloscope used for the time-domain visualization of the signals.

Presentation of the Chaotic System Used

Chaotic systems are deterministic nonlinear dynamical systems that exhibit high sensitivity to initial conditions, leading to long-term aperiodic and unpredictable behavior. Although governed by well-defined mathematical equations, these systems generate complex trajectories that may appear pseudo-random [18-19]. This property is widely exploited in the generation of complex signals and various engineering applications. In this work, a continuous chaotic system is employed to generate non-periodic signals for acoustic deterrence applications. Chaotic systems are generally described by nonlinear differential equations, whose numerical solutions can be obtained using integration methods such as the fourth-order Runge–Kutta method, which provides stable and accurate approximations of time trajectories [20]. Chaotic behavior is characterized by strange attractors and a strong dependence on initial conditions, as demonstrated in the pioneering works of Lorenz [21] and Rössler [22]. These properties make chaotic systems particularly suitable for generating unpredictable signals used in fields such as telecommunications, cryptography, and signal processing [23]. In this context, the implemented chaotic system enables the generation of a non-repetitive time signal, which serves as the basis for the acoustic deterrent signal. Equation (1) corresponds to the discrete dynamical system implemented in the microcontroller in algorithmic form to produce aperiodic signals. The numerical method implemented is the fourth-order Runge–Kutta scheme. The generated signal x_4 is then transmitted through the I2C output interface of the microcontroller.

$$\begin{cases} \dot{x}_1 = x_3, \\ \dot{x}_2 = \varepsilon_1 x_4, \\ \dot{x}_3 = \alpha(x_3 - x_4) - x_1 - \sin(x_5), \\ \dot{x}_4 = \varepsilon_2 \left(\sin(x_5) + \alpha(x_4 - x_3) - x_2\right), \\ \dot{x}_5 = \omega_0(x_3 - x_4), \end{cases} \tag{1}$$

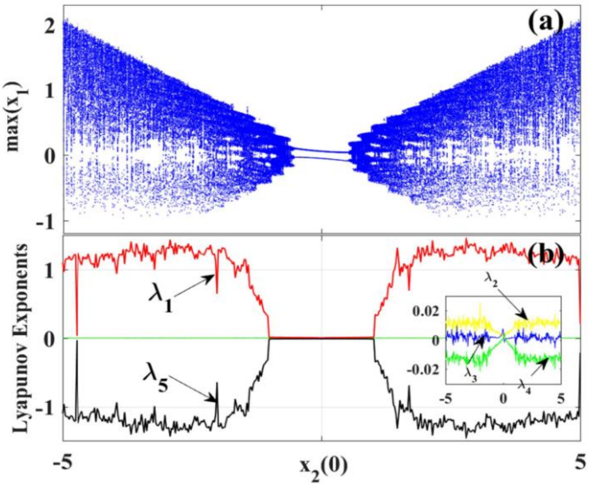

Figure 1: Bifurcation diagram (a) and Lyapunov spectra (b) [24]

The analysis and validation of the chaotic system were carried out by the authors [24] through the study of the bifurcation diagram and the Lyapunov exponent spectrum. Figs. 1a and 1b illustrate, respectively, the bifurcation diagram and the Lyapunov spectrum associated with System (1).

Deterrent Design Architecture

Fig. 2 presents the overall architecture of the proposed sound generator. It consists of a voltage power supply, a microcontroller, a digital-to-analog converter, a signal amplifier, and a loudspeaker.

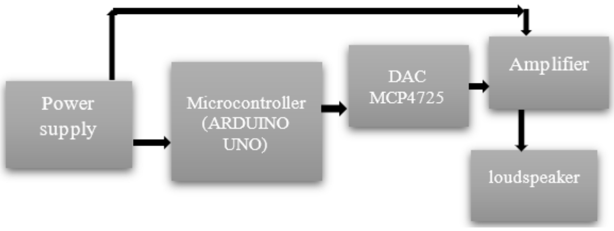

Figure 2: Functional block diagram of the aperiodic sound generator

Microcontroller

In this study, the Arduino Uno (See fig. 3) development platform was used as the central control unit of the system. This board is based on the ATmega328P microcontroller and is widely adopted in embedded systems due to its ease of integration and reliability. The board operates at a clock frequency of 16 MHz. It also supports the I2C communication protocol, facilitating interfacing with the MCP4725 module. Within this methodological framework, the Arduino Uno was programmed to generate the digital signal x_4 derived from the implemented dynamical system. This signal is transmitted to the MCP4725 module via the I2C interface, before being forwarded to the signal amplification stage of the sound system. The use of this platform thus enables a simple and efficient implementation of aperiodic signal generation algorithms.

Figure 3: Arduino Uno

Battery

The sound generation system is powered by a 12 V DC voltage source. This power supply is used both for the amplification circuit and for powering the Arduino Uno board through the Vin pin.

MCP4725 Module

In this study, an external digital-to-analog converter (DAC) of type MCP4725 (see fig. 4) was used to convert the digital signals generated by the microcontroller into continuous analog signals. This module, based on a 12-bit resolution, communicates via the I2C protocol, enabling simple integration with the embedded system while minimizing hardware resource usage.

Figure 4: MCP4725 module

The MCP4725 operates with a supply voltage ranging from 2.7 V to 5.5 V and provides an output voltage proportional to the input digital value. In this study, it is used to accurately reconstruct the aperiodic signals generated by the dynamical system implemented in the microcontroller.

Amplifier and Loudspeaker

The choice of the amplifier depends on the targeted frequency spectrum, which varies according to the type of pest to be repelled. Fig. 5 shows the amplification circuit used in the experiments. It is based on an LM386 operational amplifier and includes a variable resistor allowing the gain to be adjusted within a range of 20 to 200 Ω. This module, with a nominal power of 325 mW, operates with a supply voltage ranging from 4 to 12 V. It is used to amplify the signal x_4 provided by the microcontroller via the I2C interface.

Figure 5: LM386 module

Figure 6: Ultrasonic Speaker Piezo

The loudspeaker (see fig. 6) then converts this aperiodic signal into acoustic deterrent signals. Its bandwidth ranges from 10 to 50 kHz. Its frequency characteristics are selected according to the spectrum of the signals generated by the microcontroller in order to ensure faithful reproduction of the deterrent signal.

Fourth-order Runge-Kutta (RK4) code in C++

The programming language used for system development is C++. The integrated development environment (IDE) selected is Arduino 1.8.4, which enables code compilation and deployment on the microcontroller. The following code presents the numerical model of the system described by (1), implemented within the microcontroller.

Function Definition

Each equation of the system is implemented as a separate function, defined as follows:

```
double f1(double x,double y,double z,double u,double w,double alp,double ome,double
epsi1,double epsi2)
            {
              return  z;
             }
double f2(double x,double y,double z,double u,double w,double alp,double ome,double
epsi1,double epsi2)
            {
             return epsi1*u ;
            }
double f3(double x,double y,double z,double u,double w,double alp,double ome,double
epsi1,double epsi2)
            {
              return alp*(z-u) - x - sin(w);
            }
Double f4(double x,double y,double z,double u,double w,double alp,double ome,double
epsi1,double epsi2 )
            {
            return alp*epsi2*(u-z) + epsi2*(sin(w) - y);
            }
double f5(double x,double y,double z,double u,double w,double alp,double ome,double
epsi1,double epsi2)
            {
             return ome*(z-u);
             }
```

Numerical Modelling:

In this code, *x*, *y*, *z*, *u* and *w* respectively represent the state variables x_1, x_2, x_3, x_4, and x_5.

```
k1x=f1(x0,yy0,z0,u0,w0,alp,ome,epsi1,epsi2);
k1y=f2(x0,yy0,z0,u0,w0,alp,ome,epsi1,epsi2);
k1z=f3(x0,yy0,z0,u0,w0,alp,ome,epsi1,epsi2);
k1u=f4(x0,yy0,z0,u0,w0,alp,ome,epsi1,epsi2);
k1w=f5(x0,yy0,z0,u0,w0,alp,ome,epsi1,epsi2);

k2x=f1(x0+k1x*(h/2.0),yy0+k1y*(h/2.0),z0+k1z*(h/2.0),u0+k1u*(h/2.0),w0+k1w*(h/2.0),alp,ome,epsi1,epsi2);
k2y=f2(x0+k1x*(h/2.0),yy0+k1y*(h/2.0),z0+k1z*(h/2.0),u0+k1u*(h/2.0),w0+k1w*(h/2.0),alp,ome,epsi1,epsi2);
k2z=f3(x0+k1x*(h/2.0),yy0+k1y*(h/2.0),z0+k1z*(h/2.0),u0+k1u*(h/2.0),w0+k1w*(h/2.0),alp,ome,epsi1,epsi2);
k2u=f4(x0+k1x*(h/2.0),yy0+k1y*(h/2.0),z0+k1z*(h/2.0),u0+k1u*(h/2.0),w0+k1w*(h/2.0),alp,ome,epsi1,epsi2);
k2w=f5(x0+k1x*(h/2.0),yy0+k1y*(h/2.0),z0+k1z*(h/2.0),u0+k1u*(h/2.0),w0+k1w*(h/2.0),alp,ome,epsi1,epsi2);
```

```
k3x=f1(x0+k2x*(h/2.0),yy0+k2y*(h/2.0),z0+k2z*(h/2.0),u0+k2u*(h/2.0),w0+k2w*(h/2.0),alp,ome,epsi1,epsi2);
k3y=f2(x0+k2x*(h/2.0),yy0+k2y*(h/2.0),z0+k2z*(h/2.0),u0+k2u*(h/2.0),w0+k2w*(h/2.0),alp,ome,epsi1,epsi2);
k3z=f3(x0+k2x*(h/2.0),yy0+k2y*(h/2.0),z0+k2z*(h/2.0),u0+k2u*(h/2.0),w0+k2w*(h/2.0),alp,ome,epsi1,epsi2);
k3u=f4(x0+k2x*(h/2.0),yy0+k2y*(h/2.0),z0+k2z*(h/2.0),u0+k2u*(h/2.0),w0+k2w*(h/2.0),alp,ome,epsi1,epsi2);
k3w=f5(x0+k2x*(h/2.0),yy0+k2y*(h/2.0),z0+k2z*(h/2.0),u0+k2u*(h/2.0),w0+k2w*(h/2.0),alp,ome,epsi1,epsi2);

k4x=f1(x0+k3x*h,yy0+k3y*h,z0+k3z*h,u0+k3u*h,w0+k3w*h,alp,ome,epsi1,epsi2);
k4y=f2(x0+k3x*h,yy0+k3y*h,z0+k3z*h,u0+k3u*h,w0+k3w*h,alp,ome,epsi1,epsi2);
k4z=f3(x0+k3x*h,yy0+k3y*h,z0+k3z*h,u0+k3u*h,w0+k3w*h,alp,ome,epsi1,epsi2);
k4u=f4(x0+k3x*h,yy0+k3y*h,z0+k3z*h,u0+k3u*h,w0+k3w*h,alp,ome,epsi1,epsi2);
k4w=f5(x0+k3x*h,yy0+k3y*h,z0+k3z*h,u0+k3u*h,w0+k3w*h,alp,ome,epsi1,epsi2);

            k0x=(k1x+2*k2x+2*k3x+k4x)/6.0;
            k0y=(k1y+2*k2y+2*k3y+k4y)/6.0;
            k0z=(k1z+2*k2z+2*k3z+k4z)/6.0;
            k0u=(k1u+2*k2u+2*k3u+k4u)/6.0;
            k0w=(k1w+2*k2w+2*k3w+k4w)/6.0;

            x=x0+h*k0x;
            y=yy0+h*k0y;
            z=z0+h*k0z;
            u=u0+h*k0u;
            w=w0+h*k0w;
            t=t0+h;

             x0 = x;
            yy0 = y;
            z0 = z;
            u0 = u;
            w0 = w;
            t0 = t;
```

Oscilloscope

In this study, an oscilloscope was used to observe and analyze the analog signal x_4 generated by (1). This step enables the experimental validation of the temporal characteristics of the generated signals, including their dynamic evolution, stability, and aperiodic nature. The instrument used is a Tektronix SDO1022 oscilloscope, with a bandwidth of 25 MHz. The use of this oscilloscope provides accurate time-domain visualization of the waveforms and allows a qualitative assessment of the structure of the generated signals. This constitutes an essential step in the experimental validation of the system, confirming the consistency between the theoretical signals derived from the model and those obtained at the output of the hardware implementation.

RESULTS

Fig. 7 presents the experimental setup used for the observation of the aperiodic signal x_4 at the output of the amplifier. The test bench is composed of a power supply, a computer, and an oscilloscope, which together enable the visualization and analysis of the generated signal.

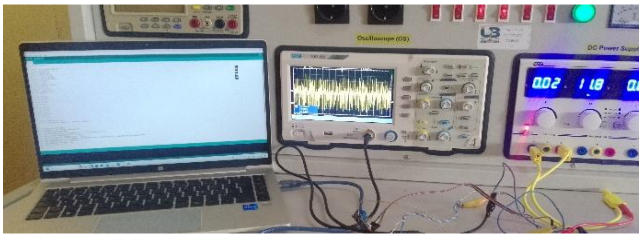

Figure 7: Experimental setup for the observation of the x_4 signal

Output Time Signal

Fig. 8 presents the aperiodic time-domain signal x4 generated by the proposed device. The signal was acquired using an oscilloscope with a time base of 5 ms per division and an acquisition depth of 10 k. The waveform analysis highlights the nonlinear behavior of the signal, confirming its aperiodic nature. This property reflects the absence of repetitiveness in the generated acoustic signal, thereby reducing the ability of pests to adapt due to the continuously varying acoustic stimuli.

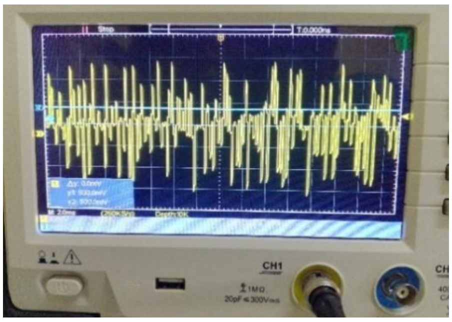

Figure 8: Time trace of signal x_4

Deterrence Test

Fig. 9 illustrates the proposed prototype used in the deterrence experiments. The tests were conducted on weevils as well as on a village hen in order to evaluate the effectiveness of the device across different types of pests and animals.

Figure 9: Complete of prototype

Deterrence Test on a Village Hen

Fig. 10 presents the experimental test conducted on a village hen. Prior to the experiment, the animal was deprived of food and water to enhance its motivation to feed and drink upon exposure to the presented rice and water. However, despite this initial condition, it was observed that even in the presence of food and water resources, the hen avoided the area exposed to the acoustic signal by seeking a blind spot, thereby exhibiting an escape behavior in response to the noise generated by the device.

Figure 10: **Experimental test on a village hen**

Test on Weevils

Fig. 11 presents the experimental test conducted on rice infested with weevils. The device was positioned above the sample to ensure the propagation of the acoustic signal within the experimental area.

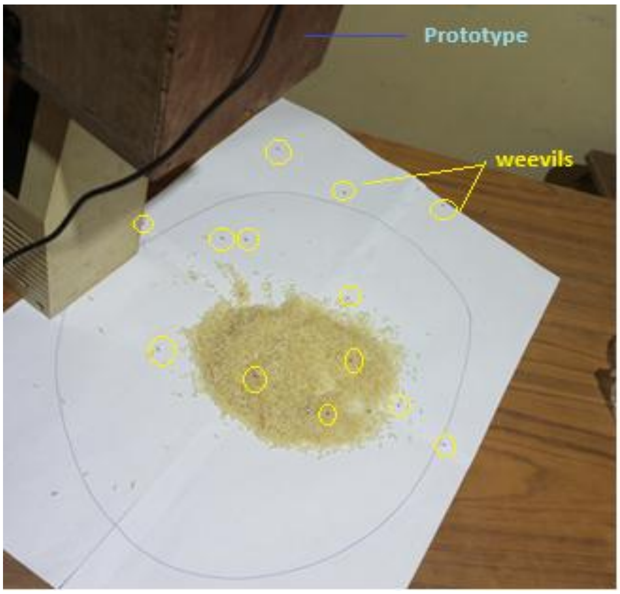

Figure 11: **Experimental test on weevils**

The experiment was carried out in darkness to eliminate any potential influence of light on insect behavior. The image shown in fig. 11 was captured immediately after switching on the lighting in the test room. The observations indicate that the weevils move away from the area exposed to high acoustic intensity toward regions where the signal level is lower, thereby exhibiting an escape response to the generated sound field.

This type of device can also be applied in post-harvest storage conditions for the protection of stored agricultural products. In particular, it may help limit infestations of insect pests such as weevils in cereal stocks by maintaining a deterrent acoustic pressure within storage facilities. This application could contribute to reducing post-harvest losses and preserving the quality of agricultural products after harvest.

DISCUSSIONS

It is well established that animals rapidly become accustomed to constant, periodic, or repetitive acoustic stimuli, leading to a progressive reduction in their deterrent effectiveness. In this context, several studies have proposed deterrent devices based on the emission of constant sounds. However, these approaches exhibit significant limitations due to the low variability of the generated signals. Furthermore, systems based on NE555 oscillators have been widely investigated. Although simple to implement, these devices are generally limited to generating a single frequency or a narrow set of periodic frequencies, which reduces their long-term effectiveness. In comparison, chaotic systems exhibit non-repetitive behavior over practical time intervals, offering temporal variability that is more suitable for deterrence mechanisms. Similarly, the use of audio players broadcasting pre-recorded sounds has been reported in the literature. However, their main drawback lies in the repetitiveness of the audio sequences, which promotes pest habituation. In this study, we propose an acoustic device dedicated to pest deterrence in agricultural environments. The system generates an aperiodic sound signal characterized by high temporal and frequency variability. Experimental results suggest that the proposed device is also applicable in post-harvest conditions, particularly for the protection of stored agricultural products.

CONCLUSION

This study presents the development of a sound generator designed for the protection of agricultural crops against pests. The adopted approach is based on the implementation of a chaotic system within a microcontroller, enabling the generation of signals with high temporal variability and without repetitiveness. This strategy helps reduce pest habituation, which is commonly observed in systems based on periodic signals. Signal analysis using an oscilloscope highlighted the dynamic characteristics of the generated waveforms, confirming their non-repetitive nature as well as the unpredictable fluctuations in amplitude. Experimental tests were conducted on two species, namely weevils and a village hen. The obtained results demonstrated satisfactory deterrent effectiveness of the proposed device.

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