Chaotic Autonomous Mobile Robot for Military Missions

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Abstract: - This work presents an autonomous mobile robot in order to cover an unknown terrain "randomly", namely entirely, unpredictably and evenly. This aim is very important, especially in military missions, such as the surveillance of terrains, the terrain exploration for explosives and the patrolling for intrusion in military facilities. The "heart" of the proposed robot is a chaotic motion controller, which is based on a chaotic true random bit generator. This generator has been implemented with a microcontroller, which converts the produced chaotic bit sequence, to the robot's motion. Experimental results confirm that this approach, with an appropriate sensor for obstacle avoidance, can obtain very satisfactory results in regard to the fast scanning of the robot's workspace with unpredictable way.

Key-Words: - Autonomous mobile robot, terrain coverage, microcontroller, random bit generator, nonlinear system, chaos, Logistic map.

1 Introduction

The subject of mobile robotιcs for military missions and especially autonomous mobile robots has acquired a keen interest during the last decade. This occurs because of their great number of applications in difficult or dangerous tasks that put human integrity in risk. Many research teams work on the design of mobile robots for the surveillance of terrains, the terrain exploration for explosives or dangerous materials or patrolling (e.g. for intrusion in military facilities), map buildings and search and rescue of human victims on disaster places [1-5].

The most fundamental issues in the design of such robotic systems are the locomotion, the sensing, the localization and the navigation. However, the choice of the navigation strategy is the most challenging issue because the designer must choose the appropriate technique that allows the mobile robot to autonomously decide where to move in the workspace in order to accomplish a given task. Also, the chosen navigation strategy has a remarkable influence over the performance of the task execution and significant contribution in building the robot's autonomy. Until now, many interesting navigation techniques depending on the application have been proposed, but the issue continues to preoccupy the scientific community.

So, the designer of an autonomous mobile robot for military missions should take into consideration all the possible problems involving the navigation strategies. In most military applications, such as the exploration of an initially unknown workspace in order to discover explosives or the patrolling of a known environment, the key-point is the robot's motion planning for the complete and fast terrain scanning. For accomplishing these two requirements, a mobile robot which is capable of crossing every region, covering systematically the entire workspace, should be designed. The obvious solution of a systematic scanning by using parallel straight trajectories is not the preferable one, because it could be easily understood by an intruder in the case of patrolling missions. Therefore, the unpredictability of the mobile robot's trajectory is

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also a crucial factor for the success of such autonomous mobile robot's tasks.

To meet this challenge Nakamura and Sekiguchi, in 2001, proposed a strategy to solve the above mentioned problem based on chaotic systems [6]. In that work the chaotic behavior of the Arnold dynamical system is imparted to the mobile robot's motion control. Since then many relative research works in the field of autonomous mobile robots have been presented by many research teams, because the chaotic motion of the robot guarantees the scanning of the whole workspace without the previous knowledge of the terrain map. The most known chaotic dynamical systems, which have been used for this purpose, are the Lorenz system [7], [8], the Standard or Taylor-Chirikov map [9], [10], the well-known Chua circuit [2], [11], and the double-scroll chaotic systems [12-14].

The majority of the works on this field, which have been presented until now, contain only numerical simulations of the autonomous mobile robots' motion. So, in this work, a new navigation strategy by designing a controller, which ensures a chaotic motion to an autonomous mobile robot, has been experimentally investigated. This new technique is implemented by using a microcontroller for realizing a chaotic true random bit generator by solving the Logistic map, which is a well-known discrete chaotic dynamical system. The proposed controller produces an unpredictable trajectory by imparting the system's chaotic behavior to the two independent active wheels of the mobile robot. As a consequence the autonomous mobile robot with a sensor for obstacle avoidance covers the whole terrain with unpredictable way, as it is observed from the experimental results.

This paper is organized as follows. In Section 2 the features of the Logistic map, which is the key-point in this work, are presented. The adopted chaotic robot's motion controller and the statistical tests of the chaotic random bit generator, which is used, are described in Section 3 and Section 4 respectively. In Section 5 the proposed model of the chaotic autonomous mobile robot is discussed. The experimental results of the robot's performance concerning the terrain coverage are presented in Section 6. Finally, Section 7 includes the conclusion remarks.

2 The Logistic Map

The Logistic map, which is described by the following equation:

$$x_{n+1} = r \cdot x_n \cdot (1 - x_n), \quad 0 \le x \le 1 \qquad (1)$$

is one of the most studied, one-dimensional, discrete chaotic maps because of its simplicity. At the beginning this iterative map is used as a simple idealized ecological model for the yearly variations in the population of insect species [15]. However, the Logistic map in the form of Eq.(1) or in various other forms was also used as a pseudo-random number generator [16-22] partly because it had a known algebraic uniform distribution.

In Eq.(1) the parameter r varies in the interval [0,4] so that x_{n+1} maps the unit interval into the unit interval. By studying the Logistic map the following regions, depending on the value of r, may be considered.

- For $r < 1$, x decays to a fixed point ($x \rightarrow 0$).
- For $1 \le r < 3$, the previous fixed point loses its stability and another fixed point ($x = 1 - 1/r$) appears.
- For $3 \le r \le 4$, the Logistic map presents a more complex behavior (such as repeated period doublings, appearance of odd periods e.t.c.) which finally leads to chaos.

The "Bifurcation diagram" of the Logistic map which shows the steady-state behavior of Eq.(1) with respect to the bifurcation parameter r, is presentd in Fig.1. The rich dynamical behavior in the third region ($3 \le r \le 4$), which is mainly characterized by the very interesting phenomenon of period-doubling route from periodic to chaotic behavior (with the black color), is illustrated in this bifurcation diagram.

As it is also shown in Fig.1, the first bifurcation occurs at the value of r=3, followed by further doublings at shorter and shorter intervals of r until the period goes to infinity at r_∞=3.5699…, signifying chaos. Also, various interspersed periodic windows beyond r_∞, are observed, in which the behavior returns to a normal periodic one, quickly followed again by bifurcations to an infinite period. So, for r_∞>3.5699… the Logistic map shows a strange complex behavior (the so-called chaotic behavior) where map function never repeats its history.

In Fig.2 the well-known Lyapunov exponent:

$$\lambda = \lim_{n\to\infty} \sum_{i=1}^{n} \ln\left|f'(x_i)\right| \qquad (2)$$

where,

$$f'(x) = r - 2 \cdot r \cdot x \qquad (3)$$

as a function of parameter r, is displayed. As it is known from the nonlinear theory a positive Lyapunov exponent indicates chaos. So, Fig.2 confirms the Logistic map's dynamical behavior as found from the bifurcation diagram (Fig.1).

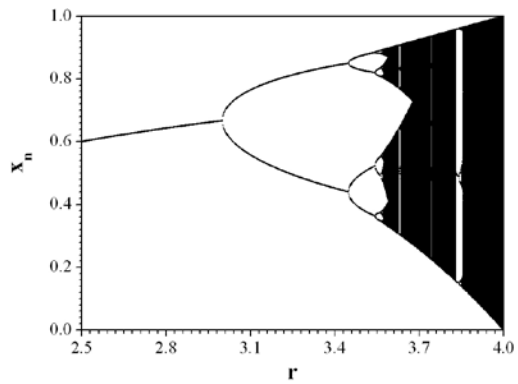

Fig.1. The bifurcation diagram of x_n vs. parameter r, for the Logistic map of Eq.(1).

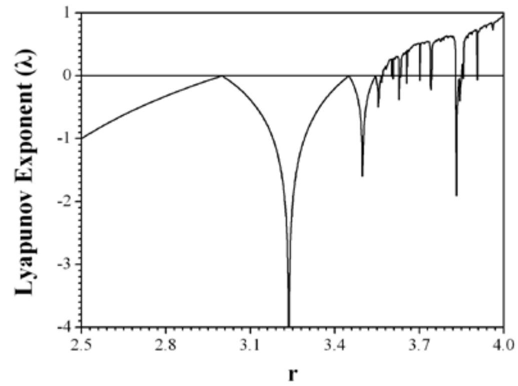

Fig.2. The diagram of Lyapunov exponent λ vs. r.

3 Robot's Motion Controller

The main part of the proposed mobile robot is the Chaotic Random Bit Generator (CRBG) based on the Logistic map, which is implemented by a microcontroller. This generator produces the motion of the mobile robot in a specific terrain. For this reason the following simple formula is used.

$$b_n = \begin{cases} 0, & \text{if } x_n \le x_c \\ 1, & \text{if } x_n > x_c \end{cases} \tag{4}$$

x_c denotes the chosen value of x while b_n is the bit generated by the n-th iteration of the Logistic map of Eq.(1). Also, for increasing the "randomness" of the produced robot's motion two Logistic Maps (Eq.(5)) with different values of parameters ($r_1 \neq r_2$), values of x_c ($x_{c1} \neq x_{c2}$) and initial conditions ($x_0 \neq y_0$), which giving motion in each of the two robot's independent active wheels are adopted.

$$\begin{cases} \text{LM1:} \; x_{n+1} = r_1 \cdot x_n \cdot (1 - x_n) \\ \text{LM2:} \; y_{n+1} = r_2 \cdot y_n \cdot (1 - y_n) \end{cases} \tag{5}$$

Next, unbiased bits with no correlation from the two defective Logistic maps are extracted by using the most known de-skewing technique [23]. In this technique, which has been proposed by Von Neumann, a digital post-processing that balances the distribution of bits is used. Post-processing converts non-overlapping pairs of bits into output bits by converting the bit pair "10" into an output "1", converting "01" into an output "0", while the pairs "11" and "00" are discarded. This technique is very easily implemented but it decreases throughput of generating approximately 1 bit from 4 bit.

Furthermore, the proposed CRBG is realized by using an open-source Arduino UNO prototyping platform made up of an Atmel AVR processor (microcontroller), based on flexible, easy-to-use hardware and software [24]. The specific microcontroller is chosen because, among all the other advantages it has, it is probably the most commercial platform, which is used in a great number of applications, especially in robotics.

4 Statistical Tests of the CRBG

The "randomness" of the produced chaotic bits sequence, by the proposed TRBG, is confirmed in this paragraph. For this reason one of the most important statistical test suites is used. This is the FIPS-140-2 (Federal Information Processing Standards) [25] of the National Institute of Standards and Technology (NIST), which comprises of four statistical tests: Monobit test, Poker test, Runs test, and Long Run test. According to the proposed FIPS statistical tests, the examined TRBG will produce a bitstream, $b_i = b_0, b_1, b_2, \ldots, b_{n-1}$, of length n (at least 20000 bits), which must satisfy the four above mentioned statistical tests.

Using the procedure described in the previous section, by chosing (r_1, r_2)=(3.998,3.989), (x_{c1},x_{c2})=(0.495, 0.497) and initial condition (x_0,y_0)=(0.300, 0.400), two bitstreams of 20,000 bits are captured from the microcontroller to a text file by using the HyperTerminal program on Windows. As a conclusion, the use of the statistical tests of FIPS in the produced bit sequences, by the proposed CRBG, has numerically verified the specific characteristics expected of random bit sequences.

5 The Autonomous Mobile Robot

In this work the experimental results concerning the coverage performance of an autonomous mobile robot, by using the previous mentioned chaotic motion controller, are presented. This occurs

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because in real-world applications some dynamical factors such as internal and external friction and other workspace restrictions play a crucial role to mobile robot's behavior. Also, the implementation of a lab-scale robot is suitable as a start, for justifying the effectiveness of the employed method and the resulting behavior.

The autonomous mobile robot of this work is a four wheels platform, in which only the two wheels are independently controlled on velocity and rotation sense by using two gear motors (Fig. 3).

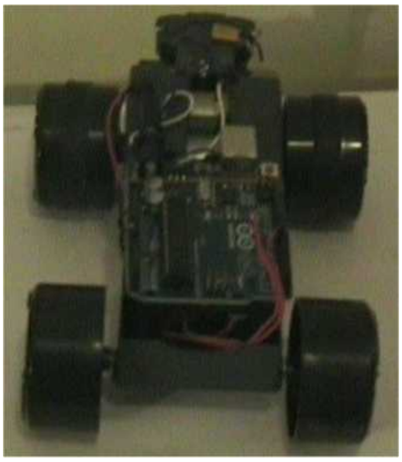

Fig.3. The chaotic autonomous mobile robot.

The motion of the proposed mobile robot is described by the linear velocity v(t) and the direction velocity ω(t). The linear velocity provides a linear motion of the medium point of the wheels axis while the direction velocity provides a rotational motion of the robot over the same point. The following system of equations:

$$\begin{pmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\theta}(t) \end{pmatrix} = \begin{pmatrix} \cos\theta(t) & 0 \\ \sin\theta(t) & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v(t) \\ \omega(t) \end{pmatrix} \quad (6)$$

describes the robot motion control, where x(t), y(t) and θ(t) are the robot position and orientation.

Each one of the two active wheels of the proposed robot is driven by each one of the two chaotic random bit generators (LM1 & LM2) discussed in Section 3. Thus, depending on the produced bits (b_1 & b_2), four possible motion commands are generated through the robot's motion controller (Table 1).

Furthermore, each one of the motion commands of Table 1 lasts two seconds and the proposed mobile robot uses the HC-SR04 ultrasonic distance sensor for providing short-range distances to obstacles or boundaries.

Also, the autonomous mobile robot moves in orthogonal horizontal terrain with boundaries and an obstacle at the center. If the boundaries or obstacles are found on the robot's trajectory in a distance less than 20cm, the robot stops and waits the next motion command.

Table 2. Motion commands produced by the robot's motion controller.

Motion Commands	**b_1**	**b_2**
Immobilization	0	0
Turning Left	0	1
Turning Right	1	0
Moving Forward	1	1

6 Experimental Results

The proposed robot's coverage performance was experimentally studied and the results are presented in details in this section. For this reason the workspace coverage is analyzed by using the well-known coverage rate (C). The coverage rate represents the effectiveness, as the amount of the total surface covered by the robot. So, the coverage rate (C) is given by the following equation:

$$C = \frac{1}{M} \cdot \sum_{i=1}^{M} I(i) \quad (7)$$

where, I(i) is the coverage situation for each cell [26]. This is defined by the following equation:

$$I(i) = \begin{cases} 1, & \text{when the cell i is covered} \\ 0, & \text{when the cell i is not covered} \end{cases} \quad (8)$$

where, i = 1, 2, ..., M.

As it is mentioned, the robot's workplace is supposed to be an orthogonal terrain of 8x11=88 cells with boundaries. Each cell of this terrain has dimension 30x30 cm. Also, the initial position of the robot is the cell (x, y) = (5, 4), while the duration of robot's motion test is 24 minutes.

The robot's motion controller produced 496 motion commands during its operation. In Fig.4 the terrain coverage by using the proposed chaotic autonomous mobile robot is shown. In this figure, the dot denotes the center of the visited cells by the robot during its motion. As it is shown, all the cells of the terrain have been visited by the robot. The coverage rate versus the number of visited cells, for the robot with the proposed chaotic motion controller, is presented in Fig.5. Especially, in this diagram, it is shown that the robot's workplace has been covered by using only 404 motion commands in time of 16 minutes. In the remaining 92 motion commands the robot covers some of the previously covered cells of the workspace.

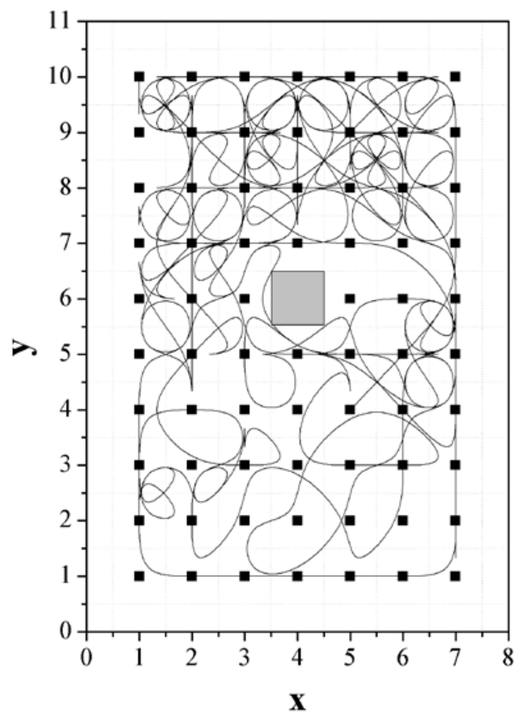

Fig.4 Terrain coverage using the proposed chaotic autonomous mobile robot.

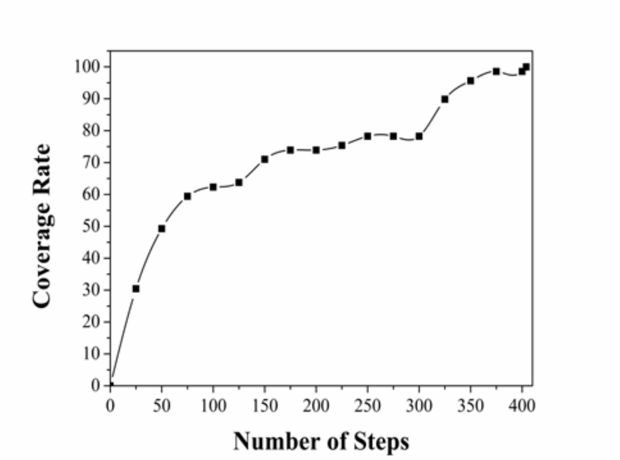

Fig.5. Coverage rate versus number of motion commands, for operation of 16 minutes.

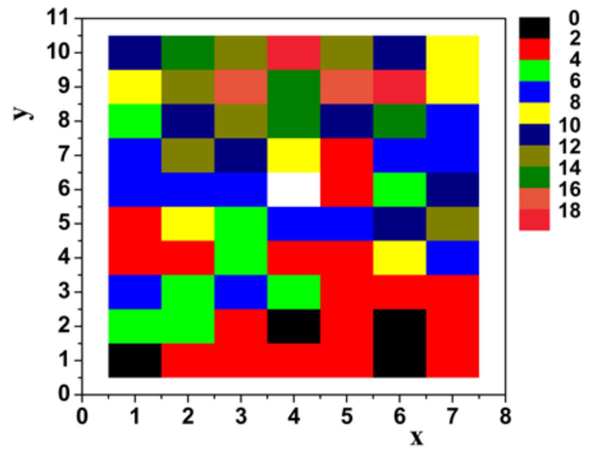

Fig.6. Color scale map of the terrain's cells versus the times of visiting.

Finally, in diagram of Fig.6, the color scale map of the terrain's cells versus the times of visiting is shown. There are cells, wherein the robot has visited from 1 to up 18 times in the 24 minutes of operation. As noted the lower region has been visited more times than the rest of the terrain mainly because the robot has its initial position in this region.

7 Conclusion

In this work, an autonomous mobile robot by using a chaotic motion controller was presented. This controller was based on a well-known microcontroller realized by two chaotic bit generators, based on the chaotic Logistic map with different initial conditions and system's parameters, which were used to drive each one of the two robot's independent active wheels. Statistical tests of the proposed chaotic bit generators guarantee the "randomness" of the produced bit sequences and consequently the "randomness" of robot's chaotic trajectory.

The study of the proposed robot's motion in a specific workspace consists of experimental results in contrary with the majority of similar works in which the validation tests were based only on numerical simulations. This feature is very important because in real conditions many dynamical factors affect the robot's behavior.

So, from the experimental results the high unpredictability of robot's trajectory, which is very crucial in many tasks, by using the proposed chaotic motion controller, was confirmed. Furthermore, other two crucial tasks, such as the complete and fast scanning of the workspace, were succeeded. Finally, the experimental results of this work ensure the applicability of chaotic systems to real

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autonomous mobile robot's control strategies for use in various military tasks such as terrain exploration for explosives, search and rescue missions, surveillance of terrains and many other.

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