Motion Direction Control of a Robot Based on Chaotic Synchronization Phenomena

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Abstract:
This work presents chaotic motion direction control of a robot and especially of a humanoid robot, in order to achieve complete coverage of the entire work terrain with unpredictable way. The method, which is used, is based on a chaotic true random bits generator. The coexistence of two different synchronization phenomena between mutually coupled identical nonlinear circuits, the well-known complete chaotic synchronization and the recently new proposed inverse π-lag synchronization, is the main feature of the proposed chaotic generator. Computer simulations confirm that the proposed method can obtain very satisfactory results in regard to the fast scan of the entire robot's work terrain.

Keywords: *humanoid robot, motion direction control, nonlinear circuit, chaos, true random bits generator, complete synchronization, inverse π-lag synchronization*

1. Introduction

Autonomous mobile robots have acquired a keen interest of the scientific community, especially in the last two decades, because of their applications in various fields of activities, such as industrial and military missions. Therefore, many interesting applications of mobile robots, such as floor-cleaning devices, industrial transportation and fire fighting devices [1–3], have been developed. Especially, the use of autonomous mobile robots for military applications, such as the surveillance of terrains, the terrain exploration for searching (e.g. for explosives or dangerous materials) or patrolling (e.g. for intrusion in military facilities) [4–6], has become a very interesting task. For such applications many mobile robots are commercially available, which in many cases focus on some features such as, the perception and identification of the target, the positioning of the robot in the terrain and the updating of the terrain's map. However, the most important from all the above features is the path planning, because it determines the success of the robot's missions especially in many military tasks.

Additionally, the research subject of the interaction between mobile robots and chaos theory has been studied intensively. The basic feature of these research attempts in a chaotic robot field is a motion controller, which is based on microcontrollers or CPUs that ensure chaotic motion to the robot. Signals, which are produced by chaotic systems, are used to guide autonomous robots. Until now, some of the most well-known chaotic systems, such as Chua circuit [6], Arnold system [7], Standard or Taylor-Chirikov map [8] and Lorenz system [9], have been used.

The problem of patrolling a terrain with a mobile robot is an issue that has to do with finding a plan for production not only of unpredictable trajectories but also a way to scan fast the entire predicted region. These are the main reasons for using nonlinear dynamic systems, because the chaotic behavior of such systems ensures the unpredictability of the robot's trajectories. The second aim, the fast scanning of the terrain, is the subject of study among the researchers for selecting the most suitable dynamic system.

This work, presents a new strategy, which generates an unpredictable trajectory, by using a chaotic true random bits generator. Also, a humanoid robot is selected because such a kind of robots has a specific way of movement and it used nowadays in many activities. The proposed motion planner of a humanoid robot's motion produces a sequence of steps in the four basic directions (forward, right, left and backward) or in eight directions (forward, diagonal forward-right, diagonal forward-left, right, left, diagonal backward-right, diagonal backward-left, backward).

This paper is organized as follows. In Section 2 basic features of chaotic systems and the synchronization phenomena, which are the base of this work, are presented. Section 3 describes the robot's motion generator block by block. In Section 4 the statistical tests of the proposed true random bits generator, is discussed. Section 5 presents the simulation results of the humanoid robot's motion and their analysis. Finally, Section 6 includes the conclusions remarks of this work.

2. Chaotic Systems and Synchronization Phenomena

A dynamical system, in order to be considered as chaotic, must fulfill the following conditions [10]:

- it must be very sensitive on initial conditions,
- its chaotic orbit must be dense and
- it must be topologically mixing.

The most important of the three above conditions is the system's sensitivity on initial conditions or on system's parameters. This means that a small variation on system's initial conditions or parameters can lead to a totally different dynamic behavior, so to a totally different trajectory. That's why chaotic systems are very good candidates for using in robot's motion planners because theirs sensitivity can contribute to robot's unpredictable trajectory, which is a necessary condition in many robotic activities as it is mentioned before.

In the last two decades the study of the interaction between coupled chaotic systems was a landmark in the evolution of the chaotic synchronization's theory [11]. The topic of synchronization between coupled nonlinear chaotic systems plays an important role in several research areas, such as biological networks, secure communication and cryptography [12–15].

The most well-known type of synchronization is the complete or full synchronization, in which the interaction between two identical coupled chaotic systems leads to a perfect coincidence of their chaotic trajectories, i.e.

$$x_1(t) = x_2(t), \text{ as } t \rightarrow \infty \qquad (1)$$

where x_1 and x_2 are the signals of the coupled chaotic systems.

From 2010 a new synchronization phenomenon, the inverse π-lag synchronization, between two mutually coupled identical nonlinear systems, has been observed [16]. More precisely, this type of synchronization, which is called inverse π-lag synchronization, is observed when the coupled system is in a phase locked (periodic) state, depending on the coupling factor, and it can be characterized by eliminating the sum of two relevant periodic signals (x_1 and x_2) with a time lag τ, which is equal to T/2, where T is the period of the signals x_1 and x_2.

$$x_1(t) = -x_2(t+\tau),\ \tau = T/2 \qquad (2)$$

Nevertheless, depending on the coupling factor and the chosen set of system's initial conditions, the inverse π-lag synchronization coexists with a complete synchronization [16]. The proposed TRBG, which is used for the motion of the humanoid robot, is based on the coexistence of these two types of synchronization, which are used as representing the states "0" and "1" in the seed generation, as it will be described in details in the next section.

3. Robot's Motion Chaotic Generator

The basic element of the proposed motion planner is a chaotic true random bits generator, which consists of three blocks. The first block includes the system of two coupled identical nonlinear circuits. The autonomous circuit (Fig. 1), which is used, is the well-known circuit of Chua oscillator, in which the nonlinearity is described by a piecewise-linear function. By the term "autonomous", a nonlinear circuit without any external voltage or current source is considered, as it is shown in Fig. 1. Although in this paper the nonlinear element N_R of the circuit, which is used, implements a cubic function. This type of circuits is capable of producing double-scroll chaotic attractors (Fig. 2). In this type of behavior the chaotic systems have two attractors, between which the process state will oscillate. So, a double-scroll oscillator needs to have at least three degrees of freedom in order to be chaotic.

The state equations describing the circuit of Chua oscillator are the follows:

$$\begin{cases} \dfrac{dx_1}{dt} = \dfrac{1}{C_1}\left[\dfrac{1}{R}(y_1 - x_1) - g(x_1)\right] \\ \dfrac{dy_1}{dt} = \dfrac{1}{C_2}\left[\dfrac{1}{R}(x_1 - y_1) + z_1\right] \\ \dfrac{dz_1}{dt} = \dfrac{1}{L}\left[-y_1 - R_0 z_1\right] \end{cases} \qquad (3)$$

where, $x_1 = \upsilon_{C1}$, $x_2 = \upsilon_{C2}$, $z_1 = i_L$ and $g(x_1)$ is the cubic function of the form:

$$g(x_1) = -k_1 x_1 + k_3 x_1^3 \qquad (4)$$

where, k_1, $k_3 > 0$. The absence of the term of the second order provides the odd symmetry to the υ-i characteristic.

The practical circuit for realizing the cubic polynomial (4) is shown in Fig. 3. This realization proposed for the first time by Zhong [17]. The two terminal nonlinear resistor N_R consists of one Op-Amp (LF411), two analog multipliers (AD633JN) and five resistors. Each multiplier implements the function:

$$w = \frac{(x_1 - x_2)(y_1 - y_2)}{10V} + z \qquad (5)$$

where, the factor 10 V is an inherent scaling voltage in the multiplier. The connections of the Op-Amp and the resistors R_1, R_2 and R_3 form an equivalent negative resistor Re, when $R_1 = R_2$ and the Op-Amp operates in its linear region, in order to obtain the desired coefficients k_1 and k_3. The driving point υ-i characteristic of N_R is as below:

$$i_N = -\frac{1}{R_3}\upsilon_{C1} + \frac{R_4 + R_5}{R_3 R_4}\frac{1}{10V}\frac{1}{10V}\upsilon_{C1}^3 = -k_1\upsilon_{C1} + k_3\upsilon_{C1}^3 \qquad (6)$$

where, $k_1 = \dfrac{1}{R_3}$ and $k_3 = \dfrac{R_4 + R_5}{R_3 R_4}\dfrac{1}{10V}\dfrac{1}{10V}$.

The values of circuit parameters are: $R_0 = 30\ \Omega$, R

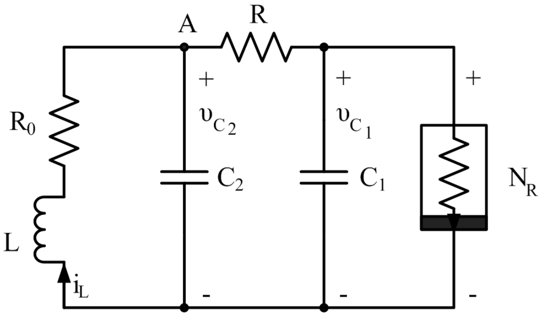


Fig. 1. *The schematic of the Chua oscillator*

= 1960 Ω, $R_1 = R_2 = 2$ kΩ, $R_3 = 1.671$ kΩ, $R_4 = 3.01$ kΩ, $R_5 = 7.887$ kΩ $C_1 = 7.4$ nF, $C_2 = 95.8$ nF, L = 19.2 mH and the voltages of the positive and negative electrical sources are ±15 V. For these values the circuit of Chua oscillator presents the desired chaotic behavior according to author's previous work [18]. So, the normalized parameters take the following values: k_1 = 0.6384 mS, k_3 = 0.0252 mS/V³.

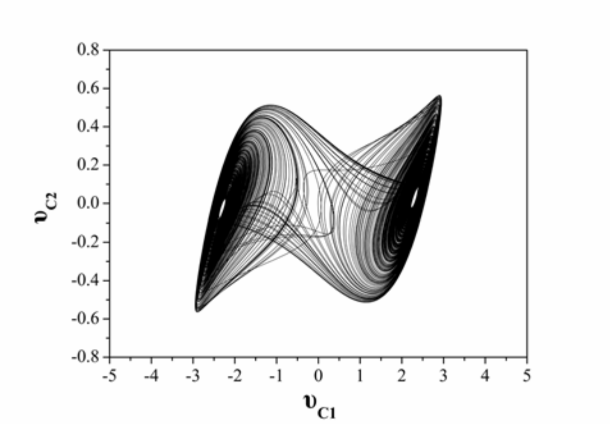


Fig. 2. *The double-scroll chaotic attractor*

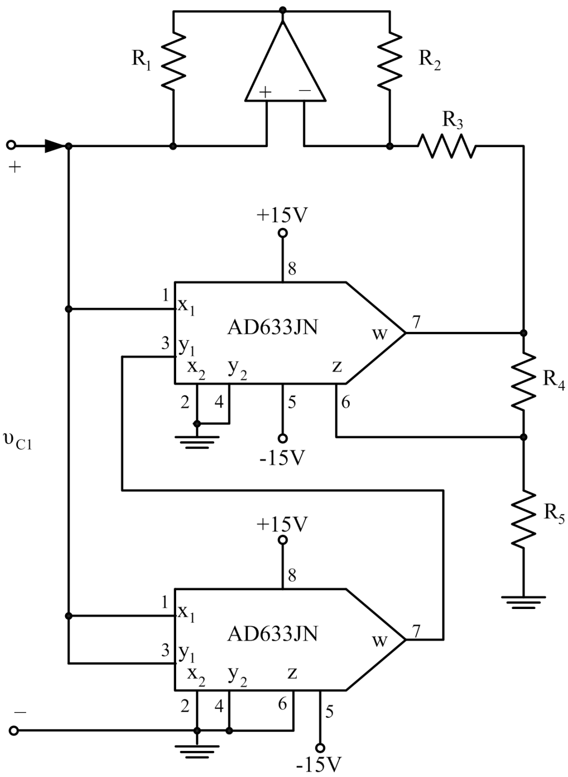


Fig. 3. *The circuit for realizing the cubic υ-i nonlinear characteristic*

The system of two bidirectionally or mutually coupled circuits of Chua oscillators is shown in Fig. 4. The coupling of the identical nonlinear circuits is achieved via a linear resistor R_C connected between the nodes A of each circuit. For small values of the resistor R_C (e.g. R_C = 250 Ω) the coexistence of the previous mentioned synchronization phenomena is observed.

Furthermore, the necessary perturbation p for changing the system's initial conditions and consequently the synchronization state of the coupled system is an external source that produces a pulse train

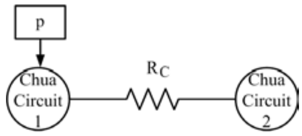


Fig. 4. *The system of two bidirectionally or mutually coupled nonlinear circuits via a linear resistor*

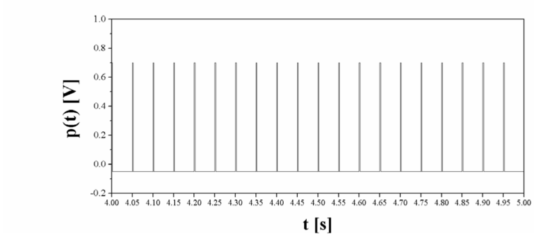
of amplitude 1 V and has a duty cycle of 4%. So, the pulse duration is 2ms, while the period of the pulse train is 50 ms (Fig. 5a).

Consequently, the first block of the proposed True Random Bits Generator (TRBG) produces the synchronization signal $[x_2(t) - x_1(t)]$ of the coupled system which varies between two states (Fig. 5b). In the first one, the signals $x_1(t)$ and $x_2(t)$ are identical and the difference $[x_2(t) - x_1(t)]$ is equal to zero because the system is in a complete synchronization mode. In the second state the signal $x_2(t)$ is inverse of the signal $x_1(t)$ with π phase difference. So, the difference $[x_2(t) - x_1(t)]$ oscillates around the value of 2.5 V.

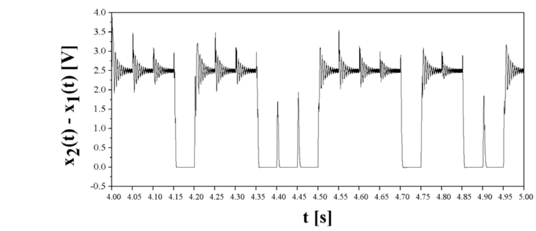
In the second block, the two different levels of the output signal $[x_2(t) - x_1(t)]$ are quantized to "0" and "1" according to the following equation:

$$\sigma_i = \begin{cases} 0, & \text{if } x_2(t) - x_1(t) < 1\text{V} \\ 1, & \text{if } x_2(t) - x_1(t) > 1\text{V} \end{cases} \quad (7)$$

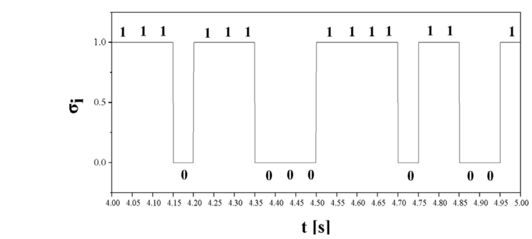
Therefore, if the system is in a complete synchronization state a bit "0" is produced, while if the system is in an inverse π-lag synchronization state a bit "1" is produced (Fig. 5c). The sampling period equals the period of the pulse train (T = 50 ms) and the sampling occurs at the middle of each pulse.



(a)



(b)



(c)

Fig. 5. *Time-series of (a) pulses p(t), (b) difference signal $[x_2(t) - x_1(t)]$ and (c) the produced bits sequence, with the*

proposed technique

Finally, the third block extracts unbiased bits, with the well-known de-skewing technique [19]. This technique eliminates the correlation in the output of the generator of random bits by converting the bit pair "01" into an output "0", "10" into an output "1", while the pairs "11" and "00" are discarded.

4. Statistical Tests of the Chaotic Generator

In this section the "randomness" of the produced bits sequence, by the proposed chaotic TRBG, is confirmed. So, the dynamical system (8) of the coupled circuits of Fig. 4 was solved numerically by using the fourth order Runge-Kutta algorithm and the signal $[x_2(t) - x_1(t)]$ is used for producing the chaotic bits sequence with the procedure described in Section 3.

$$\begin{cases} \frac{dx_1}{dt} = \frac{1}{C_1}\left[\frac{1}{R}(y_1 - x_1) - g(x_1) + \frac{1}{R_C}(x_2 - x_1)\right] \\ \frac{dy_1}{dt} = \frac{1}{C_2}\left[\frac{1}{R}(x_1 - y_1) + z_1\right] \\ \frac{dz_1}{dt} = \frac{1}{L}\left[-y_1 - R_0 z_1\right] \\ \frac{dx_2}{dt} = \frac{1}{C_1}\left[\frac{1}{R}(y_2 - x_2) - g(x_2) + \frac{1}{R_C}(x_1 - x_2)\right] \\ \frac{dy_2}{dt} = \frac{1}{C_2}\left[\frac{1}{R}(x_2 - y_2) + z_2\right] \\ \frac{dz_2}{dt} = \frac{1}{L}\left[-y_2 - R_0 z_2\right] \end{cases} \tag{8}$$

For this reason one of the most important statistical test suites is used. This is the FIPS (Federal Information Processing Standards) [20] 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. As it is known, according to 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 fact in information theory that noise has maximum entropy, initial conditions of the first (x_{01} = 0.60, y_{01} = 0.10, z_{01} = 0.05) and the second circuit (x_{02} = 0.70, y_{02} = 0.20, z_{02} = −0.10) are chosen so that the measured entropy of the TRBG is maximal. The measure-theoretic entropy [21] of the proposed chaotic TRBG with respect to system's parameters and initial conditions is calculated to be H_n = 0.69172 for n = 3 and H_n = 0.69189 for n = 4, where n is the length of the n-word sequences.

So, by using the procedure described previously, bits sequence of length 20000 bits has been obtained from the output of the proposed chaotic TRBG calculated via the numerical integration of Eq.(8). Then this bits sequence is subjected to the four tests of FIPS-140-2 suite. As a result, it has been numerically verified that the bits sequence has passed the test suite of FIPS-140-2 (Table 1).

Table 1. Results of FIPS-140-2 test, for the chaotic TRBG

Monobit Test	Poker Test	Runs Test	Long Run Test
n_1=10018 (50.09%)	2.3245	B_1=2565 B_2=1253 B_3=605 B_4=319 B_5=144 B_6=149	No
Passed	**Passed**	**Passed**	**Passed**

5. Simulation Results of the Robot's Motion

A humanoid robot, like the commercial model of Kondo KHR-2HV (Fig.6) is adopted because it is an interesting compromise of simplicity between control and implementation. In this work two different humanoid's motion approaches have been used so as to take advantage the ability of the specific type of robot. In the first case, the chaotic motion planner converts the bits pairs: 00, 01, 10 and 11, which are produced by the chaotic generator, into steps in the four basic directions: forward, right, left and backward. With the same way, in the second case, the bits triads: 000, 001, 010, 011, 100, 101, 110 and 111, are converted into steps in the following eight directions: forward, diagonal forward-right, diagonal forward-left, right, left, diagonal backward-right, diagonal backward-left and backward.

Fig. 6. *The humanoid robot Kondo KHR-2HV*

Also, in this work, for a better understanding of the behavior of the robot's chaotic motion generator, we assume that the robot works in flat area, with boundaries, without obstacles and without any sensor. So, in the case that the proposed humanoid robot reaches boundaries of the terrain waits the next direction in order to move.

In all similar works, the first step is the study of the robot's motion by using computer simulation. For this reason the terrain coverage is analyzed, by using the well-known coverage rate (C). A square terrain with dimensions: M = 25 x 25 = 625, in normalized unit cells, is chosen. The coverage rate (C) is given by the following equation:

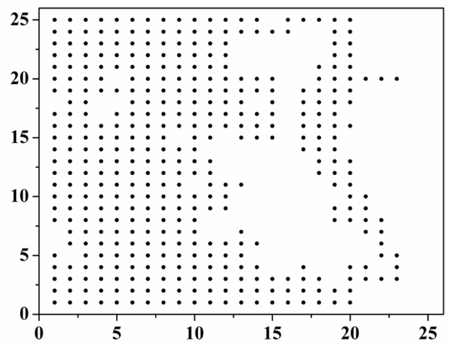
$$C = \frac{1}{M} \cdot \sum_{i=1}^{M} I(i) \tag{9}$$

where, I(i) is the coverage situation for each cell [22]. This is defined by the following equation:

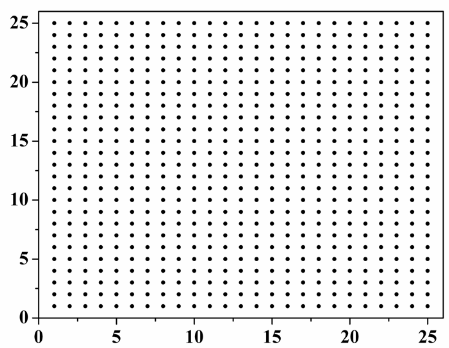
$$I(i) = \begin{cases} 1, & \text{when the cell i is covered} \\ 0, & \text{when the cell i is not covered} \end{cases} \quad (10)$$

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

So, in the following test the motion generator produces a sequence of 10000 steps in the four basic directions (forward, right, left and backward) starting from three different initial positions on the terrain: $(x_0, y_0) = \{(5, 20), (12, 12), (20, 5)\}$. The results for 2000 and 10000 robot's steps for $(x_0, y_0) = (5, 20)$, are shown in Fig. 7. Especially, in Fig. 7b the coverage of the whole terrain, can be observed. In Fig. 8, the coverage rate versus the number of steps, for the robot with the proposed chaotic motion generator, starting from the three, above mentioned, initial positions, is shown. In the three simulations, the complete terrain's coverage was calculated. Furthermore, the robot has covered, practically, all the terrain (91%) after only the 4000th step.



(a)



(b)

Fig. 7. *Terrain covering using the robot with the proposed chaotic generator in the first case for initial position (x0, y0) = (5, 20), for (a) 2000 steps and (b) 10000 steps*

For the validation of the robot's kinematic motion by using the capability of the robot to move in eight directions, an arbitrarily initial position is chosen: $(x_0, y_0) = (8, 10)$. In Fig. 9, the coverage rate versus the number of steps, in comparison to the previous case (motion in four directions) is shown. In conclusion, in the case of moving in eight directions the robot shows a more quick coverage of the terrain's space.

Especially, for the first 2000 steps the robot has shown 20% faster terrain's coverage in the second approach in regard to the first one. More precisely from the 2000th step the robot has covered the 85.6% of the total terrain. Furthermore, in the remaining 3000 steps, until 5000th step, the robot covers only 10.7% of the terrain. So, finally the total terrain's coverage percentage in the second approach was calculated to be equal to 96.3%. Therefore, the robot, with the capability of moving in eight directions, has better and faster coverage rate in regard to the case of moving in four directions.

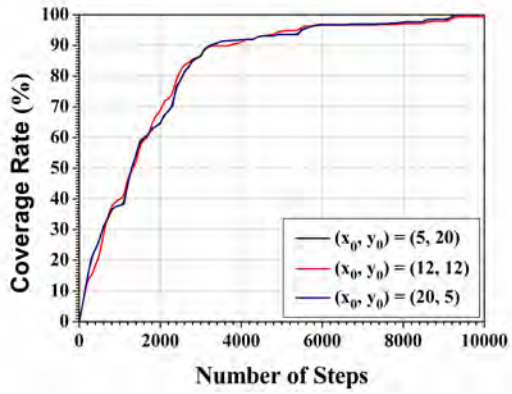


Fig. 8. *The coverage rate versus the number of steps, when the robot moves in four directions, starting from three different initial positions on the terrain: (x_0, y_0) = {(5 20), (12, 12), (20, 5)}*

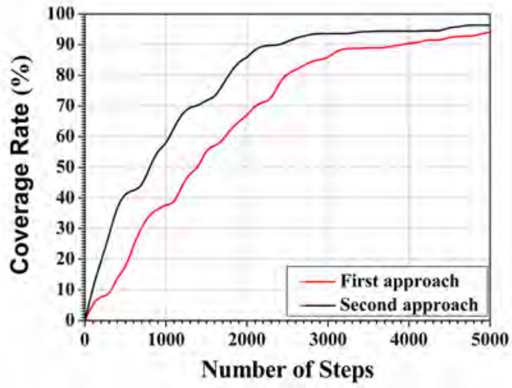


Fig. 9. *The comparison of the two different kinematic control approaches (moving in four or eight directions)*

6. Conclusion

In this work, a chaotic path planning generator for autonomous humanoid robots was presented. In contrary with other similar works, where the control unit defines the position goal in each step, here only the motion of the humanoid robot is controlled by using the coexistence of synchronization phenomena between coupled chaotic circuits. Statistical tests of the proposed chaotic generator guarantees the "randomness" of the produced bits sequence and consequently the "randomness" of the planning path.

Furthermore, validation tests based on numerical simulations of the robot's motion direction control, confirm that the proposed method can obtain very satisfactory results in regard to unpredictability and fast scanning of the robot's workplace. Finally, the use of the specific chaotic TRBG in this work provides significant advantage concerning other similar works because of the improved statistical results, which were presented in details.

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REFERENCES

[1] J. H. Suh, Y. J. Lee, and K. S. Lee, "Object Transportation Control of Cooperative AGV Systems Based on Virtual Passivity Decentralized Control Algorithm", *J. Mech. Sc. Techn.*, vol. 19, 2005, pp. 1720–1730.

[2] J. Palacin, J. A. Salse, I. Valganon, and X. Clua, "Building a Mobile Robot for a Floor-Cleaning Operation in Domestic Environments", *IEEE Trans. Instrum. Meas.*, vol. 53, 2004, pp. 1418–1424.

[3] M. J. M. Tavera, M. S. Dutra, E. Y. V. Diaz, O. Lengerke, "Implementation of Chaotic Behaviour on a Fire Fighting Robot", *In: 20th International Congress of Mechanical Engineering*, Gramado, Brazil, 2009.

[4] L. S. Martins-Filho, E. E. N. Macau, "Trajectory Planning for Surveillance Missions of Mobile Robots", *In: Studies in Computational Intelligence,* Springer, Heidelberg, 2007, pp. 109–117.

[5] S. Marslanda and U. Nehmzowb, "On-line Novelty Detection for Autonomous Mobile Robots", *Robot. Auton. Syst.*, vol. 51, 2005, pp. 191–206.

[6] P. Sooraksa and K. Klomkarn, "No-CPU Chaotic Robots: From Classroom to Commerce", *IEEE Circuits Syst. Mag.*, vol. 10, 2010, pp. 46–53.

[7] A. A. Fahmy, "Implementation of the Chaotic Mobile Robot for the Complex Missions", Journal of Automation, Mobile Robotics & Intelligent Systems, vol. 6, 2012, pp. 8–12.

[8] L. S. Martins-Filho and E. E. N. Macau, "Patrol Mobile Robots and Chaotic Trajectories", *Math. Probl. Eng.*, vol. 2007, 2007, p. 1.

[9] D. I. Curiac and C. Volosencu, "Developing 2D Trajectories for Monitoring an Area with two Points of Interest", *In: 10th WSEAS International Conference on Automation and Information*, 2009, pp. 366–369.

[10] B. Hasselblatt and A. Katok, "*A First Course in Dynamics: With a Panorama of Recent Developments*", University Press: Cambridge, 2003.

[11] L. M. Pecora and T. L. Carroll, "Synchronization in Chaotic Systems", *Phys. Rev. Lett.*, vol. 64, 1990, pp. 821–824.

[12] C. K. Tse and F. Lau, "Chaos-based Digital Connunication Systems: Operating Principles, Analysis Methods, and Performance Evaluation", Berlin, New York: Springer Verlag, 2003.

[13] Ch. K. Volos, I. M. Kyprianidis, and I. N. Stouboulos, "Experimental Demonstration of a Chaotic Cryptographic Scheme", *WSEAS Trans. Circuits Syst.*, vol. 5, 2006, pp. 1654–1661.

[14 M. Mamat, Z. Salleh, M. Sanjaya, N. M. M. Noor, and M. F. Ahmad, "Numerical Simulation of Unidirectional Chaotic Synchronization on Non-autonomous Circuit and its Application for Secure Communication", *Adv. Studies Theor. Phys.*, vol. 6, 2012, pp. 497–509.

[15] J. M. Gonzalez – Miranda, "Synchronization and Control of Chaos: An Introduction for Scientists and Engineers", Imperial College Press, 2004.

[16] Ch. K. Volos, I. M. Kyprianidis, and I. N. Stouboulos, "Various Synchronization Phenomena in Bidirectionally Coupled Double-Scroll Circuits", *Commun. Nonlinear Sci. Numer. Simulat.*, vol. 16, 2011, pp. 3356–3366.

[17] G. –Q. Zhong, "Implementation of Chua's Circuit with a Cubic Nonlinearity", *IEEE Trans. Circuits Syst, I*, vol. 41, 1994, pp. 934–941.

[18] Ch. K. Volos, I. Laftsis, and G. D. Gkogka, "Synchronization of two Chaotic Chua-type Circuits with the Inverse System Approach", *In: 1st PanHellenic Conference on Electronics and Telecommunications*, Patras, Greece, 2009.

[19] J. Von Neumann, "Various Techniques Used in Connection with Random Digits", G. E. Forsythe, Applied Mathematica Series-Notes: National Bureau of Standards, vol. 12, 1951, 36-38.

[20] NIST, "Security requirements for cryptographic modules", FIPS PUB 140-2, http://csrc.nist.gov/publications/fips/fips140-2/ fips1402.pdf, 2001.

[21] A. M Fraser, "Information and Entropy in Strange Attractors", *IEEE Trans. Inf. Theory*, vol. 35, 1989, pp. 245–262.

[22] S. Choset, "Coverage for Robotics - A Survey of Recent Results", *Ann. Math. Artif. Intel.*, vol. 31, 2006, pp. 113–126.