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A study of chaotic searching paths for their application in an ultrasonic scanner

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A R T I C L E I N F O

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A B S T R A C T

Most non-destructive ultrasonic automatic scanning tests are programmed with a complete systematic trajectory. However, when the location of a discontinuity (disturbance source) and the searching space are unknown, an exhaustive search can be time and computational inefficient. In this paper, the efficiency of chaotic trajectories to search for a discontinuity in an area with limited information is studied. The probability of detection and its relationship with topological properties of the proposed chaotic dynamic model is analyzed. The Pearson's random walk model is modified to substitute random for chaotic behavior by transferring the solutions of the chaotic dynamical model to the phase and modulus of the discrete path trajectories. This provides a simple description of the trajectories in a vector space where only magnitude and phase are required. Following this approach, the chaotic trajectories were generated in the working plane and then transferred to a Cartesian robotic ultrasonic system. The system was tested without human supervision on unknown environments for ultrasonic detection of hidden defects. The results show that the studied chaotic walk model provides efficient ultrasonic scanning trajectories for defect detection and can outperform systematic scanning when the geometry of the workspace is complex and unknown.

1. Introduction

Current nondestructive inspection and monitoring techniques use robotics systems to make them more versatile, faster, and autonomous. However, in real engineering structures, the random nature of the characteristics of discontinuities such as size, geometry, number, and location make target detection still a difficult task. Robotics, automation, and artificial intelligence can improve the efficiency and reliability of an ultrasonic search and could substitute traditional ones. One major challenge is how to efficiently inspect an engineering structure when its searching space geometry is unknown or not completely defined.

The accepted paradigm of an automatic ultrasonic c-scan involves an exhaustive systematic search following i.e. a squared wave type of parallel searching path, also known as raster or back and forth or variations of it such as the spiral-in and spiral-on method (Gertner and Zeevi, 1991). Thus, if the search step resolution is small enough, and the searching area is known, a complete scan of the inspected surface is likely. However, such a scheme can be time consuming and computationally very demanding and can also exhibit problems such as searching outside the search area and/or leaving areas unsearched. In addition, other factors that affect a successful discontinuity detection (probability of detection) are the discontinuity shape/orientation, material properties and sensor parameters, which may or may not be independent events. Probabilistic approaches have been used to account for these factors that affect detection (Williams and Mudge, 1985; Brierley et al., 2017).

The problem of searching for a stationary or non-stationary target by a mobile robot has gained considerable attention from the scientific community for its potential application in searching tasks such as in military, surveillance, or rescue operations (Benkoski et al., 1991). Several scenarios of searching can be described, if there is prior information of the target distribution, the searching problem is an optimization problem with time/path as the objective function (Yang et al., 2014); when there is no prior information then the search is a coverage problem with known or unknown environment (working-space) (Song et al., 2011). In manufacturing process optimization, detection and control using autonomous systems equipped with sensors has been studied (Al-Habaibeh and Parkin, 2003; Chauhan and Surgenor, 2017). The process task of searching for a target with an ultrasonic scanner requires an interdisciplinary approach that must account for the nature of the

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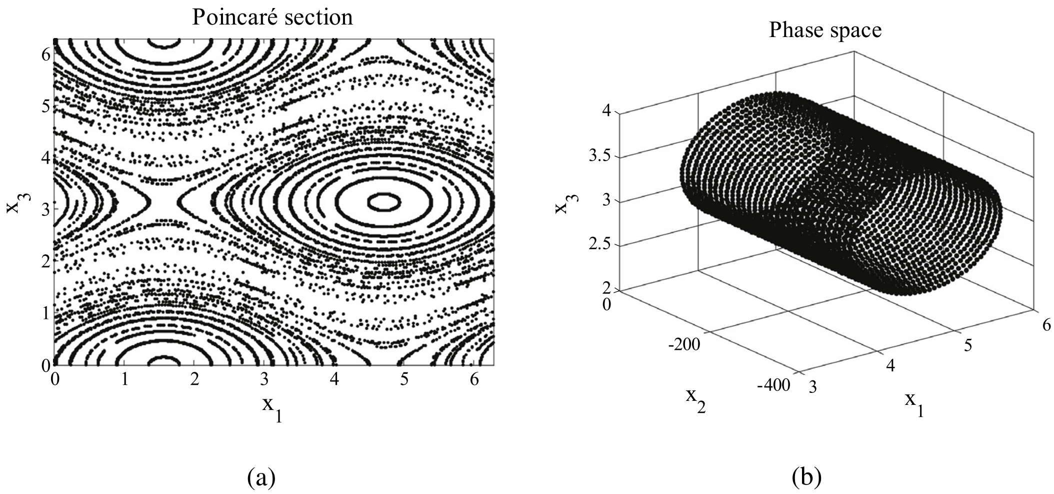

Fig. 1. (a) Poincaré map for $C = 0$; (b) solution of the system for initial conditions $x_0 = [5.25, 0, 3.67]$ which corresponds to one of points on the closed orbits of the Poincaré map.

sensor/target interaction, the agent (robot) that carries out the search, the environment, the data feedback, and finally the searching strategy (Lanillos et al., 2014).

Random walk mathematical models have been studied and applied in various areas of science and engineering. For example, in biological systems they were used to simulate moving paths for searching and survival using simple correlated random walk models (Kareiva and Shigesada, 1983); in engineering for modeling of systems such as wireless sensors networks (Nguyen, 2013); and in mathematics for global optimization search methods (Berrada et al., 2010). Here, we study the implementation of a chaotic walk to provide a simple 2D model that connects the chaotic model with a Cartesian robotic system.

In this paper, we study the solutions of the Arnold–Beltrami–Childress (ABC) dynamic system (Arnold, 1965; Dombre et al., 1986) to generate search trajectories with chaotic properties for an ultrasonic scanning system. The aim is to determine if these chaotic properties can improve the detection performance capability of the system. The specific objectives are: first, to study the topological properties of the ABC chaotic dynamical system and its effect on the probability of detection; second, to couple the 3D chaotic space of ABC model with the 2D workspace using a chaotic walk model; and third to develop a methodology that implements chaotic search in a Cartesian robotic system to inspect search areas with unknown workspace.

2. Properties of ABC chaos

Many dynamical systems with chaotic behavior have been implemented to optimize searches in multivariate analysis, the repertoire includes Logistic, Lorentz, among others. The goal was to substitute traditional, random, or classical optimization problems. This idea has been investigated in the target searching theory, by implementing chaotic maps into the searching schemes (Yang et al., 2014). In robotics, the possibility of incorporating chaotic paths in a mobile robot was investigated using the Arnold's flow equation (the so-called ABC flow equation) which is a continuous dynamic system (Nakamura and Sekiguchi, 2001). The appeal of using this model was, among others, its convenient trigonometric form that allows easy coupling with the dynamics of a mobile robot. The state equation of the ABC dynamical system can be described by:

$$\begin{Bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{Bmatrix} = \begin{Bmatrix} A\sin x_3 + C\cos x_2 \\ B\sin x_1 + A\cos x_3 \\ C\sin x_2 + B\cos x_1 \end{Bmatrix}. \tag{1}$$

This system of ordinary differential equations describes the three-dimensional (3D) steady state Euler flow for non-compressible perfect fluid (Ghrist, 2001) and was introduced by Arnold (1965). It involves three real constants A, B, C and a velocity vector $\left[\dot{x_1}, \dot{x_2}, \dot{x_3}\right]^T$. The flow in Eq. (1) can produce chaotic streamlines when all constants $A, B, C \neq 0$, that means that the particle flows of these streamlines have chaotic properties, they separate in time and appear to fill the entire space range. The solution of the system is in a 3D-torus and the flow is 2π-periodic in x_1, x_2, x_3. For chaotic flow, the role of A, B, C values have been investigated by Dombre et al. (1986), and the existence of chaotic flow and resonant streamlines was studied by Zhao et al. (1993).

In general Eq. (1) is not integrable, except for the case when one of the constants is equal to zero; for $C = 0$, Zhao et al. (1993) found the analytical solution by determining the Hamiltonian of Eq. (1). In this work, the ABC flow system is studied using the concept of the Poincaré map or section (Lynch, 2014). Fig. 1, shows results for $C = 0$ and the solution in the phase space. The Poincaré section represents resonant streamlines, exhibiting various resonant vortices with periodicity-2π in the two-torus resulting from the periodicity of Eq. (1) when $C = 0$. Each streamline in the phase space is found by selecting appropriate initial conditions as given in Fig. 1b for the initial conditions $\boldsymbol{x}_o = [5.25, 0, 3.67]$.

When $A, B, C \neq 0$, with the restriction $A \geq B \geq C > 0$, the solution generates a chaotic flow (Dombre et al., 1986). Fig. 2 shows the Poincaré section when $A = 1, B = 1/2, C = 1/2$. In contrast to previous results, here there are regions with a sea of scatter points and regions of unstable periodic orbits (Dombre et al., 1986). The magnitude of the flow ($\dot{x_i}$) in Eq. (1) changes according to the A, B and C values. If these values are increased with a fixed ratio $A:B:C$ the shape of the trajectory will remain the same but the travel distance will increase.

We further investigate the relation between the initial value vector and the statistical properties of the obtained trajectories. Fig. 3 shows statistical properties in the x_3-axis, it can be seen that there is a correlation between the shape of the histogram distribution and the location of the initial $\boldsymbol{x}_0$ values in the Poincaré map (Fig. 2). The position distribution pattern as $t \to \infty$ in regions with homoclinic orbits (in this example for $\boldsymbol{x}_0 = [.67, 0, 1.60]$) resembles that described by an harmonic function (Fig. 3a). However, at regions filled with disperse points (sea of scatter points), the statistical distribution of x_3 approaches a uniform distribution (Fig. 3b).

To summarize the observed behavior, a chaotic dynamical system has the following properties: (1) sensitivity to initial conditions, (2) topological transitivity (mixing), (3) dense periodic points. The first property implies that given a continuous function f and the points $x, y \in X$, where X is a set of points, a parameter $\delta > 0$ exists, such that for all $\varepsilon > 0$ and n iterates, the conditions $|x - y| < \varepsilon$ and $|f^n(x) - f^n(y)| > \delta$ holds showing high dependence to initial conditions. It implies that if a system is allowed to evolve from two slightly diverging initial