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A 2D chaotic path planning for mobile robots accomplishing boundary surveillance missions in adversarial conditions

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ABSTRACT

The path-planning algorithm represents a crucial issue for every autonomous mobile robot. In normal circumstances a patrol robot will compute an optimal path to ensure its task accomplishment, but in adversarial conditions the problem is getting more complicated. Here, the robot's trajectory needs to be altered into a misleading and unpredictable path to cope with potential opponents. Chaotic systems provide the needed framework for obtaining unpredictable motion in all of the three basic robot surveillance missions: area, points of interests and boundary monitoring. Proficient approaches have been provided for the first two surveillance tasks, but for boundary patrol missions no method has been reported yet. This paper addresses the mentioned research gap by proposing an efficient method, based on chaotic dynamic of the Hénon system, to ensure unpredictable boundary patrol on any shape of chosen closed contour.

1. Introduction

Mobile autonomous robots are intelligent real-time systems that operate in structured or unstructured environments without explicit human involvement. Their real-life applications are spread in a wide variety of domains where tedious or hazardous tasks must be precisely accomplished, from elderly and disabled care [1], precise agriculture [2–4], disaster intervention [5,6], to complex industrial activities [7].

The motion planning represents a fundamental issue for such robots, being tackled by numerous researchers over time. Basically a path-planning algorithm has to provide an optimal trajectory, when diverse constraints are applied, for the robot to accomplish its tasks. This is not a simple problem to solve due to the frequent and random changes in the environment. Moreover, when autonomous robots evolve in adversarial conditions, a new attribute must be considered by the path-planning mechanism for coping with possible opponents: unpredictability of the trajectory for any external observer.

Previous research addressed two basic types of robot surveillance missions: monitoring an area and monitoring points of interest. When speaking about the third kind of surveillance missions – boundary surveillance, from our knowledge, no approach for unpredictable trajectories has been reported so far. This paper fills this research gap by proposing a robot path-planning methodology based on Hénon discrete chaotic system. We started with the analysis of a mobile coordinate frame in which a Hénon chaotic system evolves. If this frame is translated with a finite velocity along a closed contour marked in a stationary frame (the origin of the mobile frame performs a periodic motion along the closed contour), we observed that a brand-new chaotic system was constructed. As a remarkable fact we find that the Lyapunov exponents are

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conserved during this transformation even though the new-type trajectories have other shapes. Practically speaking, the arbitrarily-chosen boundary that must be monitored by the patrol robot is chaotified with the means of kinematic relative motion and the use of Hénon system.

The rest of the paper is organized as follows. Section 2 presents the state of the art in the field of generating chaotic trajectories for mobile robots. Section 3 provides the theoretical support for our methodology, demonstrating that the new robot trajectories are indeed chaotic. Section 4 thoroughly presents the novel step-by-step methodology, accompanied by three illustrative examples described in Section 5. The last section outlines the conclusions and final remarks.

2. Related work

In adversarial conditions, the unpredictability of a robot trajectory represents a crucial issue. It can be addressed using either random or chaotic sequences of waypoints. In both cases, the enemy entities cannot predict the future trajectory, but due to its deterministic nature, the chaotic path represents a better alternative. The reason lies in the fact that ally entities, knowing the initial conditions and formulas of chaotic system, are able to predict the robot path and, as a result, to make proper decisions.

Chaotic systems, due to their "sensitivity to initial conditions" feature [8], provide the much-needed framework in achieving the unpredictability in all the three basic types of surveillance missions: monitoring an area; monitoring a set of points of interest (set of precise objectives); or monitoring the boundary of a specified area.

The area surveillance missions presume an efficient coverage of all sections of a specified perimeter. This particular topic was addressed by some relevant research papers [9–15].

Nakamura and Sekiguchi [9] designed and implemented a chaotic motion controller for mobile robots able to sense the workspace boundary when arriving in its proximity. Their idea was to interconnect the control variables with state variables of the Arnold equations and by this to impart the chaotic behavior of incompressive fluid flow to the robot.

Martins-Filho and Macau proposed an ingenious path-planning mechanism where the sequence of intermediary goal positions is obtained using the well-known Chirikov–Taylor standard map [10,11]. This area-preserving chaotic map, besides its chaotic features originating from the dynamics of a kicked rotor, eliminates the need for boundary sensing.

Volos, Kyprianidis and Stouboulos [13,14] based their trajectory planning methodology on the use of the Logistic map. Here, a chaotic random bit generator provides a time-ordered succession of future robot positions, with the experimental results proving highly efficient and opportunistic area coverage. Another implementation based on the Logistic chaotic map, but this time improved by arcsine and arccosine transformations, is presented in [15].

The second type of surveillance missions was tackled in two of our previous papers. The first one presented an original method to monitor two points of interest based on a modified Lorenz system [16] and was followed by a generalized method that uses two types of 3D chaotic systems (Lorenz and Chen) to develop unpredictable trajectories for surveilling an indefinite number of specified points [17].

This paper addresses another kind of patrol robot mission - boundary surveillance, with the proposed methodology being based on the kinematic relative motion concept and the chaotic nature of the Hénon system.

3. Theoretical framework

In adversarial conditions an autonomous patrol robot must follow a path that cannot be easily predicted or understood by opponents. For boundary patrol missions, the problem can be formulated as follows:

> Problem formulation. Consider a given closed contour C in a two-dimensional Cartesian frame that has to be monitored by a patrol robot. The objective is to design a trajectory, unpredictable for possible opponents, developed in the proximity of C that assures efficient boundary surveillance.

In our vision, two ways can be pursued in solving this problem: (a) to find an already known chaotic system with the same shape as the given bounding line and adapt it via diverse transformations (e.g. affine transformations); or (b) to construct a new chaotic system tailored for this specific application. The first possibility is applicable for a limited number of boundary shapes so, a general method to create customized chaos may be the proper solution.

In this endeavor we started with the analysis of the well-known Hénon chaotic system [18]. We will demonstrate that if we slide an evolving Hénon system on a closed contour, a chaotic trajectory will be obtained. Practically speaking, with the means of kinematic relative motion concept we can design unpredictable paths in the vicinity of any given closed contour.

3.1. Hénon chaotic system

Analyzing the Lorenz chaotic system [19], the French astronomer and mathematician Hénon [18], discovered a two-dimensional discrete map exhibiting similar properties. His system is described by the following set of equations: