# Unmanned Aerial Vehicle Coverage Path Planning Algorithm Based on Cellular Automata *

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*Abstract*—**Real-time unmanned aerial vehicle coverage path planning is a challenging task. Although different patterns are outlined and optimized, the algorithm of patterns generation given the width of the sensor's footprint and the map with obstacles is rarely studied. A Cellular Automaton (CA) based algorithm is proposed and implemented for the spiral pattern and tested in maps with obstacles on the corner and off the edge. The CA is asynchronously updated and there is only one UAV-cell, whose time series indexes through the computing can be assigned as the coverage path. The coverage path planning algorithm proposed in the paper is fast because of the intrinsic discreteness of CA.**

***Keywords—Unmanned Aerial Vehicle, Coverage Path Planning, Cellular Automata***

## I. INTRODUCTION

An unmanned aerial vehicle (UAV), an aircraft without a human pilot aboard, was originally used for missions too "dull, dirty or dangerous"[1] for humans mostly in military applications such as battlefield assessment and airbase reconnaissance. Then their use is rapidly expanding to commercial, scientific, agricultural, and other applications such as assessment of damage after natural disasters[2], victim detection [3], and aerial photography since it is well-suited for carrying various sensors onboard as a fast and highly maneuverable platform.

Usually the field of view of a sensor onboard is restricted (affected by the UAV's height and the required resolution) and is typically much smaller than the area of interest. To acquire the overall view of the area of the workspace, a mosaic is often built using successive images taken during the flight. This leads to the coverage path planning problem in which a flight path of UAV should be found that allows efficient capture of successive images so that they can make a coverage of the task region.

In the UAV coverage path planning problem, the convex region can be easily and efficiently covered using zigzag or spiral pattern. The total flight time consists of the time to travel along the rows plus the time to turn around at the end of the rows. [4,5] designed the zigzag flight path considering the diameter of the polygon area measured along the sweep direction to minimize the number of turns. Each UAV has to compute the sweep direction which minimizes the number of turns needed along a zigzag pattern.

In this paper, we consider algorithm based on Cellular automata (CA) to generate UAV's coverage path with given width of footprint on the ground.

The idea of CA was invented by John von Neumann and his collaborator Stanisław Ulam in the 1940s and 1950s to describe self-reproductive and evolvable behavior of living systems. Because CA is a very powerful tool in describing highly nonlinear spatial-temporal dynamics in a simple and concise manner, it has been extensively utilized for modeling various phenomena. It has also been utilized for computational applications such as random number generation, image processing, and cryptography [6]. Ioannidis [7] presented a CA-based method for solving two specific problems, collision avoidance and formation control, in the path planning problem in a cooperative robot team.

The rest of the paper is organized as follows. All necessary information for CA is provided in the next section. The proposed CA algorithm as well as the corresponding simulation results produced by the CA model is presented in section 3. The implementation of the proposed algorithm for spiral pattern coverage path planning constituted of obstacle cells, is described in full detail in the next section titled, Implementation details and simulations results. Conclusions are drawn in the final section.

## II. CELLULAR AUTOMATA

In general, CA are defined as a spatially distributed dynamical system where both time and space are discrete. A CA model consists of a set of cells (automata or sites) arranged along a regular $d$-dimensional discrete spatial grid (usually $d$ = 1, 2, or 3), each in one of a finite number of states. A set of $S(\vec{x},t) = \{s_1(\vec{x},t), s_2(\vec{x},t), \dots, s_m(\vec{x},t),\}$ of states attached to each cell $\vec{x}$ giving the local states of each cell at the time $t = 0,1,2,\cdots$. $S(\vec{x},t)$ are updated by a uniformly applied state-transition function $F = \{f_1, f_2, \dots, f_m\}$ that refers to the states of their neighbors in the following way

$$s_i(\vec{x}, t+1) = f_i\left(S(\vec{x}, t), \dots, S\left(\vec{x} + \delta_q, t\right)\right) \quad (1)$$

where $\vec{x} + \delta_q$ designate the cells belonging to a given neighborhood of cell $\vec{x}$.

In the above definition, $S$ is a function that maps cell to states, which is called a configuration of the CA at time t. A configuration intuitively means the spatial pattern that the CA display at that time.

The state transition function $F$ can be described in the form of a look-up table, some mathematical formula, or a more high-level algorithmic language. $F$ is conventionally assumed to be applied simultaneously to all cells, leading to synchronous updating. But we can break this convention to make the dynamics asynchronous. There are several asynchronous updating mechanisms are possible, such as sequential updating (cells are updated in a predetermined sequential order), random updating (a randomly selected cell is updated at each time step), state-triggered updating (certain states trigger updating of nearby cells), etc.

The neighborhood of cell $\vec{x}$ is usually set up so that it is centered around the focal cell being updated $(x_0)$ and spatially localized $(|x_i - x_0| \leq r, for\ i = 1,2,\cdots,n-1)$, where $r$ is called a radius of $N$.

CAs have sufficient expressive dynamics to represent phenomena of arbitrary complexity and at the same time can be simulated exactly by digital computers because of their intrinsic discreteness [7]. Algorithms based on CA models are fast when implemented on serial or parallel computers, because they can exploit the parallelism of the CA structure [8].

## III. CA-BASED COVERAGE PATH PLANNING ALGORITHM

The objective of the proposed algorithm is the efficient computation of the coverage path of UAV. The main idea is to generate a time series of UAV-cell indexes as the coverage path. There is only one UAV-cell at each time step and the UAV-cell and its neighbors evolve their states according to their current states according to the updating rules. Every cell can be a UAV-cell and is stands for the UAV is fly over this cell at the time being.

Let $m \times n$ cells be the dimensions of the CA and $h_{ij}$ the height of each cell. Each CA cell can take a finite number of possible states and every cell could obtain one possible state at each time step:

- White cell: $s(i,j) = 0$
- Black cell: $s(i,j) = 1$
- Obstacle cell: $s(i,j) = 2$
- UAV-cell: $s(i,j) = 3$

Where $s(i,j)$ is the state of the cell with $i$ and $j$ Cartesian coordinates.

The three-dimensional region in which the UAV operates is divided into a simple rectangular grid of identical square cells whose height information is compressed to one parameter. Each cell has a parameter of height that may be the maximum, the minimum or the mean height within the cell.

As the UAV moves between waypoints taking shots, the field of view of the camera defines an imaged area on the terrain.

Considering a plain terrain, the sensing width of the UAV moving in the x-z plane of the Base Coordinate System, fixed in the environment (x-axis towards north, y-axis west, z-axis up) is given by [5] (see Fig. 1):

$$w = 2z_{BCS} \cdot tan\gamma \left[sin\alpha + cos\alpha \cdot tan\left(\frac{\pi}{2} - \alpha - \beta\right)\right] \quad (2)$$

Where $\alpha$ is the angle of the onboard camera with respect to the x-axis of UCS (UAV Coordinate System) that changes its point of origin and its orientation with the movement of the vehicle (x-axis forward, y-axis left, z-axis up). Angles $\beta$ and $\gamma$ determine the field of view of the camera.

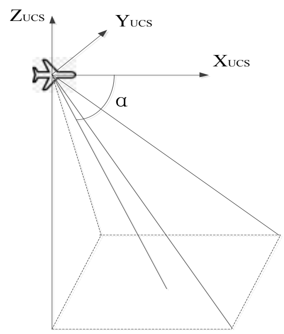



Fig. 1. The imaged area of UAV on the terrain

CA rules can be deduced from coverage path patterns such as the spiral pattern and the back and forth scanning pattern. More details will be provided for the spiral pattern in the following section. Appropriate CA rules are selected so that a coverage path of UAV-cell can be generated. The overall algorithm is shown in Fig. 1

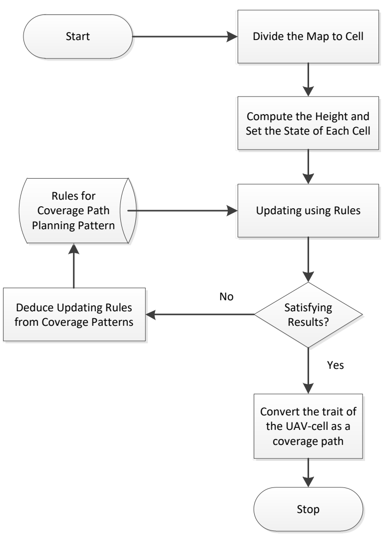



Fig. 2. CA-based coverage path planning algorithm

## IV. Implementation Details and Simulations Results

Moore neighborhood [9], which comprises the eight cells surrounding a central cell on a two-dimensional square lattice, was used for the spiral pattern.

At each time step, the UAV-cell and its neighbor of the CA evolves their state according to their current states. If there is no UAV-cell in $S(x,y,t)$, $S(x,y,t)$ will not be updated in the next time step.

For simplicity, the UAV-cell's state and the state of every neighboring cell are arranged in a counter- clockwise direction as the following states list

$$S(x,y,t) = \{s(x,y,t), s(x-1,y-1,t), s(x,y-1,t), s(x+1,y-1,t), s(x+1,y,t), s(x,y,t), s(x-1,y,t), s(x-1,y+1,t), s(x,y+1,t), s(x+1,y+1,t)\}$$

Considering a UAV-cell with the states set $S(x,y,t) = \{3,1,1,0,0,0,0,0,0\}$ , these states will evolve to $\{1,1,1,3,0,0,0,0,0\}$ in the next time step if the spiral pattern is applied as shown in Fig. 2.

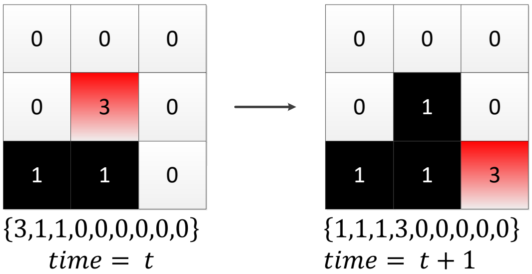


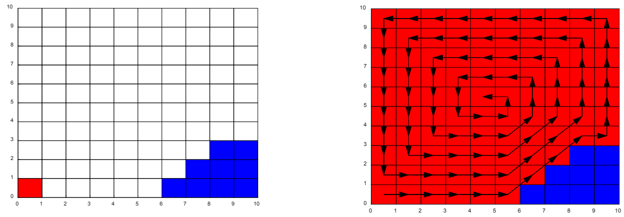
Fig. 3. An example of spiral pattern updating

All update rules for the spiral pattern are listed in Table 1. X stands for 0 or 1 for reason of simplicity.

TABLE I. CA rules for the Spiral Pattern Coverage Path Planning

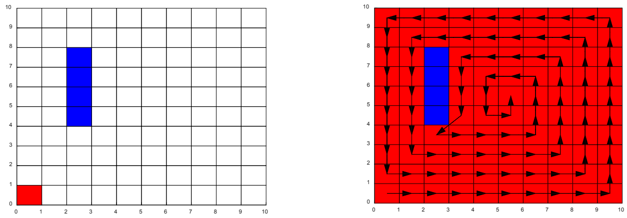
| | |
|---|---|
| Rule 1 | 3110XXXXX→1113XXXXX |
| Rule 2 | 31110XXXX→11113XXXXX |
| Rule 3 | 3X1110XXX→1X1113XXX |
| Rule 4 | 3XX1110XX→1XX1113XX |
| Rule 5 | 3XXXX110X→1XXXX113X |
| Rule 6 | 3XXXX1110→1XXXX1113 |
| Rule 7 | 30XXXXX11→13XXXXX11 |
| Rule 8 | 310XXXX11→113XXXX11 |

For a CA with 10 × 10 cells, the resulting coverage paths are shown in Fig. 3 and Fig. 4. It can be seen that spiral pattern paths have been assigned for each case with obstacle cells on and off the corner.



Initial states Final states

Fig. 4. Example of spiral pattern coverage path planning with obstacle cells on the corner



Initial states Final states

Fig. 5. Example of spiral pattern coverage path planning with obstacle cells of the corner

## V. Conclution

The algorithm of UAV coverage path planning based on CA in a three-dimensional area has been considered. The CA of the coverage path planning algorithm proposed in the paper is asynchronous, only the UAV-cell and its neighbors are updated at each time step and there is only one UAV-cell. If appropriate rules are assigned, the time series of UAV-cell updated will be a coverage path. The method was implemented in a three-dimensional area where obstacles are considered in the CA as obstacle cells.

The main advantages of the proposed CA-based algorithm, compared with other coverage path planning approaches, are that it can be implemented in a simple, discrete manner and provides a spectrum of solutions useful for real-time implementation. The algorithm can be easily extended to other patterns of the coverage path.

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