UNIVERSITI PUTRA MALAYSIA

CELLULAR AUTOMATA-BASED ALGORITHM FOR LIQUID DIFFUSION PHENOMENON MODELING USING IMAGING TECHNIQUE

ABBAS MOHAMMED ALI AL-GHAILI

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By

ABBAS MOHAMMED ALI AL-GHAILI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

July 2013

DEDICATION

TO MY PARENTS,

TO MY SISTERS,

TO MY BROTHERS,

TO MY WIFE,

TO MY SON

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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ABBAS MOHAMMED ALI AL-GHAILI

July 2013

Chairman: Khairulmizam Samsudin, PhD

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Recently, the prediction of the dynamical behavior of Liquid Diffusion Phenomenon (LDP) has been used in many applications especially in physical and biological fields. Many models have been proposed to predict the LDP behavior, but most of them require complex mathematical calculations causing computation time consumption. This thesis proposes a dynamical behavior prediction algorithm using Cellular Automata (CA) to model the LDP.

A real liquid diffusion phenomenon is recorded whereas the observed images are later extracted for comparing purpose with the predicted phenomenon. First, a mathematical method is proposed in order to track and then analyze the real diffusion behavior. This method has used thousands of original images. Then, thousands of images, as the same number of original images, are created by the CA-based algorithm. In this study, the diffusion speed of the predicted LDP is also computed by using a mathematical proposed algorithm which is the Diffusion Speed Algorithm (DSA). Finally, three benchmark strategies are used in order to compare the predicted images to the original images, which are: pixel intensity, Region-of-Diffusion (ROD) area, and ROD shape.

The experiments of this thesis are divided into original and predicted images. The original images are classified into three groups based on the temperature used, which are: ±18 °C, ±24 °C, and ±30 °C. Each temperature-based experiment contains five levels of the height of droplets source. The diffusion time has been equal to 32 seconds with 15 fps comprising 480 images per each experiment. On the other hand, the predicted images are similarly classified. There will be 15 predicted experiments created by the proposed CA algorithm. The whole predicted images are compared to their corresponding original ones. Under the experiments samples, there are 30 processed experiments comprising 14400 original and predicted images. The obtained results show that the averaged similarity percentage is equal to 94.4%. Additionally, the average computation time needed to complete processing a single experiment is 1.3 second. The result obtained from the proposed LDP model compared to other competitive LDP models has higher accuracy and less computation time. The results also show that the proposed LDP model is about 15 times faster than a neural network-based model. A detailed study to explore the effects and relationships between the model's parameters such as temperature and liquids' viscosity has been performed. The results showed that there is a direct relationship between the temperature and the diffusion speed.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ALGORITMA BERASASKAN AUTOMATA SELULAR UNTUK PEMODELAN FENOMENA PENYEBARAN CECAIR MENGGUNAKAN TEKNIK PENGIMEJAN

Oleh

ABBAS MOHAMMED ALI AL-GHAILI

Julai 2013

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Kebelakangan ini, ramalan kelakuan dinamik Fenomena Sebaran Cecair (FSC) telah digunakan dalam pelbagai aplikasi terutamanya dalam bidang fizik dan biologi. Banyak model telah diutarakan untuk meramalkan kelakuan FSC, tetapi kebanyakannya memerlukan pengiraan matematik yang rumit yang menyebabkan penggunaan masa komputasi. Tesis ini mengemukakan sebuah algoritma peramalan kelakuan dinamik menggunakan Automata Selular (AS) untuk memodelkan FSC.

Suatu fenomena sebaran cecair sebenar dirakamkan manakala imej-imej yang dilihat dikeluarkan untuk tujuan perbandingan degan fenomena yang diramalkan. Pertamanya, suatu kaedah matematik dikemukakan untuk mengikut dan kemudian mengkaji kelakuan sebaran yang sebenar. Kaedah ini menggunakan beribu-ribu imej sebenar. Kemudiannya, ribuan imej, jumlah sama dengan imej-imej asal, telah dijana oleh algoritma berasaskan AS. Dalam kajian ini, kelajuan sebaran FSC juga dikira

menggunakan algoritma matematik yang dikemukakan, yakni Algoritma Kelajuan Sebaran (AKS). Akhir sekali, tiga strategi penilaian digunakan untuk membanding imej-imej yang diramal dengan imej-imej sebenar, yakni: keamatan piksel, kawasan Persekitar Sebaran (PS) dan bentuk PS tersebut.

Ujikai-ujikaji tesis ini terbahagi kepada imej-imej sebenar dan imej-imej ramalan. Imej-imej sebenar terbahagi kepada tiga kumpulan berdasarkan suhu yang digunakan, iaitu: ±18 °C, ±24 °C, dan ±30 °C. Setiap ujikaji berasaskan suhu mengsndungi lima tahap sumber titisan. Masa sebaran bersamaan 32 saat dengan 15 fps terdiri daripada 480 imej setiap ujikaji. Manakala, imej-imej ramalan juga diklasifikasi dengan cara yang sama. Akan terdapat 15 ujikaji yang dihasilkan daripada algoritma Automata Selular. Kesemua imej-imej ramalan dibandingkan dengan imej-imej asal yang berkaitan. Di bawah sampel ujikaji, terdapat 30 ujikasi yang telah diproses terdiri daripada 14400 imej asal dan ramalan. Hasil yang didapati menunjukkan bahawa purata peratusan kesamaan adalah 94.4%. Tambahan lagi, purata masa komputasi yang diperlukan untuk menyelesaikan pemprosesan setiap ujikaji ialah 1.3 saat. Hasil yang dipperolehi daripada model FSC yang dikemukakan ini berbanding dengan model FSC saingan mempunyai ketepatan yang lebih tinggi dan masa komputasi yang lebih rendah. Hasil juga menunjukkan bahawa model FSC yang dikemukakan ini adalah 15 kali ganda lebih cepat. Sebuah kajian untuk meneroka kesan dan perkaitan di antara parameter-parameter model seperti suhu dan kelikatan cecair telah dijalankan. Hasil menunjukkan bahawa terdapat kaitan terus di antara suhu dan kelajuan sebaran.

ACKNOWLEDGEMENTS

All praise to supreme Allah (S.W.T.). The only creator, cherisher, sustainer, and able who gave me the ability to accomplish this project successfully.

I would like to thank my supervisor, Dr. Khairulmizam Samsudin, for embarking with me on this project. There is nothing greater than the gift of working in a field one loves, and you allowed for this to happen. This has been an amazing learning experience. Thank you for your time, your invaluable patience to accomplish this work successfully.

My deepest gratitude goes to Associate Professor Dr. M. Iqbal Saripan. Your help has been invaluable, as an advisor, guide, and family friend. Thank you for your trust, encouragement, and for creating opportunities and directing them my way. I will be in eternal debt to you.

Very special thanks to Dr. Wan Azizun Wan Adnan and the Faculty and Staff of the Department of Computer and Communication Systems. It has been an honor to work with you these past three years. You have provided me with professional and life experience, friendship and support, and made this dream true.

I am very grateful for the support of my friends in particular Dr. Ahmed Muhsen and Naif Mohammed.

I certify that a Thesis Examination Committee has met on 30 July 2013 to conduct the final examination of Abbas Mohammed Ali Al-Ghaili on his thesis entitled “Cellular Automata-based Algorithm for Liquid Diffusion Phenomenon Modeling using Imaging Technique” in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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DECLARATION

I hereby declare that the thesis is based on my original work except that for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at the Universiti Putra Malaysia or other institutions

ABBAS MOHAMMED ALI AL-GHAILI

Date: 30th July 2013

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LIST OF ABBREVIATIONS

1D CA	One Dimensional Cellular Automata
2D CA	Two Dimensional Cellular Automata
CA	Cellular Automata
CAA	Cellular Automaton Algorithm
CS	Cell State
DB	Diffusion Behavior
DS	Diffusion Speed
DSA	Diffusion Speed Algorithm
EHD	Edge Histogram Descriptor
fps	frames per second
FS	Flag State
HCA	High Concentration Area
LCA	Low Concentration Area
LD	Liquid Diffusion
LDP	Liquid Diffusion Phenomenon
M	update rule Move
NN	Neural Network
NRMSE	Normalized Root-Mean-Square Error
OpenCV	Open Computer Vision
PDE	Partial Differential Equation
RMSE	Root-Mean-Square Error
ROD	Region-of-Diffusion
ROI	Region Of Interest
TDBM	Tracking Diffusion Behavior Method
VNN	Von Neumann Neighborhood
VPM	Video Processing Method

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Computer-based Physical Phenomena Modeling

Computer-based modeling of several natural and physical phenomena is an important subject for researchers from different scientific fields. To model a physical phenomenon, two very important issues should be considered which are: understanding its related physical basics and formulating its mathematical equations. This is called 'mathematical modeling of physical phenomena'.

Recently, due to that the capability of computers to numerically calculate the output of complicated and huge calculations has made a real evolution of the use of the mathematical modeling, thereby, the computer-based modeling has become an important technique in applied science and technical research.

To well understand the physical phenomenon, a qualitative observation is needed first [1]. Quantitative measurements are then required to answer the question: "what is the reason of that phenomenon?" Once the question is answered, the phenomenon could be mathematically formulated and modeled.

There is no a specific mathematical formulation must be used to model such a phenomenon. There are, however, different mathematical-based techniques could be used and consider the physical nature of the modeled phenomenon.

1.1.2 Liquid Diffusion Phenomenon (LDP) Modeling

One of the commonly occurred phenomena in nature is the liquid diffusion. Modeling this phenomenon could be performed by pouring an amount of liquid on the water surface [2]. The liquid is slightly heavier than water. The diffusion process will then generate a two dimensional view on the liquid surface inside the container. This phenomenon could be observed and captured as a video scenario. This could generate a real images sequence.

To model the Liquid Diffusion (LD), the dynamical behavior of diffusion growth movement should be predicted. Before the prediction process is built, the real scenario of Liquid Diffusion Phenomenon (LDP) must be clearly observed under different conditions, such as temperature and viscosity variation. Then, the mathematical equations should be formulated and numerically modeled. Finally, the computer code is written by using a suitable programing language in order to achieve the prediction process and to further physically model the LDP.

1.1.3 Cellular Automata (CA)

1.1.3.1 CA History

Originally, S. Ulam and Von Neumann [3-5] have defined the CA concepts and proposed a method in which different computations and operations had been executed [6]. Later, many developments have been proposed to enhance this theory and make it practical to model various phenomena [7, 8].

1.1.3.2 CA Definition

Cellular Automata (CA) are dynamical systems, discrete in space and time [9], performing complex computations in a simple mathematical way by depending on the local information. CA are thus used to model many natural phenomena [6, 7].

1.1.3.3 CA Components

Usually, CA are performed as a network in which each node is considered as a single cell with a finite number of states. Each cell will be updated with a specific value (cell state) in accordance with an updating rule (local rule or transition function). The current cell state (e.g., at time *t*) depends on the cell state and neighboring cells' states at time *t-1*. Mainly, CA have three components, as follows:

1- Cells array: this can be in a form of one dimension, two or three.

2- Cell state: this is the value that can be assigned for the current cell.

3- Update rule (transition function): this is a mix of mathematical operations in order to create the next state of a cell, by depending on the current states of neighboring cells. The transition function is applied on all cells of processed images within a model [7].

1.1.3.4 CA Features

One of the key features of CA is the highly performed efficiency in modeling complex natural phenomena and/ or predicting their dynamical behaviors. Scientists and researchers from various fields have therefore been encouraged to exploit such a feature [6]. To achieve high CA performance, the update rule has to be precisely defined. The update rule plays an important role in CA systems because it controls the next state and affects the model's accuracy. Therefore, the update rule should be dynamically defined in accordance with the nature of the modeled phenomenon and the desired application [10]. The reason is that each phenomenon in nature has its own distinguishable dynamical behavior [11-16].

1.1.3.5 CA Types

There are different dimension-based CA types while designing the lattice of the CA model. It could be in a form of One Dimensional CA (1D CA), Two Dimensional CA (2D CA), or more. For each type, there will be different designs of neighborhood relationships and the state of updating rule. In the 1D CA type, the neighborhood of the current state will be the nearest two neighbors in one direction. The next state will be updated based on its current state and those two neighbors. Quite similarly, the neighborhood of the 2D CA lattice could be whether Von Neumann-based (4-neighbors) or Moore-based (8-neighbors) [17].

Consequently, CA could be considered as a powerful tool to be used to simulate several diffusion problems with high accuracy as well as high speed. Simply, the simulation procedure of CA depends on local rules, unlike other methods which need to give a governing equation for the whole proposed model [18]. In addition, the CA-based models, at most, use discrete variables; so that no accumulated numerical error will be occurred.

1.1.3.6 CA Applications

CA have been used to model different applications in different fields such as error correcting code [19], in cryptography field [20], gaming field [21], parallel processing [22, 23], modeling of physics laws [24], and so on.

1.2 Motivation

This work was motivated by the problem of predicting the dynamical behavior of LD through other liquids. The currently existed models depend on complex mathematical methods. Therefore, there is a need to reduce this complexity and gain more saving time. Another motivation is that the proposed models have used whether a specific temperature of room and liquids or a specific height of droplets source. Thus, a wide range of temperature and varied height also will be studied in this research work to consider the reality conditions and circumstances.

1.3 Scope

Many researches have been proposed to predict the dynamical behavior of LDP by using Partial Differential Equation (PDE) and Neural Network (NN). The research study, in this thesis, focuses only on the LDP model from a cellular automaton point of view in order to reduce the complexity of modeling. So that the computation time could be reduced compared to other works and researches.

This research will focus on:

1. The computation time of the LDP model.
2. The exploitation of CA's features.
3. The possibility of building a LD prediction model.
4. Simplification of prediction the dynamical behavior of the LD.

1.4 Contribution

A new algorithm has been proposed to predict the dynamical behavior of LDP by using CA to create the output with high similarity compared to the original behavior. In addition, a fast LDP model could be used in real-time applications; whereas the computation time of the proposed model much overcomes other competitive models'.

Additionally, other applications could use it as a math descriptor to graphically present the behavior for a number of similar phenomena, such as clouds movement prediction [18], dye diffusion, and injection diffusion through human's blood.

Furthermore, another contribution has been made by proposing two algorithms for tracking the diffusion behavior as well as calculating the diffusion speed.

1.5 Problem Statement

In recent years, researchers have worked on the area of the dynamical behavior prediction of LDP by using PDE or NN. One example of these works is the approach proposed to predict the dynamical behavior of liquid diffusion in water [2] by using 2D NN. For the PDE-based models, Eq. (1.1) is usually used:

$$\frac{\partial}{\partial t}\phi(x,t) = D\nabla^2 \phi(x,t) \tag{1.1}$$

where ϕ is the density of the diffused particles, x is the diffusing particle's location, t is the moment of time, D is the diffusion coefficient, and ∇ is the vector differential operator del.

To solve Eq. (1.1), numerical approximation, such as the finite element method is used. This strategy requires more computation time. Furthermore, this equation depends on boundary conditions and several other parameters. As seen, the PDE-based or NN-based models require further computation time caused by the complexity of the calculations or the training time. This thesis aims to propose an LDP model by using CA in order to overcome the complexity and to reduce the computation time.

On the other hand, the prediction of the dynamical behavior of LDP is important since it commonly occurs in nature in different conditions. However, most of the proposed LDP models have been working under strict conditions, such as the distance between the droplets and liquid container is fixed, the temperature is fixed, or the viscosity of liquids is fixed. In this thesis, these parameters are considered and analysed. Furthermore, the relationships between each others are derived and concluded.

1.6 Aim of Work

While the aim of this work is to predict the dynamical behavior of natural phenomenon, thus there is a need to show the predicted output in a suitable form in which the observation of the output change with time passing is comparable with the real behavior of the simulated/ predicted phenomenon. Simply, a set of sequential images to be displayed on a screen could fulfill this purpose. In this case, the chosen time interval has to have two features; the ability to be as smooth as possible to mimic the real behavior and also the ability to enable the proposed model to be used with real time applications.

Since the LDP behavior has its own dynamical behavior in the nature, the prediction process requires building a method in which the sequence of output images is smoothly moving. The proposed model for this purpose has a set of steps. One of the most important steps in the proposed model is the algorithm that processes every pixel in the input image in order to output a new image after passing a certain period of time. The mode the LDP behaves requires the proposed algorithm to be repeatedly applied for a period of time.

Based on this, two issues have to be considered in building the wanted model. These are the iterations of the process of each image to simulate the LDP real behavior and the process of a huge number of pixels which are created from iteration process in the prior step.

1.7 Objectives

The objectives of this thesis are to:

- Propose, design and implement a CA-based LDP algorithm.
- Propose a method to track the liquid diffusion behavior using image processing.
- Propose a fast LDP model to a suitable real-time application usage.

1.8 Thesis Organization

This thesis is divided into five chapters, as follows:

- Chapter One provides an introduction to the research work. Several related topics to this study, such as computer-based physical phenomena modeling, liquid diffusion phenomenon, and cellular automata are introduced. The scope, motivation, contribution, problems, objectives, are stated and discussed as well.

- Chapter Two discusses the theoretical background of the LDP models. In this chapter, the previous studies and works for modeling different phenomena by using cellular automata have been reviewed. Also, the proposed works that model the liquid diffusion phenomenon have been reviewed and highlighted. A brief review about the motion-based velocity measurement algorithms and edge-based image description algorithms has been included. This chapter has also discussed the limitations of the liquid diffusion phenomenon. At the end of this chapter, a general summary has been provided.

- The methodology of the proposed model is given in Chapter Three. It consists of hardware and software parts; the architecture of the proposed model is illustrated. The software part has five main components. Each component consists of one or more proposed algorithms.

- Chapter Four introduces the proposed algorithm for predicting the dynamical behavior of the liquid diffusion by using Cellular automata. Additionally, it discusses its applied mathematical steps on OpenCV.

- In Chapter Five, the proposed algorithm for measuring the diffusion speed inside the predicted images is explained.

- Chapter Six discusses the proposed benchmark strategies that have been used to compare the predicted images to the original ones.

- The results derived from the experimental work are discussed in Chapter Seven. A topical evaluation for the performance of the proposed methods is also discussed. In this chapter, two types of comparison are made; one compares the predicted phenomenon to the real phenomenon and the other compares the proposed model results to other competitive models.

- Chapter Eight draws the conclusions of the overall work in this thesis and suggests future works in this area.

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