SIMULATION OF SUBMARINE GROUNDWATER DISCHARGE OF DISSOLVED ORGANIC MATTER USING CELLULAR AUTOMATA

Lars Nolle, Holger Thormählen and Harald Musa
Department of Engineering Science
Jade University of Applied Science
Friedrich-Paffrath-Straße 101
26389 Wilhelmshaven, Germany
Email: lars.nolle@jade-hs.de

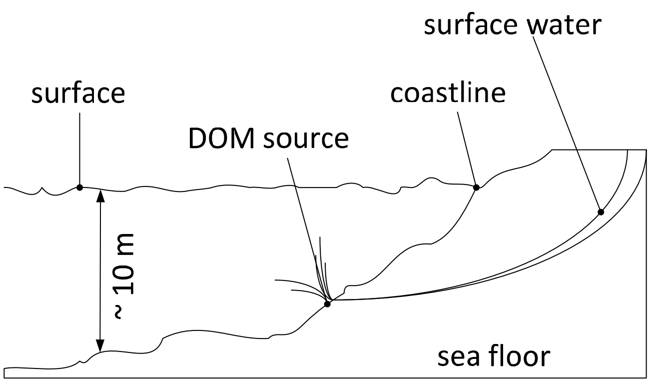
KEYWORDS
Dissolved organic matter, costal water simulation, cellular automata.

ABSTRACT

In order to design new search strategies for collaborating autonomous underwater vehicles, a 2D simulator was developed to simulate costal water environments. This allows for evaluating the new strategies without running the risk of losing expensive hardware during the tests. The simulator developed is based on the concept of cellular automata. Details of the simulator are described before preliminary qualitative results for three different scenarios are discussed. Finally, planned further improvements are presented.

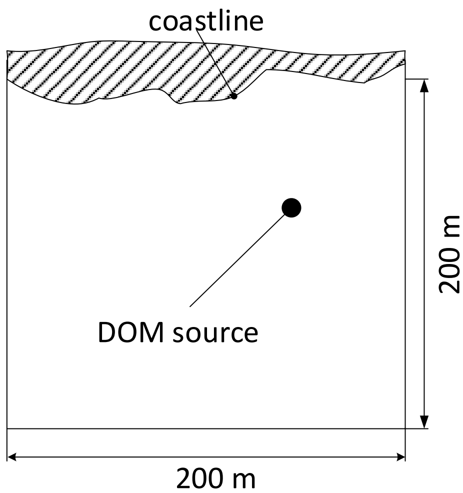
INTRODUCTION

Marine scientists are sometimes interested in locating submarine underground discharges of dissolved organic matter (DOM) (Suryaputra 2012) near the coastline. The major source of DOM in coastal waters is the degradation of terrestrial plant matter, which is dissolved and, for example, transported through river systems and estuaries to the marine environment (Stedmon et al. 2003). DOM sources or springs may appear if surface water transporting DOM percolates through the sea floor and exits beneath sea level (Figure 1).



Figures 1: Submarine Groundwater Discharge of Dissolved Organic Matter Near the Coastline

The area of interest, i.e. the search area, is reasonable small. Figure 2 shows the top view of a typical scenario. The long term of this project is to develop a swarm of small autonomous underwater vehicles (AUVs) (Figure 3) to locate any DOM sources, i.e. locations of highest DOM concentration, within a predefined area of interest (Nolle 2015).



Figures 2: Top View of the Area of Interest

In the first stage of the project, suitable search strategies for the coordinated operation of collaborating AUVs are to be developed and successively evaluated.

Figures 3: OpenROV to be Modified for Autonomous Operation

Proceedings 30th European Conference on Modelling and Simulation ©ECMS Thorsten Claus, Frank Herrmann, Michael Manitz, Oliver Rose (Editors)
ISBN: 978-0-9932440-2-5 / ISBN: 978-0-9932440-3-2 (CD)

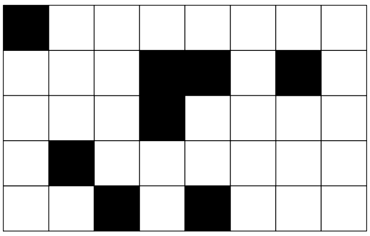
In order to be able to test different collaboration schemes for AUVs, without the risk of losing expensive hardware during the trials, a simulation of the marine environment is required. The next section describes the simulation of submarine groundwater discharges of DOM using cellular automata.

SIMULATION

Since the simulation developed is based on cellular automata, this section introduces briefly the concept of cellular automata before providing details about the simulation tool developed.

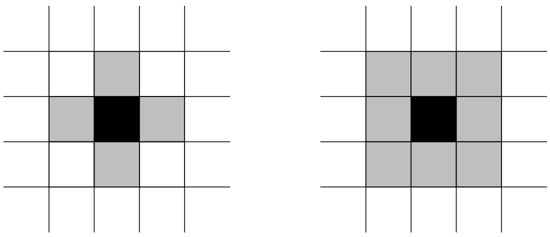
Cellular Automata

Cellular automata (CA) are general dynamic models of complex systems, which are discrete in time and space (Wolfram 1984). They consist of ordered collections of simple identical cells. Each cell has a current (discrete) state, which is updated after every time step (iteration). Figure 4 shows an example of a 2-dimensional cellular automation. It has the dimension 8 x 5. Here, black cells are in state "1" whereas white cells are in state "0".



Figures 4: Cellular Automation of Size 8 x 5

The new state of a cell is calculated based on its own current state and the current states of its neighbours. Figure 5 shows two of the most commonly used neighbourhoods for 2-dimensional cellular automata (Gerhardt and Schuster 1995). These neighbourhoods are the von-Neumann neighbourhood (Figure 5a) and the Moore neighbourhood (Figure 5b). Here, the grey cells belong to the neighbourhood of the black cell in the middle, i.e. they determine the next state of the cell in question.



a) von-Neumann Neighbourhood

b) Moore Neighbourhood

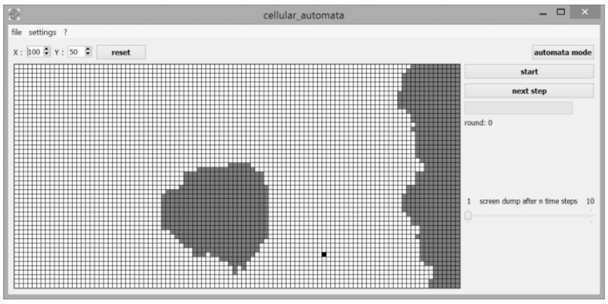
Figures 5: Common Neighbourhood Definitions for 2D Cellular Automata

The updating is performed following a set of application specific rules, i.e. these rules define the dynamic behaviour of the model.

Although cellular automata date back to the late 1940 (von Neumann 1966), they became popular after Conway presented his Game of Life in 1968 (Berlekamp et al. 1982). Conway developed this game to study complexity in nature whereas another well-known example of CA, the lattice gas cellular automation, was developed to simulate the physical world. Lattice gas CA was first introduced in 1973 by Hardy, Pomeau and de Pazzis. Their approach is known as HPP gas and is used to simulate fluid flows (Hardy et al. 1973). For a more comprehensive survey of the theory of cellular automata see for example (Kari 2005).

Simulation Tool Developed

The simulation tool that was developed in this work offers a variable size of the simulated environment (grid) and a graphical user interface (Figure 6).



Figures 6: Cellular Automata Tool

The software is written in C++ using Qt (Thelin 2007) for the graphical user interface.

In the simulator, the user can set any particular cell to either *land*, *water* or *DOM source* simply by clicking the cell with the mouse. A scenario created in this way can then be saved for later use. The user can also define an interval after which the state of the world is saved to disk. This data can be used to visualize the evolution of the world over time. Last but not least, the world state can be saved as a C-function to be included in other C or C++ programs.

EXPERIMENTS

For the experiments, three different scenarios were simulated. The first one involves a coastline, one obstacle (island) and one DOM source (Figure 7). The second scenario is a variation of the first scenario with one additional obstacle (Figure 10) whereas the last scenario also includes an additional DOM source (Figure 13). The rules used in the simulations and the results of the experiments are presented below.

Rules

The cellular automation uses the Moore neighbourhood as described above. Each cell can be in one of 1 billion states, each represents one DOM concentration level *L* respectively the *land* state or the *DOM source* state.

The updating process is non-conventional in a way that a cell *i* is not updated by its neighbours. Instead, a cell updates all the cells in its neighbourhood; if the state of a neighbour is not the *land* state, the cell transfers part of its state (DOM level) ΔL_i to it (Equation 1). Each cell accumulates the donations it receives from all of its neighbours in order to determine its state for the next time step (Equation 2). Cells at the border treat the non-existing neighbours as sinks. As a consequence, state transferred to them is lost in the next iteration.

$$\Delta L_i(t) = \frac{L_i(t)}{n_i + 1} \tag{1}$$

Where:

$\Delta L_i(t)$	:	fraction of state at time step t
$L_i(t)$	:	state of cell i at time step t
n_i	:	neighbours of cell i that are not land or DOM source

$$L_i(t+1) = \Delta L_i(t) + \sum_{j=1}^{n_i} \Delta L_j(t) \tag{2}$$

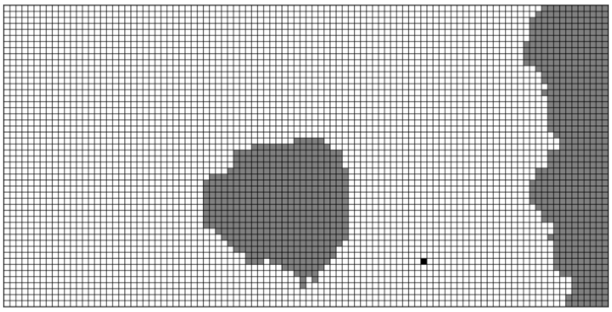
Where:

$L_i(t+1)$	:	state of cell i at time step t+1

The next section presents the results obtained by running three different scenarios.

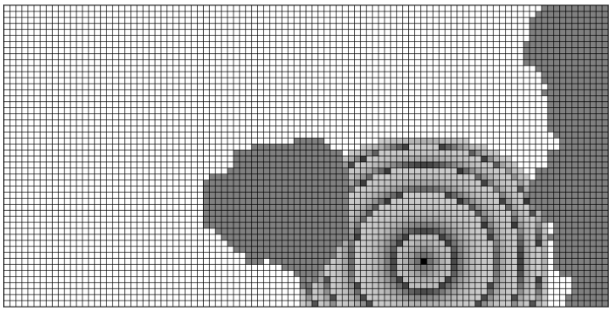
Results

Figure 7 shows the setup of the first scenario. It comprises of a coastline on the right hand side of the grid and an island in the lower middle part of the grid. There is also a single DOM source releasing a constant flow of DOM into the simulated environment.

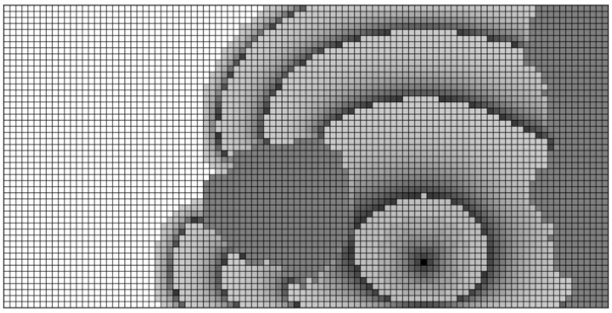


Figures 7: First Scenario at Time *t*=0

In Figures 8 and 9 show the concentration levels of DOM after time step 25 respectively 100.



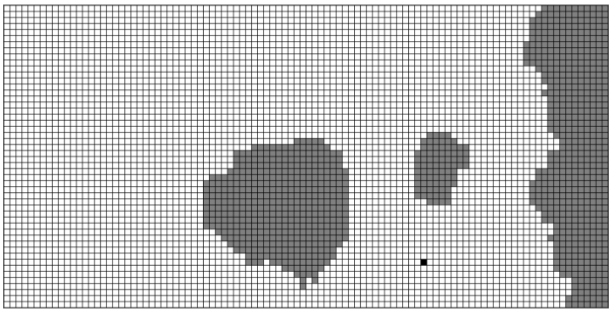
Figures 8: First Scenario at Time *t*=25



Figures 9: First Scenario at Time *t*=100

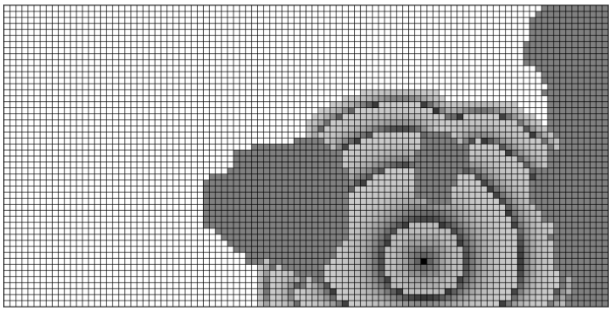
It can be seen that the DOM is diffused in the expected way. It eventually surrounds the island from both sides until it reaches a stady-state.

In the second scenario (Figure 10) a second obstacle (island) was introduced and the simulation was repeated.

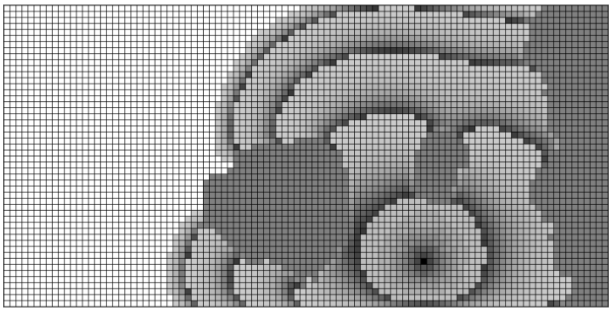


Figures 10: Second Scenario at Time *t*=0

It can be seen from Figures 11 and 12 that the simulated DOM behaved also as expected: the DOM surrounds both islands and the shape of the concentration level is rather complex.

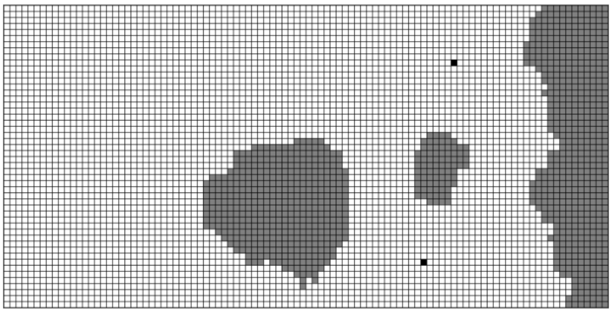


Figures 11: Second Scenario at Time t=25



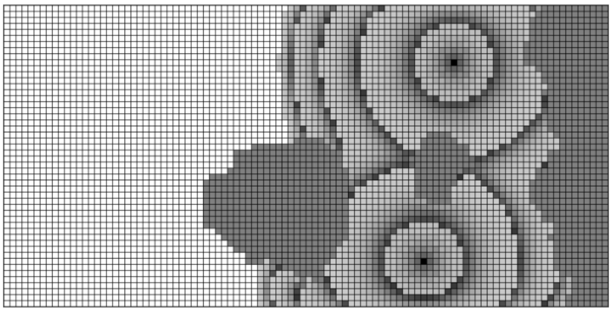
Figures 12: Second Scenario at Time t=100

The third scenario differs from the second one in way that a second DOM source is added (Figure 13).

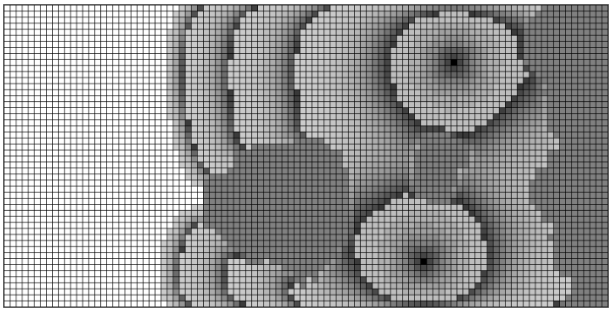


Figures 13: Third Scenario at Time t=0

Figures 14 and 15 show that here too the DOM concentration levels develop as expected.



Figures 14: Third Scenario at Time t=25



Figures 15: Third Scenario at Time t=100

CONCLUSIONS AND FUTURE WORK

The aim of this research was to develop a simulation program that can be used for the evaluation of search strategies for autonomous underwater vehicles. The simulator developed here is based on cellular automata. That means that both the search space and time are discretised. Also, it is limited to a 2-dimensional representation of the costal section to be simulated.

Results obtained from first experiments that were conducted using the simulator were promising and shoed expected behaviour. However, these results are only preliminary and qualitative. In order to improve the simulation, the rules need to be fine-tuned and the accuracy of the simulation needs to be analysed quantitatively.

The next step will be to include perturbation and wave mechanics to the model. The long term goal is to extend the simulator so that it works in three dimensions.

REFERENCES

Berlekamp, E.R., Conway, J.H., Guy, R.K. 1982 *Winning Ways for Your Mathematical Plays II*, Academic Press.

Gerhardt, M. Schuster, H. 1995 *Das digitale Universum*, Vieweg & Sohn.

Hardy, Pomeau, J.Y., de Pazzis, O. 1973 "Time evolution of a two-dimensional model system. I. Invariant states and time correlation functions ", *Journal of Mathematical Physics*, Vol. 14, Issue 12, pp 1746-1759.

Kari, J. 2005 "Theory of cellular automata:A survey", *Theoretical Computer Science*, Vol. 334, pp 3-33.

Nolle, L. 2015 "On a search strategy for collaborating autonomous underwater vehicles", Proceedings of Mendel 2015, 21st International Conference on Soft Computing, Brno, CZ, pp 159-164.

Stedmona, C.A., Markagera, S., Rasmus Bro, B. 2003 "Tracing dissolved organic matter in aquatic environments using a new approach to fluorescence spectroscopy", *Marine Chemistry*, Vol. 82, pp 239-254.

Suryaputra, I.G.N.A. 2012 *Fluorescent dissolved organic matter (FDOM) in the coastal ocean: characterization, biogeochemical processes, and the possibility of in situ monitoring*, Doctoral Thesis, Carl von Ossietzky University, Oldenburg, Germany.

Thelin, J. 2007 *Foundations of Qt Development*, Apress.

von Neumann, J. in:. Burks, A.W. (Ed.) 1966 *Theory of Self-Reproducing Automata,* University of Illinois Press.

Wolfram, S. 1984 "Universality and complexity in cellular automata", *Physica D: Nonlinear Phenomena*, Vol. 10, Issue 1-2, pp 1-35.

AUTHOR BIOGRAPHIES

LARS NOLLE graduated from the University of Applied Science and Arts in Hanover, Germany, with a degree in Computer Science and Electronics. He obtained a PgD in Software and Systems Security and an MSc in Software Engineering from the University of Oxford as well as an MSc in Computing and a PhD in Applied Computational Intelligence from The Open University. He worked in the software industry before joining The Open University as a Research Fellow. He later became a Senior Lecturer in Computing at Nottingham Trent University and is now a Professor of Applied Computer Science at Jade University of Applied Sciences. His main research interests are computational optimisation methods for real-world scientific and engineering applications.

HOLGER THORMÄHLEN graduated from Jade University of Applied Science with a degree in Electrical Engineering and is currently studying for an MSc.

HARALD MUSA graduated from Fachhochschule Wilhelmshaven with a degree in Electrical Engineering. He subsequently obtained an MSc in Electrical Engineering from Jade University of Applied Science and is currently working as a Lecturer in the Department of Engineering Science.