MODELING OIL SPILL IN COASTAL WATERS USING CELL-DEVS

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ABSTRACT

A Cell-DEVS model was implemented using the CD++ simulation engine to study the movement of an oil spill in coastal waters. The model was initialized to have a given mass of oil spilled on the surface of the water. Mass conservation and other physical oil transport rules including the effect of wind and obstacles in the path of the spill, the combination of water and oil to cause a vertical dispersion of the oil slick were used. The movement of the oil spill was studied for different scenarios to capture an area of 100km^2 and 3 layers of water 10m apart. The model successfully mimics the spread of an oil spill

Keywords: oil spill, cell-DEVS, fluid dynamics.

1 INTRODUCTION

Oil spill accidents have happened very often in the last decade, the related tasks, such as oil spill monitoring, prediction, and management, became very important issues (Shyue et al. 2007). The oil spill that occurs during exploration and production of crude oil in coastal waters can have devastating effects on the environment and on living things and hence should be prevented. Oil spill models are widely used and can be particularly helpful for contingency planning. By modeling a series of the most likely oil spill scenarios, for example, spill response training activities can then make use of this information to educate trainees to react to simulated spill scenarios with varying circumstances.

In situations where oil spills are unavoidable or when they occur by accident, it is important to investigate the ways in which these spills are transported in coastal waters, so that appropriate plans to mitigate its impact can be made, this can be achieved by applying relevant techniques in modeling and simulation.

When oil is spilled on the surface of a water body, it is dispersed due to the concept of mass conservation. It can be transported along the surface of the water because of wind and/or water current. The oil spilled can mix with sea water causing an increase in the density of the mixture and this could cause a downward vertical movement of the spill. (Shyue et al. 2007). From the foregoing, the movement of an oil spill can be very complex and can vary significantly depending on the condition of the water body and the environment in which it was spilled.

In this paper, we model the spread of an oil spill by considering mass conservation, the effects of wind, the vertical movement of oil slick due to increased density when mixed with water, and the effect of vegetation and other obstacles as regards the spread of an oil spill. The model is implemented using Cell DEVS which offers the unique advantage of a discrete event model in that it provides a framework for the construction of hierarchical and modular models allowing model reuse (Wainer and Fernández 2016).

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A cell DEVS model of an oil spill would be created in a three-dimensional cell array size of 100 x 100 x 3.

2 BACKGROUND

Several models have been developed to simulate and predict the behavior of oil spills on water bodies. The various models follow a series of different approaches, ranging from simple vector calculations to sophisticated motion computer models and three-dimensional oil distribution, as well as predictions of variation in the composite properties of oil as it potentially becomes a mixture. To model oil movement, the most important input parameters include but are not limited to, the type and amount of oil spilled (some modelling proposals also explore the rejection rate), the state of the fluid medium (water) as affected by main environmental contributions include wind strength and direction, ocean currents, tides and air and sea temperatures, the presence of islands or vegetation within or about the fluid medium, among all others. Often, the accuracy and availability of this data can be problematic (Forth et al. 2017).

In (Reed et al. 1999), the authors give an in-depth overview of a diversity of numerical approaches applied to modeling the behavior of oil spills in marine environments. They focused largely on oil spill incidents and developments since about 30 decades ago and building on work done in the literature within this period to buttress their contributions and assertions.

Authors of (Afenyo, Veitch, and Khan 2016; Guo and Wang 2009; Zheng and Yapa 2010; Lončar, Leder, and Paladin 2012) conducted an extended state-of-the-art review of oil spill trajectory and fate modeling using a numerical approach. In the review conducted by authors of (Afenyo, Veitch, and Khan 2016), they took into consideration certain factors like advection, spreading, evaporation, dissolution, dispersion, emulsification, biodegradation and sedimentation properties, which helped in their study of oil behavior in spills on rivers. They also paid special attention to the dispersion of oil from the sea surface and influence on the diffusion, the role of currents, wind, Temperature, ice conditions and a variety of shore types. Authors of (Guo and Wang 2009) developed a hybrid particle tracking / Euler-Lagrange approach for coastal oil spill simulation. In their approach, releases of oil from the source were modeled by the release of particles. When the thickness of the oil slick reaches the critical value, the particles were then mapped to a smooth or non-concentric thickness, while calculations took place in the Euler-Lagrange mode. In (Zheng and Yapa 2010), the authors also investigated oil spill based on an integral Lagrangian technique. Their model simulated oil behavior in stratified or unprotected marine environments. They also considered shear-induced driving and forced training in their model design.

In the literature, a lot of authors have researched into this subject and have largely adopted the numerical approach in their modeling of oil spills. Numerical approaches are good but are not the best in studying and modeling of oil spills. In such models, there is usually approximations in equations used to the end that results do not converse because of increasing error margins. Authors of (Afenyo, Veitch, and Khan 2016; Guo and Wang 2009; Zheng and Yapa 2010) also did some approximations in the equations used for their model design.

The modeling of fluid displacement can be broadly classified under two carried out using different methods; Macroscopic Grid Methods or Particle methods. These methods are governed by certain equations and characteristics (Duan et al. 2017).

The methods describe above can be classified under particle methods. As regards the grid methods for modeling Oil Spills, although there has been some work done in (Shyue et al. 2007) in which cellular Automata was used to model oil spill processes by considering; spreading on the water surface, evaporation, dissolution, and vertical dispersion. The results obtained looked good, but the complex timing of cellular automata makes it inefficient and time-consuming.

In this paper, we replicate the results obtained in (Shyue et al. 2007), using Cell-DEVS formalism. Whereas cellular automata are discrete dynamic systems that provide a mathematical framework for modeling, studying and predicting the behavior and response of systems in many different disciplines and areas, the Cell-

DEVS formalism offers a discrete event approach, defining cellular models with time delay constructs and uses a simple definition of complex timing (Wainer and Fernández 2016).

2.1 The DEVS Formalism

DEVS (Discrete Event Systems specifications) is a modeling paradigm based on general systems theory (Zeigler, Kim, and Prähofer 2000).

A DEVS model is built using a set of behavioral components called Atomic, which can be combined to form coupled ones. A DEVS atomic model can be formally described as:

$$M = < X, S, Y, \delta_{int}, \delta_{ext}, l, D >$$

Where X represents a set of input events, S is a set of states, and Y is a set of output events. Four functions control the behavior of the model. Conversion of internal transition (δ_{int}), conversion of external transition (δ_{ext}), output, D is the duration of the state. Each model is considered to have an input port and an output port for communicating with other models. The input and output events determine the values displayed on these ports. Input external events are received at the input port and in the model specification you need to define actions under such input. An internal event causes a state change. The result is sent out through the output port. Whether these values are sent to other models depends on the effect of the port (Wainer and Giambiasi 2001).

Coupled models are integrated by other DEVS models, formally defined as:

$$CM = < X, Y, D, \{M_i\}, \{I_i\}, \{Z_{ij}\}>$$

Where,

X is the set of input events, and Y is the set of output events. D is an index of the components, and for each i Î D, M_i is a basic DEVS model. I_i is the set of influences of model i. For each j Î I_i, Z_{ij} is the i to j translation function. Coupled models are composed of a set of basic models connected through input/output ports (Wainer and Giambiasi 2001). The influences of a model are used to define which output values must be sent to the others. The translation function uses an index of influences, created for each model (Ii). This function defines which outputs of model Mi are connected to inputs in model M_j. (Wainer and Giambiasi 2001)

Cell-DEVS (Reed et al. 1999) is an extended DEVS formalism that allows for the implementation of cellular models. Each cell is defined as an atomic model using timing delays, and it can be later integrated to a coupled model representing a cell space. Cell-DEVS atomic models can be specified as:

$$TDC=< X, Y, I, S, N, delay, d, \delta_{INT}, \delta_{EXT}, \tau, \lambda, D >$$ (Wainer and Giambiasi 2001)

Where, X represents external input events, Y represents external outputs, I the model's interface, S is the set of states for the cell, and N is a set of input events. Delay represents the kind of delay for the cell this could be transport or inertial delay and d its duration.

The functions are defined as follows: δ_{INT} for internal transitions, δ_{EXT} for external transitions, τ for local transitions, λ for outputs and D for the state's duration function (Wainer and Giambiasi 2001). N inputs to compute the future state for each cell, they are received through the model's interface and are used to activate the local function. A delay can be associated with each cell, allowing deferring the transmission of the execution results (Amegino, Trocolli, and Wainer 2001).

3 METHODOLOGY

3.1 Fluid Phase Dynamics and Kinematics of Fluid-Phase Regions

In the study of an oil spill, it is important to understand the composition of this spill in terms of fluid miscibility, phases, and the dynamics of fluid flow. Fluid phase dynamics can be studied on a microscopic scale or on a macroscopic scale, where the macroscopic equations are obtained from the microscopic equations by averaging theorems which utilize integration of elementary volume in space. (Gray et al. 2015). This shows that studying fluid dynamics on a macroscopic scale is not independent of the equations that govern the microscopic flow of fluids. Another interesting point to consider when considering fluid phase dynamics is the fluid phases and the kind of mixture these phases form and how they might affect the dynamics of fluid flow. The kinematics of the space occupied by a fluid phase is described by changes in position and phase distribution, which is completely independent of the actual fluid dynamics and even the phase itself, which means we can identify a space and observe how fluids occupy that space depending on the properties of the space, whether it has a boundary or the space density that may alter the motion of the fluid. (Gray et al. 2015; Hirt and Nichols 1981). In modeling movement of oil spills, we considered fluid phase dynamics and kinematics.

3.2 Mass Conservation and the Volume of Fluid Method

The equations governing flow can be categorized as the conservation of mass, conservation of momentum and the conservation of energy. In General, mass can be added and removed, and the conservation law must be obeyed.

Final Mass = Original mass + Mass Added – Mass Removed. (Elger and Roberson 2016)

With the mass conserved according to equation above (Elger and Roberson 2016) we can deduce that the rate at which the mass increases would be equal to the rate at which there is an influx of mass. Hence, if we have a control volume we can monitor this change in mass according to the Navier Stokes equation. Details about this equations and laws can be found in (Elger and Roberson 2016; Charnyi et al. 2017). In this paper, the control volume is the 100 by 100 grid space and the mass inflow would be the initial mass of oil spilled and to complete the model we would ensure that we obey the mass conservation equation.

The volume of Fluid is a method for defining the shape of a fluid near a boundary. In each cell of the grid, we use only one value each dependent variable defining the fluid state in a coarse interface according to the Volume of fluid method (Nakayama 2018). In addition to defining the cell within the boundary, we also define fluids located in the boundary cell. With proper definitions of the boundary cells and the fluid proportions close to the boundary then we can compute the direction of the fluid near the boundary by finding the slope which is simply a line that cuts the cell. In this work, the volume of fluids method was used to compute the flow direction of the oil spills near the boundary. (Hirt and Nichols 1981)

In modeling oil spill dynamics in coastal waters, we basically must model two things as described above. Firstly, we must model the dynamics of the fluid, in this case, we adopt macroscopic scale fluid dynamics, and secondly, we need to model the kinematics of the fluid flow which is determined by the portion of space in which the fluid is bound to flow through. While we adopted mass conservation equations for modeling the dynamics of the fluid on a macroscopic scale, in the case of space modeling we considered different scenarios which are described below.

In the implementation of the model being described in this report, the model is designed to be a 3-dimensional model called “oil spill” and the cell space is 100x100x3. This is 3 planes with each plane representing a certain depth, the surface (layer 0), 10m below the water surface (layer 1) and 20m below the water surface (layer 2). Different cases of the model would be analyzed, and the final model would be a combination of these cases.

To model the oil spill, masses were assigned to conform to what obtains in the real world as follows, maximum mass of crude oil that can occupy a cell is 790kg, a cell with a value of 2000kg means that sell is occupied by coastal vegetation, a cell with 0kg means the cell has 0kg mass of oil and hence completely occupied by water.

Oil spreading in this model is studied based on surface movement through conservation of oil mass and wind/water currents, and vertical downward movement of the oil because of the mass gained when oil and water have mixed.

In various equations for oil spreading the constants m = 0.098 and d = 0. 0176 (Shyue et al. 2007)

3.3 Model Definition

3.3.1 2D oil spreading without wind and current on the surface

Each plane contains 10,000 cells (100*100). One can think of each cell as a small fraction of the water body which is occupied by either water (0 oil) or Crude oil (790) or a mixture of both oil and water (Greater than zero but less than 790). All mass values are in Kilogram. The cell space has a Moore neighborhood of 9 cells and the rule governing the cells is as follows;

A cell occupied by oil would disperse to its neighbors, but the mass of the oil is always conserved according to equation 1 (Shyue et al. 2007):

$$M_{i,j}^{t+1} = M_{i,j}^{t} + \{m[(M_{i-1,j}^{t} - M_{i,j}^{t}) + (M_{i+1,j}^{t} - M_{i,j}^{t}) + (M_{i,j+1}^{t} - M_{i,j}^{t}) + (M_{i,j-1}^{t} - M_{i,j}^{t})]\} + \{md[(M_{i-1,j+1}^{t} - M_{i,j}^{t}) + (M_{i+1,j+1}^{t} - M_{i,j}^{t}) + (M_{i-1,j-1}^{t} - M_{i,j}^{t}) + (M_{i+1,j-1}^{t} - M_{i,j}^{t})]\} \quad (1)$$

Where,

M_y^x is the oil mass in cell y at time x.

m is the spreading constant in the four adjacent cells.

d is the spreading constant for diagonal cells.

3.3.2 2D oil spreading with the effect of wind/water current and vegetation present on the water surface

Each plane contains 10,000 cells (100*100). Which is zoned into two zones? One can think of each cell as a small fraction of the water body which is occupied by either water (0 of oil) or Crude oil (790) or a mixture of both oil and water (Greater than zero but less than 790) or vegetation (2000). The vegetation is zoned separately from the oil and water hence has a different set of rules for this simulation. All mass values are in Kilogram. The neighbourhood in this case considers the wind direction hence each cell has 6 neighbours (itself included).

The oil would spread in the direction of the wind/water current and avoid any existing vegetation in accordance with the rules stated below.

For zone one the rule is that the oil disperses in the same direction as the wind/water current. A cell occupied by oil would disperse to its neighbors that contain water or a mixture of oil and water, but the mass of the oil is always conserved according to equation 2. In this case, we consider the water current flowing from south to north. (Shyue et al. 2007)

$$M_{i,j}^{t+1} = M_{i,j}^{t} + \{m[(M_{i-1,j}^{t} - M_{i,j}^{t}) + (M_{i+1,j}^{t} - M_{i,j}^{t})(M_{i,j+1}^{t} - M_{i,j}^{t})]\} + \{md[(M_{i-1,j+1}^{t} - M_{i,j}^{t}) + (M_{i+1,j+1}^{t} - M_{i,j}^{t})]\} \tag{2}$$

For zone two a cell containing vegetation would remain the same no matter what happens around it.

Where,

M_{y}^{x} is the oil mass in cell y at time x.

m is the spreading constant in the four adjacent cells.

d is the spreading constant for diagonal cells.

3.3.3 2D oil spreading with the effect of wind/water current and vegetation present on the water surface.

In this case, the oil spill disperses based on the concepts discussed in case 1 above, but this case introduces complex vegetation.

3.3.4 3D oil spill spreading with complex bathymetry

In this case, we simulate the spread of an oil spill incorporating the rules above to different layers of water depth. The spread of the oil spill on the surface of the water body is like what has already been discussed in cases 1 and 2 above. However, to simulate the vertical movement of the oil spill (downward), we redefine the neighborhood as follows:

3.3.5 Rule Zone (oil and water zones)

A cell occupied by oil would disperse to its neighbors that contain water or a mixture of oil and water, but the mass of the oil is always conserved according to equation 3. Oil being dispersed will avoid other zones hence, different rules apply to other zones that contain vegetation. Same equations apply but, in this case, the neighborhood is different because the cell in question would consider the cell above it in addition to those previously considered.

3.3.6 Rule Vegetation Zones

A cell containing vegetation would remain the same no matter what happens around it.

3.4 Simulation results

The simulation results are shown below. The images on the left correspond to the initial state of the cells before simulation while those on the right correspond to the state after simulating after some time. The following color specification describes the cases and occurrences in the pictures: Blue: represents the water body Black: represents the crude oil between its maximum mass of 790kg and 20% below its maximum mass. Grey: represents the crude oil between the mass of 632mg and 20% below 632mg.Ash: represents the crude oil mass below 508mg. Green: represents the thick vegetation on top of the water body.

3.4.1 2D oil spreading without wind and current on the surface

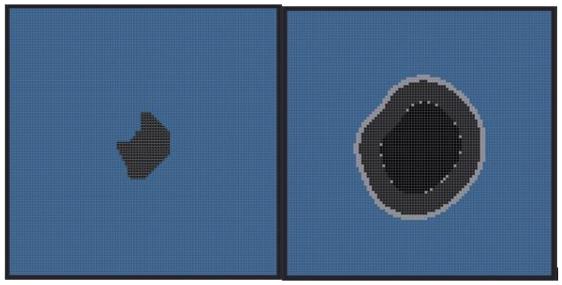

Figure 1: Simulation results for case 1 showing initial condition and simulation after 5seconds

3.4.2 2D oil spreading with the effect of wind/water current and vegetation present on the water surface

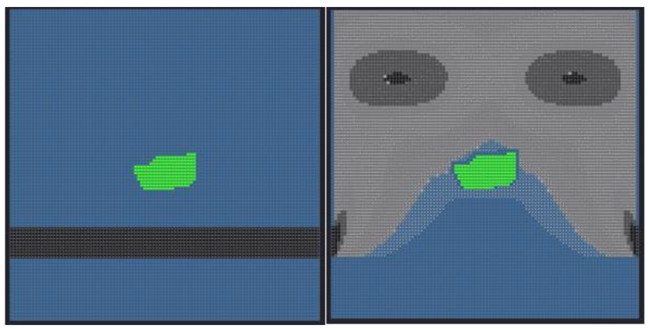

Figure 2: Simulation results for case 2 showing initial condition and simulation after 10 seconds

3.4.3 2D oil spreading with the effect of complex vegetation present on the water surface

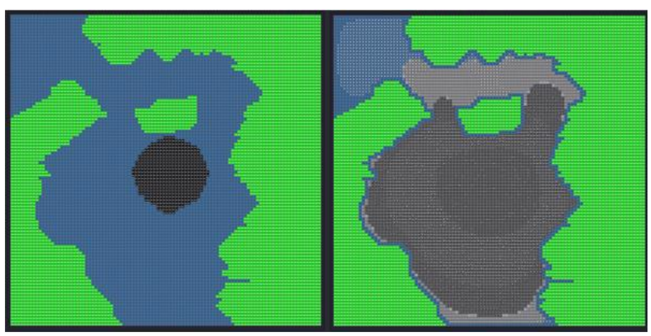

Figure 3: Simulation results for case 3 showing initial condition and simulation after 30 seconds

3.4.4 3D oil spreading with the effect vegetation present on the water surface

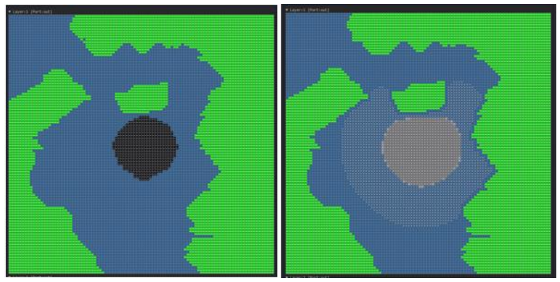

Figure 4: Simulation results for case 3 layer 1 showing initial condition and simulation after 10 seconds

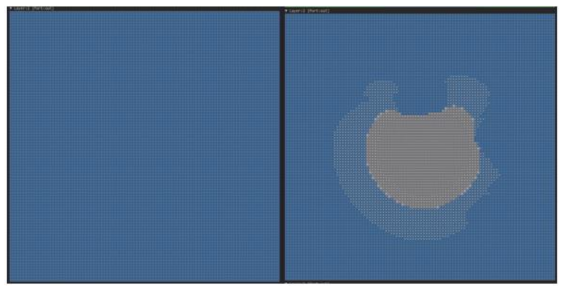

Figure 5: Simulation results for case 3 layer 2 showing initial condition and simulation after 10 seconds

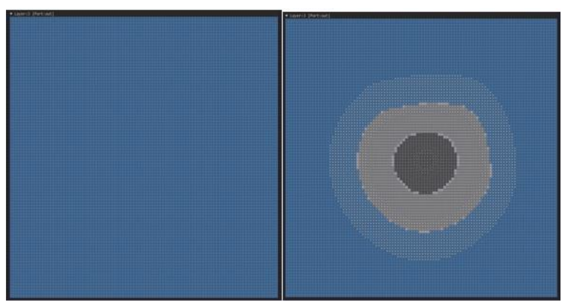

Figure 6: Simulation results for case 3 layer 3 showing initial condition and simulation after 10 seconds

4 CONCLUSIONS

We have applied the DEVS formalism in modeling oil spills while incorporating useful physical concepts that are relevant to the movement of fluids. The results obtained look good and closely mimics what happens when oil spill moves within a water body. The paper considered physical concepts including wind, gravity and mass conservation. However, the physical concepts that govern fluid flow go beyond what was considered, hence for future work other fluid concepts including miscibility and slick formation should be considered in the modeling of oil spill movement.

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