**Predictive Modelling and Simulation of Marine Debris Dispersion in Maltese Territorial Waters**

**Progress Report**

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**December, 2023**

**Abstract:**

The accumulation of surface marine debris in the territorial waters of Malta presents a severe ecological and environmental challenge, adversely impacting marine life and human activities. This project focuses on the application of a practical system integrating a physics-based Lagrangian dispersion model with an AI-enhanced predictive model. Utilizing historical wind and surface ocean current data, the system employs the Lagrangian model to simulate and visualize past movements of marine debris. Concurrently, an AI model using a CNN-LSTM architecture is developed and trained on the same dataset. This model predicts critical environmental parameters for future scenarios, which are then fed into the Lagrangian model to project future debris dispersion. Hosted on a web platform, this approach offers a significant advancement in marine debris management by facilitating real-time data visualization and predictive analytics. This project not only demonstrates a method for enhancing marine conservation efforts through accurate predictions of marine debris movement but also underlines its vital role in planning and executing effective cleanup operations, thus contributing to a more comprehensive understanding of marine pollution dynamics.

1. **Introduction**
   1. **Problem Definition/Motivation**

Marine debris around Malta’s territorial waters presents a significant environmental challenge. Consisting largely of plastics and other non-biodegradable materials, this debris poses a direct threat to marine ecosystems, endangering aquatic life and disrupting the natural balance. The presence of marine debris also compromises the ecological value of coastal areas, adversely impacting recreational activities. This project seeks to address these challenges by developing an integrated system that aims to track and predict the movement of marine debris. The goal is to provide actionable insights that can guide effective cleanup operations and inform strategies for long-term marine conservation in Maltese waters.

* 1. **Aims and Objectives**

The aim of this project is to develop an integrated, AI-enhanced system for simulating and predicting the movement of marine debris in the territorial waters of Malta, thereby supporting marine conservation efforts.

To achieve this aim, the following objectives have been identified:

1. Data Integration: To preprocess and integrate the datasets, which include wind and sea surface current data to be used for both models.
2. Lagrangian Model Development: To utilize the Ocean Parcels library for simulating the movement of marine debris, employing historical data to ensure accurate simulations.
3. AI Model Development: To create a CNN-LSTM model capable of predicting future wind and sea surface currents weather data.
4. Integrating CNN-LSTM with Lagrangian Model: To integrate the CNN-LSTM model's predictions into the Lagrangian model. This fusion aims to create future simulations of marine debris movement, enhancing the project's predictive capabilities for marine conservation.
5. Web-based Visualisations: To develop a web-based platform that facilitates the visualization of both past data and predicted future simulations, providing essential tools for marine conservation and debris management.
6. **Background** 
   1. **The datasets**

The datasets form the backbone of any research project, and their careful selection and processing are critical in producing accurate models. In this project, two essential types of datasets are utilized, both provided by the Geosciences Faculty of the University of Malta.

The first dataset is the Sea Surface Currents Dataset, derived from a model generated by HF radars located around the islands of Malta and southern Sicily. This dataset, in the NetCDF format is the standard for weather data and the only format accepted by the Lagrangian Model. This dataset includes longitude, latitude, time, eastern Ocean Current Velocity, and Northern Ocean Current Velocity. It offers data in hourly increments over three years, from 2020 to 2023. The second dataset is from the Copernicus Atmosphere Monitoring Service, also in NetCDF format. This dataset encompasses longitude, latitude, time, and the Northern and Eastern wind components. The data is provided in 12-hour increments, centered at 00:00 and 12:00 over three years, from 2020 to 2023 like the previous dataset.

Both datasets are integral to the project, providing comprehensive environmental parameters essential for the subsequent development of predictive models and simulations. The precise and systematic handling of these datasets lays the groundwork for the project's success, ensuring that the modelling efforts are based on accurate and reliable data.

* 1. **Lagragian Model**

The Lagrangian model, a critical component in environmental simulation, offers a dynamic method for tracing the movement of particles through fluid mediums. This model is central to studying phenomena such as marine debris dispersion, as it allows for precise tracking of individual particles over time. The Lagrangian approach incorporates several key functions:

Custom Kernels: Can be defined and executed, allowing for specific, tailored simulation scenarios​

Advection: This process describes how particles are transported by fluid currents, typically modeled by the equation *v=u⋅Δt*, where *v* is the particle's velocity, *u* is the current's velocity, and *Δt* is the time increment.

Diffusion: Representing the random motion of particles, diffusion is often modeled using algorithms like random walks or Gaussian distributions, simulating the effects of molecular diffusion and turbulence.

The Ocean Parcels project, the chosen tool for this project, is a set of Python classes and methods specifically designed for simulating the movement of particles in the ocean. It provides the ability to customize and execute particle tracking simulations using data on ocean currents, wind fields, and other environmental factors. Furthermore, it provides functionalities like starting and removing particles during execution. While other libraries like PyGnome and Matslick also offer similar functionalities, Ocean Parcels is particularly suited for this project due to its flexibility and ease of integration with various data formats, including NetCDF. The library outputs include detailed trajectories of each particle, enabling the visualization of their movement over time. This output is crucial in understanding the dispersal patterns of marine debris, aiding in the development of effective conservation strategies.

* 1. **CNN-LSTM Model**

The CNN-LSTM model combines Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) networks, making it highly effective for time series forecasting. CNNs excel in identifying patterns in spatial data, like images, while LSTMs are adept at processing sequential data, capturing long-term dependencies. For predicting sea currents and wind conditions, this model is particularly suitable due to its ability to process complex, multi-dimensional datasets, like those in NetCDF format.

In this project, the CNN-LSTM model will be trained on the same dataset used for the Lagrangian model, focusing on historical wind and sea surface current data. By learning from these parameters, the model will be able to predict future weather conditions. These predictions, once processed, can be input into the Lagrangian model, enabling it to simulate future scenarios of marine debris movement. This approach not only utilizes the strengths of both CNNs and LSTMs but also aligns perfectly with the project’s aim of integrating predictive modelling with environmental simulations.

1. **Literature Review**

**3.1 Impact of Marine Debris on Ecosystems**

The environmental and ecological impact of marine debris, particularly in coastal and marine ecosystems, has been a subject of extensive research [7][8]. Studies in this area reveal significant negative effects, ranging from harm to marine wildlife due to ingestion and entanglement [9], to the disruption of natural habitats [10]. The impact on coastal ecosystems extends beyond the environment, affecting economic sectors reliant on marine health, such as tourism and fishing [11]. Further research delves into the long-term ecological consequences, highlighting the urgent need for effective management and mitigation strategies [12]. These studies collectively emphasize the critical nature of addressing marine debris for ecosystem sustainability and conservation.

**3.2 Physics-Based Lagrangian Model**

The Physics-Based Lagrangian model [13], a common model used for oceanic debris dispersion simulation, is acclaimed for its effectiveness, as detailed in studies [3], [6]. Its implementation through Ocean Parcels [4], a set of Python-based tools, is particularly noteworthy for leveraging the Lagrangian method in particle tracking, a choice corroborated by its robustness in marine simulations [5]. Further research [7], [8] delves into the model's adaptability and precision across varied oceanographic scenarios, from localized studies to larger, intricate systems. Its versatility is highlighted in applications ranging from tracking pollutant spread to studying biological entities in marine ecosystems [13]. This underscores the model's integral role in environmental research, offering insights and fostering advancements in marine conservation methodologies.

**3.3 CNN-LSTM Environmental Forecasting**

The CNN-LSTM model has emerged as a leading approach in environmental forecasting as seen in [1] and [2]. Hence my implementation will adopt this hybrid model for predicting the sea currents and wind conditions. Its combination of Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTMs) networks makes it highly adept at processing complex time-series data, crucial for environmental variables [14]. CNNs excel in identifying spatial patterns, while LSTMs effectively capture temporal dependencies, making this hybrid model especially suitable for forecasting environmental phenomena [14]. Studies have demonstrated its efficacy in scenarios similar to marine debris dispersion [15]. The model's compatibility would allow me to work with NetCDF files as seen in [16]. Its adaptability to diverse forecasting scenarios further validate its utility. This versatility positions the CNN-LSTM model as an ideal candidate for integration with the Lagrangian model in subsequent phases of this project.

**3.4 Feasibility of Integrating AI with Lagrangian Modeling**

Integrating the Lagrangian model with an AI weather forecasting model, akin to the approach seen in [17], is both feasible and advantageous for predicting future marine debris movement. The CNN-LSTM model's ability to accurately predict environmental conditions, in this case sea currents and wind, will be crucial. These predictions enhance the Lagrangian model's capability to simulate future debris dispersion scenarios, offering a more comprehensive tool for marine conservation efforts. This approach, combining an AI-driven weather forecasting model with particle dispersion modeling, promises to provide deeper insights and more effective strategies in addressing marine debris challenges.

**3.5 Visualization Techniques for Lagrangian Model Analysis**

The visualization of Lagrangian models in marine environmental plays a crucial role in understanding and communicating complex data. Studies [5], [6], [18] highlight various techniques and tools developed for visualizing particle movements for Lagrangian models, emphasizing their importance in conveying the dynamics of phenomena like marine debris dispersion. Advanced visualization technologies, including interactive maps and 3D simulations [19], have been instrumental in providing clearer insights into marine ecosystems. Research in this field also focuses on enhancing user interfaces for broader accessibility, ensuring that these visualizations can be effectively used for educational and decision-making purposes [20].

**3.6 The Role of Web-based Platforms**

Developing a web-based platform to host simulations of marine debris movement, both past and future, represents a positive step in marine conservation and education. This platform will make it easier for users to access and interpret the simulated data. This will enhance user understanding and engagement. Studies [21], [22] show the effectiveness of web-based tools in aiding users to interact and understand complex scientific data. It also enables sharing information to a wider audience. The integration of visualizations, as discussed earlier, into this platform will further aid in conveying the intricacies of marine debris dynamics [20]. Such accessibility is crucial for informed decision-making in conservation efforts and provides an educational resource for understanding marine ecosystems.

1. **Proposed Solution & Methodology**

The Python programming language was selected for implementing and achieving all the objectives of this project.

1. **Testing and Evaluation**
2. **Conclusion**

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