Speed Modelling for Path Planning of a Wave-Propelled USV: An independent validation in the Atlantic Ocean

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***Abstract*—This paper presents a study that aims to validate and improve the speed-over-ground (SOG) model and estimator for a wave-propelled Unmanned Surface Vehicle (USV) originally presented in [1]. In this work, as compared to [1], the authors have used an independent set of data collected by a similar vehicle in another oceanic region with different wind and wave regimes. While the estimator model was trained using the same approach presented and discussed in [1] for a field campaign in the Norwegian Sea, the validation was carried out using a dataset collected during a long-duration exercise in the Northeastern Atlantic Ocean, off the coasts of Western Ireland. The estimator uses a non-linear Gaussian Process Regression (GPR) model trained using SOG measurements gathered from the onboard global navigation satellite system (GNSS) unit. The trained GPR model was implemented for datasets collected in the Atlantic Ocean using specific metocean data obtained from the Copernicus Marine Services. The results showed that the GPR model can accurately predict the USV's speed in the Atlantic Ocean with a mean absolute error (MAE) of 0.03 m/s. The results of this study validate [1] and demonstrate the benefits of the proposed prediction method. In addition, it indicates the possibility of using this estimation approach as a starting point to improve navigation performances and mission planning capabilities in the short and long temporal operational horizon.**

I. Introduction

Wave-propelled surface vehicles are being increasingly employed in scientific research at sea mainly because of two reasons. First, their large volume allows them to accommodate bigger payloads; secondly, given the nature of their propulsion, they show persistent ocean monitoring capabilities, as opposed to conventional autonomous underwater and surface vehicles. Furthermore, such vehicles require little human intervention from shore, making it a potentially cost-effective solution for long-duration oceanic tasks [2].

The AutoNaut is a wave-propelled surface vehicle whose heading, course-over-ground (COG) and speed are influenced by the environmental forces due to winds, waves and surface currents. The AutoNaut is a commercially available platform [3] equipped with a patented, passive propulsion system, and manufactured by the British AutoNaut Ltd company[1].

An AutoNaut mission usually lasts from a few days to several months, some lasting up to a year, depending on the task it is being deployed for. For a wave-propelled USV, the speed-over-ground results from environmental forces acting on the vehicle. These include wind, waves, surface currents, and other vehicle's internal and external properties. Although the vehicle is equipped with a small stern thruster, it is observed that its contribution to the USV's speed is negligible in most of ocean applications. Because of this, it can be concluded that the speed of the AutoNaut cannot be actively controlled, making mission planning routines depend on speed prediction models to estimate the future positions of the vehicle.

This study builds on the work presented in [1], and it aims to validate the model and speed estimator approach using an independent dataset for comparison in another oceanic region with different wind and wave regimes using, however, a similar 5 meters AutoNaut USV.

Fig. 1. Correlation matrix indicating the correlation coefficient of the selected environmental features for the GPR model and SOG for the AutoNaut. γ is the angle of attack calculated from [1].

II. Methodology

Firstly, following the approach in [1], the GPR model has been prepared using the same metocean dataset acquired on the Norwegian coast [4] to guarantee coherence in the results. The GPR model is very accurate in incorporating non-linear features and the results, as expected, were the same in [1].

Further, the GPR model trained on the Norwegian Sea dataset has been used to explore another AutoNaut mission dataset in the Atlantic Oceans during the iFADO [2] project

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[1] https://www.autonautusv.com/

[2] https://www.ifado.eu/

mission in 2021. This long-endurance mission was carried out by one AutoNaut in the ocean for a period of six-months.

A. Data preparation

The training dataset consists of a subset of 0.5 million SOG measurements gathered over a time period of approximately 6 days. The model was trained on these data points and further used to predict the SOG in different weather conditions, in the Northeast Atlantic Ocean.

The dataset for the Atlantic Ocean was prepared similar to that prepared for the Norwegian Sea, as described in [1]. The speed of a wave-propelled USV is influenced by several environmental features of the ocean, namely wind, wave, and surface current. These environmental features were obtained from the Copernicus Marine Services[3] weather forecast. All the parameters were obtained in a two-dimensional local earth-fixed coordinate frame for the entire duration of the AutoNaut's mission.

Moreover, the SOG values of the corresponding location were obtained from the data collected by the AutoNaut mission. The USV's SOG was obtained from the onboard GNSS receiver operating at 1Hz. A total of 2 million valid data points spanning 24 days across the 6 months of the USV mission were gathered. Together with the environmental features from forecasts, a data set of Irish-Atlantic oceans was prepared. This dataset is used for validation of the trained model.

Since the wind, waves and currents parameters have different levels of impact upon the target variable (SOG), feature selection was made to find a subset of the forecast parameters most relevant to the target, as discussed in [1] and shown in Figure 2. Following features were found to have most correlation with the output label: SOG, wave height, wave frequency, wave direction, wind speed and direction, and surface current speed and direction. See the correlation matrix in Figure 1.

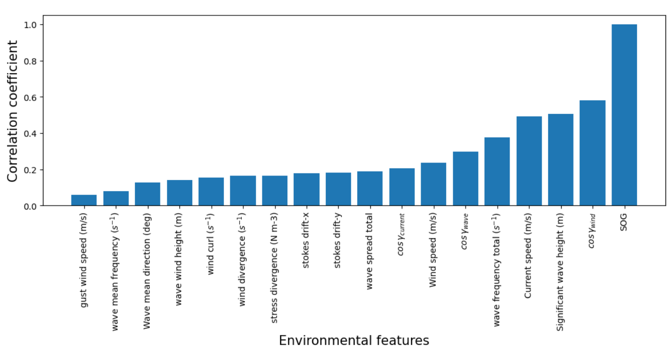

Fig. 2. Environmental variables selected before feature selection.

The trained models, with the same coefficient parameters resulting from the approach in [1], are then used to predict the speed based on forecast data. For the training data, the heading is known, and the correct angle of attack for wind, current, and waves can be computed directly. In the dataset used for testing, the heading is considered unknown, and the constant heading toward the next waypoint is used instead. For the evaluation metric, we used cumulative velocity error (CVE):

$$CVE := \sum_{i=1}^{N} \left(U_i - \hat{U}_i \right), \tag{1}$$

where U and $\hat{U}$ are the measured and predicted SOG respectively.

B. Model

This research explores the development of a Gaussian Process Regression model, which is known for its ability to handle non-linear features when predicting the speed and course-over-ground of wave-propelled vehicles [5]. This non-parametric kernel-based probabilistic model produces predictions based on prior knowledge. The prediction is made by learning a multivariate normal distribution as the underlying distribution from the training data. The following is the mathematical expression for calculating the continuous response from features using a GPR:

$$y = f(\boldsymbol{x}) \sim GP\left(m(\boldsymbol{x}), k\left(\boldsymbol{x}, \boldsymbol{x}'\right)\right), \tag{2}$$

where $m(\boldsymbol{x}), k\left(\boldsymbol{x}, \boldsymbol{x}'\right)$ are the mean and covariance functions.

III. Results and Conclusion

We implemented the GPR model trained against the Norwegian Sea dataset to explore the Atlantic Ocean region. We used the cumulative velocity error metric to evaluate the model's performance and found that the model does very well with an error of 0.03 m/s [3],. However, when applied to the Irish-Atlantic dataset, we found that there is a significant difference in the parameter values, as shown in Figure 3. The cumulative velocity error of the GPR model applied to Atlantic regime was found to be 0.5 m/s.

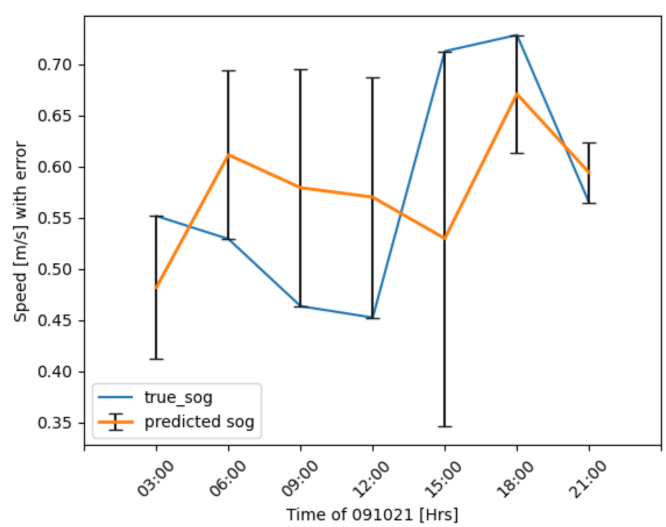

Fig. 3. Display of the model performance along with errors in Atlantic Ocean for one day mission.

[3]https://marine.copernicus.eu/

The significant climatic differences can explain the offset between the predicted and in-situ data, which impacted the validation results. The differences in wind regime (magnitude and direction relative to vehicle propagation direction) and wave regime (significant wave height, wave period, and direction) must be considered in the discussion of the results and future work. In addition, long missions can increase the possibility of biofouling, increasing the roughness in the USV's hydrofoils, hence increasing the drag force while reducing the speed. Several improvements were achieved in this study to reach, in the future, a more general model approach for better predicting AutoNaut's speed and other wave-propelled USVs.

IV. Acknowledgment

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