ASV-Swarm: a high-performance simulator for the dynamics of a swarm of autonomous marine vehicles in waves

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Abstract—The energy of ocean waves is the key distinguishing factor of a marine environment compared to other aquatic environments. Waves have a significant impact on the dynamics of marine vehicles. Hence, it is imperative to model waves and the dynamics of vehicles in waves when developing efficient control strategies for autonomous marine vehicles. However, most marine simulators available open-source exclude the realistic modelling of ocean waves and the efficient computation of wave forces on surface vehicles. This paper presents ASV-Swarm, a simulator which provides high fidelity and computationally efficient model of ocean waves and vehicle dynamics in waves. The simulator is suitable for applications requiring high run-time performance, such as with swarms of autonomous marine vehicles, or in developing optimal vehicle control strategies using reinforcement learning techniques. ASV-Swarm also has a low computational overhead making it ideal for onboard simulation for applications such as online learning for adaptation to changes in the environment.

I. INTRODUCTION

Robot swarms consist of relatively simple and independently acting robots coordinating together to achieve behaviours and tasks that are complex and well beyond the capacity of individual robots [1]. A distinguishing characteristic of robot swarms is the decentralised control architecture [2]. Such systems do not have a common mode failure point or vulnerability and are thus suitable for operations in remote and hostile environments such as the marine environment. For instance, swarms of marine robots may be used for collecting spatially and temporally dispersed environmental data over vast tracts of the ocean [3].

Testing the behavior of robot swarms in a marine environment is very expensive, hence requiring simulators. Simulators are also essential as virtual training environments for marine vehicles to learn behaviour controllers via trial-and-error. To the best of our knowledge, most marine vehicle simulators that are available open-source are primarily designed for the simulation of underwater vehicles, and consequently do not simulate irregular ocean waves and the dynamics of vehicles in waves. However, waves may have a significant impact on the dynamic positioning and manoeuvrability of marine surface vehicles [4]. Moreover, wave forces also need to be accounted for when designing coordination strategies for swarms of marine vehicles, for instance to synchronize long-range low-latency line-of-sight communication links between vehicles in a swarm.

Computing wave forces on a vehicle has a significant computational overhead. Wave forces are computed by integrating the wave pressure along the wetted hull surface, which is computed as the intersection of geometries representing the hull surface with that of the instantaneous sea surface. The computational overhead is even higher for the simulation of individual vehicles in a swarm due to the increased number of hull surfaces and the larger ocean surface to be modelled that is encompassed by the entire swarm.

One method to reduce computation is to simplify the hull geometry to an equivalent bounding box [5] or to divide the hull into smaller segments and assume a constant waterline for each segment [6]. An alternative method to reduce computation and improve performance is to use a combination of the following: (i) clustering of neighbouring facets over which wave forces are computed; (ii) parallelisation of wave force computation across these clusters; and (iii) a reduction in the number of instances the wave force computation is repeated in the simulation [7].

A common thread in the above heuristics is, (i) the use of time-domain analysis for computing wave forces on the vehicle i.e., integrating the wave pressure on the wetted hull surface at each time step of the simulation, and (ii) the use of a simplified hull mesh to reduce computational expense. However, simplifying the hull mesh alone does not provide a scalable solution; for example, when simulating individual vehicles of a swarm, the gains from reducing the complexity of each hull are negated by the higher number of hulls and the larger ocean surface to be simulated. While parallelisation may reduce the computation time it does not reduce the computation itself; high-degrees of parallelisation may not be supported onboard small-sized low-cost marine vehicles in a swarm.

This paper describes ASV-Swarm, a high-performance simulator which uses frequency-domain analysis to simulate the dynamics of a swarm of marine surface vehicles in ocean waves while accounting for the effects of winds and currents. Frequency-domain analysis models the irregular sea surface as a linear superposition of several regular waves. It assumes that each regular component wave induces a periodic force on the vehicle and the net force on the vehicle at any instant of time is the sum of forces due to each component wave. In the frequency-domain analysis, the computation of wave force by integrating the wave pressure along the wetted hull is performed only once for each component wave, versus time-domain analysis where the computation is repeated at each time step of the simulation. ASV-Swarm computes wave forces on the marine surface vehicle in two stages. The first stage computes wave forces on the vehicle for each component wave, and reduces the force due to each wave to a cosine function of vehicle’s position and time. The second
stage computes the net wave force on the vehicle by summing the instantaneous values of the cosine functions.

Dividing the computation into two stages offers some key benefits. The first stage of computation, which has a higher computational overhead, is performed offline, thereby reducing the computation at run-time. Low run-time overhead makes the simulator ideal for the simulation of swarms and applications in reinforcement learning. Such a splitting of the computation into two stages also makes it ideal for simulation onboard a vehicle.

ASV-Swarm has been implemented with a clear and simple programming interface written in C programming language, making it easy to integrate with any existing or future software. ASV-Swarm, at its core, is a software library that provides an efficient computation for irregular sea surface waves and forces on the marine surface vehicle due to irregular waves.

II. RELATED WORK

We consider the following features as essential in a marine vehicle simulator: (i) ability to simulate realistic ocean waves corresponding to a meteorologically given sea state; (ii) ability to simulate vehicle dynamics in waves in all six degrees of freedom; (iii) high run-time performance to enable simulation of a swarm of vehicles and for applications in reinforcement learning; and (iv) low computational overhead to enable applications onboard the vehicle. In this section, we review existing open-source marine vehicle simulators considering these features.

UWSim [8] is a well-referred open-source simulator and was used for developing many other marine simulators. It is a hardware-in-the-loop simulator and provides a wide range of sensor modules and realistic rendering of the underwater environment. However, the simulator is not suitable for the simulation of ocean waves and the dynamics of surface vehicles. The hydrodynamic forces are computed outside the simulator in a separate module written in Matlab, resulting in poor run-time performance.

USVsim [6] is a simulator based on UWSim [8] and is capable of simulating surface vehicles. USVsim models forces due to wind and water current and provides simulation for vehicle dynamics in waves. However, the wave force computation is limited to hydrostatic forces and excludes hydrodynamic forces due to waves.

UUV Simulator [9] is based on Gazebo [10] and provides functional integration with ROS [11]. UUV Simulator can simulate multiple vehicles simultaneously and hence is suitable for the simulation of a swarm. The simulator was designed with the assumption that the simulated vehicles operate outside the wave zone. Consequently, UUV Simulator is limited to marine underwater vehicles and is not suitable for simulation of dynamics of marine surface vehicle in waves.

MARS [12] is a marine simulator that is suitable for the simulation of both underwater vehicles and surface vehicles. It can provide a real-time simulation of multiple vehicles simultaneously, making it suitable for simulation of a swarm of vehicles. MARS can simulate forces due to water current and waves, but like USVsim, the simulator ignores the hydrodynamic forces due to waves and limits the wave force computation to hydrostatics forces.

Kelpie [5] is capable of simulating surface vehicles and aerial vehicles and was developed for testing and debugging control algorithms. The simulator simulates ocean waves as regular waves and considers simulation of irregular waves as not necessary for testing and debugging control algorithms. This assumption has been contradicted in Paravisi et al. (2019) [6], where an accurate modeling of natural disturbances is considered essential, especially for small vehicles with low inertia, for developing efficient guidance, navigation and control strategies. Also, the wave force computation in Kelpie is limited to hydrostatic forces and ignores the hydrodynamic forces due to waves. The source code of the simulator is not publicly available.

Thakur et al. (2011) [7] explores the challenges of computing vehicle dynamics in waves and proposes various wave-force computation heuristics to improve the run-time performance. However, its use of time-domain analysis for wave force computation is still computationally expensive and not suitable for achieving the high run-time performance required for the simulation of swarms of marine vehicles.

In summary, most marine vehicle simulators either ignore waves forces or limit the wave force computation to hydrostatic forces, ignoring the hydrodynamic forces due to waves. Although works such as that of Thakur et al. [7] model vehicle dynamics in waves, these models employ time-domain analysis for computing wave forces, a computationally expensive procedure repeated at each and every time step of the simulation, and thus not suitable for achieving a high run-time performance.

III. METHODOLOGY

Here we propose a method for realistic simulation of ocean waves and their impact on marine vehicles. In ASV-Swarm, the irregular ocean surface is modelled as a linear superposition of several regular waves with varying amplitude, frequency, and heading. This follows, to some extent, the earlier work in the realistic rendering of ocean waves [13], [14]. To model the vehicle dynamics in waves, we assume that each regular component wave induces a regular wave force on the vehicle and the net wave force, \( F_{\text{net}} \), on the vehicle at any instant of time is the linear superposition of forces due to each component wave.

This section is structured as follows: Section III-A gives an overview of the governing equation of dynamics of marine vehicles and the computation of their instantaneous acceleration, velocity and displacement. Section III-B details our computationally efficient model for the simulation ocean waves and the forces on the vehicle due to waves.

A. Dynamics of marine vehicle

The simulator computes the displacement, velocity and acceleration of the vehicle in 6 DoF for each time step based on the equations of rigid body dynamics:

\[
(M + M_A)a + C(v)v + K\Delta x = F_P + F_E, \tag{1}
\]
where \((M + M_A) a\) is the inertia force, \(M\) is the mass matrix, \(M_A\) is the added mass matrix and \(a\) is the acceleration vector. The added mass is computed using an empirical formula [15], assuming the hull shape equivalent to an elliptical cylinder with a length of major axis equal to the length at waterline, length of minor axis equal to breadth at waterline and height of cylinder equal to the floating draught of the vehicle. \(C(v)v\) is the hydrodynamic damping force, \(C(v)\) is the damping matrix, and \(v\) is the velocity vector. The hydrodynamic damping force acting on the vehicle is the sum of potential damping due to radiated wave, linear viscous damping due to skin friction and quadratic drag. At low speed (below 2 m/s), the potential damping and linear viscous damping due to skin friction and quadratic drag can be considered equal to quadratic drag ([16], pp.126-130). The drag force on the vehicle is computed based on an empirical formula [15], assuming hull geometry equivalent to an elliptical cylinder. \(K\Delta X\) is the hydrostatic restoring force, \(K\) is the hydrostatic stiffness matrix and \(\Delta X\) is the displacement from the equilibrium floating attitude. The excitation force acting on the vehicle \(F_P + F_E\) is computed as the resultant of propeller force, \(F_p\), and environmental force, \(F_E\), which is the sum of the wave, wind and current forces. \(F_w\) is the wave force acting on the vehicle, and its computation is described in detail in Section III-B.

The instantaneous acceleration \(\mathbf{a}(t)\) of the vehicle at time step \(t\) is computed from Eq. 1. The velocity \(\mathbf{v}(t)\) and position \(\mathbf{X}(t)\) of the vehicle are then computed by forward integration with a fixed time step size of \(\Delta t\).

**B. Computing wave forces**

1) **Modelling ocean waves:** The irregular sea surface is considered as the result of superposition of many regular waves and the state of the sea is defined using Pierson-Moskowitz spectrum ([17], pp. 545-546), which is a single parameter spectrum based on wind speed as input and provides the correlation between wave frequency and variance, or wave energy ([18], p. 14). Pierson-Moskowitz spectrum is defined as:

\[
S(f) = \frac{A}{f^3} e^{-\frac{g}{2f}},
\]

where:
\[
A = \alpha g^2 (2\pi)^{-4}
\]
\[
B = \beta (2\pi f_g^2)^{-4}
\]
\[
\alpha = 8.10 \times 10^{-3}
\]
\[
\beta = 0.74
\]
\(U\) is the wind speed in m/s measured at a height of 19.5 m above the surface.

The Pierson-Moskowitz spectrum is a point spectrum and hence using it directly would model the irregular sea surface as infinitely long crested. However, the sea is short crested because waves are heading in many different directions. Consequently, ASV-Swarm converts the point spectrum to a directional spectrum using the ITTC recommended spreading function ([19], p. 4-29):

\[
G(\mu) = \begin{cases} 
\frac{2}{\pi} \cos^2(\mu) & (\theta - \frac{\pi}{2}) \leq \mu \leq (\theta + \frac{\pi}{2}) \\
0, & \text{otherwise} 
\end{cases}
\]

where \(\theta\) is the wind direction measured with respect to geographic North. The equation for the resultant directional spectrum is:

\[
S(f, \mu) = S(f) G(\mu). \tag{4}
\]

For ASV-Swarm, the continuous wave spectrum is converted to a discrete spectrum with frequency bands of uniform width and frequencies ranging from the minimum threshold frequency, \(f_{0.1}\), to the maximum threshold frequency, \(f_{99.9}\). The minimum and maximum threshold frequencies for Pierson-Moskowitz spectrum are computed as per ITTC recommendations as ([17], pp.545-546):

\[
f_{0.1} = 0.652 f_p, \tag{5}
\]
\[
f_{99.9} = 5.946 f_p, \tag{6}
\]

where \(f_p\) is the peak spectral frequency = \((\frac{2}{\pi} \mu)^{\frac{1}{2}}\).

The discrete direction spectrum is used to generate a list of regular waves such that each frequency band in the spectrum represents a regular wave, and the area of the band in the spectrum is equal to the variance of the regular wave. Amplitude, \(\zeta_0\), of the regular wave can be computed from variance, \(S(f)\), as ([18], p.12):

\[
\zeta_0 = \sqrt{2S(f)}. \tag{7}
\]

Wave elevation for a regular wave at position \((x, y)\) at time \(t\) is computed as:

\[
\zeta(x, y, t) = \zeta_0 \cos[k(x \sin \mu + y \cos \mu) - \omega t + \epsilon], \tag{8}
\]

where \(\zeta_0\) is the wave amplitude, \(\omega\) is the circular frequency, \(k = \frac{\omega}{g}\) is the wave number, \(\mu\) is the wave heading and \(\epsilon\) is the phase angle. The sea surface elevation at any instant of time is the sum of elevations of all regular component waves and is computed as:

\[
z(x, y, t) = \sum_i \zeta_i \cos[k_i(x \sin \mu_i + y \cos \mu_i) - \omega_i t + \epsilon_i]. \tag{9}
\]

The process to generate the component waves based on wave spectrum is described in Algorithm 1.

2) **Computation of wave force due to an irregular sea:**

The wave force on the vehicle is the sum of Froude-Krylov force and diffraction excitation force. The Froude-Krylov force is due to the pressure variation around the hull due to the wave and the diffraction excitation force is due to the modification of the incident wave due to presence of the vehicle. The diffraction excitation force is negligibly small due to the relatively small size of the marine vehicles of a swarm, which is of the order of 10 m or less while wave length is of the order of 100 m; therefore, the wave force is approximated equal to Froude-Krylov force ([18], p. 43). The Froude-Krylov force on the vehicle due to the irregular
Algorithm 1 Algorithm to generate the regular component waves

\[
\begin{align*}
\text{Define } U & / \text{ wind speed in m/s} \\
\text{Define } \theta & / \text{ wind direction in radians} \\
g & \leftarrow 9.81 / \text{ acceleration due to gravity in m/s}^2 \\
\alpha & \leftarrow 8.10 \cdot 10^{-3} \\
\beta & \leftarrow 0.74 \\
A & \leftarrow i\alpha g^2 (2\pi)^{-4} \\
B & \leftarrow \beta (2\pi f_p^2)^{-4} \\
f_p & \leftarrow \left( \frac{i\alpha}{2\pi} \right)^{\frac{1}{2}} \\
f_{0.1} & \leftarrow 0.652 f_p \\
f_{99.9} & \leftarrow 5.946 f_p \\
\text{waves} & \leftarrow \text{new 2D array } / \text{ to hold properties of all component waves to be created} \\
i & \leftarrow 0 / \text{ counter for wave directions} \\
j & \leftarrow 0 / \text{ counter for wave frequencies} \\
\text{Define } n_f & / \text{ number for frequency bands} \\
\text{Define } n_\mu & / \text{ number of heading directions} \\
\Delta_f & \leftarrow \frac{f_{99.9} - f_{0.1}}{n_f} \\
\Delta_\mu & \leftarrow \frac{\pi}{n_\mu} \\
\text{for } \mu \text{ in range } (\theta - \frac{\pi}{2}) \text{ to } (\theta + \frac{\pi}{2}) \text{ do} \\
\text{for } f \text{ in range } f_{0.1} \text{ to } f_{99.9} \text{ do} \\
\quad / \text{ Compute variance as per equation 4} \\
\quad S & \leftarrow \left( \frac{A}{7}\alpha g^2 \right) \left( \frac{2}{g} \cos^2(\mu) \right) \Delta_f \Delta_\mu \\
\quad / \text{ Compute amplitude as per equation 7} \\
\quad \zeta_a & \leftarrow \sqrt{2S} \\
\quad / \text{ Generate a random number in range } [0, 360] \text{ from a uniform distribution, for the wave phase} \\
\quad \epsilon & \leftarrow \text{random number} \\
\quad / \text{ Store the properties of the wave in waves} \\
\quad \text{waves}[i][j].amplitude & \leftarrow \zeta_a \\
\quad \text{waves}[i][j].frequency & \leftarrow f \\
\quad \text{waves}[i][j].heading & \leftarrow \mu \\
\quad \text{waves}[i][j].phase & \leftarrow \epsilon \\
\quad j & \leftarrow j + 1 \\
\end{align*}
\]

Since the vehicle dimensions are much less than the wave length, it is reasonable to assume the wave pressure within the limits of the vehicle to vary linearly. Consequently, equation 11 for the wave forces acting on a marine vehicle in 6 DoF can be simplified as:

\[
\begin{align*}
F_{\text{wave}} &= p_c \alpha A_z, \\
F_{\text{wave pitch}} &= (p_{\text{fore}} - p_{\text{aft}}) A_y, \\
F_{\text{wave roll}} &= (p_{sb} - p_{ps}) \frac{A_z B}{2}, \\
F_{\text{wave sway}} &= (p_{fore} - p_{aft}) \frac{A_y L}{2}. \\
\end{align*}
\]

where \( p_c \) is the wave pressure at the centre of gravity of the vehicle, \( p_{\text{fore}} \) and \( p_{\text{aft}} \) are wave pressure at a distance of \( \frac{B}{4} \) from the centre of gravity of the vehicle measured towards the aft and fore respectively, and \( p_{sb} \) and \( p_{ps} \) are wave pressure at a distance of \( \frac{B}{4} \) from the centre of gravity of the vehicle measured towards the starboard side and portside. \( A_z \) is the waterplane area of the vehicle, \( A_y \) is the transverse sectional areas of the vehicle below water line at a distance of \( \frac{B}{4} \) from center of gravity, and \( A_y \) is longitudinal profile areas of the vehicle below water line at a distance of \( \frac{B}{4} \) from center of gravity.

IV. RESULTS

A. Validation of surface vehicle dynamics simulated with ASV-Swarm

ASV-Swarm was validated by comparing simulation results with data generated from running a remote-operated vehicle, SMARTY, in a towing tank capable of generating waves. SMARTY has a cylindrical shape and is equipped with four thrusters. The Fig. 1 shows its top view, side view and thruster configuration. The physical specifications of SMARTY are given in Table I.

| Parameter                  | Value         |
|----------------------------|---------------|
| Diameter                   | 0.32 m        |
| Height                     | 0.21 m        |
| Draught                    | 0.11 m        |
| Mass                       | 8.4 Kg        |
| Thrusters                  | BlueRobotics T100 Thruster [10] |

To investigate vehicle motion trends, we simulated SMARTY to move forward for 50 m in an open sea, while varying each of significant wave heights and wave headings in separate and independent experiments. The significant wave heights (in m), and wave headings were of \{0.5, 0.625, 0.75, \ldots, 2.0\} and \{0°, 11.25°, 22.5°, \ldots, 360°\}, respectively. Experiment were replicated 100 times with different random seed values. Therefore, in total, 42900 (13 significant wave heights \times 33 wave headings \times 100
replicates) experiments were performed. In each experiment, forward motion was generated by applying a constant force of 1 N to each of the four thrusters, while constraining yaw motion to achieve a constant wave heading. The vehicle was simulated with a fixed time step size of 40 ms. In each experiment, the 6 DoF position of the vehicle at each time step was recorded.

Fig. 2 shows the vehicle motion trends observed by plotting the mean of significant motion amplitudes for each trial. The heave motion of the vehicle increases with an increase in wave height. However, the roll and pitch amplitude at first increases with an increase in wave height and then decreases; this is because as the sea state increases from calm to high, the spectral peak of the ocean waves moves towards a lower frequency. The waves become higher but also longer, making the waves less steep. The heave motion does not show any correlation with the wave heading due to the circular waterline of the SMARTY platform. By contrast, the roll and pitch motions show a strong correlation with the wave heading. The pitch motion is highest in the head sea condition (wave heading at 180°), followed by the following sea condition (wave heading at 0° or 360°) and lowest in the beam sea condition (wave heading at 90° or 270°). The roll motion is highest in the beam sea condition and lowest in the head sea and following sea condition. These motion trends of the simulated vessel are in line with motions observed on a seagoing vessel and assert the validity of the ASV-Swarm simulator.

B. Analysis of performance of ASV-Swarm

Experiments were also performed to estimate the performance of the ASV-Swarm simulator. Performance is measured as the time required for completing the simulation and is expressed as the ratio of real time to simulation time. Real time is the time taken for the vehicle dynamics in the real world and simulation time is the time taken to complete the same dynamics in simulation.

The two key variables that influence the performance of ASV-Swarm are the number of wave components used to generate the irregular sea surface, and the size of the simulated swarm. To assess the impact of these variables, the forward motion experiment of the SMARTY platform was repeated.

In the first set of experiments, with a single vehicle, the number of wave components was varied to observe its effect on performance (see Table II). It is expected that a higher number of component waves while costly to simulate, model a more realistic sea-surface with better short-crested waves. Our results indicate that ASV-Swarm is capable of providing a high performance even with a larger number of component waves than recommended (75 wave components with 15 frequency bands per wave direction, see [18], p.13).

In a second set of experiments, the performance of the simulator was tested by simulating marine vehicle swarms of varying size, while fixing the number of wave components at 75 (see Table III). Results indicate that ASV-Swarm was able to simulate 10 vehicles at 220x faster than real time, with the performance reducing to a two-fold speed-up for very large swarms of 1000 vehicles.

| Component wave count (wave directions × frequency bands) | Performance (real time / simulation time) |
|----------------------------------------------------------|------------------------------------------|
| 15 (3 × 5)                                               | 2290x                                    |
| 30 (3 × 10)                                              | 1200x                                    |
| 75 (5 × 15)                                              | 467x                                     |
| 135 (9 × 15)                                             | 244x                                     |
| 195 (13 × 15)                                            | 178x                                     |
| 260 (13 × 20)                                            | 142x                                     |

| Swarm size | Performance (real time / simulation time) |
|------------|------------------------------------------|
| 10         | 220x                                     |
| 50         | 50x                                      |
| 100        | 23x                                      |
| 150        | 15x                                      |
| 200        | 12x                                      |
| 250        | 9x                                       |
| 500        | 5x                                       |
| 1000       | 2x                                       |
V. CONCLUSION AND FUTURE WORKS

ASV-Swarm is a simulator that models realistic ocean waves for a given sea state and the dynamics of surface vehicles in the waves. Its use of frequency domain analysis and its two-phase computational structure allow a high runtime performance even with many component waves and large swarm sizes. ASV-Swarm is implemented based on the assumption that the irregular sea surface is composed of many regular waves and the net wave force at any instant of time is a linear summation of wave force due to each component wave. Also, the wave pressure variation along the hull is approximated as linear due to the relatively small size of ASVs used in marine swarms with respect to the wavelengths. These assumptions hold for most use cases of current ASVs, which are slow-moving vehicles operating predominantly in mild sea conditions. High-speed simulation with high fidelity of non-linear systems, such as the dynamics of a high-speed planning craft or environments with wave breaking, is currently not possible with ASV-Swarm but may be achieved in future work by combining it with computational fluid dynamics (CFD) based approaches.

VI. SUPPLEMENTARY INFORMATION

The simulator is publicly available as open source at https://github.com/resilient-swarms/asv-swarm.git.

VII. ACKNOWLEDGEMENT

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