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RESEARCH ARTICLE

Simulation and Coordination of Autonomous Bio-Inspired Underwater Agents

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ABSTRACT This paper presents the preliminary results of the MAXFISH project, which aims to develop an integrated methodological and technological framework for modeling, simulating, and controlling coordinated bio-inspired robotic fish shoals. The system combines a Digital Twin platform, implemented in MATLAB/Simulink, with a max-plus algebraic model to address multi-agent coordination for underwater survey and monitoring missions. The Digital Twin enables the estimation of travel times based on the kinematic and dynamic behavior of the robotic fish, while the max-plus framework allows formal scheduling analysis of cyclic exploration tasks, ensuring mutual exclusion on shared resources and respecting mission constraints. A Graphical User Interface further supports mission planning, enabling users to define points of interest and automatically compute overall mission times. The novelty of this approach lies in the integration of max-plus algebra techniques with simulation tools for underwater inspections. The proposed framework also supports Hardware-in-the-Loop (HIL) and Software-in-the-Loop (SIL) testing, facilitating the validation of coordination strategies with real robotic agents and communication buoys. Simulation results on a representative mission scenario confirmed the feasibility of the framework. The platform produced consistent mission completion times and demonstrated effective coordination under diverse task configurations, validating the integration of max-plus algebra with the Digital Twin.

INDEX TERMS Max-plus algebra, digital twin, multi-agent systems, underwater robotics.

I. INTRODUCTION

Navigation, Guidance and Control (NGC) strategies for underwater vehicles have long been the focus of extensive research in the scientific literature, particularly in the context of bio-inspired systems. Biological swimmers exhibit intrinsic features such as high propulsive efficiency, precise maneuverability, and adaptability to complex fluid environments. These capabilities have inspired a new generation of underwater robotic platforms to replicate such performance, from AI-driven and bio-inspired propulsion prototypes [1], [2], to works on biomimetic robot design and control [3], [4], [5].

These developments have led to sophisticated single-agent systems capable of operating in unstructured marine environments. More recently, research has expanded to include

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cooperative strategies for coordinated *swarms* of vehicles, fueling growing interest in Multi-Agent Systems (MASs) for underwater applications [6], [7]. A recent survey [8] categorizes underwater MAS cooperation across task, motion, and sensing spaces, underscoring the need for formal strategies to coordinate agents in complex marine environments.

MAS architectures offer several advantages, including robustness to individual agent faults, scalability, and the ability to accomplish complex collective tasks. Notable examples of underwater MAS include the WiMUST project, focused on cooperative Autonomous Underwater Vehicles (AUVs) for geophysical surveying [6], and the DAMPS project for acoustic source localization [7]. Nevertheless, limited progress has been made in formal modeling frameworks for coordinated team-based interventions, especially for survey and patrol missions in confined or fragile underwater areas.

The MAXFISH project [9], from which this work originates, addresses this gap by proposing a comprehensive methodological and implementation framework that combines MAS principles with max-plus algebra tools for modeling and controlling synchronized cyclic missions. This integration is particularly innovative: while max-plus algebra is a well-established formalism for modeling discrete-event systems (DESs) [10], [11] with widespread applications in industrial domains for production planning and scheduling [12], [13], [14], its use in coordinating underwater MASs is still largely unexplored.

Within this context, the present work introduces a Digital Twin (DT) platform to simulate the behavior of fish-like robots during underwater missions, while briefly outlining the associated physical demonstrator —- comprising robotic fish and communication buoys —- envisioned to support future integration with Hardware-in-the-Loop (HIL), Software-in-the-Loop (SIL), and Model-in-the-Loop (MIL) testing.

Digital Twin technologies have recently gained attention in robotics for enabling real-time and high-fidelity simulations with sensor feedback [15], [16]. In MAXFISH, the DT currently takes the form of a simulation platform integrated with max-plus algebra modeling, laying the groundwork for future connection with physical assets.

The proposed approach enables conflict-free synchronization of agents executing cyclic tasks and is adaptable to dynamic mission scenarios. It is particularly relevant for applications such as environmental monitoring, underwater archaeology, and reef preservation, where coordinated robotic shoals can provide efficient and minimally invasive surveys of sensitive and complex sites.

Max-plus algebra facilitates the formal definition of coordination policies based on concepts of the geometric approach to linear systems [17], [18]. Earlier efforts extended foundational ideas of the structural geometric approach to the max-plus linear domain [19], [20]. Recent progress includes the definition of structural solvability conditions for the Model Matching Problems [21], [22], forming the theoretical and methodological basis for the work proposed here.

This study builds upon a previous max-plus-based model for fish robots [23], where a predefined survey was involved to obtain a max-plus linear system modeling the survey, and an early GUI [24] to have an extended and more general max-plus system. This work extends the previous results with a simulation platform to estimate mission timings starting from the latitude and longitude of each Point of Interest (POIs) to be reached and/or surveyed. The estimated mission timings are computed in Simulink, which embeds the fish robot model and simulates water dynamics, to obtain the movements of the devices in the simulated scenario. Moreover, the survey can be dynamically configured by defining the path of each robot, considering three robots and four Points of Interest (POIs). The connection with the DT in Simulink is novel and is used to estimate the travel times of the robots, which are then inserted in the max-plus-based GUI that computes the estimated mission completion times.

The integration of max-plus algebra into a GUI-based DT simulation platform represents a key novelty, enabling the calibration and evaluation of mission timing parameters to be inserted within the modeled max-plus system. In this way, it is possible to simulate the coordinated behavior of robots in underwater conditions. The resolution of the mentioned system is crucial for obtaining preliminary information about the cooperative behavior of the devices under realistic simulated operational conditions. This framework adopts a unified xIL (HIL/MIL/SIL) methodology, bridging theoretical modeling and future practical deployment, and it facilitates iterative design, testing, and refinement of cooperative multi-agent control architectures for underwater environments. To the best of the authors' knowledge, this is the first framework that integrates max-plus-based coordination with interactive mission definition and simulation, with an architecture designed to support future xIL validation in underwater multi-robot systems.

It is worth noticing that, within the scope of the project, a significant activity has been done on distributed estimation of a moving target by means of acoustic sensors, following the trend's activity started in [7]. The work addressed the specific issues of the underwater domain, where acoustic waves bring both information and communication, and their speed is limited [25], [26]. Numerical issues [27] and configuration optimization of the vehicles are also addressed [28].

The paper is structured as follows. Section II introduces the materials and methods of the work, starting with the developed physical system, divided into the bio-inspired solution for AUVs and the surface communication and localization system with intelligent buoys. The same section continues with the introduction of the theoretical framework of the max-plus algebra. Section III presents the considered case study, with its general description and the process to obtain the max-plus linear system that describes the robot coordination. Section IV introduces the developed software in terms of a Graphical User Interface (GUI) to define the latitude and longitude of the Points of Interest to be reached by three robots, considered in the project, to obtain

FIGURE 1. The external structure and biomimetic design of Poseidrone, the underwater robotic fish.

the estimated timings to reach every point, then inserted in another platform that computes the max-plus linear system describing the evolution of the coordinated behavior of the robots to produce an output in terms of estimated timing for the whole underwater survey. Then, Section V presents the results obtained from the simulations, and Section VI outlines the conclusion of the work, including potential future developments.

II. MATERIALS AND METHODS

A. PHYSICAL SYSTEM DESCRIPTION

The physical system developed consists of two main components: a set of bio-inspired underwater vehicles equipped with various onboard sensors, and surface buoys designed to support communication and geolocation. The robotic fish act as autonomous agents, performing cooperative tasks, while the buoys serve as a communication gateway and positioning reference, enabling data exchange between the underwater agents and the shore-based control infrastructure. The following subsections provide a detailed description of both the underwater vehicle and the surface communication system.

1) BIO-INSPIRED UNDERWATER VEHICLE

Poseidrone is a custom-designed robotic fish developed by ANcybernetics S.r.l. (www.ancyb.it/), shown in Fig. 1. Inspired by biological swimmers, it mimics real fish locomotion and supports cooperative survey and patrol operations in confined aquatic environments. Its propulsion system consists of a flexible tail actuated by three servomotors, which generate a body–caudal fin (BCF) undulatory motion. Vertical movement is controlled by a BLDC motor, including a PID controller to maintain a stable depth during the operational process. The vehicle, which weighs around 9.5 kg for a length of 106 cm, integrates an onboard camera featuring Artificial Intelligence (AI) capabilities for visual perception tasks such as object detection, environmental awareness, or potential future applications in target recognition. Environmental monitoring is further supported by a pressure and temperature sensor, which contributes to both navigation accuracy and data acquisition. At the core of the vehicle's electronics is an ESP32 microcontroller, responsible for low-level control, sensor data processing, and communication management. An inertial measurement unit (IMU), composed of magnetometers, gyroscopes, and accelerometers, provides attitude estimation and motion tracking. The robot is powered by a self-contained energy system, providing full autonomy for operations. The power management includes a relay mechanism that selectively activates or deactivates specific actuators. Moreover, it operates as a shallow-water AUV, currently reaching depths of up to 1.5 meters, with positioning assistance provided by the surface buoy, which acts as a localization and relay node.

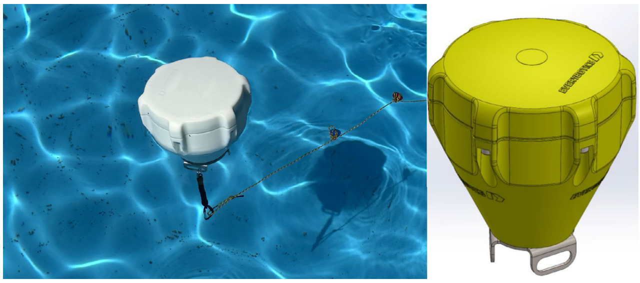


FIGURE 2. The marine buoy serving as a communication gateway and positioning reference for the underwater robotic fish Poseidrone.

2) SURFACE COMMUNICATION AND LOCALIZATION SYSTEM

The Surface Communication and Localization System is represented by a marine buoy developed by EveryBotics S.r.l, shown in Fig. 2. In particular, the latter shows an experimental scenario on the left and a 3D rendering of the buoy on the right, respectively. As can be easily observed from the 3D rendering, the buoy is formed by a main body that is closed by a suitable lid on the top. At the bottom, it presents a support foot that acts as ballast. This ballast can be adjusted by adding/removing metal discs of the proper size. Moreover, the support foot is designed with a ring shape to facilitate the buoy coupling to the underwater fish for towing. Inside the main body, the electronic components set is present, running the entire communication gateway. More in detail, the core component is represented by an ESP32 microcontroller, which manages sensor data processing and communications. Then, an LTE (Long-Term Evolution) and GNSS (Global Navigation Satellite System) module provides the localization of the buoy with the possibility of communicating over cellular networks. An IMU is integrated as well, providing the buoy attitude estimation, which is useful for analyzing buoyancy properties during towing phases. The entire electronics is powered by a proper battery system able to guarantee a working time, i.e., buoy autonomy, of several hours. Since it serves as a communication gateway and positioning reference for the underwater fish Poseidrone, it is provided with a proper communication link with the latter based on a serial protocol, i.e., I^2C (Inter-Integrated Circuit).

B. MAX-PLUS ALGEBRA THEORETICAL FRAMEWORK

This section presents some basic concepts of max-plus algebra, fundamental to the developed approach, and to obtain the general max-plus linear system used for simulations.

First of all, max-plus algebra is defined over the set $\mathbb{R}_{\max} = \mathbb{R} \cup \{-\infty\}$, equipped with two fundamental operations: the *maximum* (denoted $\oplus$) and the *addition* (denoted $\otimes$). For any two elements $x, y \in \mathbb{R}_{\max}$, the operations are:

$$x \oplus y = \max(x, y)$$
$$x \otimes y = x + y$$

These operations endow $\mathbb{R}_{\max}$ with the structure of a semi-ring, where $e = 0$ is the multiplicative identity and $\epsilon = -\infty$ is the additive identity, which also acts as an absorbing element under multiplication. In this sense, such elements e and ϵ act as the 0 and 1 of the conventional algebra. The semi-ring satisfies associativity, distributivity of $\otimes$ over finite sums $\oplus$, and the existence of neutral elements.

The algebra naturally extends to matrices and vectors in $\mathbb{R}_{\max}^{m\times n}$ with $m, n \in \mathbb{N}$ and with elements in $\mathbb{R}_{\max}$.

Given matrices $A, B \in \mathbb{R}_{\max}^{m\times n}$, their sum is defined element-wise as $(A \oplus B)_{ij} = A_{ij} \oplus B_{ij}$. The product between $A \in \mathbb{R}_{\max}^{p\times n}$ and $B \in \mathbb{R}_{\max}^{n\times m}$, written as $A \otimes B$ or as AB, is given by:

$$(A \otimes B)_{ij} = \bigoplus_{k=1}^{n} A_{ik} \otimes B_{kj}.$$

Moreover, scalar multiplication for $\lambda \in \mathbb{R}_{\max}$ and $A \in \mathbb{R}_{\max}^{p\times n}$ is defined componentwise as $(\lambda \otimes A)_{ij} = \lambda \otimes A_{ij}$, with $i = 1, \ldots, p$, and $j = 1, \ldots, n$. The null matrix is denoted by ϵ, and the identity matrix of size $n \times n$ by I_n, which contains e on the diagonal and ϵ elsewhere.

This algebra is particularly suited to describe Discrete Event Systems (DESs), where concatenation and synchronization of tasks, without concurrency, are crucial. The operator $\otimes$ models concatenation, which is the sequential execution (e.g., durations in a processing pipeline), while $\oplus$ captures synchronization constraints (e.g., tasks that must all be completed before proceeding).

A key concept in max-plus modeling is the *dater*, which encodes the timing of recurring events. An n-dimensional dater $d(k)$ is a vector whose i-th component $d_i(k)$ represents the time at which the k-th occurrence of event type i takes place. To remain physically meaningful, the dater must satisfy a monotonicity condition: $d(k + 1) \geq d(k)$ for all $k \in \mathbb{N}$.

A max-plus linear system models the evolution of such event timings through the following state-space form:

$$\Sigma \equiv \begin{cases} x(k+1) = A \otimes x(k) \oplus B \otimes u(k+1) \\ y(k) = C \otimes x(k) \\ x(0) = \epsilon. \end{cases} \qquad (1)$$

Here, $x(k) \in \mathbb{R}_{\max}^{n}$ is the state vector encoding the internal events dater, $u(k) \in \mathbb{R}_{\max}^{m}$ is the control input or input events dater, and $y(k) \in \mathbb{R}_{\max}^{p}$ is the output dater, with $k > 0$ which is the event instance index.

Matrices $A \in \mathbb{R}_{\max}^{n\times n}$, $B \in \mathbb{R}_{\max}^{n\times m}$, and $C \in \mathbb{R}_{\max}^{p\times n}$ encode the system structure. The initial condition is assumed to be $x(0) = \epsilon$, i.e., no prior activity.

The system evolves in discrete steps indexed by $k \in \mathbb{N}$, and the output $y(k)$ depends linearly (in max-plus sense) on the state vector. Given $u(k)$ and $x(0) \in \mathbb{R}_{max}^{n}$, the output solution is uniquely determined.

III. CASE STUDY

A. GENERAL DESCRIPTION

To assess the proposed coordination framework and its practical applicability, a simulated case study was designed based on the real-world layout of the engineering pool at Universitá Politecnica delle Marche (UNIVPM), in Ancona, Italy. Although no physical deployment was carried out, the simulation environment was configured using the actual dimensions and geospatial coordinates of the pool —- retrieved from satellite imagery —- to reproduce a realistic and spatially constrained mission scenario. This testbed allows for evaluating the behavior of a coordinated multi-agent system in a confined aquatic environment, preserving real-world geometrical proportions while benefiting from the repeatability and flexibility of a simulation-based approach.

The demonstrator involves three robotic fish—instances of the custom-designed platform ‘‘Poseidrone’’—and three surface communication buoys. At the current stage, the Poseidrone robots are remotely guided, relying on the buoy as the main localization and coordination reference. Each robot features a flexible caudal fin actuated by three servomotors to generate undulatory Body–Caudal Fin (BCF) propulsion. Additional on-board components include a pressure sensor, IMU, depth controller, ESP32 microcontroller for local control and communication, and variable payload configurations (e.g., camera, sonar, or AIDD module [29]).

In the simulated mission, four Points of Interest (POIs) are defined within the pool environment. Robots are assigned to sequentially visit a subset of these POIs, with the constraint of mutual exclusion: only one agent may operate at a given POI at any time. The specific payload configuration of each robot impacts its estimated travel speed and energy profile. The considered configurations are:

- Robot 1 is equipped with a single camera and has the highest relative speed.
- Robot 2 is equipped with a camera and a sonar and operates at 0.75× the speed of Fish 1.
- Robot 3 is equipped with the Artificial Intelligent Dolphin Deterrent (AIDD) [29] and a sonar, and operates at 0.65× the speed of Fish 1.

Battery constraints are also included in the simulation: a full recharge cycle is assumed to take 10 hours, with a 70% charge requiring approximately 7 hours in wireless mode.

Each robot begins its mission from an initial location, performs its assigned exploration tasks, and returns to the start after recharge. Travel and repositioning times are estimated using a Simulink-based simulator of the fish dynamics, configured to emulate the ‘‘Only Caudal Fin’’ actuation mode. The computed timing data are then used as input to a MATLAB-based max-plus algebra platform, which models synchronization constraints and computes the round completion times.

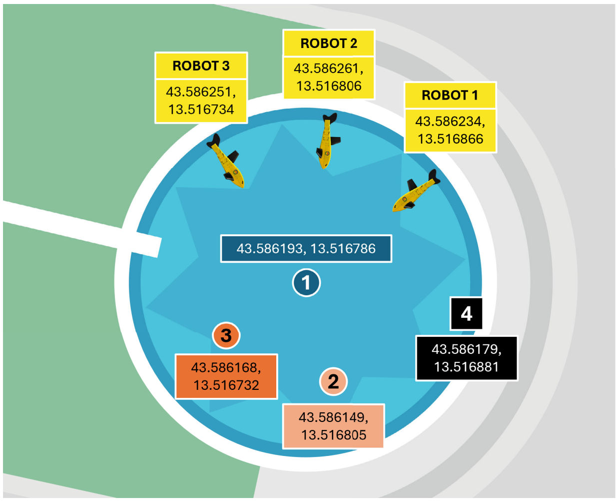


FIGURE 3. The coordinates of the chosen scenario and its POIs.

A dedicated Graphical User Interface (GUI) allows users to configure the mission by entering POI coordinates and timing parameters. The GUI supports scenario configuration, automatic max-plus system generation, and visual inspection of timing outputs and robot trajectories.

This case study serves as a representative validation scenario for the proposed methodology, highlighting its ability to coordinate heterogeneous agents in time-constrained, spatially confined underwater missions.

Fig. 3 details the latitude and longitudes of the chosen POIs, which are the starting points for each robot, the underwater POIs, and the collection POI.

B. THE MODELED MAX-PLUS SYSTEM

To model the coordination among multiple robotic fish engaged in underwater exploration, a generalized max-plus linear system of the form (1) is employed. The first max-plus system modeled for these devices was originally introduced in [23], considering a specific and fixed sequence of robot operations. That system was then extended in terms of more general and parametric equations, to adapt to any changes in the robot routes and through a configurable graphical interface detailed in [24], to provide a formal structure for describing the timing relationships between mission events in discrete-event systems.

Each agent is assigned a mission path that includes up to three POIs and concludes at a designated surface location. The progression of the mission is structured in rounds, each indexed by k. For every round, the initiation of the task is triggered by external commands represented by an input vector $u(k+1) \in \mathbb{R}^3_{\max}$, where each entry corresponds to one of the three robots. The internal dynamics of the mission are captured by a state vector $x(k) \in \mathbb{R}^{24}_{\max}$, whose components encode the time instants of key events, such as travel to and exploration of POIs, surfacing, and repositioning. Finally, the output $y(k) \in \mathbb{R}_{\max}$ is the overall round completion time.

Coordination constraints are embedded in the system structure. In particular, mutual exclusion is ensured by enforcing a static priority among robots when accessing the same POI: Robot 1 has the highest priority, followed by Robot 2 and then Robot 3. This prevents concurrent access to shared resources and guarantees sequential exploration when required. All mission timings, including travel, exploration, and recovery durations, are inserted through the GUI into the system matrices accordingly. If a robot skips a POI, the corresponding timing variable is set to the max-plus null element $\epsilon = -\infty$, effectively disabling that event transition.

This modeling approach allows a compact yet expressive representation of multi-agent coordination strategies, supporting automated construction of the max-plus linear system from user-defined mission parameters.

The constructed system is detailed in [24], and it adheres to the canonical form (1) of a max-plus linear system. Here, the matrix $A \in \mathbb{R}^{24\times 24}_{\max}$ encodes the internal logic of the mission, describing how each event in the state vector $x(k)$ depends on previous ones through travel, exploration, or repositioning steps. Matrix $B \in \mathbb{R}^{24\times 3}_{\max}$ specifies the effect of external start commands on the activation of the internal events. Finally, the output matrix $C \in \mathbb{R}^{1\times 24}_{\max}$ extracts the maximum completion time among the robots' cycles, representing the duration of each mission round.

To handle indirect dependencies and recursive relationships among the events, the system is initially described as

$$\begin{cases} x\left(k+1\right) = A_0 x\left(k+1\right) \oplus A_1 x\left(k\right) \oplus B' u\left(k+1\right) \\ y(k) = Cx(k). \end{cases} \tag{2}$$

This intermediate set of matrices is composed of:

- A_0, that contains the direct dependencies among internal events occurring within the same round,
- A_1, which encodes temporal constraints across rounds, e.g., those involving repositioning before restarting,
- B', that maps external triggers to internal activations.

Using these components, the system (2) is made explicit by applying:

$$A = A_0^* \otimes A_1, \quad B = A_0^* \otimes B',$$

where A_0^* denotes the max-plus Kleene star of A_0. This operator is used to solve implicit equations of the form $x = A_0 x \oplus b$, obtaining $x = A_0^* b$. It is defined as

$$A_0^* = \bigoplus_{n\in\mathbb{N}} A^n = I \oplus A_0 \oplus A_0^2 \oplus A_0^3 \oplus \cdots$$

and simplifies to a finite sum thanks to its lower triangular form, which leads to $A_0^i = \epsilon \forall i \geq \dim A_0$. As a consequence,

$$A_0^* = \bigoplus_{i=0}^{23} A_0^i.$$

This operator captures the cumulative effect of multiple sequential transitions, allowing the resolution of systems with internal cycles or delayed dependencies.

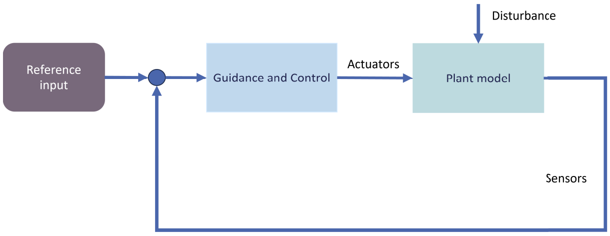


FIGURE 4. Logical architecture of the NGC system. Navigation is coordinated using a max-plus algebra approach; guidance is implemented through an LOS algorithm, while control is managed via PID controllers. The plant model represents the dynamics of the robotic fish, with actuation performed by the caudal tail mechanism.

The complete formulation of the coordination system is omitted here for brevity and clarity, but can be found in [24], where the full recursive structure is explicitly reported.

The resulting model is automatically generated within the platform, based on the user-defined mission structure and input timings. This approach supports rapid scenario reconfiguration while ensuring formal correctness of synchronization constraints.

IV. SOFTWARE DESCRIPTION

A. FISH ROBOT SIMULATOR FOR DYNAMICS AND CONTROL VALIDATION

To support the analysis and validation of the max-plus algebra-based modeling approach, a MATLAB/Simulink simulator of the robotic fish has been developed. Its objective is to offer a high-fidelity and controllable virtual environment that accurately reproduces the fish dynamic behavior, along with the NGC architecture, as illustrated in Fig. 4.

The navigation subsystem enables customization of both the path and actuation configuration of the robotic fish. Three actuation modes are available: *Normal*, which uses the caudal fin for surge motion, lateral propellers for steering, and a combination of pectoral fins and a vertical propeller for depth control; *Only Propellers*, where the propellers handle all motion functions; *Only Caudal Fin*, where the caudal fin is used for surge and steering, while depth control is disabled. In this study, the simulation was restricted to the "Only Caudal Fin" configuration to reflect the real setup of the Poseidrone prototype, which does not include active lateral thrusters.

In terms of reference, the user can choose between two selection methods for the POIs – here also called waypoints: *Waypoints-Based Path*, where a predefined path is generated using the Signal Builder tool; *Manual Waypoint Selection*, where users can manually input a series of (x, y, z) coordinates, defining the desired waypoints. The robot sequentially navigates through the targets, transitioning to the next point once it reaches the current waypoint within a tolerance of 0.5 meters.

To validate the max-plus algebra model, the *Manual Waypoint Selection* is used by assigning them through the Graphical User Interface. Users specify the POIs, after which the simulator computes the arrival times at each waypoint. These time references are then used to coordinate motion and inter-agent synchronization.

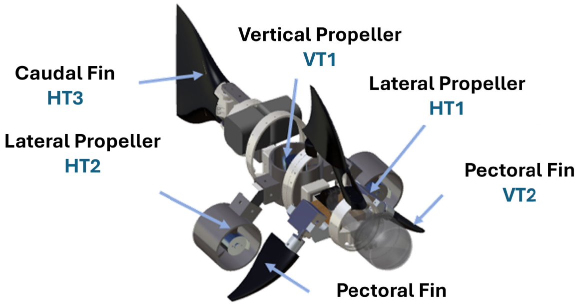


FIGURE 5. 3D model of the simulated robotic fish with the main actuation components. The system includes a caudal fin (HT3), two lateral propellers (HT1, HT2), a vertical propeller (VT1), and two pectoral fins (VT2, VT3).

The guidance system is implemented using a Line-of-Sight (LOS) guidance law, which computes the required heading corrections based on real-time navigation data. This module receives as input the desired waypoint coordinates, along with the robot's current position and orientation. Based on this information, the system generates a guidance vector, denoted as LOS, which contains the horizontal distance to the target, the desired yaw angle, and the vertical error. The control system then uses this vector to steer the vehicle toward the next waypoint in a smooth and dynamically consistent manner.

The control system receives the guidance vector as input and computes the appropriate commands for the actuators through two main subsystems: the Control Law and the Control Allocator. The Control Law module implements three independent PID controllers, each responsible for surge thrust, steering moment, and depth control force. Each controller output is passed through saturation limits to ensure actuator protection and prevent damage. The Control Allocator translates the control efforts into actuator-level commands by solving a control allocation problem. This involves a system of equations tailored to the selected actuator configuration, distributing the control inputs across a set of seven actuators, shown in Fig. 5:

- f_{uHT3} – oscillation frequency of the caudal fin,
- $Theta_{uHT3}$ – steering angle of the caudal fin,
- $uHT1$ – rotational speed of the left lateral propeller,
- $uHT2$ – rotational speed of the right lateral propeller,
- $uVT1$ – rotational speed of the vertical propeller,
- $uVT2$ – deflection angle of the left pectoral fin,
- $uVT3$ – deflection angle of the right pectoral fin.

The robotic fish model is composed of the Propulsion System and the Kinematics and Dynamics Model. The Propulsion System block computes the external forces and moments generated by the actuators. These are separated into horizontal and vertical components, depending on the

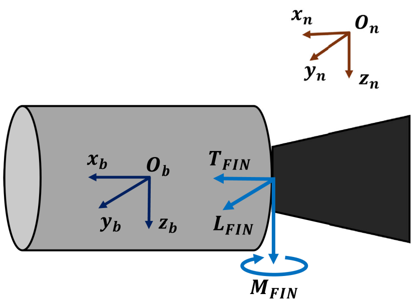


FIGURE 6. **Forces and moments generated by the tail.**

contribution of the horizontal thrusters, vertical thrusters, and caudal fin.

A specific mathematical model for the oscillatory motion of the caudal fin is implemented for the thrust generation and steering effect, reflecting the bio-inspired propulsion behavior of the robotic fish. Fig. 6 shows moments and forces generated by the caudal fin and applied to the body of the fish. They are defined as follows:

$$\begin{aligned} T_{\text{FIN}} &= K_{T1} f^2 \left[K_{T0} + K_{T2} \sin(4\pi f t + \beta)\right] \\ L_{\text{FIN}} &= K_{L1} f^2 K_{L2} \cos(2\pi f t + \sigma) \\ M_{\text{FIN}} &= K_{M1} f^2 K_{M2} \cos(2\pi f t + \varepsilon) \end{aligned}$$

where f is the oscillation frequency, and $K_{Ti}, K_{Li}, K_{Mi}, \beta, \sigma, \varepsilon$ are empirical coefficients determined through Computational Fluid Dynamics (CFD) simulations, derived from previous works [30], [31]. Basically, the forces and moments the fin generates are applied to the main body as if they were external inputs. When the mean oscillation angle $\bar{\theta}$ (i.e., the axis about which the tail oscillates) is zero, the thrust is aligned with the longitudinal axis, and T_{FIN} and L_{FIN} can be directly used in the body frame. However, when the mean angle is non-zero (e.g., during turning maneuvers), the forces must be projected onto the body-fixed frame centered at the center of gravity (CoG). In this case, the transformed force components become:

$$\begin{aligned} F_{\text{surge}} &= T_{\text{FIN}} \cos(\bar{\theta}) - L_{\text{FIN}} \sin(\bar{\theta}) \\ F_{\text{sway}} &= T_{\text{FIN}} \sin(\bar{\theta}) + L_{\text{FIN}} \cos(\bar{\theta}) \\ M_{\text{yaw}} &= M_{\text{FIN}} + x_{bf} F_{sway} \end{aligned}$$

where x_{bf} is the distance between the CoG and the point of the application of the forces from the fin.

The Kinematics and Dynamics block models the fish's rigid body motion and hydrodynamic interactions. The main body of the fish is approximated as a rigid cylindrical structure, fully submerged and symmetric with respect to its principal planes. The mathematical formulation is based on the standard marine vehicle model proposed by Fossen [32], which describes the motion in terms of position, orientation, and body-frame velocities. The equations incorporate kinematics and dynamics of the system, including rigid-body, hydrodynamic, and hydrostatic forces, and are expressed as follows:

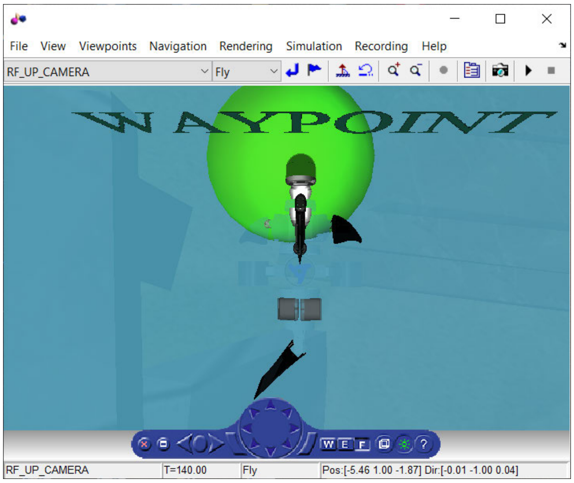
$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\boldsymbol{\nu} \tag{3}$$

$$\underbrace{M_{RB}\dot{\nu} + C_{RB}(\nu)\nu}_{\text{rigid-body forces}} + \underbrace{M_A \dot{\nu}_r + C_A(\nu_r)\nu_r + D(\nu_r)\nu_r}_{\text{hydrodynamic forces}} + \underbrace{g(\eta) + g_0}_{\text{hydrostatic forces}} = \tau. \tag{4}$$

For a complete description of the modeling assumptions and detailed matrix expressions (mass, Coriolis, damping, and restoring terms) and the variables' meaning, the reader is referred to [33].

A virtual reality environment is integrated into the framework to visually represent the motion of the robotic fish in real time. This is implemented using a VRML (Virtual Reality Modeling Language) block within the Simulink 3D Animation toolbox, which connects the dynamic Simulink model to a 3D underwater scene created with the native VRML World Editor. The animation allows users to observe the robot's behavior through a graphical interface while simulation data drives the motion and orientation of the virtual model.

The fish tail is currently modeled and displayed with a single movable joint, which is the external one, while the remaining two joints are kept fixed. This simplification is primarily aimed at reducing computational complexity and simulation overhead. Although a fully actuated tail may result in increased swimming speed, the adopted simplification ensures physical feasibility and provides reliable travel time estimates, which are sufficient for the mission planning goals of this study. Hence, the travel time estimates remain qualitatively representative and useful for coordination strategy validation. This simplification represents a conservative modeling assumption, ensuring robustness of the estimated timings while remaining consistent with the current hardware capabilities.



RF_UP_CAMERA T=140.00 Fly Pos:[-5.46 1.00 -1.87] Dir:[-0.01 -1.00 0.04]

FIGURE 7. **The simulated fish robot reaching a POI.**

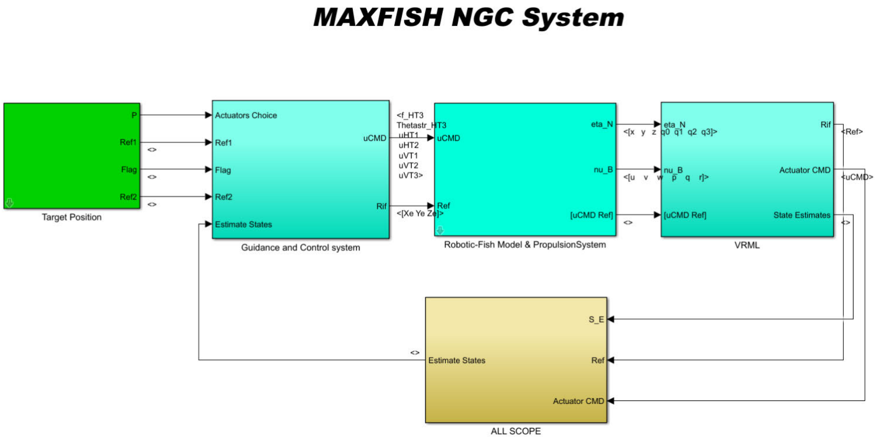


FIGURE 8. **Block diagram of the MAXFISH NGC system implemented in Simulink. The system includes: (i) a Target Position module; (ii) the Guidance and Control subsystem; (iii) the Robotic-Fish Model & Propulsion System; (iv) a VRML block for real-time 3D visualization; and (v) an ALL SCOPE block for logging estimated states, control inputs, and reference trajectories.**

A screenshot of the animated fish robot reaching a POI is shown in Fig. 7, whereas the complete Simulink scheme is depicted in Fig. 8.

B. GRAPHICAL USER INTERFACES

To support mission planning and timing analysis, a first Graphical User Interface (GUI) has been developed to compute estimated travel times between Points of Interest (POIs), followed by a second GUI to compute the max-plus linear system, which outputs the estimated completion timings for each round. Both GUIs are designed within the MATLAB environment, using MATLAB App Designer [34] and exploiting the existing Max-Plus Algebra Toolbox [35], to avoid the manual implementation of algebraic rules.

1) MISSION SETUP GUI

In the first GUI, the user is asked to input the geographical coordinates (latitude and longitude) of the starting points and target POIs for each robotic fish. Upon clicking the "Run Simulation" button, these coordinates are converted into metric distances, which are used to calculate the corresponding travel times between POIs. The estimation is based on the Simulink-based digital twin of the robotic fish, which simulates its movement according to predefined actuation parameters and dynamic models, as presented in Section IV-A, allowing users to retrieve realistic travel times for various mission configurations. The Simulink-based simulation platform not only estimates travel times to be inserted as parameters in the max-plus modeled system, but also serves as a mission-aware calibration environment, aligning the algebraic coordination model with realistic motion profiles derived from physical simulations of the robotic fish.

By providing time-consistent values derived from the physical dynamics of the fish robot, the simulator ensures that the timing behavior encoded in the algebraic system reflects realistic mission conditions.

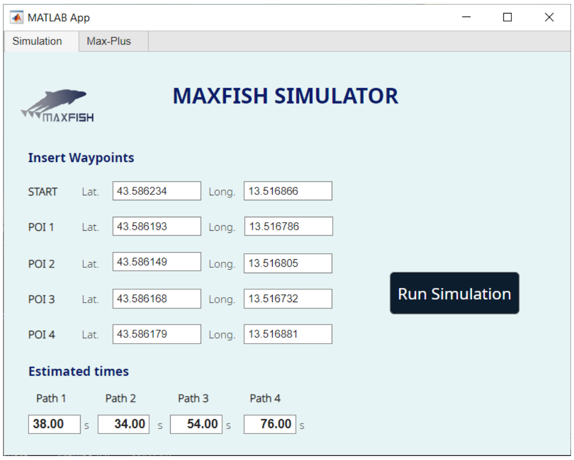
The layout of the interface, with the data of the Fish Robot 1 crossing all POI and the corresponding computed estimated travel times, is shown in Fig. 9.

The resulting durations of each path are stored and used as input parameters in the subsequent max-plus system, inserted within the GUI described in the next section.

2) MAX-PLUS INTERFACE

To support user-friendly configuration of coordinated missions, a dedicated max-plus-based interface has been developed. The platform is composed of a GUI and a computation engine for max-plus algebra operations relying on the Max-Plus Algebra Toolbox for MATLAB [35].

This interface enables intuitive definition and adjustment of mission parameters without requiring users to manipulate algebraic constructs directly. Specifically, the GUI allows the



MAXFISH SIMULATOR

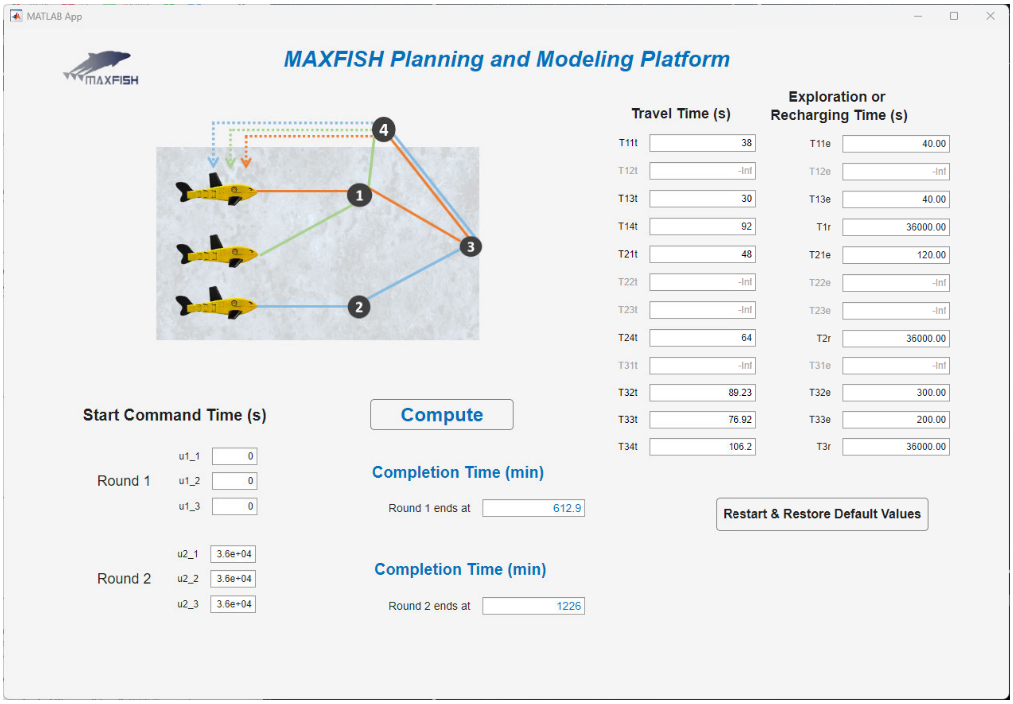
Insert Waypoints

START	Lat.	43.586234	Long.	13.516866
POI 1	Lat.	43.586193	Long.	13.516786
POI 2	Lat.	43.586149	Long.	13.516805
POI 3	Lat.	43.586168	Long.	13.516732
POI 4	Lat.	43.586179	Long.	13.516881

Estimated times

Path 1	Path 2	Path 3	Path 4
38.00 s	34.00 s	54.00 s	76.00 s

FIGURE 9. **The GUI to compute the estimated travel times.**



Travel Time (s)		Exploration or Recharging Time (s)	
T11t	38	T11e	40.00
T12t	-Inf	T12e	-Inf
T13t	30	T13e	40.00
T14t	92	T1r	36000.00
T21t	48	T21e	120.00
T22t	-Inf	T22e	-Inf
T23t	-Inf	T23e	-Inf
T24t	64	T2r	36000.00
T31t	-Inf	T31e	-Inf
T32t	89.23	T32e	300.00
T33t	76.92	T33e	200.00
T34t	106.2	T3r	36000.00

Start Command Time (s)

Round 1
u1_1 0
u1_2 0
u1_3 0

Round 2
u2_1 3.6e+04
u2_2 3.6e+04
u2_3 3.6e+04

Completion Time (min)
Round 1 ends at 612.9

Completion Time (min)
Round 2 ends at 1226

FIGURE 10. The GUI with the default scenario, where each robot is assigned a reduced number of POIs.

user to configure a mission involving three robotic agents, each tasked with visiting at most three underwater POIs, before returning to a designated end location (POI n.4) representing a surfacing point, where they are collected by a human operator who puts them on charge and then brings them back to the starting point, to begin a new survey when required. In this way, it is possible to plan robot movements, providing input parameters such as travel durations, exploration times at each POI, and external triggers for round initiations, expressed in seconds. From these values, the platform automatically constructs the max-plus linear system that models the mission, and it computes the completion times, expressed in minutes, for each round of coordinated activity.

The GUI, shown in Fig. 10, enforces constraints on mutual exclusion, ensuring that no two robots occupy the same POI simultaneously, and integrates prioritization rules to resolve scheduling conflicts. Dynamic reconfiguration of robot paths and mission timings is supported, and changes in robot routing are immediately reflected in the visual layout.

The system includes built-in consistency checks to prevent invalid input combinations. For instance, invalid travel times or inconsistent start commands trigger visual warnings, guiding the user toward correct scenario configuration. This capability improves reliability and supports iterative testing of mission strategies.

Overall, the platform provides an integrated environment for modeling, simulating, and evaluating the coordination of robotic agents under temporal and structural constraints.

While the current implementation supports two inspection rounds, the architecture is modular and easily scalable to larger teams and more complex missions. The combination of both GUIs represents an important step toward validating coordinated robotic behaviors in simulated environments, offering a foundation for future real-world-based validation.

V. RESULTS

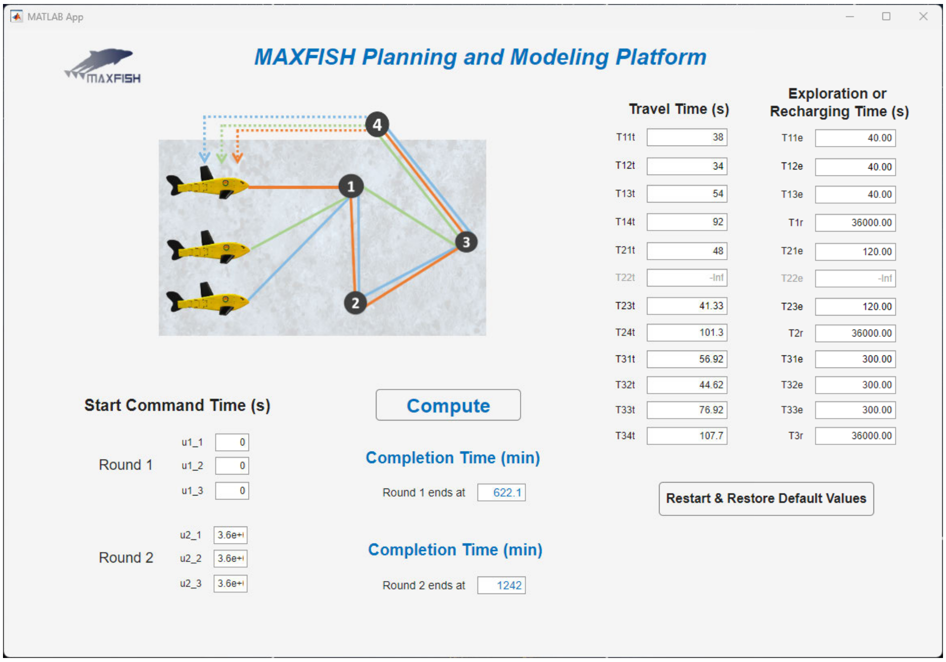
In this section, the results obtained through the GUI-based simulation platform are presented to explain the full workflow from mission configuration to the estimation of completion times of each round.

The platform is tested in two representative mission scenarios involving a team of three robotic fish assigned to explore different subsets of underwater Points of Interest (POIs). These case studies are designed to validate the simulation-to-scheduling workflow and to highlight the impact of path configuration and task assignment on mission duration.

In both scenarios, detailed in the next paragraph, the user defines the POIs using geographic coordinates through the GUI. These are automatically converted into Cartesian coordinates and passed to the Simulink-based simulator. This allows the computation of realistic travel times considering the path lengths and the dynamic model of the robotic fish. The estimated travel durations are then used as inputs to construct the corresponding max-plus system, which produces mission completion times. Table 1 summarizes the computed estimated times for all possible configurations.

TABLE 1. Points of interest and estimated travel times for each fish robot.

ROBOT	START	POI 1 Lat: 43.586193 Lon: 13.516786	POI 2 Lat: 43.586149 Lon: 13.516805	POI 3 Lat: 43.586168 Lon: 13.516732	POI 4 Lat: 43.586179 Lon: 13.516881	Estimated Time (s)			
						Path 1	Path 2	Path 3	Path 4
1	Lat: 43.586234 Lon: 13.516866	X	X	X	X	38	34	54	76
		–	X	X	X	49	44	71	–
		–	–	X	X	61	93	–	–
		X	–	X	X	38	30	92	–
		X	–	–	X	38	63	–	–
		X	X	–	X	38	34	53	–
		–	X	–	X	49	62	–	–
2	Lat: 43.586261 Lon: 13.516806	X	X	X	X	48	38.67	65.33	93.33
		–	X	X	X	76	62.67	93.33	–
		–	–	X	X	74.67	110.67	–	–
		X	–	X	X	48	41.33	101.33	–
		X	–	–	X	48	64	–	–
		X	X	–	X	48	38.67	68	–
		–	X	–	X	76	70.67	–	–
3	Lat: 43.586251 Lon: 13.516734	X	X	X	X	56.92	44.62	76.92	107.69
		–	X	X	X	89.23	76.92	106.15	–
		–	–	X	X	67.69	109.23	–	–
		X	–	X	X	56.92	60	115.38	–
		X	–	–	X	56.92	64.62	–	–
		X	X	–	X	56.92	44.62	69.23	–
		–	X	–	X	89.23	69.23	–	–



Travel Time (s)

T11t 38
T12t 34
T13t 54
T14t 92
T21t 48
T22t -Inf
T23t 41.33
T24t 101.3
T31t 56.92
T32t 44.62
T33t 76.92
T34t 107.7

Exploration or Recharging Time (s)

T11e 40.00
T12e 40.00
T13e 40.00
T1r 36000.00
T21e 120.00
T22e -Inf
T23e 120.00
T2r 36000.00
T31e 300.00
T32e 300.00
T33e 300.00
T3r 36000.00

Start Command Time (s)

Round 1
u1_1 0
u1_2 0
u1_3 0

Round 2
u2_1 3.6e+
u2_2 3.6e+
u2_3 3.6e+

Completion Time (min)

Round 1 ends at 622.1

Completion Time (min)

Round 2 ends at 1242

FIGURE 11. Scenario 2, with a denser mission plan with shared POIs and longer paths.

The first chosen scenario is depicted in Fig.10, while the second one is summarized in Fig.11.

In Scenario 1 (Fig. 10), each robot is assigned a minimal number of POIs, typically one or two, before surfacing. In detail, the following configuration is evaluated:

- Robot 1 visits POI 1 and 3;
- Robot 2 is assigned only to POI 2;
- Robot 3 travels through POIs 2 and 3.

Each agent then returns to POI 4 to be recovered. Due to the limited tasks and reduced contention on POIs, round 1 completes in 612.9 minutes, and round 2 ends at 1226 minutes. The robots operate with minimal waiting, and the platform demonstrates effective coordination and timing resolution.

In Scenario 2 (Fig. 11), a denser mission is simulated:

- Robot 1 visits POIs 1, 2, and 3;

- Robot 2 is assigned POIs 1 and 3;
- Robot 3 reaches POIs 1, 2, and 3.

This configuration introduces more overlapping tasks, increasing the complexity of coordination. In this case, the first round ends at 622.1 minutes, while the second concludes at 1242 minutes. Although the difference is not large, the increase reflects longer cumulative travel distances, higher exploration durations, and the effect of synchronization constraints, especially at POIs 1 and 3, which are visited by all three robots. In this second case, Robot 3 is also assigned long exploration durations (300 *s*) at multiple POIs, showcasing how the framework integrates user-defined timing parameters to reflect realistic execution dynamics. The shared POIs activate prioritization logic to enforce mutual exclusion, leading to waiting times that ripple through the schedule. This scenario demonstrates the platform's ability to model realistic delays and to support mission planning strategies that balance workload and timing across agents.

In both scenarios, the start commands are set identically for all robots: they begin round one at time 0, and round two at 36000 seconds (i.e., 10 hours). This delay reflects the expected full recharge duration, ensuring that round two can start directly after the previous round. This happens because, in the max-plus system, the maximum time between the end of one round and the repositioning of the robots at the start is taken. The model thus enforces physical consistency between mission scheduling and recharge requirements.

It is worth noting that the GUI also supports asynchronous start commands, allowing each robot to begin a round at a different time, if needed.

In summary, the platform successfully incorporated all user-defined values and solved the related max-plus system to determine the mission timing. The visualization features further enable the user to understand how task allocation and route changes impact overall completion time, supporting mission optimization. These examples confirm the practical utility of the MAXFISH platform for planning, modeling, simulating, and evaluating coordinated multi-robot underwater surveys with configurable mission logic.

VI. CONCLUSION

This paper presents a comprehensive framework for modeling, simulating, and coordinating bio-inspired robotic fish shoals in underwater environments. The proposed approach integrates a Digital Twin platform, a max-plus algebraic model for mission scheduling, and two user-friendly GUIs for mission configuration and timing analysis. This combination bridges the gap between theoretical models and practical implementations, enabling the simulation and evaluation of multi-robot cooperative strategies before deployment.

The use of max-plus algebra to formally encode synchronization constraints and mission timing in multi-agent systems represents a novel aspect, since this method is largely unexplored in underwater robotics. The framework is aimed to support Hardware-in-the-Loop and Software-in-the-Loop testing, and it has been validated in a representative simulated case study involving three robotic fish operating in a confined pool with predefined Points of Interest.

Future work will address polytopic uncertainties in the max-plus matrices, a theoretical extension currently under development by some authors, to account for time variations and disturbances in real deployments. This will enable the application of the Model Matching Problem to enforce adherence to a predefined reference model, representing desired round completion times. Moreover, the simulation will be complemented by the insertion of three movable joints for the fish tail, both in the virtual animation and in the Simulink model. These features, along with the planned integration of real survey data collected from the robotic fish and buoys, will pave the way for scaling the system to larger and less structured environments, such as lakes or coastal areas.

Since the proposed framework has also been designed to support future Hardware-in-the-Loop (HIL) and real-world deployments, integration with Poseidrone —- a newly developed fish-like AUV —- is currently underway to transfer the max-plus coordination logic to multi-robot underwater missions in controlled environments. This integration will represent the final validation step of the proposed model in real underwater environments, enabling the deployment of bio-inspired autonomous missions with timing guarantees.

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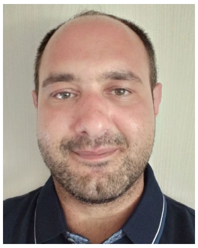

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