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A Max-Plus Algebra-based Approach for Modelling Shoals of Fish Robots during Underwater Exploration

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ABSTRACT

This paper introduces a novel approach to modelling fish robots for underwater exploration, focusing on a shoal of three biomimetic vehicles, each equipped with distinct sensors. The aim is to efficiently model the coordinated behaviour of the robots within the team in exploring an area with certain Points of Interest (POIs) through predefined cyclical paths. Depending on their capabilities, robots are assigned diversified tasks and paths. The resulting model, represented as a max-plus linear system, effectively manages task concatenation and synchronization. Simulation tests confirm the model’s efficacy in capturing the devices’ coordinated behaviour in underwater repetitive patrolling.

KEY WORDS: Modelling; fish robots; max-plus algebra.

INTRODUCTION

Max-plus algebra has been widely employed in modelling various situations, events, and tasks. It constitutes a category of discrete algebraic systems, renowned for its efficacy in modelling and analysing timed discrete event systems as linear systems, particularly in scenarios involving synchronization without concurrency. Additionally, it finds application in the performance evaluation and design of networked systems.

Within this framework, the operations *max* (\oplus) and *plus* (\otimes) of traditional algebra are interpreted as addition and multiplication, respectively, where ambiguity is not introduced. As it will be presented, max-plus algebra, appropriately named given its operations, does not possess the same properties as conventional algebra.

Linear systems defined over the max-plus algebra were introduced by Cohen and co-authors (Cohen, Dubois, Quadrat and Viot, 1985) in the middle of the eighties to model a special class of discrete event systems. Further developments were then presented in the book of Baccelli, Cohen, Olsder and Quadrat (1992). A survey on current and future perspectives of the max-plus algebra approach in systems and control theory at

the end of the nineties was produced by Cohen, Gaubert and Quadrat (1999), whereas a more recent paper in this regard is by Komenda, Lahaye, Boimond and van den Boom (2018), in which the history of max-plus algebra is presented focusing on the field of discrete event systems. The main concern of this paper is the modelling of the coordinated behaviour of various robots within a team of vehicles. An earlier version of the model of the cooperating vehicles was introduced in the work of Bartolucci (2024). When dealing with vehicles tasked with patrolling specific areas, max-plus algebra can be an interesting approach also to manage their coordination. From the perspective of multi-agent exploration by patrolling vehicles, a theoretical framework is required to facilitate effective modelling of their behaviour and max-plus algebra stands out as a crucial tool in this context. In fact, it can enable the effective coordination and synchronization of vehicles’ activities during patrolling. In this work, a precise model of the patrolling vehicles is provided, leveraging max-plus algebra to ensure their coordinated and efficient behaviour. Regarding the choice of the devices studied in this paper, it is important to note that fish robots, which are here biomimetic cooperative devices, represent, in general, a team of Autonomous Underwater Vehicles (AUVs). These robots have significant engineering applications of interest for civilian purposes, and there are many situations and real cases where such robots, with different actuation, sensory capacities, and characteristics, are tasked with patrolling or exploring various points of interest according to a predefined strategy. The use of such fish robots is compelling due to their non-invasive nature towards the ecosystems they inhabit, including marine species. Indeed, the areas under consideration could range from submerged archaeological sites to ecosystems like coral reefs, or even sites of shipwrecks. From a methodological standpoint, the formalization of these scenarios through max-plus algebra can prove beneficial. Modeling the team of underwater robots based on task-driven requirements, rather than time-driven constraints, can effectively facilitate the management of cooperation among agents with different trajectories and timelines, as elaborated below.