WAVE: Wave Agents in a Virtual Environment; a Proof of Concept Applied to Longitudinal Distance Regulation in Platoon Control

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***Abstract*—Since a decade multi-agents became a widespread solution to tackle different kinds of issues in various application fields. Among the two main trends in multi-agent approaches (cognitive *vs.* reactive), the reactive one is particularly interesting for applications that require both fast response time, adaptability and robustness. Reactive Multi-agent Systems rely on simple interaction schemes between entities that can be inspired whether by Biology or Physics. The goal of this paper is to explore the possibility of using interference fringes and waves properties from a multi-agent standpoint so as to tackle a real problem, longitudinal platoon regulation, already explored by different strategies including particle agents approaches or standard PID controller.**

I. Introduction

Multi-Agent Sytems (MAS) have become a widespread solution to tackle different kinds of issues in various application fields such as pedestrian simulation [1], robot control [2], complex system description [3], battery management systems... Among the two main trends in multi-agent approaches (cognitive *vs.* reactive), the reactive one is particularly interesting for applications that require both fast response time, adaptability and robustness [4]. Reactive Multi-agent Systems rely on simple interaction schemes between entities that can be inspired whether by Biology or Physics. Even if the biological approaches are the most represented in the literature [5], [6] the physical ones also allow to obtain good properties especially when they are applied to Cyber-physical systems control and/or modeling [7]. Most of the models used are inspired by particles which interact through forces (conservative or not) and/or potential fields [8]. Few of them are dealing with waves propagation and their associated interaction pattern, known as interference fringes. The goal of this paper is to explore the possibility of using interference fringes and waves properties within a multi-agent standpoint so as to tackle a real problem, longitudinal platoon regulation, already explored by different strategies including particle agents approaches or standard PID controller [9].

A platoon system is defined as a set of vehicles that move together without any material coupling, while maintaining a predefined geometric configuration. Platoons have been studied in different research projects for urban transportation systems applications, such as in the PATH project [10], Sartre, Cristal... Most of these research works deal with column configuration, where vehicles are placed one behind the other, this configuration being the more suitable for urban environments. In other contexts, like military or agricultural applications for instance, a platoon can adopt other configurations. A line configuration, where vehicles are placed one beside the other, is useful for agricultural environments, since its helps to reduce harvesting time. Arbitrary configuration are useful in military environments, for security and strategic purposes.

Platoon control algorithms are generally decoupling longitudinal and lateral regulations. In the target application exposed in this paper, only longitudinal regulation is considered. Thus, this paper presents a longitudinal regulation for platoon control based on an approach involving wave agents (*i.e.* a system where agents behaviors are based on wave propagation characteristics as wavelength and amplitude, depending on the context). The goal is then to explore this concept, showing with the experimentation in the case study of platoon control, that this kind of models can bring interesting properties. The paper is structured as follows: Section II presents a review of existing multi-agent approaches. Section III exposes the core of our contribution by describing the WAVE model. Finally, simulations results in the case study of platoon control (Section IV) highlight the ability of the approach to cope with such complex problems.

II. Relative work

The distributed artificial intelligence research field is divided into few topics. In one hand, multi-agent models, based on symbolic and explicit knowledge representation, able to exhibit high-level capabilities such as deliberation, consensus or elections [11]. In the other and, reactive multi-agent models, based on the stimulus/reaction paradigm and devoid to environment representation [8]. In this paper, we consider only reactive multi-agent systems, since the problem environment is at the center of the problem. In this context, platoon system could be modeled as a classical attraction/repulsion problem between agents representing the vehicles [12].

MAS emergent properties are one of the main expected features by multi-agent designers. In [13], the authors provide a definition of the emergence focused on the requirements needed to generate an emerging phenomenon in a dynamic system. In this type of system, emergence refers to the apparition of a phenomenon (the process, steady state or invariant) perceived by global entities, and monitored by an observer or by entities themselves. The aims of Multi-agent System design is to achieve global objectives through local agent's behavior specifications. Then, its evolution directly depends on the environment modeling choices. Emergent behaviors can be exploited in the same way as convergence properties of classical systems. The study of emergent properties has to cope with some classical issues such as : stability, convergence, and robustness. Moreover, due the generally huge number of agents, the computational cost can be important especially when one need to deal with a high number of high-level agent perceptions. One of the possible solution to overcome this issue is to use the environment as an active entity, thus not limiting its definition to a place where agents are living, and then giving the environment an active role for the global system behavior [14]. For this reason, using waves to propagate information through the environment can be an interesting way to reduce the perception computational cost issues.

Other critical points are linked to the control of the system entities and to the characterization of emergent phenomena [15]. Generally, emergent properties are observed or measured by an external entity. This observation can then be used to design control laws or can be interpreted as a solution to the targeted problem. The main challenge is to characterize the emergent property as a stable global feature of the system, whereas it stems from numerous dynamical interactions. In this way, we argue that waves can overcome this apparent contradiction by providing emergent global properties (interference fringes) arising from waves dynamical propagation. Thus, in opposition to classical MAS approaches based on a bottom-up modeling (*i.e.* from agents behavior to system properties) we propose to minimize the non-deterministic aspects of multi-agents systems by transferring a part of the interactions in the environment model and dynamics using waves.

III. WAVE: Wave Agents in a Virtual Environment

In this paper, we introduce the first version of a multi-agent model called WAVE: Wave Agents in a Virtual Environment. WAVE is a generic approach developed to tackle non-linear decision-making problems. The originality of the approach relies on the use of concepts from wave mechanics to generate emergent stable behaviors. In this framework, the role of the environment is at the center of attention since it supports agents interactions, modeled using waves propagation. Wave agents are mobile virtual entities, situated in this wave-like environment, able to generate and perceive dynamic waves.

A. Objectives

The main goal of our work is to ensure a system high-level stability using low-level interactions from a reactive multi-agent system. As described in Section II, emergent properties of MAS are somehow difficult to predict or control. However, they offer the ability to model or generate complex behaviors at the system scale, using simple low-level agent behaviors. To enhance the stability of a system, WAVE proposes to use an apparently unstable phenomenon (waves propagation) to generate stable patterns (fringes). Thus, the proposed model has to cope with a new kind of interaction and brings an innovative environment model. We propose several reactive agent behaviors that are interacting with each other through the environment to detect and follow stable patterns.

B. Overview

From the conceptual point of view, the main goal of WAVE is to come with a problem-solving framework based on a reactive MAS. Following this high-level needs, the WAVE general framework is described in Figure 1. The first step is to extract the key feature of the problem, and can be done using prior knowledge. Then the problem can be modeled using WAVE as a physics-inspired MAS environment using waves, distortions and classical Newtons laws. Surfer agents, that can

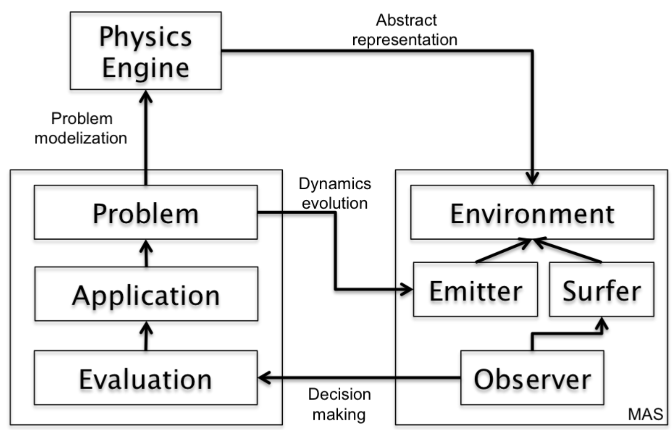

Fig. 1. Global overview

be considered as elementary particles, evolve freely following the waves produced by specifics "emitter" agents tied to the problem. The final decision-making process relies on a dynamic and statistical evaluation of the agents population.

C. The virtual WAVE environment

The WAVE environment is modeled as a continuous 2-dimensional plane in a 3-D space (Figure 2), where situated mobile agents are evolving.

The wave environment supports, models and propagates waves emitted by problem-related agents. In this work, the environment is considered as homogeneous and isotropic, meaning that its characteristics are the same for each position and does not depend on the wave propagation direction. This

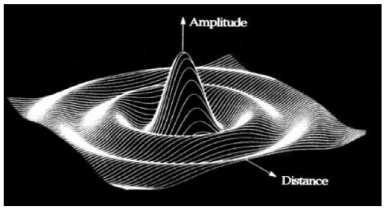

Fig. 2. The WAVE environment

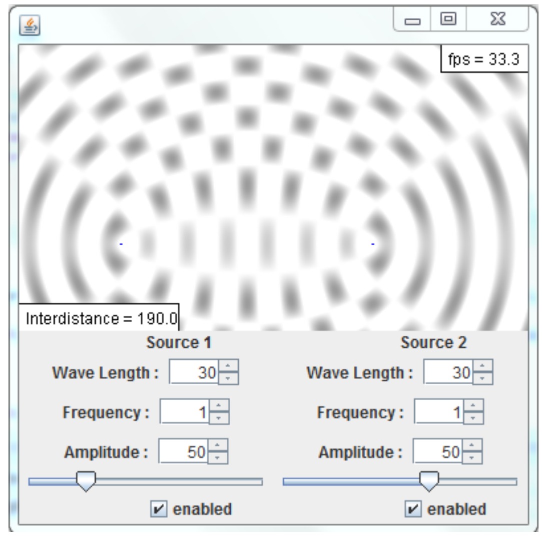

Fig. 3. Screen-shot of the experimental prototype of WAVE featuring the wave propagation model and using two emitter agents (black dots). The selected wave sources parameters generate distinct patterns called interference fringes.

assumption ensures a fixed wave velocity and allows to use traditional propagation model such as:

$$s(t) = A\cos(\omega t + \Phi) \quad (1)$$

where $s(t)$ denotes the amplitude at a given position for time t; A is the maximum amplitude of the emitting source; ω is the source frequency and Φ is the phase difference (set to zero in the model since the synchronization is ensured by the environment). The environment computes the instantaneous wave amplitude on the local neighborhood of all agents, using the wave propagation model. In the case where several wave sources are emitting at the same time, the model basically computes the sum of the amplitudes at a given position. This allows combining dynamically a high number of influences from several agents with a low computational cost. Hence, the WAVE environment is the support of interaction of several surfer agents, sharing the common goal of finding and exploiting stable perceived patterns.

D. Agent roles

By observing the resulting amplitude of the WAVE environment in their field-of-view, the agents goal is to identify and track stable patterns generated by their neighbors. We define two agents roles that are combined to generate a collective emergent stable behavior at the system scale. The generic description of the WAVE system allows to adapt the implementation to different problems. Thus, the agents roles introduced in this section can to be extended, regarding the considered problem. The proposed behaviors, called ”emitter” and ”surfer”, respectively describe the process of a wave source and of a simple entity reacting to perceived waves.

1) Emitters: Emitter agents are basically wave sources. They generate waves, according to their intrinsic parameters, that are propagated through the WAVE environment. The purpose of the environment is to model the combination of several waves, leading to the apparition of an interference fringe pattern, as plotted in Figure 3. The goal of emitter agents is to model the several goals of the system, defined by the problem we want to tackle. Identical parameters for wave emissions are not mandatory but they are required to generate stable patterns. Otherwise, the fringes generated in the environment could not remain static. Although we do not consider such a case in this work, this setting could be exploited to tackle problems were a system have to choose between several not equivalent goals. In the simulations presented in section IV, we use two emitter agents with the same emission parameters to model a leader and a follower vehicle in a column platoon configuration.

2) Surfers: A population of moving entities called surfer agents is generated by the WAVE model. The goal of each individual is to reach a stable position in the interference fringes pattern. The key idea is to make use of a combination of the interaction of very simple agents to observe, as an evaluation, the collective behavior at the system scale. The resulting behavior of a surfer agent is a composition of three basic behaviors:

- **Surf**: surfer agents are attracted by low wave amplitudes (near to 0);
- **Separate**: surfers tend to flee each other, enabling an increase of spatial spreading;
- **Source Attraction**: agents are trying to stay as close as possible of a given source.

Each behavior is modeled using simple attraction-repulsion equations, based on gravitational laws, involving a mass (taking the same value for all surfer agents). The combination of interactions is performed in the decision process of each surfer agent by applying weighting coefficients to each behavior output. It can also be done by modifying the mass affected to the agents (surfers and emitters).

E. Decision making

The decision-making system in WAVE relies on the resulting position of the population of surfer agents. Emitter agents represent the goal of the system while the surfers are using the patterns generated by the emitted waves combination. The decision making relies on an evaluation at the system scale of the positions of the surfer agents relatively to the system goal, modeled by emitters. Hence, we choose to use the vector starting from the emitter position and going to the barycenter (*i.e.* the weighted average) of the surfers positions. This vector can be directly used as an influence vector for the system or can be aggregated (for instance considering the distance or the direction only). Thus, the computation of the decision is expected to be robust since it relies on the individual behavior of all the WAVE agents. In the following simulation experiment, we use the decision-making process of WAVE to provide a longitudinal regulation command to an unmanned vehicle following a leader trajectory and hence, ensuring the string stability in a column platoon configuration.

IV. SIMULATION RESULTS

In order to validate our approach, we select the case study of longitudinal platoon regulation.

A. MAS platform

Instantiating a multi-agent model requires a platform that aggregates agents, computes interactions and applies influences. To achieve this goal, a *tinyMas* plugin was developed using distributed objects and implemented in Java. *tinyMas* is a multi-agent platform specifically designed to deal with the implementation and deployment of continuous environment, reactive agents and holonic multi-agent systems [16]. It is based on an organizational approach and its key feature is the support of the concepts of role and organization as first-class entities in the implementation. This consideration has a significant impact on the agents implementation since it allows them to easily and dynamically change or adapt their behavior and thus contributes to fill the gap between conception and implementation phases in this domain.

B. Implementation

The first stage of the implementation of the WAVE environment is to extract the main characteristics of the problem. In the case study of platoon regulation, the goal is to provide a stable longitudinal command to a vehicle which follows a leading vehicle. The leader is freely driven by a human driver and the follower is driven by an embedded automated system. The goal of the decision making using WAVE is to compute a command vector. Thus, we model the positions of both vehicles in the environment as emitter agents and we generate a population of surfer agents executing their behavior, using the follower vehicle as their target for Source Attraction behavior. The physical behavior of the vehicle then results from a physics-based model which rules the final motion of the vehicle in the real (or virtual) world.

1) Emitter : Vehicles model: The emitter agent location is determined by the leader position perceived by the follower sensors. Vehicles used in the simulation represent (graphically and physically) real experimental vehicles of the laboratory. They are equipped with two 270 degrees virtual laser range finders, a replica of LMS SICK 200 sensor and with a simulated GPS-RTK receiver required to follow and study trajectories. Simulations are performed on a 3-D geo-localized model of a part of the city of Belfort (France).

2) Surfer agent for platoon: Surfer agents for platoon have no real representation and do not match with anything in the real world problem. They are devoted to decision-making and are based on the generic surfer agents definition given previously. These agents have only one simple behavior, they are attracted by the leader, considered as an emitter, in the virtual environment. Agents motion is determined by gravitational-like laws and the environment dynamic topography updated by waves emission. Surfing toward the waves hollow, they collectively describe a balance point that corresponds to the desired system control.

C. Simulation

1) Scenario: This work is a preliminary step toward a complete platoon application. As a proof of concept, we start the experimentation with the design of a simple scenario. The WAVE environment is used to provide a longitudinal platoon regulation command. To validate the approach, we design a simulation where a leading vehicle and a follower are stopped and aligned on the same lane. The leader starts and quickly reach a speed of 30 km/h, remains at this speed during 2 minutes and then stops. The follower is expected to follow the leader with a very stable inter-distance while the vehicles speeds are the same.

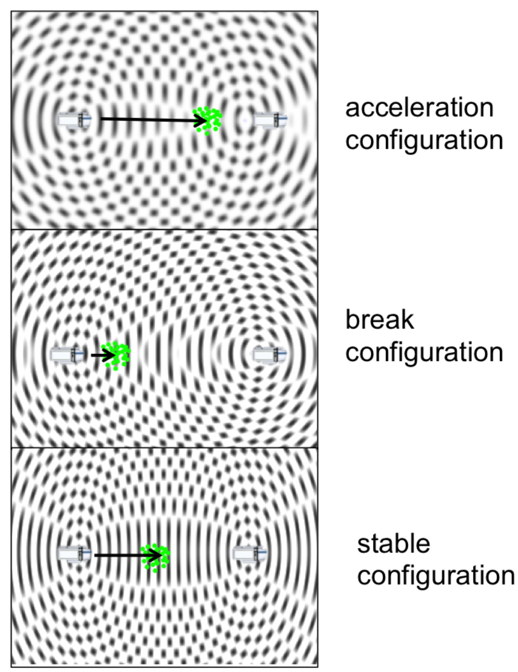

Fig. 4. Screen-shot of the environment view. The green dots are the Surfer agents, moving along the interference fringe generated from the addition of the waves emitted by the leader vehicle (white) and the follower (blue). The wave amplitude is represented by a gray-scale (from 0 – white – to 100 – black.

Figure 4 depicts a view of the environment where the leader and follower vehicles are modeled as wave sources (*i.e.* emitters with the same parameters: amplitude = 50, wavelength = 100 and frequency = 3). The surfers agents are attracted by the source, towards the leader position and generates the longitudinal control.

2) Result: The behavior resulting from WAVE interaction is the longitudinal behavior of the following vehicle. In order to assess the effect of the model on the stability of the generated behavior, one can observe the inter-distance evolution during the designed scenario (Figure 5). The inter-distance, initially

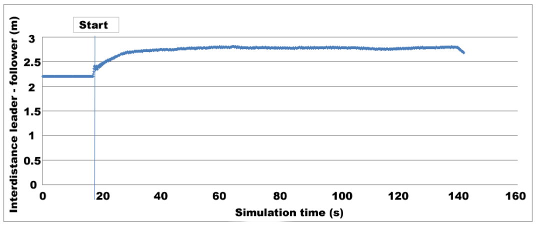

Fig. 5. Inter-distance between leading and following vehicles in a platoon configuration driven in straight line where the longitudinal control is regulated by a WAVE environment.

set to 2.2 m, is increasing after the leader start, then remain very stable (around 2.7 m) during the cruise period, and finally drops to 2.6 m. While the leader and the follower are driven at full speed, the inter-distance remain quite stable. This confirms the potential of the use of the pattern generated in the virtual WAVE environment. Nevertheless, we can observe that the initial inter-distance is not reached at the end of the simulation (time = 140 s) meaning that the following vehicle is delayed. Besides, the inter-distance value reached during cruising is not easily controllable, since it highly depends on the characteristics of the emitted waves (mainly the wavelength). Indeed, an interesting result is that the interference fringes are spaced from each other from half of the set wavelength in the initial configuration (Figure 4). As a matter of fact, some properties of the interference fringes are not exploited by the agents yet and require an extension of the work, proposed in this paper, to make a better use of the wave interference properties.

V. Conclusion and future work

Platoon control and regulation has been widely studied, since its offers a first step toward vehicles automation. With an increasing number of vehicle in the same platoon configuration, the main challenge is to provide a stable regulation of the longitudinal behavior, ensuring the whole string stability. Taking inspiration of wave mechanics, we use emergent patterns resulting from the dynamic combination of waves in an environment to perform a multi-agent based platoon control algorithm. Our multi-agent model, called WAVE features a virtual wave environment where the agents take advantage of the waves propagation to find stable patterns in the environment. A first implementation in the WAVE environment for platoon regulation highlights the potential of the use of physics-based individual agents behavior to generate a complex high-level and stable decision making. As a first step, the experimentation framework has been kept simple and shows some limitation of the model such as the difficulty to provide a matching between agents environment and real world parameters.

Next step will be to integrate high-level characteristics of the waves patterns as a new source of interaction for the agent. Thus, we can expect to extend the decision taken by the WAVE environment to the lateral distance regulation. The generic definition of the model also allows to deal with other applications. We plan to model a problem of Complex Event Processing (CEP), using the emitter agents as several dynamic events, and using the decision from the surfer agents to manage the selection process.

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