

# Bio-inspired Coordination and Control of Autonomous Vehicles in Future Manufacturing and Goods Transportation

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**Abstract:** The will to apply bio-inspired techniques to coordinate and control *autonomous X vehicles (AXVs)* has increased tremendously during the last decade due to their advantages in the face of complexity in today's demanding applications. Thus, several bio-inspired approaches for *multiple-entities optimization* have been proposed in the literature for various limited applications, e.g., drone coordination, mobile robot formation maintenance. In all these strategies, the entities must plan their path and control their movements while coordinating their behavior w.r.t. the other members, and they must avoid collisions, so the task could be very difficult in the unstructured environments present in future manufacturing plants and goods transportation. Future applications of these bio-inspired techniques for coordination and control of AXVs include large warehouses, manufacturing, logistics, last-mile delivery, etc. The AXVs could be grouped to carry larger goods or they can act as swarm members when they do not have a common goal, but they must interact while they move to complete the allocated tasks and intersect their paths with the paths of other entities. As such, this paper illustrates the concept of applying such bio-inspired coordination and control techniques for the development of future manufacturing and goods transportation, a discussion being carried out regarding the advantages and disadvantages of several techniques for their use in specific applications.

*Keywords:* Bio-inspired coordination, Bio-inspired control, Autonomous vehicles, Intelligent manufacturing systems, Goods transportation, Last-mile logistics, Formation maintenance

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## 1. INTRODUCTION

An autonomous system is a goal driven process for which an operator sets the objective and the system decides between a number of approaches that are based on other situational data it may have collected and the current status of the objective. Recently, the autonomous vehicles (AVs) have been grouped under the terminology *autonomous X vehicles (AXVs)*, where X stands for driving on land (unmanned ground vehicle - UGV, automated guided vehicle - AGV, driverless car), diving underwater (autonomous/unmanned underwater vehicle - AUV/UUV), flying in the air (autonomous/unmanned aerial vehicle - AAV/UAV), or through space (unmanned space vehicle - USV, uncrewed spacecraft). These AXVs are used in many applications, ranging from warehousing, to cross-docking, mining, farming, and even to military cases. The problem of operating these vehicles in a safe and secure manner and with maximum efficiency becomes very stringent as more and more entities are deployed in the above mentioned applications and their control and coordination algorithms have to consider all the possible interactions and complementarities of the involved members to solve a certain task that requires either their cooperative maneuvering

or their disjunctive path generation. The current solutions are based on classical strategies for trajectory planning and control (Berman and Edan, 2002; Vis, 2006; Oyelere, 2014; Fazlollahtabar et al., 2015; Hayashi and Namerikawa, 2018) which do not provide a viable solution for large-scale applications, with tens or hundreds of entities to be cooperatively controlled.

One of the most important feature in the design of AXV formations is choosing an appropriate perceptible architecture, which provides them the interaction capabilities with the working environment (including other entities, e.g., AXVs, obstacles), to achieve the desired objectives. To this end, each AXV in the formation needs to constantly exchange information with its environment, i.e., by receiving various inputs from its sensors, and performing different actions, ranging from simple movements to complex assembly/disassembly operations (Bekey, 1996).

The will to apply bio-inspired techniques to coordinate and control AXVs has increased tremendously during the last decade due to their advantages related to autonomy, evolution, adaptability, self-organization, scalability, configurability, plug-ability, and robustness. Thus, several bio-inspired approaches for *multiple-entities optimiza-*

tion based on, e.g., bee swarming, bacterial foraging, ant colony, bird flocking, have been proposed, and used in various limited applications, e.g., drone coordination, mobile robot formation maintenance. In all these strategies, the entities must plan their path and control their movements while coordinating their behavior w.r.t. the other members, and, at the same time, they must avoid collisions, so the task could be very difficult in the unstructured environments present in future manufacturing plants and goods transportation.

In the manufacturing domain, there are already proposed approaches in which the decentralized coordination and control of heterogeneous multi-agent systems is developed based on bio-inspired techniques (Codesa-Prime) (Durica et al., 2015), which was tested in simulations for AGV systems. Moreover, a bio-inspired reference architecture for production systems (BIOSOARM - BIO-inspired Self-Organizing Architecture for Manufacturing) that focuses on highly dynamic environments for AGVs is proposed in (Dias-Ferreira et al., 2018). In (Kulkarni and Venayagamoorthy, 2010), the real-time autonomous deployment of sensor nodes from an UAV using bio-inspired algorithms is presented. To enhance multi-agent systems to solve complex engineering problems, in (Leitao et al., 2012), some bio-inspired techniques were designed to obtain reconfigurable manufacturing systems with their desired characteristics. In (Jabbarpour et al., 2014) a comprehensive review and classification is made regarding the usage of ant-based algorithms that are adopted in vehicle traffic systems to guide vehicles to less congested paths. A decentralized approach is proposed in (De Rango et al., 2018) for a swarm of robots to perform cooperative tasks intelligently without any central control.

Future applications of these bio-inspired techniques for coordination and control of AXVs include large warehouses (even in ports and airports) with immense quantities of goods received and delivered daily, last mile logistics (goods delivery service robots, urban goods transportation), manufacturing, logistics (vehicle platooning or grouping, drone coordination). The AXVs could be grouped to carry larger goods or they can act as swarm members when they do not have a common goal, but they must interact while they move to complete the allocated tasks and intersect their paths with the paths of other entities. At the same time, these techniques could be applied for vehicles and trucks that travel on roads, and the transport companies would benefit from the reduction of fuel consumption and the increase of efficiency.

As such, this paper aims to provide a comprehensive analysis of the current state of art with respect to the possibility of applying such bio-inspired coordination and control techniques for the development of future manufacturing and goods transportation. Furthermore, a discussion is carried out about the advantages and disadvantages of several techniques for their use in specific applications.

## 2. AUTONOMOUS X VEHICLES

This section discusses firstly on the applications of AGVs and AAVs that could be also exploited in future manufacturing and goods transportation, followed by the de-

scription of the most commonly used mathematical and/or simulation models for AXVs.

### 2.1 Applications of AXVs

The AGVs excel in applications with the following characteristics: repetitive movement of materials over distance, regular delivery of stable loads, medium throughput/volume, critical on-time delivery (with inefficiency caused by late deliveries), operations with at least two shifts, processes where tracking material is important. As such, the industries in which the AGVs are used to handle raw materials (paper, steel, rubber, metal, plastic) and to transport materials from receiving to the warehouse and delivering them directly to production lines are: pharmaceutical, chemical, manufacturing, automotive, paper and print, food and beverage, health-care, warehousing.

Typically, AGV-based solutions are trying to solve routing and (re)scheduling problems considering the minimum waiting and traveling times as the optimization criteria. Several issues are known in the routing problems (Qiu et al., 2002): *congestion* - using the same path by too many AGVs, *crossing lines* - more vehicles meeting at an intersection, *deadlock* or *livelock* - mutual waiting to release a path or an intersection, *heterogeneous vehicles* - different behaviors and goals, *continued flow* - reserving the path all the time and excluding unknown intersections/bottlenecks. To solve the conflict-free and optimization problems, several assumptions are generally considered (Chawla et al., 2018): the location and the number of working centers are fixed, there exist multiple paths between two centers, no priorities are associated for the tasks, and the speed of the vehicles is constant. The last assumption is not suitable for stochastic and dynamic conditions, any disruption of the whole system requiring a rescheduling process.

The impact of AGVs on travel behavior and land use is analyzed in (Soteropoulos et al., 2019). The introduction of AGVs changes the paradigm of urban transport system, by changing or totally replacing the existing transportation network. Another task suitable for AGVs can be the logistic of goods transportation, in which tons of goods need to be moved between multiple points (shops, warehouses, ports, etc.). The transport time will be reduced by using AGVs, thus improving the quality and minimizing the losses (especially for perishable goods, e.g., meat, poultry, fish, milk, fruits, vegetables).

As previously mentioned, AGVs can be used in a manifold of applications, each one with specific requirements and topology. In (Vis, 2006), the design and control of AGV architectures used in manufacturing, distribution and transportation systems is given. In (Sharma et al., 2017) two robots (see Fig. 1) that are used to transport a rigid object together are modeled and controlled. A robot is formed by a platform with four wheels and a 2-link planar arm fixed in the mid-front axle of the platform. These robots have to cooperate in order to transport objects from a start point to a final point following a desired path with obstacles.

The applications in which AAVs are successfully used range from aerospace, to military and mostly civil, that include archaeology, cargo transport, health-care, search

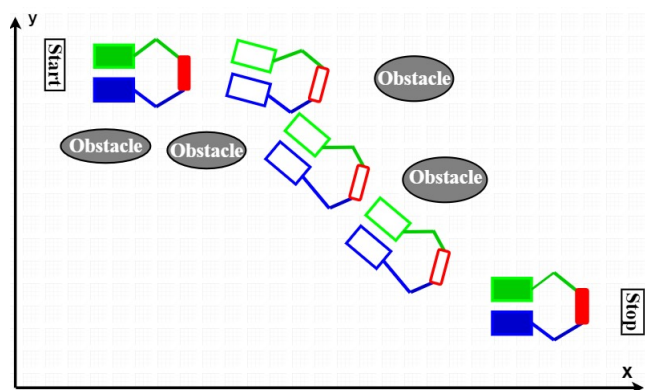


Fig. 1. Two robots transferring an object.

and rescue, surveying, agriculture, personal transportation and goods delivery, just to name a few. Currently, there are six common uses of agricultural AAVs (drones): soil and field analysis, seed planting, crop spraying and spot spraying, crop mapping and surveying, irrigation monitoring and management, real-time livestock monitoring (Kulbacki et al., 2018). Deploying a larger number of drones for the above mentioned applications can have a huge advantage because they can cover a larger field in a shorter period of time, but they have to coordinate their behavior to make sure that every part of the field is covered only once and with the highest efficiency of the available drones w.r.t. the total duration to finalize the task and energy consumption.

### 2.2 Modeling of AXVs

Usually, the robotic systems are controlled under the assumption that a complete, disturbance-free model for the robot and its surroundings is available (Bekey, 1996). However, this stringent hypothesis can be further simplified, by employing techniques inspired from biology when designing such systems. In this manner, the mathematical burden of an accurate model is replaced by behavioral descriptions of the basic components (Bekey, 1996). The design of an AGV system with many interacting decision variables uses either simulation or a combined analytical and simulation model, which is further used for performance analysis and estimation (Vis, 2006). In (Fazlollahab et al., 2015), for trajectory planning, a model in which the AGVs have constant velocity and neglected mass and dimension is employed. The AGVs are modeled by a kinematic nonlinear model that describes the position and velocity of the robot, the orientation and the angular velocity of its links in (Sharma et al., 2017). To model the lateral dynamics of the AGVs, the bicycle model was used in (Rajamani, 2011), whereas the longitudinal dynamics can be modeled by a second order model (Ulsoy et al., 2012; Caruntu et al., 2019b). These models describe the position and orientation of the vehicle in relation to a coordinate system. In (Oyelere, 2014) both nonlinear car-like and bicycle models are used to describe the dynamical motion of AGVs.

The available modeling studies related to urban transportation focus on travel behavior (Zhang, 2017) (e.g., ride sharing between multiple clients with an optimal route planing), traffic impact (Milakis et al., 2017) (i.e., avoiding road congestion) and transport supply (Chen and

Kockelman, 2016) (investigating first-come first-serve principle for vehicle allocation). In (Fagnant and Kockelman, 2014) an agent-based model scenario with environmental implications is provided, whereas in (Levin et al., 2017), a general framework for modeling shared autonomous vehicles, with realistic traffic flow models is proposed.

### 3. COORDINATION AND CONTROL OF AXVS

This section introduces firstly some classical techniques used in the coordination and control of AXVs and afterwards it focuses on the bio-inspired techniques and their advantages and disadvantages in various applications.

#### 3.1 Classical techniques

Despite the fact that the most robotic systems are designed using a biologic paradigm, their core control strategies are still part of the classical linear controllers and are not suitable for the desired tasks (Bekey, 1996). In manufacturing, distribution and transportation applications, the most important control objective is to ensure the transportation demands using an efficient distribution of the available AXVs and conflict solving policies. As such, the controller in charge of the entire AV system must manage an optimal load distribution, AXV selection, route planning and time schedule among others (Vis, 2006). These tasks can be performed off-line at a centralized level, if all the required information is a priori available, or with a complete decentralized methodology (Berman and Edan, 2002), using local controllers on board of the vehicles. The disadvantage of the former strategy is the catastrophic system failure risk, and the high computing and information processing requirements. As for the latter, the collision avoidance policy is difficult to enforce, when all the route planing is performed decentralized. In (Fazlollahab et al., 2015), a solution for scheduling and path planning of AGVs in a manufacturing system is proposed, in which the AGVs need to deliver goods between two work points. The aim is to schedule the robots and find the path for them so that the earliness and tardiness to and from work points are minimized. If the local position is exchanged between AGVs, than a more efficient path planning can be performed, with a minimal collision risk. Moreover, the load distribution for each AGV can be optimized with respect to the shortest distance or individual fuel consumption from the entire AGV fleet perspective. Usually, a model predictive control (MPC) strategy, e.g., nonlinear (Oyelere, 2014) or decentralized (Hayashi and Namerikawa, 2018), is employed in self-driving AGV applications.

A more efficient control approach consists on fully taking advantage of the characteristics of the distributed model predictive control (DMPC) strategy, which is suitable for multiple-entities systems, such as an AGV fleet used to move product pallets from an air-plane cargo hold to the airport storage warehouse. The idea is to ensure that the transportation operates safely (in terms of product loses for perishable goods) and efficiently (within the strict time schedule and allowed operation costs) with minimal human intervention. This goal can be reached if the fleet travels with constant velocity and in the same direction, maintaining at all times the formation. In this application

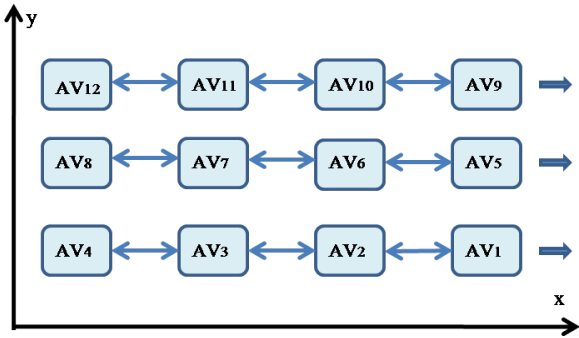


Fig. 2. AGV fleet.

(see Fig. 2), each local AGV is individually controlled, but the relevant information (e.g., local position and speed) is shared between different entities, ensuring that the AGVs maintain a safe distance among them. Considering this, the global control problem can be further simplified, by regarding the three rows of AGVs from Fig. 2 as independent systems, consisting of unidirectional coupled sub-systems, which broadcast information from the first ones  $AV_{1,5,9}$  to the next in line  $AV_{2,6,10}$ , respectively. After that, the information is propagated towards the AGVs at the end of the rows. In (Maxim et al., 2016; Caruntu et al., 2018), a non-cooperative DMPC strategy suitable for vehicle platooning applications is proposed, which can be easily used to control the fleet. However, this conceptual simplification is not always satisfactory, when for example one AGV wants to exit or to change its current position in the fleet, or the object to be carried has a non-uniform weight that requires a formation which is not symmetrical, or taking into account the actions needed to rotate the object for placing it in a certain position in the warehouse. In this case, a suitable approach is the coalitional control strategy formulated in the DMPC framework, which combines both non-cooperative and cooperative control features (Maxim et al., 2018). Hence, at each sampling period, each AGV is locally controlled with a non-cooperative DMPC algorithm. However, if the circumstances change within the fleet, then some AGVs from a neighborhood can form a coalition and solve a cooperative optimization problem, from the group point of view. For example,  $AV_7$  communicates information with all the AGVs placed directly in front ( $AV_{2,6,10}$ ), in the back ( $AV_{4,8,12}$ ) or lateral ( $AV_{3,11}$ ). However, if one of its neighbors exits the fleet, only the neighboring coalition re-shapes, thus ensuring an optimal solution with minimal costs.

### 3.2 Bio-inspired techniques

In (Byrne et al., 2018), the bio-inspired algorithms are classified as: Ant Colony Optimization, Beeclust Foraging, BEEPOST, Shepherding, Termite-Inspired Collective Construction, Fish-inspired Goal Searching, Gillespie Self-Assembly, while (Darwish, 2018) presents the state-of-the-art regarding the bio-inspired algorithms: Genetic Bee Colony, Fish Swarm, Cat Swarm Optimization, Whale Optimization, Artificial Algae, Elephant Search, Chicken Swarm Optimization, Moth Flame Optimization, and Grey Wolf Optimization.

The pioneering biological inspired control strategy, using concepts of awareness and understanding applied to a robotic system was presented in (Bekey, 1996). The developed architecture was presumed able to successfully accommodate its operation in unexplored and uncertain environments. Moreover, the performance of the strategy was improved by means of communication between two robots assigned to a cooperative action (Bekey, 1996).

A recent survey of algorithms for collective behavior (Rossi et al., 2018), including bio-inspired ones, shows a diverse list of approaches and their maturity regarding the applicability. Beeclust or Beepost (Ogunsakin et al., 2018) algorithms were considered in self-organizing flexible manufacturing system (SoFMS) to optimally organize the layout of a production system based on some mobile processing stations. These mobile units remain individually autonomous and depend on the distributed methods for their coordination. Similarly, the merge-able modular robots nervous approach (Mathews et al., 2017) can be considered when the changeable production cell is seen as a nervous system - mobile units can physically interconnect to merge into a larger unit. In some situations, the flexible manufacturing systems are optimized by using AGVs to carry the product among processing units (Bechtsis et al., 2017). Another approach, namely intelligent/smart product, combines a physical and information-based representation of a product (McFarlane et al., 2002) to enable autonomous manufacturing based on the collaborative interaction with other resources.

Swarm intelligence (SI) is based on the following quote: locally decide the most appropriate action for the group as a whole, which means to think globally, but to act locally and benefit from the experience of other entities (Dias-Ferreira et al., 2018). Particle swarm optimization (PSO) (Kennedy and Eberhart, 1995) is an iterative search algorithm based on populations that tries to model the social behavior of bird flocks. It has been found effective in solving several kinds of multidimensional optimization problems. PSO has seen many modifications lately and has been adapted to different complex environments, many versions of PSO being proposed and applied in areas that include multi-robot navigation (Chawla et al., 2018), obstacle avoidance (Nuredini et al., 2018), or vehicle grouping (Caruntu et al., 2019a,b). (Chawla et al., 2018) proposes a modified memetic particle swarm algorithm to solve the multi-load AGVs scheduling problem in the FMS combining two bio-inspired techniques, namely the memetic and PSO algorithms.

Swarming uses the principle of collective intelligence for solving the problem of traveling in formations, i.e., the vehicles are considered as simple particles that cooperate while updating their velocities. The tasks of each entity are derived from emergent cooperative biological systems. This allows considering decentralized, self-organized formations, in which each participant can have a specific behavior. By employing SI concepts in vehicle traffic, expected achievements include: optimized/smoothed traffic flow, increased road capacity and reduced number of congested streets and highways; increased safety by reducing the number of accidents; reduced fuel/energy consumption and lowered pollution; reduced operating costs for the transport sector; reduced vehicle components wear;

efficient use of infrastructure (Caruntu et al., 2019a,b). Most behavioral-based approaches refer to swarm robotics and extend the Boid model proposed in (Reynolds, 1987), using rules defined via potential fields or consensus control, in order to trigger appropriate movements of the robots (Ekanayake and Pathirana, 2009; Oh et al., 2017). For instance, (Lee and Chong, 2008) considers a partition rule for obstacle avoidance, a unification rule for joining to a close formation, and a maintenance rule for keeping an appropriate geometry of the formation; (Min and Wang, 2011) integrates two escape scenarios corresponding to the cases when an obstacle is detected by the robot itself or by another robot of the formation. When the entities are vehicles moving on roads, the rules should integrate specific additional constraints related to lanes' geometry. Some traveling scenarios compatible with multiple lane roads are analyzed in (Li et al., 2018); they permit joining to single-lane platoons and overtaking. In (Caruntu et al., 2019a,b) a first attempt to conceptualize *vehicle flocking* by considering both the lateral and longitudinal dynamics of vehicles to create and maintain a group of vehicles on multiple lanes was proposed.

#### 4. CONCLUSION AND FUTURE OUTLOOK

The new frontier of future manufacturing can be extended with these bio-inspired approaches to accomplish global performances in autonomous yet intelligent ways at different levels. By identifying the potential of multi-AXV systems for dynamically organized groups, pattern-guided behaviors, coordination, cooperation and negotiation, and admitting smooth deviations from plans/schedules, new applications could be found. For the global objectives that interleave with the local objectives, a possible optimization or disruption of AXVs can be undertaken by the collective behavior algorithms.

The majority of collective behavior algorithms are only demonstrated in simulation/hardware and few approaches are proved in real-time deployment. Moreover, the bio-inspired techniques applied in the routing and scheduling problems of AXVs solve collision conflicts, congestion, and give optimal solutions by considering only constant speed, which could be a problem in the highly dynamical future manufacturing plants and goods transportation. Furthermore, there is a huge problem in achieving optimization and also an impossibility to predict the future states of the system, which are research directions that should be followed in the near future.

The techniques briefly presented in Section 3 should be applied in domains where control of non-linear, heterarchical, large-scale systems in dynamic, heterogeneous and unpredictable environments is needed. The manufacturing conditions are stochastic and the systems are usually highly dynamical, which leads a centralized algorithm to solve a NP-hard problem. Thus, the bio-inspired coordination methods for self-organized groups of AXVs could solve many issues encountered in a centralized approach. For example, the congestion is reduced when the vehicles interact with each other and they apply some conventions: asking for or allowing to overtake, travel in predefined formations or changing the path when they intersect.

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