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Communication Approach and Framework for Distributed Path Planning Optimization of Industrial Vehicles

Keywords: Service-oriented Architecture (SOA), Edge Computing, Machine Fleets, Mobile Work Machines, Data-driven Systems

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1 Background

The current efforts for green energy and decarbonization span all industries, including mobile machinery. Carbon neutrality is a goal in European Union and should be reached by 2050 [1]. Mobile machinery must participate in this with electrification, supporting renewable energy sources (RES) and adapting to fluctuation in energy production. Fluctuation is a characteristic in RESs that lack a mechanism to control the amount of production [2]. This must be considered in machinery regarding the scheduling of operation and recharging.

Practically, green transition requires fleets where the machines make autonomous decisions considering the conditions. The machines should autonomously decide when to take another task and when to recharge, considering their battery state, the availability of charging facilities, and the price of electricity. This functionality could be designed in a centralized fashion, but such a decision logic would lead to a complex monolith, which would cause a single point of failure as well as a bottleneck in an arbitrarily large fleet. In contrast, the selected approach applies edge computing, enabling more of local intelligence in the machines and a better resilience (see Fig. 1). Although the decision making is distributed, soft coordination is still possible, for example, with a pricing mechanism.

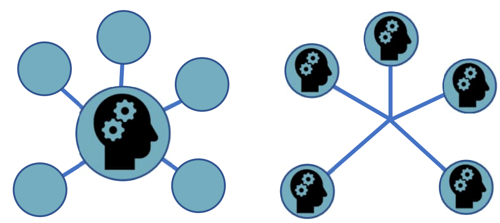

Fig. 1. Fleet-wide path planning can be either centralized or distributed.

2 Aims

This article aims to design a communication approach for exchanging data in the distributed optimization and control of industrial vehicles. The design will be conceptual and abstract, which enables re-use in multiple contexts as well as extensibility with either case-specific architecture-level requirements. Nevertheless, the study delivers evidence from a concrete demonstration.

The study takes the use case from container handling in ports. This introduces requirements regarding scheduling and routing to enable a high utilization ratio and throughput. Additionally, the machines operate in a limited space with plenty of other machines nearby.

3 Materials and Methods

As the research method, this study applies *design science research* [3]. This method aims to produce novel system and software designs to help in real-world problems. The method starts with a study of the requirements. Based on these, a solution is designed. Finally, the design is evaluated with the help of a prototype implementation. Unlike many research methods, design science replies to the question "what is effective" rather than "what is true" [4].

On a high level, the requirements cover information exchange in distributed optimization and control. This must consider latency requirements, scalability, cyber and information security (including integrity, confidentiality, and privacy), and platform independence. Although the system is distributed over an arbitrarily wide communication network and therefore cannot strictly guarantee response times, the latency should still enable timely decisions in the machines with the resolution of approximately one or at most a few seconds. The system must scale for an arbitrarily large fleet that does not necessarily operate in a single physical sub-network. A large fleet size means that the amount of data is presumably too high for any communication protocol or platform that relies on multicast without message routing capabilities. Despite the security requirements, it must still be possible to add new machines easily while still recognizing machine identities. Additionally, as the system is data intensive, data autonomy should be considered [5]. Finally, platform-independent communication is necessary as the machines can represent various system vendors and generations.

The aforementioned requirements must be fulfilled in the design of the communication framework. Concretely, the framework specifies a common information model to enable interoperability with the machines. Furthermore, the communication occurs via a message broker, enabling the various machines to listen to events in the fleet and the supporting infrastructure. Fig. 2 illustrates the features of the framework: low latency, scalability, security, and a service-oriented application programming interface (API) for communication. The concrete solution is built around a data streaming platform, such as Apache Pulsar [6].

The suggested approach differs from conventional middleware or Enterprise Service Bus (ESB). In ESBs, some of the business logic tends to reside within the middleware itself, which is no longer fully distributed and is therefore ill scalable, difficult to maintain, and

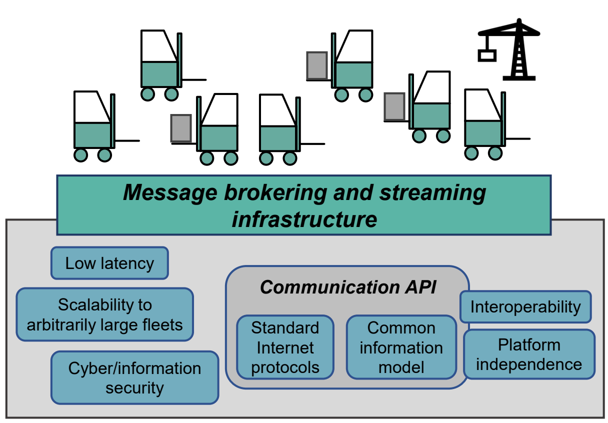

Fig. 2. Distributed path planning requires multiple features from the communication infrastructure and its application programming interface (API).

tied to a particular platform [7]. Instead, when the logic occurs in the connected machines, the designers must keep the design truly distributed. This approach has already proven successful in distributed production facilities [8]. However, the referred study has looser timing requirements compared to vehicle control and routing.

Finally, the developed solution is applied and evaluated in a use case example for container handling in ports. The use case is simulated to provide concrete evidence about the feasibility of the communication approach. The simulation aims to, first, model the environment where the fleet operates and, second, include algorithms capable of decision making in the machines. The simulation will apply multi-agent pathfinding (MAPF [9]) in a distributed fashion.

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