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Technical Report: LoadRunner® [1], a new platform approach on collaborative logistics services

Technischer Bericht: LoadRunner®, eine neue Fahrzeugplattform für kollaborative Logistikservices

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This article describes a concept for collaborative logistics services on the basis of a new autonomous vehicle platform and a corresponding digital infrastructure for its operation. The basis is an open source infrastructure including the optimization of the vehicle swarm, the order management, the participant management, the billing of the services provided as well as the connection to external services while maintaining the data sovereignty.

[Keywords: Swarm, autonomous vehicle platform, AGV, artificial intelligence, algorithms, decentral control, Silicon Economy, data economy, platform economy, International Data Spaces, cyberphysical systems, B2B platforms]

Dieser Beitrag beschreibt ein Konzept für kollaborative Logistikservices auf Basis einer neuen, autonomen Fahrzeugplattform und einer entsprechenden digitalen Infrastruktur für deren Betrieb. Grundlage ist eine Open Source Infrastruktur, die sowohl die Optimierung des Fahrzeugschwarms, die Auftragsverwaltung, die Teilnehmerverwaltung, die Verrechnung der erbrachten Leistungen als auch die Anbindung an externe Systeme zur Leistungserbringung (Services) unter Erhaltung der Datensouveränität abbildet.

[Schlüsselwörter: Schwarm, autonome Fahrzeugplattform, FTF, Künstliche Intelligenz, Algorithmen, dezentrale Steuerung, Silicon Economy, Datenökonomie, Plattformökonomie, International Data Spaces, Cyberphysische Systeme, B2B-Plattformen]

1 Introduction

Swarms of autonomous vehicles are the symbol of Logistics 4.0. They symbolize highly distributed artificial intelligence and the flexibilization of logistics in times of the fourth industrial revolution. They are representatives of a new technology that will act and negotiate based on their own artificial ingelligence in the near future. Vehicle swarms will organize themselves and connect to people, other swarms and platforms to fulfill their mission. At the same time, the central hypothesis is that vehicle swarms used for internal transport are logically continued in the global design of flow of material on the basis of intelligent systems and devices.

The future operation of such an innovation cannot take place in a "vacuum". An intelligent, digital infrastructure is needed in which swarms can interact securely with their environment. This requires an adequate digital, open and federal ecosystem in terms of a "Silicon Economy" [Hom19]. Vehicle swarms are an almost ideal entry point for establishing an omnipresent digital infrastructure beyond, as they are autonomouly acting elements that can negotiate, dispose and fulfill complete orders individually as well as acting cooperative. An adequate infrastructure must support a large number of (autonomous) cyber-physical systems (CPS) and IoT devices (Internet of Things) simultaneously in real time operational scenarios for collaborative logistics systems.

[1] LoadRunner® is a registered trademark

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The concept described in this article addresses the development of a corresponding digital infrastructure for logistics. This will be composed using mainly existing technologies that will be brought together to form of a novel open (source) ecosystem. The aim is to give small and medium-sized companies in particular the possibility to access new technologies and minimize their entry threshold. The evaluation will be based on a novel highly dynamic collaborative AGV swarm.

2 USE CASES FOR COLLABORATIVE LOGISTICS SYSTEMS

Within the context of this chapter, three exemplary use cases for collaborative logistics systems based on a new kind of high speed AGVs – the LoadRunner - are presented to describe the potentials on the one hand and to define the requirements on the other hand.

The internal transport connects the value-adding service units within companies and also provides the foundation for efficient logistics processes. In addition to the simple transport between two positions, the extended functions of buffering, distributing and sorting are relevant for the industrial internal transport.

When coordinating different transport units, a challenge in transport control can arise in the simultaneous arrival of different transports at one place at the same time, e.g. to organize the demand-oriented combination of loads for the external transport. This also applies to the picking workstations where adherence to a predefined packing sequence for the picking order may even require the need to a precisely predefined sequence for the transport processes. The flexibility in choosing the routes and the possibility of overtaking individual transport vehicles give rise to the expectation that using a swarm of vehicles has an advantage over conventional conveyor technology for exactly this purpose in addition to the inherent scalability of the hardware setup of a swarm.

2.1 DYNAMIC PARCEL SORTING

Up to now, the classic sorting of physical objects in the material flow takes place by bringing together sorting objects on a sorting line that traverses along closely arranged destination points. In addition to the efficiency of centrally identifying of the sorting features (scanner or image processing system, e.g. for recognizing the addressing), this principle benefits from the use of fast conveyor technology for the sorting and from the possibility of closely arranging the destination points when using appropriately dynamic discharge principles, such as cross belt conveyors, tilt trays or trapdoors. The named technologies require a fixed installation for the application. Compared with that, the swarm of vehicles on which this scenario is based (and implemented in the demonstrator (cf. Chapter 5)) has the advantage of being able to provide a likewise or even higher sorting capacity on a free area without fixed installations, if the infeed and item discharge are optimally arranged. Together with the desired high speed and dynamics of the transport vehicles, the benefits of the swarm can also be transferred to sorting and distribution processes.

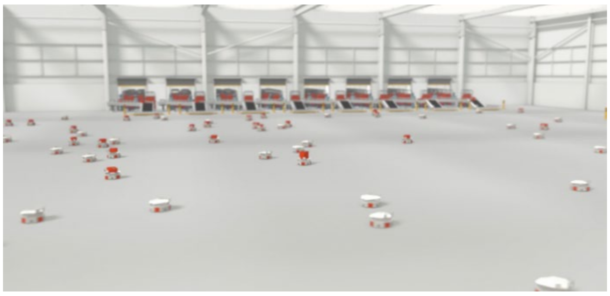

Figure 1.: Highly dynamic sorting of parcels with swarms of agv's

Currently, the state-of-the-art is represented by high-speed sorting systems that implement sorting processes on a continuous conveyor line with 3 m/s conveying speed. The advantage of flexibly choosing the route layout in a swarm enables direct trips between source and destination for distributing and sorting. Within the context of the first scenario, an implementation as a high-speed swarm was tested. Figure 1 visualizes a relevant sortation use case.

2.1.1 PRODUCTION SUPPLY AND COLLABORATIVE TRANSPORTS

Another application domain is production supply and collaborative transport with several vehicles. The supply and disposal of machines with raw materials, semi-finished goods or components for assembly is usually carried out manually, semi-automatically at appropriate transfer points with manual loading of the machine (e.g. tugger trains, shooters, etc.), automatically linked to specific AGVs or via continuous conveyor technology. Depending on the machine, production or assembly cycles, such high speeds are generally not necessary. To control the vehicles, it is necessary to connect planning and control of transport with the company's production program planning as well as the ERP system. Production is a particulary ideal use case for collaborative platforms for billing the provided (autonomous) services. Here, for example, it is possible that several service providers operate each parts of the transport vehicle fleet (e.g. focused on special transport tasks such as heavy loads).

Figure 2.: Line feed in production and assembly

The cooperative driving of logically or physically coupled individual vehicles allows the transport of a wide range of dimensions and weights of objects. All objects are suitable for this application that can be transported safely on the flat support surface of the vehicle as piece good or with a suitable loading equipment.

In mixed operation with people and machines, the LoadRunner cannot move at the same high speed. It requires an appropriate (sensor-based) safety system and reduced speed to avoid collisions with people.

As a whole, the use of an autonomous transport swarm based on the LoadRunner allows a very flexible operation of production and assembly plants without having to permanently link the machines (cf. visualization in Figure 2).

2.2 Baggage Handling at Airports

The third scenario (Figure 3) deals with the baggage handling and its partly necessary buffering. On the one hand, freely navigating vehicles can replace or complement conventional conveyor technology (e.g. conveyor belts). On the other hand, the function of coupling and uncoupling several trailers – non actuated plattforms - to one vehicle can also enable the implementation of buffer functions in the material flow. This buffering is, for example, used for early checked baggage at airports.

The trailers, also known as carriers, are thus additional elements of the vehicle swarm without own drive and are classified as passive. They have the same equilateral octagonal shape and dimension of the driven vehicle and can be magnetically coupled to one or more vehicles at the four orthogonal outer edges. In addition to the above-mentioned buffer option, another function of the trailer is to extend the dimensions of a single vehicle, to couple vehicles to increase load capacity or to carry out collective transport with several trailers.

Figure 3.: Buffering of baggage for ULD-specific consolidation on apron

Compared to today’s buffering in shipping or in baggage handling, advantages in efficiency can be achieved in manually executed handling or even a reduction in effort compared to a static automation. This is particularly interesting in an airport environement, as varying departure and arrival times of aircrafts and, for example, the seasonal passenger load factor of the flights require very specific performance peaks, which today can in principle only be faced by overcapacity of the facilities.

2.3 Interim Conclusion

The internal transport connects the value-adding service units in companies and also forms the basis for efficient logistics processes. In addition to the simple transport between two destinations, the extended function of bringing together, buffering, distributing and sorting are also relevant for the industrial internal transport.

Combining the different transport units can be challenging for the transport control as to the simultaneous arrival of different transports at the same place at the same time. This also applies to picking workstations where adherence to a predefined packing sequence for the picking order may even require adherence to an exactly predefined sequence for the transport processes. The flexibility in choosing the routes and the possibility of overtaking individual transport vehicles give rise to the expectation that the use of a swarm of vehicles is advantageous to conventional conveyor technology for exactly this purpose.

Based on highly dynamic swarms of vehicles, standard tasks in logistics systems can be performed efficiently. The essential basis for this is not only a robust and reliable vehicle that can be used in a wide range of applications, but also a digital infrastructure in which the processing orders can be managed efficiently and with a high degree of “usability” for users and providers of logistical services such as sorting, transport and buffering. Cross-scenario potential lies in the flexibilization and scalability of internal material flow systems and in the reduction of commissioning and modification costs, especially with regard to control (configuration, adaptation, etc.). As to the requirements, robust and powerful wireless communication, timely coordination of the vehicles, an efficient safety concept in mixed operation with people, a floor quality corresponding to the application and integration of the control of the entire system into production planning and control can be mentioned.

3 State of the Art

3.1 Automated Guided Vehicles and Vehilcle Swarms

Goods and articles must be transported from one place to another in warehouses, factories, sorting and distribution centers. The automated transport can take place via contionuous conveyor systems or automated guided vehicles (AGV). Contionuous conveyor systems are of statical nature and require relatively more effort and time to change them if necessary. AGVs can both, replace these and improve the flexibility and versatility of the intralogistic material flow.

Some market-available implementations and concepts of AGV are:

- KARIS PRO [Col16]
- ADAM (mobile robot) Cimcorp Oy[2]
- G-Pro[3] Grenzebach Group
- Lynx[4] Adept Technology GmbH
- NDC8 (AGV AGV Control System) Kollmorgen Steuerungstechnik GmbH
- cubeXX from STILL GmbH [Klu15]
- APAS[5] Bosch GmbH
- TORU Picking Robot Magazino GmbH [Wur15]

Various combinations of AGV and robot arms were recently implementetd, for example for the automatic loading and unloading of machine tools.

If a conventional AGV - consisting of a control system and the vehicles - is to be used in a system, the control system and the vehicles with their local vehicle control system must be adapted to the existing system environment. This includes the mapping of the respective topology for navigation, the domain-specific transport execution or the communication with the superordinate IT systems on site and much more. Subsequent system changes, such as adding more vehicles or changing the topology, generally require further manual adjustments. Therefore, modifications in such long-lasting production and assembly facilities are rare. The processes follow strictly sequential steps in a previously estimated order that is generated offline.

AGVs receive orders from a control system. Control systems are responsible for the global routing control, planning of the AGV transport paths from pick-up to the destination, avoidance of AGV, prioritization of transport orders etc.

Laser rangefinders and bumpers guarantee people's safety which is mostly ensured by stopping the respective AGV – in rare cases, the vehicles are able to automatically bypass blocking objects and people.

Usually, AGVs use predefined paths (magnetic, optical tapes as means of tracking) for navigation or a laser-supported, (partially) free navigation. Within the context of guided route navigation, the AGVs follows a predefined path by means of various sensor types. The corresponding sensors are mostly fixed to the lower edge or to the bottom part of the vehicle and guide it along the predefined path. The paths are marked with optical, magnetic or electromagnetic markers such as tapes or wires permanently laid in the ground. If the routing (markings) is relatively easy to change, as it is the case with coloured adhesive tapes, it can, however, get easily dirty or damaged.

Intelligent Transport Systems overcome these limitations of conventional AGVs. They cover several fields of application with a high degree of adaptability to rapidly changing tasks or system layouts. In addition, they offer scalability of transport capacity over a wide range and sufficient redundancy through a large number of similar transport vehicles. Most of these AGVs navigate without artificial landmarks. The topics of navigation cover several sections such as localization, mapping, global trajectory planning, local trajectory optimization and collision avoidance. A common method for localization and assigning in robot systems is SLAM (Simultaneous Localization and Mapping). Multi-robot SLAM uses a fleet of reconnaissance robots, each of which acting as sensor node [Gân14]. Novel approaches that use this method nowadays are implemented in highly dynamic environments to reduce the time for setting up the initial map and to avoid a single point of failure. Algorithms like Timed-Elastic-Band [Rös15] (TEB) or potential field methods [Kor91] are implemented for local trajectory planning and optimization. Various algorithms, e.g. A*, D* or Dijkstra's algorithm, are used to solve the global task of trajectory planning. In collision avoidance, procedures such as the time-window approach [Mor10] or the heuristic priority shift [Reg08] are used to either avoid conflicts or exclude them right from the start.

At the same time, new solutions for the management and control of transports are researched and implemented. In the context of the fourth industrial revolution, more and more decentralized system architectures are being developed. They are supposed to avoid "Single Point of Failure" and follow the hypothesis of achieving a higher degree in flexibility, adaptability and efficiency by the self-organization of autonomous AGVs. The software-technical basis for such decentralized systems are mostly multi-agent systems (MAS), with which various tasks such as dynamic routing or the allocation of transport orders can be solved cooperatively within the context of AGVs [Ble17].

Many principles of the organisation design such as networking and information transparency are directly reflected in the MAS development: as precursor of Industry

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[2] http://www.adamrobot.com/en-ca/page/home, 14.06.2020

[3] https://www.handling.de/material-handling/grenzebach-erweitert-die-moeglichkeiten-der-fts-laer-auf-grosser-fahrt.htm, 14.06.2019

[4] https://www.adept.com/home/?region=eu, 14.06.2019

[5] https://www.bosch-apas.com/start/, 14.06.2019

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4.0, SmartFactory KL e.V. offers a manufacturer-independent demonstration and research platform for testing and further development of innovative information technologies and their implementation in a realistic industrial production environment.

Subject to the MAYA research project is the development of simulation methods and multidisciplinary tools for design, engineering and management of CPS-based factories.

Decentral control has been a research topic for decades. However, it has gained in practical importance especially related to Industry 4.0. In this context, several research projects have defined and extended the state of the art. The BMBF projects ProduFlexil [Sch09] and SmartFace [Boc16] can be exemplarily mentioned as national projects. The Living Lab Cellular Transport Systems of Fraunhofer IML is still one of the few prototypical implementations of an autonomous vehicle swarm on an industrial scale. What these projects have in common is that they break with traditional hierarchical control concepts and develop new concepts from decentralized software architecture to demonstration for various industrial scenarios. The concepts mainly concentrate on Service Oriented Architecture (SOA), microservices and decentral algorithms of artificial intelligence like multiagent systems. With their flexibility and scalability, they show the advantages over central control architectures, but also the great potential such as high system transparency or life-long optimization in industrial operation.

While all these projects are successful within their own objectives, the efficiency and robustness of such systems have not yet been compellingly substantiated for a wide industrial application. Therefore, further and more profound development is necessary to enable systems on the basis of swarms of AGVs. These must adadpt independently to the operating environment and thus enable a flexible and scaleable solution.

3.2 Digital Infrastructure

The development of vehcile swarms cannot be done in isolation. It needs an intelligent, digital infrastructure in which swarms can safely interact with their environment and that requires an adequate digital, open and federal ecosystem. Swarms of vehicles are an almost ideal entry point for setting up a digital infrastructure, as they are independently moving elements that can negotiate, plan and fulfil complete orders individually and as a whole. An adequate infrastructure must support a large number of (autonomous) cyberphysical and IoT devices to be future-oriented.

As to digitial infrastructures, there are numerous technical solutions on the basis of open source software. These solutions usually offer an open source framework in which companies remain free to introduce proprietary or changeable elements. At this point, the four open source projects FIWARE, FIROS, openTCS and ROS are exemplarily presented.

FIWARE aims at providing a standardized open source platform for the development of new internet services and applications. FIWARE was launched in 2011 and funded by a number of different EU projects[6] [7] [8] [9]. The entire platform is supposed to serve as license-free, independent open source for future, intelligent cities – this is also to avoid dependencies and license fees for commercial software.

The core of the FIWARE platform are the so-called Fiware Generic Enablers, which consist of open source components and must comply with a corresponding standard[10]. The central unit is the so-called FIWARE Context-Broker, named “Orion” in its implementation[11] [12]. Orion represents a persistent storage from the current state of applications. In addition to the provision of information, interested parties can register for the changes to specific objects. In case of a status change of the respective object, all subscribers will receive an update.

To enable the connection of ROS-based vehicles to the FIWARE platform *FIROS*[13] [14] was started and will be included in the FIWARE GENERIC Enabler catalogue.

FIROS is developped within the EU Logistics for Manufacturing SMEs[15] (L4MS) project. L4MS focusses on the complete digitization of intralogistics automation in factories. In the context of L4MS a market place will be developed, a so-called one-stop shop with a catalogue of various services to provide an integrated platform in order

[6] https://cordis.europa.eu/project/rcn/99929/factsheet/de

[7] https://cordis.europa.eu/project/rcn/206763/factsheet/en

[8] https://cordis.europa.eu/project/rcn/205595/factsheet/en

[9] https://cordis.europa.eu/project/rcn/207032/factsheet/en

[10] https://fiware-requirements.readthedocs.io/en/latest/

[11] https://fiware-orion.readthedocs.io/en/master/

[12] https://github.com/telefonicaid/fiware-orion

[13] https://firos.readthedocs.io/en/latest/

[14] https://github.com/iml130/firos

[15] https://www.l4ms.eu

to bring together both, SMEs and technology suppliers. Fraunhofer IML is leading the development of both, FIROS and applications for the market place.

openTCS[16] is a manufacturer-independent and flexibly applicable control system software for automated guided vehicles (AGVs) and other discontinuous conveyors such as electric monorail systems (EMS). For many years, Fraunhofer IML has maintained the software and continued the development. The openTCS software was introduced by many well-known companies, e.g. BMW.

The Robot Operating System (ROS)[17] is an open source framework for the development of (also autonomous) robots of all kinds. It was created in 2007 at the Stanford Artificial Intelligence Laboratory within the context of the Stanford AI Robot Project (STAIR). From 2009, the further development was mainly carried out at the Willow Garage Robotics Institute, before being transferred to the non-profit Open Source Robotics Foundation organization (OSRF) in 2012. Due to its long history and modularization, it has become the de facto standard in research and industry. Companies such as Bosch, BMW and Boeing use it, as do research institutes and universities. Individual modules of the open source ecosystem to be developed in this project are therefore to be published as ROS packages and are thus available to the large ROS developer community.

3.3 DATA SOVEREIGNTY

The distinction between ownership and possession of data can become a problem in so far as data can be used and reproduced as often as desired without losing quality [Moo99]. Data sovereignty expresses itself in the balance between the requirement not to lose control over one's own database and to enable its common use in business ecosystems [Ott16]. Such business ecosystems are characterized by the joint development of innovative services, end-to-end view at customers and a dynamic formation and resolution [Moo06]. Therefore, technical and legal precautions are necessary to enable digital self-determination over data. Trustworthiness and transparency play a key role, particularly for techical infrastructures, so that these are usually operated by independent institutions which guarantee adherence to the rules. This problem has been recognized at many places; however, practical solutions have not been in sight for a long time.

One approach can be found in the project "ODiL"[18], which includes the development, implementation and demonstration of an open software platform for agricultural enterprises. The focus of attention is here on the representation, processing and communication of data under system-wide enforcement of property and access rights.

The same applies for the "**Vertra**uenswürdiger Austausch **g**eistigen Eigentums in der Industrie – VERTRAG"[19] project (trustworthy exchange of intellectual property in industry) which was funded by the BMBF in the context of the Research for Civil Security program. It deals with the comprehensive protection of company documents against industry espionage by means of trustworthy platforms. Because of the increasing digitazation of data exchange, the focus is on the consideration of the up-to-date encryption and authorization procedures ("Enterprise Rights Management", ERM) which are directly affecting the data stocks.

In 2014, the "Industrial Data Space" (IDS, now International Data Spaces Association, IDSA[20]) initiative came together to preserve digital sovereignty over data and services for business and society. The initiative is supported by companies and Federal Ministry of Education and Research (BMBF), the Federal Ministry of Economics and Energy (BMWi) and other institutions [Moo06]. IDS position themselves as alternative and supplementing archtitectural design that stands out from existing concepts that either manage the data centrally and monopolistically or negotiate every single data exchange individually [Ott19].

In the BMBF-funded InDaSpacePlus[21] project (also based on the IDS), various mobility use cases are currently being investigated and verified with partners from the transport provider side. A great deal of interest from various public transfer providers (throughout Germany) was identified and a willingness was signalled to make data records available. This preliminary work can also be included in this project.

IDS is currently the most promising approach to implement secure data exchange in decentrally organized ecosystems with currently over 110 companies and organisations. The (reference) architecture and many software components of the IDS are open source so that they can be used and adapted free of charge.

[16] https://www.opentcs.org/en/index.html

[17] https://www.ros.org/

[18] https://www.odil-projekt.de/de/startseite.html

[19] https://www.sifo.de/de/vertrag-vertrauenswuerdiger-austausch-geistigen-eigentums-in-der-industrie-2425.html

[20] https://www.internationaldataspaces.org/

[21] https://www.internationaldataspaces.org/wp-content/uploads/2019/09/InDaSpace-plus-Anforderungsdokument-1.pdf

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4 OPEN SYSTEM FOR COLLABORATIVE SERVICES

The open system for collaborative services mainly consists of two parts – i.e. the open source platform and the LoadRunner vehicles.

The control of global material, information and financial flows are essential for pratically every company. In intra-logistics and in large parts of the supply chain management, (highly) distributed and global artificial intelligence will emerge in the future. They will learn to operate beyond human acting and thinking and help to design the coming high-frequence change to grain resilience to market dynamic in a manageable way. To pave the way for this, environmental conditions for autonomous systems must be created that enable a fully virtualized data and platform economy.

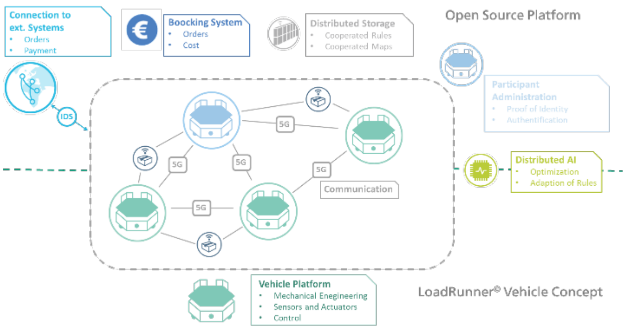

Figure 4.: *Concept of a vehicle swarm open to cooperation for intralogistic services*

Due to the extensive preliminary work of the Dortmund Fraunhofer Institutes IML and ISST, a concept was developed for a digital infrastructure basing on the above-mentioned environmental conditions in terms of an ecosystem. Figure 4 gives an overview of the conceptual structure. Using the example of an autonomous swarm of vehicles, besides the vehicles (mechanical platform) the software platform for controlling and managing the services (open source platform) and the connection of external services are elementary components of the concept.

Following the open source idea, the question arises which prerequisites (also in terms of software) have to be created in order to design systems of operative and interacting autonomous entities in a self-organizing way and, at the same time, enable external participants (e.g. service providers, customers, etc.) a functional access to the systems. This includes the identification and authentification of potential participants (e.c. mobile robots, IoT devices, trucks, service providers in logistics). Furthermore, the minimum requirements regarding common communication standards, data distribution and control are defined with regard to an autonomous system. In addition, particular attention was also focused on the technical requirements of communication. The interaction of autonomous entities on the described scale considerably exceeds the limits of a conventional company WiFi with respect to latency, availability, number of participants and throughput. The use of next-generation communication technologies, i.e. 5G, is an obvious choice. Based on the IDS architecture, an IDS connector was designed as an interface for dispatching (transport) orders into the (autonomously coordinated) system. Within the context of a demonstrator, the concept was implemented using the example of an autonomous vehicle swarm. For this, existing vehicles were adapted and further developed according to the tasks, and a control software was designed and implemented (cf. chapter 4.2.2).

4.1 OPEN SOURCE PLATFORM FOR AUTONOMOUS SYSTEMS

This chapter deals with the ecosystem core (infrastructure) concept for autonomous systems, focussing the use of established open source standards. The first use case is the application of autonomous transport systems, such as the LoadRunner, but within the concept other autonomous entities could be also connected. The necessary functions and services for the operative process are provided by the (open source) platform. The functions were designed in a way that they can be implemented by third parties in the form of modules for different hardware and therefore allow (vendor-independent) use of the digital infrastructure.

4.1.1 BASIS COMPONENTS OF THE PLATFORM

The platform for the LoadRunner vehicle swarm (a system of autonomous systems) consists of four basis components (cf. Figure 5). The components communicate with each other and with external services based on certain events (like order acceptance, completion, errors).

The **IDS Connector** is responsible for connecting the platform to external services. The entire communication with external services takes place exclusively via IDS, ensuring both, the IT security of communication and the security and preservation of data sovereignty – the data owner decides what is going to happen with the data and which (partial) information may leave IDS.

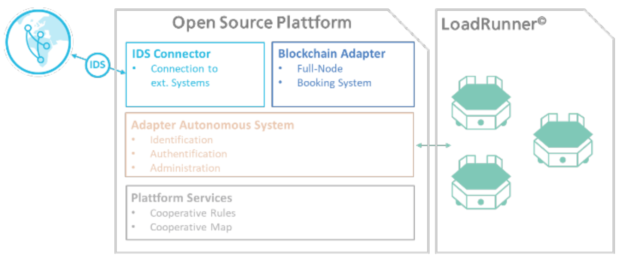

Figure 5.: *Overview of the platform components*

The **autonomous system adapter** is responsible for the communication with the autonomous systems and encapsulates all features such as real-time protocols and data models and converts them into protocols (e.g. http, MQTT) and message formats (e.g. JSON, XML). The adapter can be directly extended with optimization services for autonomous systems that should not be executed directly in the systems. This adapter is also used to negotiate the acceptance of transport orders from external services in coordination with the individual vehicles. For example, the negotiation considers at which costs (resources, driving distance and time) a vehicle can execute an order.

The **platform services** cover the basis functions for an event-driven communication between the individual components of the platform, caching for the communication and data, functions for the administration of orders and requests of external services to the vehicle swarm.

The **blockchain adapter** is responsible for storing processes in a private blockchain. For the LoadRunner, the following three processes are mainly stored using a smart contract in the blockchain: order acceptance (an autonomous system accepted an order at certain costs), completion of the process (the order was processed) and payment. The characteristics of an order acceptance are determined in the autonomous system adapter component in direct cooperation with the vehicles. In addition to the actual acceptance, conditions (like price and time) are stored in the blockchain.

The blockchain adapter is a full node in terms of a blockchain. That means it can set up processes in a blockchain and saves a copy of the blockchain. In contrast to that, a light node sets up processes in a blockchain but does not save a copy of the blockchain.

All components are executed in the application container framework Docker[22]. In addition to the actual component, these containers also include all libraries and frameworks that are necessary for the execution of the components. Accordingly, no further software (except the docker environment) needs to be installed on a target system to execute the container. This approach makes it easy to run the components on different environments. This allows a distributed execution of the components and was implemented accordingly. In combination with event-based communication, the components are decoupled from each other, only one communication bus is central. In case of the used MQTT protocol, this is a message broker. This is used in several instances to increase the system robustness and to protect against message loss. All instances are connected with each other and share all messages.

This architecture results in a decentral realisation of the platform. The individual components can run on different environments and be operated in several instances. The administration and access to the individual instances is controlled by the Kubernetes open source container orchestration system[23]. Via Kubernetes new environments can be integrated into the platform and individual components can be added, started and stopped on it.

4.1.2 Connection to External Systems

The platform aims at decoupling the connection of external systems for the transfer of transport orders and requests to a vehicle swarm (e.g. for an order status). It is of no significance for an external system which individual vehicle executes an order. On the one hand, the platform serves to accept and manage corresponding requests and, on the other hand, to pass on and process the orders to the swarm. Here, important functions are the transformation of messages into the right format, the protocols of the vehicle swarm and the caching of the messages until they are processed.

Explicitly, the transfer of orders and requests is only carried out via IDS connectors as a uniform standard for the connection of various external systems. Via IDS it is built on the existing preliminary work for IT security (security and privacy) for the connection of external systems. It also builds on the IDS mechanisms for ensuring data sovereignty (usage control).

Finally, the platform sets up all accepted orders, their succesful completion and payment in a private blockchain. In contrast to a public blockchain like Bitcoin, all participants in a private blockchain know each other and are not anonymous.

4.1.3 Proof of Identity of Autonomous Systems

Autonomous systems like the LoadRunner typically consist of several independently operating vehicles. These can be supplemented by further vehicles during operation. In combination with the connection to external systems and the autonomous processing of orders, a clear proof of identity must be created for each vehicle and validated at any time. Only, if the identity of a vehicle was succesfully validated, it can be integrated into the overall system and therefore in the communication and order processing.

The proof of identity of autonomous systems bases on the blockchain in combination with IDS. It is implemented in the platform as described below: the IDS connector of the platform must be registered with an identity provider of IDS. The identity provider issues the connectors with a certificate with which it can prove its identity. This gives the platform a unique identity. Then, this is also stored in the blockchain via the respective adapter. Thus, information is available to all blockchain participants. The vehicles are not directly connected to IDS but only via the platform.

[22] https://www.docker.com/

[23] https://kubernetes.io/

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They receive their individual identity from the blockchain. The platform provides a light node for each new vehicle. This is integrated into the blockain network and is thus given a unique identity. The platform has this assignment available in the vehicle management. If a new transport order is transmitted via IDS and executed by a vehicle, this is confirmed by a new entry in the blockchain network with the correct identity of the vehicle.

4.1.4 Data Sovereignty

The trustworthy handling of data is of great significance for the use of autotnomous systems. This is for example the case when transporting luggage from an automatic self bag drop to the departure gate at an airport. Here the gathering and processing of personal data (e.g. passenger data) takes place. For the transport with an autonomous system like the LoadRunner only certain information (such as destination and ID of the transport order) is needed to carry out the transport. No further information needs to be transmitted to the transport system. By using IDS, this is guaranteed for all participants. Although all information, e.g. passenger data, is gathered, only those details are transmitted to the LoadRunner which are relevant for the transport. No personal data leaves the IDS data room.

The exact procedure for keeping the data sovereignty is realized by the following procedure. The transport of luggage from check-in to the correct gate at the airport is sent via the IDS Connector of an external company, e.g. operating the automatic bag drop, to the IDS Connector of the vehicle platform with the corresponding terms of service. There, the order data is interpreted accordingly and processed according to the terms of use. Only the permitted information is forwarded to services outside the IDS connector. This mechanism guarantees that the data processing takes place within IDS or the connectors and that only certain data and information may leave IDS (cf. Figure 6).

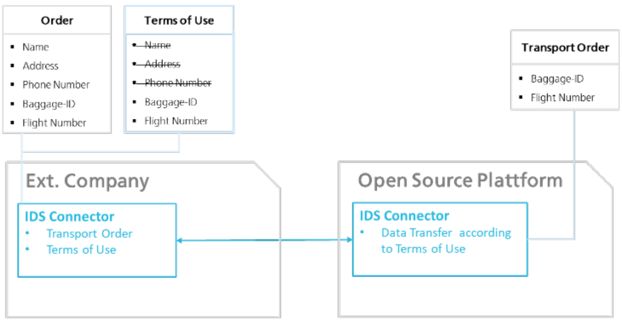

Figure 6.: *Keeping the data sovereingty by means of IDS*

4.2 LoadRunner Vehicle Concept

Mechanical basis and essential vehicle of the collaborative logistics services is the LoadRunner as a novel vehicle platform. This chapter describes both, the design and the system control architecture of the new vehicle class.

4.2.1 Vehicle Hardware Design

The fields of application and functionalities of a high-speed swarm described in the use cases (Chapter 5.2) lead to high demands on the basic vehicle. In order to be able to represent the flexibility and throughput requirements of the scenarios, each LoadRunner must have high driving dynamics with maximum autonomy. Advanced hardware was therefore used consequently and consistently during development. The LoadRunner is a completely novel hardware platform in its composition beyond the established autonomous guided transport vehicles presented in Chapter 3. The fundamental design is sketched in Figure 7.

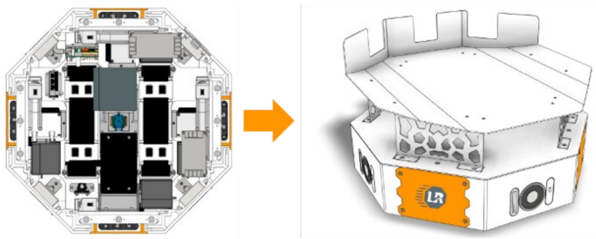

Figure 7.: *Fundamental design of the vehicles*

In order to achieve maximum maneuverability, the kinematics of the vehicle bases on four omni-directional wheels. This allows the LoadRunner omnidirectional maneuverability with simultaneous overlapping rotation. In contrast to mecanum wheels, however, omni wheels allow high driving dynamics in addition to omnidirectional flexibility. With four direct drives using gearless asynchronous engines and an output of 3.6 kW each, speeds in excess of 30 m/s (110 km/h) can theoretically be achieved. With a height of only 14 cm and a diameter of 55 cm, the platform has a payload of 30 kg. This enables numerous applications in the field of intralogistics. Depending on the application scenario, the platform can be equipped with different load handling devices.

To increase flexibility, the vehicles are moreover equipped with electromagnets at four sides. This means that passive "trailers", so-called carriers, can be connected and uncoupled. Moreover, several LoadRunners can be coupled to form a rigid platform and, for example, bulky loads can be transported (cooperatively).

4.2.2 Control System Architecture

Apart from the mechanical construction, a high-speed swarm also poses new challenges to the control system of the individual vehicles. Classical electronics for the control of and sensor technology installed in conventional AGV stretch to their technical limits in this class of vehicles.

What applies to the local control of the vehicles also applies to the coordinaton of the vehicle swarm. The central coordination of about 10 vehicles with a speed of 10m/s is

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already reaching the limits of real-time capability of established industry standards, such as WiFi. The decentralization and autonomy of decisions is therefore a crucial part of the LoadRunner system concept.

But also in decentral decision-making the entities must coordinate decisions between each other. To guarantee a new scalability of the system, novel communication processes like 5G were tested as to their technical implemenation under hard real-time conditions[24].

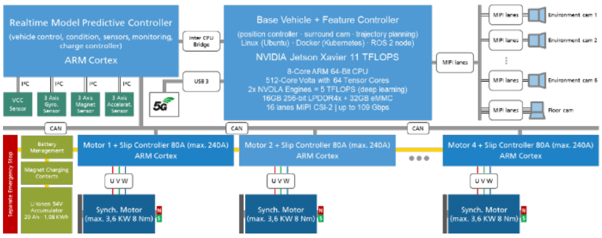

Figure 8.: *Structure of components*

Decentralized control of the swarm requires a high autonomy of each individual. The control performance required for autonomous and flexible decision-making at travel speeds above 10 m/s cannot be provided by conventional programmable logic controllers (PLC). A novel class of control computers was used for the control system of the LoadRunner. This is based on a modular design of small and micro computers of the latest generation (cf. Figure 8). Crucial functions of the system can thus be encapsuled, developed, optimized and guaranteed in a modular way. The modularity of the design allows the realization of a progression development and adaptation of the LoadRunner at the same time. Despite increased system complexity, this reduces the complexity of the individual components considerably and, at the same time, improves the component-based development and the basis for certification as well as the monitoring of functionality and possible redundancy and reliability of components at reasonable effort.

A mobile high-performance computer for artificial intelligence (AI) applications performs task control, coordination and autonomous functionality. This class of computers are characterized by an enormous computing power for more parallelizable software architectures. The high number of GPU cores (512) ensures the future applicability of scaling methods of artificial intelligence and accelerates the evaluation of data from imaging sensors and filters with high energy efficiency. The actuators are controlled each by a new class of hybrid real-time ultra-low-power microcontrollers with Co-Linux processor, the development of which is mainly driven by the entertainment industry. This new class of AI computers and microcontrollers enables a new level of performance and flexibility while reducing costs compared to conventional PLCs.

The manufacturers of LoadRunner components were selected by looking at the industrializing viewpoint. Both, NVidia (Jetson AGX Xavier) and ST-Microelectronics (STM 32) are well-known for the industrial versions of their components and the guarantee of robustness and long-term availability.

Foundation of any autonomy is the sensor technology of the vehicle. A precise localization – especially when coupled with high driving dynamics – is particularly crucial for the coordination and targeted task execution of the vehicle swarm. As with autonomous driving on the road, this can only be guaranteed at high speeds by the fusion of different sensors. A high-speed camera with frame rates of more than 400 frames/s in combination with GPU cores allows a sufficiently fast interpretation of the structure of the ground to position the vehicle even while driving. Suitable SLAM algorythms and AI proceedings are a subject for ongoing research and development.

The safety of human beings can only be guaranteed as a function of the entire system and not as a function of an individual vehicle. One of the reasons for this is that safe stopping distances and the resulting safety distances considerably exceed the usual dimensions due to the "ballistic" nature of motion dynamics.

5 Operation and Fields of Application

This chapter presents a physical demonstrator as proof of concept, describes three different application areas for different configuration and a simulation study for high-performance sorting use case.

5.1 Physical Demonstrator

As physical demonstrator for the digital infrastructure, an autonomous vehicle swarm was realized especially for transport tasks. First and foremost, this results from the high relevance of internal transport for industrial processes in production and logistics, and moreover from the intuitive transferability of the selected scenarios to other fields of application. The scenarios are very well suited to emphasize the special features of the vehicle swarm and make them comprehensible. For the implementation of the demonstrator, Fraunhofer IML based on existing vehicle prototypes with suitable characteristics. These include, in particular, above state of the art driving speed and dynamics as well as an omnidirectional kinematics resulting in motion dynamics are only limited by traction. To achieve this, the vehicles were adjusted to the high requirements of dynamic transport processes which are therefore suited for the implementation of a vehicle swarm

[24] First prototype implementation for the Digital Summit 2019.

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5.2 Use Cases / Operating Scenarios

On the one hand, the vehicle swarm is supposed to be able to transport and sort standardized parcels of a typical range of size on identically powered swarm vehicles and, on the other hand, to move large components in special processes through cooperative driving and the coupling of several vehicles and passive auxiliary platforms. These auxiliary platforms are additional elements of the vehicle swarm – so-called carriers – that have no drive and are classified as passive. They have the same equilateral octagonal shape and dimension as the self-propelled vehicle and can be magnetically coupled to one or more vehicles at the 4 orthogonal outer edges. On the one hand, these trailers can be used for buffering by placing them with the load to be buffered at a specific position. In this case the object has a dimension up to the projected size of the vehicle. On the other hand, another function of the trailer is to extend the dimension of a single vehicle, to couple vehicles to increase load capacity or to carry out collective transport with several trailers.

The adjustments to the existing vehicle prototypes do not only include a revision of the mechanical platform but also the sensor technology for localization and collision avoidance as well as actuators (drives) and control. The communication of the vehicle swarm is designed for reliable and efficient data exchange with low latencies.

5.2.1 High Speed Sorting

An example use case of the LoadRunner vehicle swarm is the **highly dynamic sorting** of parcels. Up to now, for the classic sorting of physical objects in the material flow, the sorting objects are first brought together on a sorting line that passes closely spaced destination points. The advantage of this principle lies in the use of fast conveyor technology for sorting and the possibility of a dense arrangement of many destination points by using corresponding dynamic discharge principles such as driven cross belt conveyors, tilting trays or bomp bay / split tray. The named conveying technologies require a fixed installation, which makes it hard to apply changes to the layout or adapt to different workloads. In contrast, the LoadRunner swarm offers the advantage of being able to provide a comparable or, with optimized arrangement of the sources and sinks, an even higher sorting capacity without fixed installations on a free area.

For the highly dynamic sorting of parcels, the upper part of the vehicle is equipped with a tray with partial borders so that the object can be picked up safely and is not lost even during rapid movements. A prototype (cf. Figure 9) showed that such highly dynamic sorting systems can be implemented on the basis of vehicles that reach the performance ranges of conventional sorting systems.

Figure 9.: *LoadRunner as sorting vehicles (© Michael Neuhaus / Fraunhofer IML)*

5.2.2 Cooperative Transport

The **cooperative driving** of individual vehicles logically or physically coupled with each other, allows the transport of a wide range of dimensions and weights of different load objects. All objects, which can be transported safely on the flat supporting surface of the LoadRunner as piece goods or with a corresponding loading aid, are suited for this application. Just as with sorting, it is possible that the vehicles could be fitted with load-bearing devices adapted for transport, but in view of the far-reaching universality of use they should only be used if absolutely necessary. In the demonstration mode of the vehicle swarm, the function of the logical coupling could be shown when transporting a cross beam. (cf. Figure 10).

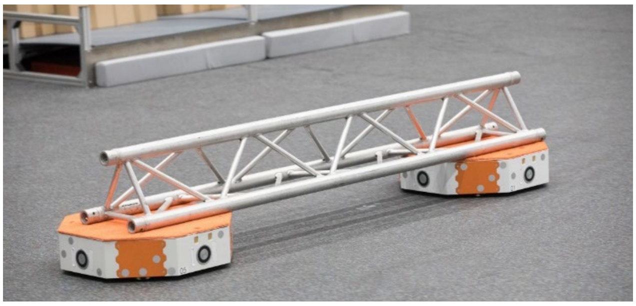

Figure 10.: *Collaborative transport of a crossbeam (© Michael Neuhaus / Fraunhofer IML)*

5.2.3 Buffering Using Passive Carriers

The function of coupling and uncoupling several carriers of the vehicle swarm also enables the realization of **buffer functions** in the material flow. Industrial applications of buffering arise, for example, in the preparation of goods out and loading or for the buffering of early checked baggage at airports. This short-term buffering, mostly in a period of some minutes or few hours, is typically implemented with a large number of continuous conveyor lines arranged in parallel or with small dynamic storage systems. The passive carriers offer an excellent opportunity to arrange the loaded carriers systematically on a flat driving surface and thus to create an arrangement that can even be dynamically changed by vehicles in their order of assembly without any further infrastructure. Compared to today's design of the buffering in shipping or baggage

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handling, which was previously mentioned as an example, efficiency advantages can be achieved in manually executed handling or expenditure reductions can be achieved compared to a statically executed automation. Figure 11 shows the prototypical implementation of the buffering of baggage on a carrier.

Figure 11.: *Implementation of buffer function on a carrier (© Thomas Willemsen – Fraunhofer IML)*

All in all, the use of the newly developed vehicle swarm provides many variations of flexibility and beats the characteristics of conventional transport and conveying systems with the possible range of applications.

5.3 Simulation Study

For the conception, development and evaluation, different aspects of the vehicle system were digitally modeled and simulated in various complexities. This ranged from the simulation and emulation of the voltage curves in the drives to the mapping of the vehicle swarm, including the entire control logic. Figure 12 shows two views of the simulation surfaces. In this case, the set-up of the demonstrator was implemented with eight vehicles. Different scenarios were tested and evaluated virtually.

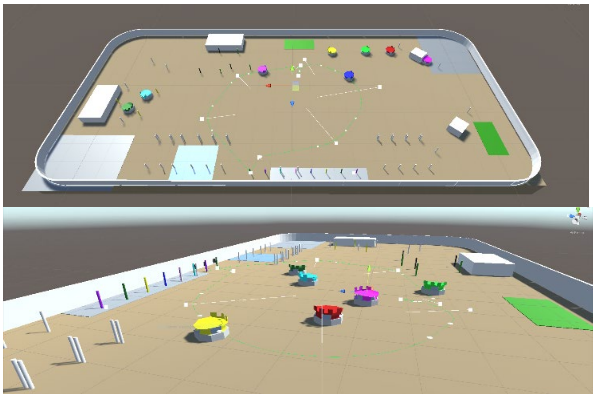

Figure 12.: *Simulation and real-time monitoring of the demonstrator scenarios*

The simulation environment was based a 3D simulation development platform capable of realtime physics simulation. Crucial advantages of the platform are the easy integration with the motion capturing system and, fast development cycles thanks to rapid prototyping support. This real-time system data is used to validate the simulation behavior. The high-precision simulation validated in this way allows uncertain and complex maneuvers to be developed and tested in the swarm system without risk.

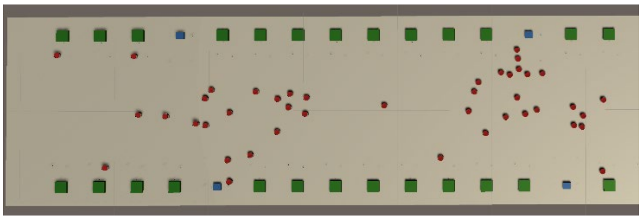

Figure 13.: *Simulation of a high-speed sorting system*

The validated simulation environment can then be scaled to determine the performance of large systems. For this purpose, a typical sorter system is simulated. With 6 infeeds and 50 chutes, such a system usually reaches a capacity of approx. 12,000 orders per hour when using a tilt tray sorter. The movement area is 115 x 20 m and, taking advantage of the LoadRunner, the infeeds are evenly distributed between the chute (see Figure 13). The simulation runs are performed with two different acceleration values, 4 m/s^2 and 5 m/s^2 respectively, and between 40 and 100 LoadRunners are used. It is shown that with 60 LoadRunner a comparable performance to a classical sorting system can be achieved. If a larger number is used, the performance will continue to increase significantly. The simulation also shows that a higher acceleration value of the LoadRunner has a significant effect on the performance of the entire system (see Tables 1 and 2).

Table 1. Performance of a LoadRunner-based sorting system with 4 m/s^2 acceleration, 5 infeeds, and 50 chutes

Number of Vehicles	Orders per hour
40	9,000
60	13,000
80	16,000
100	18,500

Table 2. Performance of a LoadRunner-based sorting system with 5 m/s^2 acceleration, 5 infeeds, and 50 chutes

Number of Vehicles	Orders per hour
40	10,300
60	14,600
80	18,000
100	21,000

In the context of the development and evaluation of vehicle control algorithms (localization, routing, collision avoidance etc.), the simulation environment has proven to be a powerful and efficient tool; this is considered a high potential for the further development of autonomous control concepts in the future.

6 SUMMARY / OUTLOOK

The concept of the new open source platform for collaborative logistics services provides a basis for further applications in logistics and production. With the LoadRunner, a new class of driverless, autonomous transport vehicles was developed, which enables a multitude of (logistical) functions through particularly high speeds and increased flexibility. In particular, the platform lays the foundation for a paradigm shift in organizing logistics services in terms of a federal platform economy with open participation of various players. First simulation results show very high potential for the (partial) replacement of current sorting systems, particularly for the sorting of parcels with a high-speed swarm.

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