Enabling Communication Technologies for Automated Unmanned Vehicles in Industry 4.0

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Abstract

Within the context of Industry 4.0, mobile robot systems such as automated guided vehicles (AGVs) and unmanned aerial vehicles (UAVs) are one of the major areas challenging current communication and localization technologies. Due to stringent requirements on latency and reliability, several of the existing solutions are not capable of meeting the performance required by industrial automation applications. Additionally, the disparity in types and applications of unmanned vehicle (UV) calls for more flexible communication technologies in order to address their specific requirements. In this paper, we propose several use cases for UVs within the context of Industry 4.0 and consider their respective requirements. We also identify wireless technologies that support the deployment of UVs as envisioned in Industry 4.0 scenarios.

Index Terms
Wireless communication, Industry 4.0, 5G, AGV, UAV, factory automation

I. INTRODUCTION

Under the umbrella of the Industry 4.0 paradigm, wireless communication is gaining more importance in industrial environments. It drives several of the planned solutions for intelligent manufacturing scenarios in smart factories. One of the suggested scenarios are material handling systems which employ AGVs for transportation of tools and products within a production facility from one location to another [1]. Another possibility to transport smaller goods is to employ UAVs for this task [2]. Such applications place very high requirements on latency and reliability of the communication links which many of the existing wireless technologies struggle to satisfy. Also, the proposed wireless technologies have to be flexible enough to account for the wide range of UVs used in the industry. For instance, UAVs, also commonly known as drones, in logistics applications have completely different requirements in comparison with ground-based AGVs. While both types of UVs require highly reliable communication and accurate localization, UAVs control is more challenging due to their higher degrees of freedom and higher speed. Therefore they require lower latency for the communication technology used [3]. AGVs on the other hand, might require higher data rates for video transmission in remote control applications [4].

For an efficient operation of UVs, path planning is essential. Ideally, path planning should optimize the UVs routes by minimizing the distance traveled, minimizing the travel time or maximizing the utilization of UVs [5]. Depending on how they navigate through a facility, for instance, AGVs can operate in either of the following modes: fixed-guide-paths, or open-path. The former requires embedding physical guidance paths, usually using inductive or optical guides, in the factory floors. Whereas the open-path approach allows AGVs to roam freely in their environment, therefore adjusting to changes in their surroundings [6].

Earlier AGVs in industrial applications used a fixed-path induction-based guidance system, where wires are buried in the factory floor and a floor controller sends an electric current through the wires. An AGV can detect and follow the currents in the wired paths [6]. Other fixed-guide-path systems include magnetic or optic tapes to mark the ground paths. Without additional sensors, these systems allow the AGVs to follow a predetermined path. However, the AGVs do not have knowledge of where they are located. This can be rectified by having the location information encoded in radio frequency identification (RFID) tags next to the tracks. With the help of techniques such as odometry it is possible for the AGV to acquire refined position estimates [7]. These systems while offering robustness, they suffer from inflexibility and relatively high-cost of their infrastructure.

In contrast to the fixed-guide-path systems, open-path systems allow vehicles to move freely inside a facility. The prerequisites for such systems are a method to localize the AGV and a map. There are different systems for a vehicle

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to localize itself indoors. One possibility is RFID tags with position information distributed over the factory floor. The location can be estimated using gyroscopic sensors for angular information and wheel encoders for the distance [8]. Other existing positioning systems are based on laser sensors and reflective beacons with known positions. AGVs equipped with laser sensors or cameras can also use landmark identification schemes to determine their position [9]. All these systems, however, need a map of their environment in order to calculate the path they need to take. These systems are more flexible than fixed guide-path schemes, but require more expensive hardware, more involved coordination, and more computational resources. Wireless communication between the UVs themselves (UV-UV) and the production facility's network (UV-infrastructure) can improve global path planning and facilitate coordination amongst the UVs. Thus, it is essential for a smooth operation of future production facilities.

In Section II, we first introduce existing use cases for AGVs and future ones anticipated in Industry 4.0 scenarios. The new use cases bring along a new set of requirements. We identify them in light of specifications set by the third generation partnership project (3GPP). We provide an overview of current wireless technologies and examples of their deployments in Section III. Additionally, we list the open challenges for existing technologies in Section IV, as well as introduce future solutions that are promising to fulfill the needs of UVs in smart factories in Section V.

II. USE CASES AND REQUIREMENTS

Future production facilities should be able to support on-demand product customization. Therefore, production lines will be supplemented by small mobile transport robots, upon which the unfinished products can be redirected for further modifications inside the factory. Thus, UVs are needed. UVs can transport single workpieces, whole production batches or can deliver the needed resources according to the production schedule [10]. The following use cases based on [4], [11] and [12], reflect possible applications for UVs in industrial automation settings.

A. Smart modular production

Factories of the future are envisaged to be highly reconfigurable and connected such that they can easily adapt to customization of products whenever required. Smart factories shall support a modular paradigm [13], which renders them independent from the physical location. Short production lines can be disassembled, transported from one location to another, and reassembled in short time. Therefore, future production facilities will consist of compact discrete workstations that can perform single work steps. These modules can also be plugged together to build longer linear production processes. To support a smooth operation in smart factories, AGVs are essential for an undisrupted flow of components, products and workstations to their intended destinations within the facility.

B. Factory automation

Automation in factories continues to expand and evolve with the objective to realize smart and efficient production. Human workers' tasks under automation has shifted from performing the physical work task to making high-level decisions for the robotic systems to complete the work. In relation to material handling, workers will no longer have to drive vehicles, e.g., forklifts or cranes, loading from the high rack storages to the production machines. Instead, AGVs and UAVs are used. Future UVs will support smart algorithms for self-coordination and collaboration within a fleet to optimize their route planning and adjust there distribution in a production facility. For local coordination environments, such as a workshop, UVs can communicate amongst each other and with neighboring machines to minimize transportation time such that the closest UV to a scheduled task will pick it up as requested by the machine. As for global coordination on the factory level, a higher-level fleet management system, that has the knowledge of the current UVs distribution and their respective tasks, can assign UVs to emerging tasks as needed while ensuring an optimal routing and movement on the factory floor.

C. Material and inventory live-tracking

Flexible manufacturing requires the ability to track materials', workpieces', and products' flow throughout the entire supply chain. Whereas it is possible to implement tracking on individual items while being transported from one location to another, usually via RFID tags and reader gates [14], it is more efficient to transmit tracking data of a batch of carried items through the UV transporting it. Particularly when live-tracking is in question.

D. Mapping and surveillance

In dynamic industrial environment, e.g., modular smart factory, AGVs and UAVs can be used to keep track of the workshop floor plan with the help of technologies like simultaneous localization and mapping (SLAM) [15], [16], where the UV constructs a map of its surroundings while it simultaneously estimates its current position using that map. Additionally, cameras and sensors mounted on an UV can be employed for surveillance of workshops and premises to keep track of intruders to restricted areas on the factory ground. It is also possible to build a virtual representation of the factory. This "digital twin" can be used to detect when changes occur in the factory floor and predict possible issues that might cause a halt to the production line [17].
Table I

| Requirement     | Vertical: Factories of the future |
|-----------------|----------------------------------|
| Reliability (%) | 99.9999                          |
| Latency (ms)    | 40 - 500 *                       |
| Speed (km/hr)   | up to 50                          |
| Data rate (Mbps)| up to 10 Mbps                    |
| Coverage (m)    | 1000                              |
| Number of UVs   | up to 100                         |

* for standard UV operation.

Requirements

In order to realize the suggested use cases for UVs in industrial environments, several requirements need to be accounted for when deciding on the enabling technologies. The 3GPP technical specification (TS) 22.804 [4] provides a study of automation in vertical domains for future 5G systems. We base the derivation of requirements for our suggested use cases on those set by the 3GPP for the "Factories of the Future" use case in [4] and listed in Table I. The requirements for each use case are depicted in the radar chart shown in Figure 1, where they are indicated and quantified on the axes with levels starting 0 for no requirement; 1 for a low requirement level; 2 for a medium requirement level; 3 for a high requirement level; and 4 for a very high requirement level. Reliability defines the maximum rate of packet loss tolerable for the application within the maximum tolerable end-to-end latency. For all suggested use cases involving UVs the requirement on reliability is set to higher than 99,9999 %. Latency requirements vary for UVs; e.g., communications with machines as in the smart factory have very high requirements within 10 ms range, whereas for standard UVs’ operation the requirement on latency is relaxed to up to 500 ms. All UVs use cases require mobility, however; the maximum speed possible while maintaining service reliability can vary from one use case to another. The higher the permissible speed, the tighter the execution of handover is within the required latency. The estimated data rate for the regular operation of UVs is within 1 Mpbs, except when video transmission is desired, as in surveillance, then higher data rates up to 1 Gbps need to be supported. The coverage area, where the communication services for UVs are supported, extends up to 500 m indoors and up to 1000 m for outdoor operation. The expected number of UVs is around 100 for a given use case. For the modular factory use case, the number of UVs required is limited compared to other use cases.

III. Existing Technologies

In this section, we discuss current wireless communication technologies that are used to support the operation of UVs.

A. Wireless local area network (WLAN)

The IEEE 802.11 WLAN, also known as WiFi, is considered to be one of the most ubiquitous wireless technologies in use. It was initially designed for operation in office buildings and home networks, providing high data rates (up to 433 Mbps for 802.11ac using single antenna [18]) with no real-time guarantees. However, it was possible to employ it in various other areas that require real-time communications including industrial applications [19], [20], [21]. To ensure fulfillment of the rigid timing requirements, IEEE 802.11 is configured in such scenarios to operate in the point coordination function (PCF) mode; in which a point coordinator manages users’ access to the medium. This centralized mode allows a deterministic operation for users. For instance, Siemens AG extended some of the features of the IEEE 802.11 standard to support the requirements of industrial communications [21]. By introducing industrial WLAN (IWLAN) with proprietary extensions to the 802.11 medium access control (MAC) layer, which operates in the PCF mode, and to protocols such as parallel redundancy protocol (PRP); it is possible to provide real-time communication with seamless roaming for terminals using PROFINET and EtherNet/IP industrial Ethernet standards. IWLAN is designed for applications involving mobile robots, e.g. AGVs, cranes, and overhead conveyors. Researchers in [22] compared the performance of PCF to other IEEE 802.11 MAC mechanisms in simulation. Namely, distributed coordination function (DCF), enhanced distributed channel access (EDCA), and HCF controlled channel access (HCCA), which is based on the hybrid coordination function (HCF). They considered conditions prevalent in industrial settings for real-time traffic. The results showed that the current IEEE 802.11 MAC mechanisms struggle to support real-time traffic, particularly as the number of users and network traffic increases.
B. Cellular networks: Long term evolution (LTE)

As the requirement for the communication in the mobile users and inter-machine domains differ, the need to adjust the available cellular technologies arose, to better accommodate the tighter requirements, e.g., in terms of latency, for industrial automation. The 3GPP LTE release 10 included the first provisions to enable machine-type communications (MTC) over LTE networks [23]. Within this context, MTC technologies provide solutions to connect machines, sensors, and actuators to support their autonomous operation, as intended for the use case of UVs. LTE can address several of the MTC requirements thanks to its features. These include: low latency, high reliability, and wider coverage compared to other wireless technologies, e.g., WiFi [24]. For instance, Huawei’s adaptation of LTE; enterprise LTE (eLTE), which is based on LTE in unlicensed bands and designed for industrial automation has been already deployed for the automated control of AGVs in Yangshan Port, China [25].

C. Radio frequency identification (RFID)

RFID technology is commonly used for inventory tracking and less frequently for localization and positioning applications. Researchers in [26] and [27], studied and developed RFID-based indoor location tracking systems for AGVs. For positioning applications, location information can be stored on the RFID tags, which can be placed on the floors, ceilings, and throughout the area where UVs are operating. The UVs are equipped with an RFID reader that detects the RFID tags and uses the location information along with estimates of the distance between the tag and the reader to localize itself. The more tags an RFID reader detects at a given location, the better the estimate. While localization using RFID is an attractive solution for its relatively low cost and ease of deployment, it is susceptible to interference resulting from the surrounding environment.

IV. CHALLENGES

The Industry 4.0 paradigm raises plenty of new requirements on communication and localization technologies for UVs which existing solutions fall short to fulfill. Particularly within the fields of communication and localization technologies, demands are high on latency, data rate and handover mechanisms while simultaneously maintaining a good level of accuracy and reliability. We summarize in this section the open challenges, that UV systems face, where new requirements
for factory automation have been introduced.

**Communication technologies**

Low-latency and reliable communication technologies are indispensable for the operation of UVs in factory automation scenarios. Yet, current technologies lack a solution that can satisfy the wide range of requirements on data-rate, latency, reliability, scalability, and energy efficiency at once. Also, due to mobility of UVs, reliable and quick handovers are necessary such that data transmission is not disrupted when the UV moves from the coverage of one cell/access-point to the next. When UAVs are in question, communication technologies must be energy efficient since the flying-time for a UAV is strictly limited by its fuel supply or battery lifetime. Another great challenge that is prominent in industrial environments is the hostility of propagation channels, due to electromagnetic interference caused by machinery and the common presence of reflectors in an industrial facility's infrastructure that enriches multipath components [28].

**Localization systems**

For outdoor localization scenarios of UVs, global navigation satellite system (GNSS)-based localization is the norm. Current UAV systems are using global positioning system (GPS), global navigation satellite system (GLONASS) receivers, or a combination of both, as well as global inertial navigation systems (INSs) to estimate their position. However, indoor localization scenarios are much more challenging. GNSSs are not used since their receivers cannot acquire a signal indoors. Moreover, propagation conditions in industrial environments cause severe reflections and absorption of signals which produces inaccurate location estimates. As a result, path planning and SLAM algorithms, that depend on the initial position estimate would be imprecise. Thus leading to difficulties for the UVs when navigating their vicinity, particularly when the environment is dynamically changing due to other participants in a workshop or factory floor. Therefore, a reliable localization technology has to be used in order to introduce AGVs in production facilities.

**Other challenges**

The heterogeneity of systems in a production facility creates the need for open-source based interfaces, protocols, and data formats that allow interoperability between the various systems for a functioning production line. This compatibility must be introduced starting from the top-level administrative and management tools to the bottom-level shop-floor machinery and device. In reality however, many of the current production systems have vendor-specific interfaces, protocols, and data formats which complicates the process of integrating and realizing flexible production. Additionally, future manufacturing systems have to be ideally backward-compatible with the current technologies. Since upgrades to the production systems' infrastructure are not only expensive but also time consuming. Thus, enabling communication and localization technologies for UVs should either make use of the existing wireless infrastructure, or be decoupled and designed such that modularity and ease of deployment are ensured.

**V. Future 5G Technologies**

One of the major areas where future 5G technologies are envisioned to be applied is industrial networks. Service requirements, coupled with the operational conditions, in industrial networks constitute a challenging setting for current wireless technologies. In the use case of UVs in particular, the requirements on reliable communication and relatively low latency are high.

A. 5G new radio (NR)

The next generation of communication technologies, 5G, is still under ongoing definition. 5G technologies are designed while keeping flexibility and scalability in mind to account for the requirements of future use cases. 5G NR is the newer generation of radio interface and protocols for 5G networks proposed by the 3GPP. In the latest 3GPP TS [29], ultra reliable low latency communication (URLLC) is supported as one of the use cases of verticals for 5G NR. UVs are considered within URLLC use cases. The special adjustments in 5G NR for supporting URLLC include logical channel prioritization (LCP) restrictions as well as enabling packet duplication at the LTE’s MAC and packet data convergence protocol (PDCP) layers, respectively. The radio resource control (RRC) is the entity responsible for configuring protocol layers in the network and user equipment (UE). For instance, LCP restrictions made by the RRC, e.g., transmission time interval (TTI) size, cell and numerology for logical channels [29], aim to prioritize URLLC data traffic. Packet duplication at the PDCP is also carried out by the RRC and it ensures reliability and minimizes latency by sending protocol data unit (PDU) duplicates simultaneously over two distinct channels [30].

B. software-defined networking (SDN)

SDN is an emerging technology that simplifies management of networks by separating the control and data planes in traditional network devices, such as routers and switches [31]. This approach allows centralizing the forwarding decisions
and network logic at the SDN controller and confining the network devices to solely enforcing those decisions. The SDN controller acquires a global view of the network which enables it, for instance, to detect changes in the network topology. Therefore, it can keep track of the constantly moving UVs through information contained in the OpenFlow (OF) messages being exchanged, these include: the internet protocol (IP) and MAC addresses, the switch, and the port number the UV is associated with. This information is updated whenever a host, in our case UV, joins or leaves the network. As a result, better path planning and resource management can be achieved with the help of SDN.

C. Network slicing and network function virtualization (NFV)

A novel paradigm that is planned for future 5G networks offers network as a service (NaaS) for businesses and industries. The network is divided logically into network slices, based on the services they support, while still using a shared physical infrastructure. These network slices are operated independently and further optimized for the specific requirements of the vertical users. This allows, for instance, the verticals to operate their own private networks. Giving them full control and the ability to customize the network according to their needs and quality of service (QoS). Network slicing depends heavily on virtualization of the network infrastructure components using NFV concepts. It is also simplified via SDN for control. NFV abstracts network functions from underlying specialized networking hardware, allowing their deployment on general-purpose servers or on cloud computing infrastructures. Whereas SDN technology facilitates management of the slices through its centralized control plane.

D. Edge computing

For tasks requiring powerful processing and large computation power, e.g., SLAM, UVs might not have the sufficient resources to carry them out. Edge computing is needed for such applications. It is a recent approach that aims to bring the cloud computation power at the network edge. As a result, it supports offloading extensive computations and storing large amounts of sensors’ or video data, thus saving a UV’s energy as well as its computational resources and reducing the overall delay in the network for time-critical applications. For example, the authors in [35] developed and implemented a test-bed for crowd surveillance with facial recognition using UAVs. The performance of processing the captured videos on board of the UAV versus offloading it to an edge computer showed the advantage of the latter approach.

VI. Conclusions

In this paper we outlined enabling communication technologies for material handling using UVs, which is a crucial component for the advancement and realization of future production automation ecosystems. We considered various use cases for UVs within the context of the Industry 4.0 initiative and derived their respective requirements in accordance with those set by organizations such as Verband Deutscher Elektrotechniker (VDE), 3GPP, and 5G Public-Private Partnership (5G-PPP). The highest requirements for the UVs’ use cases are on latency and reliability, which current wireless technologies, such as WiFi and LTE, struggle to fulfill. We focused on the existing wireless communication technologies that support UVs’ operation and denoted the challenges facing UV systems under industry 4.0. The design of future 5G technologies takes into consideration industrial scenarios for factories of the future. With the help of prospective 5G techniques such as 5G NR, SDN, and edge computing, vertical industries will have better control over their private network and could fine-tune their networks according to the specific needs of individual use cases and ensure the required level of QoS.

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