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► **To cite this version:**

Marius Greger, Daniel Palm, Louis Louw, Konrad Von Leipzig. Classification of Optical Technologies for the Mapping of Production Environments. IFIP International Conference on Advances in Production Management Systems (APMS), Sep 2019, Austin, TX, United States. pp.197-205, 10.1007/978-3-030-30000-5_26 . hal-02458391

HAL Id: hal-02458391

<https://inria.hal.science/hal-02458391v1>

Submitted on 28 Jan 2020

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Classification of optical technologies for the mapping of production environments

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Abstract. Indoor localization systems are becoming more and more important with the digitalization of the industrial sector. Sensor data such as the current position of machines, transport vehicles, goods or tools represent an essential component of cyber-physical production systems (CCPS). However, due to the high costs of these sensors, they are not widespread and are used mainly in special scenarios. However, especially optical indoor positioning systems (OIPS) based on cameras have certain advantages due to their technological specifications. In this paper, the application scenarios and requirements as well as their characteristics are presented and a classification approach of OIPS is introduced.

Keywords: Optical Indoor Localization Systems, Cameras, Marker-based Tracking, changeable and reconfigurable manufacturing.

1 Introduction

In order to meet the requirements of Industry 4.0, a high degree of adaptability of production systems is required [1]. In this context, there is a focus on the so-called smart factory, in which people, machines, objects and products are intelligently linked with each other through the provision of hardware and software. This enables increasing automation and autonomous reaction to unpredictable events. [2]

For this purpose, embedded systems are integrated into objects, devices, buildings, forklifts as well as into production facilities and logistics components, whereby these become cyber-physical systems (CPS). These systems, also known as intelligent objects, can then autonomously and decentrally communicate with each other and optimize themselves. The result is a virtual image of reality, which is continuously updated with the help of real-time data. [3]

Westkämper [4, 5] considers the ability to unambiguously identify and localize objects and the individuality of systems, processes, objects and products as well as the controllability of the increasing complexity to be particularly important. Indoor positioning systems (IPS) are architectures of tags, location sensors, a locating engine and a locating application that can be used to determine the position of a person or an object

in buildings [6]. Tags are used as spatial reference points or for unambiguous identification and the location sensor provides ID and position values. The location engine uses this data to derive the actual position of the specific location object. The location application is the software solution for further processing the position data [7].

Positioning can be relative or absolute. The relative positioning determines the position of the location object relative to a reference point. In absolute position determination, the position is specified in a global coordinate system [8]. A variety of systems and technologies using different algorithms, techniques and technologies are available for the unambiguous identification and localization of objects, which differ in their degree of maturity and their performance [9–11]. Due to the high cost of these systems, they are actually only applied in a limited amount of scenarios, such as the navigation of autonomous transport vehicles [12]. In particular, optical indoor positioning systems (OIPS), which use cameras or other optical sensors to determine the position of localization objects in their field of view, [13, 14], have proven to be precise and robust in industrial applications [15–17]. Compared to radio-based approaches, which have also gained popularity, they are not influenced by reflections on metal, multipath propagation, interferences, scattering or absorption by liquids [18]. They are highly scalable and can work with tags that can be printed by the user inexpensively, or even without any tags. Therefore, they seem to be especially promising for the application within small and medium sized enterprises (SME).

2 Characteristics and Requirements of Indoor Location Systems

The wide field of application of indoor localization systems leads to a multitude of requirements. An overview of requirements mentioned in literature is given in Table 1. The authors have been assigned to the requirements mentioned in their works.

Table 1. Identified requirements towards indoor positioning systems (IPS)

| Author | Günthner et.al.[19] | Hohenstein [6] | Mautz [18] | Liu et.al. [20] | Han [21] | Malik [7] |
|---------------------------------|---------------------|----------------|------------|-----------------|----------|-----------|
| Localization function | | | | | | |
| Continuity | | x | x | | | x |
| Output data | | x | x | | | x |
| Required infrastructure | | x | x | | | x |
| Localization performance | | | | | | |
| Accuracy | x | x | x | x | x | |
| Coverage | x | x | | x | x | |
| Repeat accuracy | x | | x | | | |
| Update rate | x | x | | x | x | |
| Overall system | | | | | | |
| Scalability | x | x | x | x | x | x |
| Availability | | | x | | | |
| Robustness | x | x | x | x | | x |

In the following section, a short description of the requirements is provided.

- **Continuity** refers to the ability of a system to repeat a certain function in time and space. An IPS is continuous if position determination is not limited to a few predefined measurements [6].
- **Output data** refers to the location data provided by an IPS, e.g. 2D or 3D coordinates, orientation, ID, etc.
- **Required infrastructure** refers to the infrastructure needed for position determination that goes beyond the location sensor and the location engine. Mautz [18] distinguishes between OIPS with or without markers.
- **Accuracy** refers to a numerical measure in a given metric unit and results from the deviation between nominal and actual position.
- **Coverage** refers to the maximum range between an IPS and a location object, in which the object can still be identified and its position be determined.
- **Repeat accuracy** or precision, describes the repeatability of a measurement result, given that the measurement is carried out under the same conditions.
- **Update rate** refers to the frequency at which the position data can be determined by a system. An important aspect of the update rate is the latency, which is the time required by a system to determine the actual position of a localization object.
- **Scalability** refers to the achievable number of localizable objects and structures.
- **Availability** refers to the amount of time a system is available for use with the required accuracy and integrity.
- **Robustness** refers to the resistance towards unwanted influences of a system, e.g. changes in temperature, reflections, occlusion, etc.
- **Architecture** refers to the fact that systems can be realized in a way that the localization system is attached to the localization object, the position data are thus recorded directly at the object to be located (inside-out). In contrast to this approach in an outside-in approach, the localization system is attached to the infrastructure. [6]

| Requirements | Characteristics | | | | | |
|-------------------------|-----------------|---------------|-----------------|-----------------------|--|------------------|
| Continuity | continuous | discontinuous | | | | |
| Output data | undefined | xy position | xy position, ID | xyz position | | xyz position, ID |
| Required infrastructure | none | markers | | | | |
| Accuracy | < 5 cm | < 10 cm | < 5 cm | < 1 m | | |
| Coverage | < 1 m | < 5 m | < 10 m | | | |
| Repeat accuracy | 69 % | 93,3 % | 99,96 % | | | |
| Update rate | on request | event-driven | periodically | | | |
| Latency | < 1 s | < 15 s | | | | |
| Scalability | low | medium | high | | | |
| Availability | low | regular | high | | | |
| Robustness | occultation | reflection | interferences | changing environments | | |
| Architecture | inside-out | outside-in | | | | |
| Number of objects | ≤ 10 | ≤ 50 | ≥ 50 | | | |
| Computing power | low | medium | high | | | |
| Power supply | active | passive | | | | |

Fig. 1. Requirements towards indoor positioning systems (IPS) and their characteristics

Moreover, the number of localization objects, the required computing power and power supply are important aspects, as they influence the costs and the components of a system. Based on a literature review (see e.g. [16, 18, 22, 23, 6]), the characteristics of the requirements were determined. The results are shown in Figure 1.

3 Application scenarios of OIPS

After the introduction of the requirements for OIPS in section 2, this section presents various application scenarios explored in the literature and clustered according to their main application area. A short description of the application scenario is given (see Table 2 and Table 3). The list of scenarios represents the use cases mentioned in literature. The objective of the collection was not so much absolute completeness, but rather a representative selection, which makes it possible to assign the application scenarios to basic system configurations in the following section.

Table 2. Application scenarios of optical indoor positioning systems (OIPS) in Logistics

| Area | Application scenario | Description |
|-----------|---|---|
| Logistics | Automatic goods recognition at arrival | Delivered goods can be automatically identified and posted directly at the arrival. [17] |
| | Component search | Comprehensive localization of components and intermediate products. [27] |
| | Intelligent tool control | Through the localization of tools and the intelligent analysis of this data, it is possible to determine and optimize the utilization. [27, 28] |
| | Inventory management | Stocks are often unnecessarily increased because the storage location or filling level of containers cannot be determined. [24] |
| | Navigation and localization of mobile robots | Equipped with an RTLS, mobile robots can find their way around in industrial environments. The determination of their absolute position at any time is crucial for optimal navigation. [26] |
| | Optimization of routes | Optimization of in-house transport routes to avoid empty runs and traffic jams. |
| | Quality management | Reduction of picking errors, packed goods are counted and compared with the packing list. [17, 24] |
| | Route inspection | Before a transport process is started, the system checks whether the route is blocked or not. |
| | Tracking of intralogistics transport vehicles | Current position determination of transport vehicles (e.g. forklifts, trolley trains) and their status. Optimization of availability, assignment, routes and transparency. [24] |
| | Tracking of material flows, load carriers or workpieces | Material movements can be recorded with Real-Time Locating Systems (RTLS) and passed on to higher-level system for analysis purposes and process optimisation. [6, 24, 25] |

Table 3. Application scenarios of optical indoor positioning systems (OIPS) in Production and Production-related Areas

| Area | Application scenario | Description |
|------------|--|---|
| Production | Automation in production lines | The position data of work pieces or containers are used to improve automation in transportation and feeding processes avoiding delays in the production process. [27] |
| | Digital twin of factory, layout of the production system | Creation of the digital twin of the production system. The constant position determination of machines and vehicles enables the digital representation of the physical production system and the proactive reconfiguration of production systems. This information plays a decisive role especially in the case of increasing automation or even the introduction of autonomous system components. [27] |
| | Intelligent tool control | Depending on the position of a tool (e.g. a screwdriver) relative to a work piece to be machined, its control is automatically enabled. For instance the torque is adjusted depending on the tool position. [24] |
| | Operational optimization | The position determination of every single batch, tool and employee enables extensive process optimization by means of analysis. [28] |
| | Quality management | Observation and reduction of assembly errors, [24] |
| Security | Access control | Monitoring of safety areas, increasing workplace safety. [24, 27] |
| | Anti-theft protection | Continuous presence check, inspection of a known object. [18] |
| | Evacuation management | In emergencies (e.g. fire, release of dangerous substances, danger of terrorism, etc.) companies must be able to determine whether employees are still in the building and ideally in which areas. [29] |

4 Classification of OIPS

The biggest challenge for (potential) users is the fundamental definition of the architecture and identification method of the overall system. While the technological capabilities of individual components can easily be adapted on the basis of the specific requirements of the scenarios, the decision whether the camera system is located on the object to be localized or not and if a marker-based system or a non-marker based like a feature-based-tracking system should be used. Therefore, four classes were formed based on their characteristics (see Table 4) and the application scenarios are evaluated to determine, which of these classes could be used to implement the respective scenario (see Table 5).

Table 4. OIPS-classes based on architecture and infrastructure

| Class | Architecture | Required infrastructure |
|--------------|--------------|-------------------------|
| OIPS Class 1 | outside-in | markers |
| OIPS Class 2 | outside-in | none |
| OIPS Class 3 | inside-out | markers |
| OIPS Class 4 | inside-out | none |

The results show that the outside-in architecture where the localization system is attached to the infrastructure (Class 1 and 2) covers a significantly wider range of scenarios than the inside-out architecture. In practice, this gives an initial indication of a technology to be introduced if the concrete application is still unspecified. All scenarios except the self-navigation of mobile robots can be solved with the outside-in architecture. For a detailed specification, further aspects of Figure 1 have to be considered.

Table 5. Classification of optical indoor positioning system (OIPS)-scenarios

| Scenario | OIPS Class 1 | OIPS Class 2 | OIPS Class 3 | OIPS Class 4 |
|---|-----------------|-----------------|-----------------|-----------------|
| Access control | x | x | | |
| Anti-theft protection | | x | | x |
| Automatic goods recognition at arrival | x | | | |
| Automation in production lines | x | x | | |
| Component search | x | x | | |
| Digital twin of factory | x | x | x | x |
| Identification workplace | x | x | | |
| Intelligent tool control | | x | | x |
| Inventory management | x | | | |
| Navigation and localization of mobile robots | | | x | x |
| Operation optimization | x | x | | |
| Optimization of routes | x | x | x | x |
| Quality assurance (reduction of picking errors) | x | | | |
| Route inspection | | x | | |
| Tracking of intralogistics transport vehicles | x | | x | |
| Tracking of material flows, load carriers or workpieces | x | x | | |
| Number of viable scenarios | 12 | 11 | 4 | 5 |

The minimum specification of an OIPS that can meet the requirements of all the scenarios listed in Class 1 must have an accuracy of better than 5 cm, a coverage of at least 10 meter, a frame rate of more than 15 frames per second (fps) to track moving objects, a periodic update rate, a latency of under 1 second, a high scalability, the ability to identify more than 50 objects, and use an active power supply. This gives users an indication how to set up an OIPS with a maximum of flexibility in relation to the scenarios. Individual application requirements of each scenario are shown in Figure 2.

5 Summary and Conclusion

In this paper, the literature in regard to IPS and OIPS was analyzed and application scenarios as well as their requirements and characteristics were derived. The classification framework can be used by practitioners to determine the technical requirements to realize a specific application scenario. It was shown that OIPS is a relevant technology that can cover a wide range of scenarios and that an outside-in architecture with localization system attached to the infrastructure (mounted set of cameras and marker- or non-marker-based identification and localization of the objects) covers a significant

higher range of scenarios in the production environment than the inside-out architecture. Here it could be proven that this architecture has the broader application possibilities.

The high proportion of low-cost computing power and image sensor chips on the market make cost-effective positioning solutions that can meet the requirements more attractive for a wider range of scenarios. This in combination with the possibility to paper-print a marker for identification purposes for literally no costs, opens up a cost-efficient realization of high number of scenarios presented and characterized.

| Classes | Accuracy class | Application scenarios | Architecture | Required infrastructure | Accuracy | Coverage | Frame rate | Update rate | Latency | Number of subjects | Scalability | Computing power | Power supply | Output data |
|--------------|------------------------|---|--------------|-------------------------|----------|----------|--------------|--------------|---------|--------------------|-------------|-----------------|-----------------|------------------|
| OIPS Class 1 | 1 | Automation in production lines | outside-in | markers | < 5 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | medium | low | active | xy position, ID |
| | | Identification work station | outside-in | markers | < 10 cm | < 1 m | < 15 fps | periodically | < 1 s | ≥ 50 | low | low | active | xy position, ID |
| | 2 | Inventory management | outside-in | markers | < 10 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | | Quality assurance (Reduction of picking errors) | outside-in | markers | < 10 cm | < 1 m | < 15 fps | periodically | < 1 s | ≥ 50 | low | low | active | xy position, ID |
| | | Automatic goods recognition at arrival | outside-in | markers | < 50 cm | < 5 m | < 15 fps | event-driven | < 1 s | ≥ 50 | low | low | active | xy position, ID |
| | 3 | Component search | outside-in | markers | < 50 cm | < 10 m | < 15 fps | on request | < 1 s | ≥ 50 | high | low | passive | xy position, ID |
| | | Digital twin of factory | outside-in | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | | Operation optimisation | outside-in | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | | Tracking of material flows, load carriers or parts | outside-in | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | 4 | Access control | outside-in | markers | < 100 cm | < 5 m | < 15 fps | periodically | < 1 s | ≤ 10 | low | low | active | undefined |
| | Optimisation of routes | outside-in | markers | < 100 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≤ 50 | medium | low | passive | xy position, ID | |
| OIPS Class 2 | 1 | Automation in production lines | outside-in | none | < 5 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | medium | high | active | xy position, ID |
| | | Identification work station | outside-in | none | < 10 cm | < 1 m | < 15 fps | periodically | < 1 s | ≥ 50 | low | high | active | xy position, ID |
| | 2 | Intelligent tool control | outside-in | none | < 10 cm | < 1 m | < 15 fps | event-driven | < 1 s | ≤ 10 | medium | high | active | xyz position |
| | | Component search | outside-in | none | < 50 cm | < 10 m | < 15 fps | on request | < 1 s | ≥ 50 | high | high | passive | xyz position, ID |
| | 3 | Digital twin of factory | outside-in | none | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | high | active | xy position, ID |
| | | Operation optimisation | outside-in | none | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | high | active | xy position, ID |
| | | Route inspection | outside-in | none | < 50 cm | < 5 m | < 15 fps | event-driven | < 15 s | ≥ 50 | high | high | passive | xyz position |
| | | Tracking of material flows, load carriers or parts | outside-in | none | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | high | active | xy position, ID |
| | 4 | Access control | outside-in | none | < 100 cm | < 5 m | < 15 fps | periodically | < 1 s | ≤ 10 | low | high | active | undefined |
| | | Anti-theft protection | outside-in | none | < 100 cm | < 1 m | < 15 fps | periodically | < 1 s | ≤ 10 | low | high | active | undefined |
| | Optimisation of routes | outside-in | none | < 100 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≤ 50 | medium | high | passive | xy position, ID | |
| OIPS Class 3 | 2 | Navigation and localisation of mobile robots | inside-out | markers | < 10 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≤ 10 | high | low | passive | xy position |
| | | Digital twin of factory | inside-out | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | low | active | xy position, ID |
| | 3 | Tracking of intralogistics transport vehicles | inside-out | markers | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≤ 10 | high | low | passive | xy position, ID |
| | 4 | Optimisation of routes | inside-out | markers | < 100 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≤ 50 | medium | low | passive | xy position, ID |
| OIPS Class 4 | | Intelligent tool control | inside-out | none | < 10 cm | < 1 m | < 15 fps | event-driven | < 1 s | ≤ 10 | medium | high | active | xyz position |
| | 2 | Navigation and localisation of mobile robots | inside-out | none | < 10 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≤ 10 | high | high | passive | xy position |
| | 3 | Digital twin of factory | inside-out | none | < 50 cm | < 10 m | ≥ 15 fps | periodically | < 1 s | ≥ 50 | high | high | active | xy position, ID |
| | 4 | Anti-theft protection | inside-out | none | < 100 cm | < 1 m | < 15 fps | periodically | < 1 s | ≤ 10 | low | high | active | undefined |
| | Optimisation of routes | inside-out | none | < 100 cm | < 5 m | ≥ 15 fps | periodically | < 1 s | ≤ 50 | medium | high | passive | xy position, ID | |

Fig. 2. Optical indoor positioning system (OIPS)-application scenarios and their characteristics

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