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Procedia CIRP 104 (2021) 671–676

www.elsevier.com/locate/procedia

54th CIRP Conference on Manufacturing Systems

Real-time locating systems (RTLS) in future factories: technology review, morphology and application potentials

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Abstract

Real-time location systems (RTLS) allow a spatial and time related tracking of objects in their environment. An increasing number of technologies and providers are available nowadays. Besides applications in e.g. healthcare and general logistics, RTLS bear also interesting potentials in context of factories. Some manufacturing related use cases can already be found in research and industrial practice. While overcoming an isolated perspective on single solutions, this paper aims at providing a structured overview and common understanding on technological potentials and challenges. Based on that, a systematic design of RTLS based solutions is enabled.

Keywords: real time location systems, RTLS, industry 4.0

1. Introduction

The increasing digitalization in manufacturing - often connected to terms like Industry 4.0, smart manufacturing, or industrial internet – is a topic of strong relevance in industry [1]. This (r)evolution goes hand in hand with the implementation of technologies in the context of the Internet of Things (IoT) in industrial settings [2], typically referred to as the Industrial Internet of Things (IIoT) [3]. IIoT is strongly characterized by the interconnectivity of industrial equipment and the collection and transparency of data across all levels and processes within a factory [4]. Based on advanced digital models an improved decision support for humans or even direct control of machines is enabled [5].

Within the IIoT paradigm, real-time information about the location of different factory objects is an important component that enfolds manifold application fields [6][7]. The typical approach to localize unique objects in an environment is tracking technology [9]. Current systems that track individual (moving) objects are called Real-Time Locating/Location Systems (RTLS, this paper will stick to this term) or Indoor Positioning Systems (IPS). Figure 1 gives an overview of the functional principle of a RTLS.

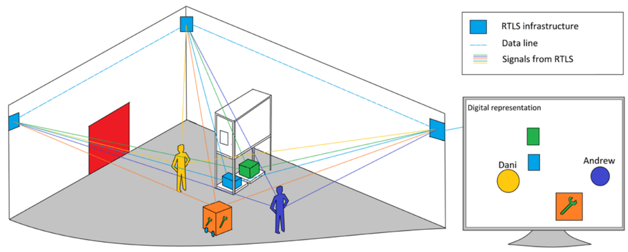

Fig. 1. RTLS functional principle

This work strongly focuses on tag based RTLS that typically makes use of Radio Frequencies (RF) to determine the relative location of a tracked object (equipped with a tag) with respect to multiple so-called 'anchors' within a grid. Besides

10.1016/j.procir.2021.11.113

transmitting the location (coordinates) of an item, more data such as temperature or status can be sent to the system [9]. Fundamental RTLS principles and appropriate technologies and algorithms are well established. Also, many use cases for RTLS in diverse domains can be found in research and practice, ranging from sports (e.g. tracking of players) via hospitals (e.g. position of beds/patients/doctors) to warehouses and factories.

This paper focuses on RTLS applications related to manufacturing. Documented solutions in this domain are typically quite case specific descriptions. This impedes comparison of use cases as well as a systematic development and implementation of new solutions for factories. Against this background, this paper aims to provide common understanding and a guiding framework for defining RTLS related use cases. This framework is based on a review of available technologies but also on a connection matrix as base for a structured description of use cases.

2. Technical Background

2.1. RTLS architecture and components

This paper mainly focuses on tag based RTLS which typically consist of two main parts as shown in Figure 2: a set of hardware that collects and communicates the data to a central IT system (typically called location engine/LE) that interprets the data and prepares it for further applications [9] [10]. To provide a reliable location of the tags within the multidimensional environment, anchors are placed at known locations and ideally the tag can receive strong signals from several anchors for tracking. Tags are available in different variants in terms of geometry, power supply and sensoring capabilities. Depending on those specifications, tags can be attached to any factory object, such as machines, logistic elements (e.g., fork lifters, automated guided vehicles/AGV), raw materials and/or (semi-)finished products as well as humans (e.g., operators, visitors).

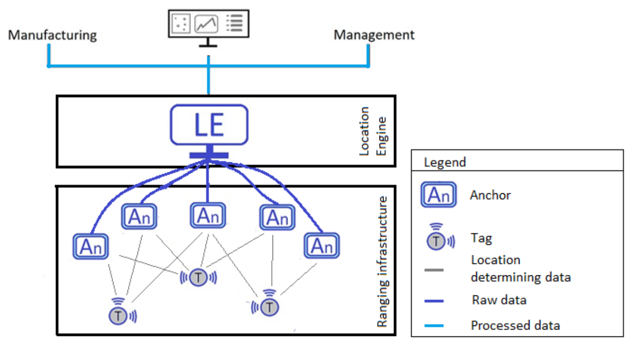

Fig. 2. RTLS architecture with typical components and connection to applications in manufacturing/management

The data gathered through tags and anchors is fed through a network to the LE, which interprets the measurements to determine the real-time location of an object in the grid [11]. The LE can only accurately determine the location of tags within the fixed layout/space given by the anchors [12]. Most LEs are programmed and designed to track objects in a two-dimensional environment. This 2D environment consists of X, and Y coordinates. There are, however, products that can track in a three-dimensional environment.

Along this general architecture, numerous specific example systems can be found in research but also in industrial/commercial practice. Those differ regarding the type of tags and anchors, used communication protocols but also embedded algorithms for localisation. The communication between the tags and anchors is where there is much variance between manufacturers of RTLS systems [9] [10]. Some overview on this is given in the next sections.

2.2. RTLS positioning algorithms

Radio-frequency technologies and protocols facilitate multiple types of algorithms to calculate the position of tags within a grid of anchors (a comprehensive overview can be found in e.g. [9]). The algorithms mentioned are the most used, some manufacturers also make use of combinations.

- **Angle of Arrival (AoA)**: Calculates the angles to transmitters or receivers through directionally placed antennae. When the angle of the signal from a blind node is calculated to two receivers, the location can be determined. To accurately measure angles throughout an entire factory, many receivers are needed. Increase in accuracy also leads to an increase in costs [15], the resulting angle measurements are sensitive to multipath propagation which is common in buildings.
- **Time of Flight / Time of Arrival (ToF / ToA)**: ToA systems register the time when a signal is dispatched and when a signal arrives at the receiver. The time is taken from dispatch to receiving multiplied by the speed of light yields the distance to a node. When this is performed from three nodes it yields a location [9] based on the time taken to receive the signal from the anchors or the tag. This relates it to a distance from the anchors. With three distances, the position can be known. The accuracy achieved is around 1 to 2 meters, and a three-dimensional tracking can be realized by combining sets of receivers and location engines [10]. The disadvantages are caused by the expensive accurate clocks, the signal can also be disturbed by noise or other frequencies depending on the communication technology used [10].
- **Time Difference of Arrival (TDOA)**: ToF measures the time that a signal travels from tag to the receiver. The TDOA algorithm uses a signal that is sent simultaneously from multiple anchors, the difference in time of reception of this signal is measured. The method is very similar to TOA, yet it calculates the time difference in the synchronized clocks between all anchors and the tag. This is a method that is can be very accurate when UWB technology is used as a communicating platform. The system also has the same drawback as ToF, requiring very accurate clock times.
- **Received Signal Strength Indicator (RSSI)**: The Received Signal Strength (RSS) is the most basic method for indoor range finding [11]. With the RSS technique, the distance between a tag and a receiver is estimated by the signal strength of different receivers. The technique and implementation are very simple and cheap but prone to

electromagnetic noise and shows poor accuracy with NLOS (non-line-of-sight) situations.

- **Symmetrical Double Sided Two Way Ranging (SDS-TWR)**: The two-way ranging principle is called two-way since signals from the anchor, received by the sensor are sent back to the anchor. The time it takes for the pulses to 'travel' is used to calculate the distance between sensor and anchor. Through repeating that for multiple anchors, the exact location can be determined. This technique has high precision and stability but typically at higher unit costs.
- **Phase Difference of Arrival (PDoA)**: An anchor with two antennas sends signals to the object, the phase difference between both antennas can be used to calculate the sensor's position. The system can handle the real-time location of many objects and it can be implemented in restricted infrastructures.

2.3. RTLS communication protocols

As of 2020, RTLS systems based on Wi-Fi, UWB, BLE (Bluetooth Low Energy), RFID, GPS, or a combination of those systems can be found. Each of the technologies has advantages and disadvantages. These are briefly described below, more details about the localization/positioning methods are given in the section afterwards.

- **UWB** (Ultra-wideband) technology is a broadband technology that utilizes frequency bands with a bandwidth of 500 MHz at a minimum, thus preventing interference with other radio-frequency systems. UWB technology facilitates high accuracy tracking but at higher unit costs [15]. UWB can be used in various methods to locate the tag within the grid. Some manufacturers use a combination of AoA, TDoA, ToA, PDoA, and TWR to find the position of tags [9]. The high bandwidth associated with this technology allows to have a higher resolution in timestamp signals. Therefore, multipath (e.g. interferences caused by signal reflections leading to multiple signals) is detected more reliably. While accuracy decreases when multipath is present, UWB is the least prone to this effect [16].
- **Wi-Fi** is a common technology to facilitate indoor positioning [13], [9]. Wi-Fi can be used to determine the location of assets using several localization methods (e.g. AoA, ToA, RSSI) [9],[14]. Although most Wi-Fi networks are not intended to function as anchors in a ranging infrastructure, they can be used as such so Wi-Fi RTLS [15]. This can, however, limit the accuracy [9].
- **Bluetooth** (e.g. BLE/Bluetooth Low Energy) uses the same frequency range as Wi-Fi [15]. The underlying technology only facilitates RSSI positioning technology. However, with Bluetooth 5.1 directional information such as AoA and AoD can also be provided [15], [17].
- **GPS** (Global Positioning System) is a technology that uses signals sent by satellites to acquire the position of an object. Signals from at least three satellites are needed to locate the position of an object. However, this method works best with a clear line of sight toward the satellites. This makes it less usable in an indoor setting [13]. Given those characteristics, GPS with its underlying technology is certainly quite different compared to other approaches but also opens up other use cases. This includes applications with larger spatial scope even outside the factory limits. For the sake of comprehensiveness and comparison it will be considered here as well.
- **RFID** (Radio-frequency identification) is a system that uses a combination of scanners to find the proximity of a tag. Only this is not a long-range technology [15]. It is a technology that requires close contact between scanner and tag (<1 m for passive tags). Furthermore, the location of assets or people can only be found at the time instant they are scanned. However, in combination with other technologies the technology can be very useful to find the location of smaller assets, yet there are major drawbacks to this technology since RFIDs can be falsely scanned or the location of a tag can be mistaken due to multipath [18].
- **5G** is the so-called 5th generation of digital wireless communication systems based on cellular network in distinct geographical areas. 5G supports high data rates of up to 10 Gbit per second and a latency of less than 1mS [4]. While being way more powerful than previous cellular networks, advanced real-time applications for manufacturing and beyond are enabled.

Figure 3 provides a qualitative comparison of the different communication protocols (mainly related to references [10]-[15]) which is related to potential use cases in an indoor factory setting. The comparison is based on different criteria which are introduced in the following.

- **Range** is referring to the spatial limitations given through the tag/anchor interactions. While BLE and (passive) RFID are working in distances below a meter to several meters, Wi-Fi and UWB are operating with distances of up the 150-200 meters. 5G (based on general communication network cells) and even more GPS (based on satellites) do not operate with typical local anchors in the factory itself and can theoretically cover long range distances.
- **Positioning accuracy** is also quite different among the communication protocols and of course strongly depends on specific implementation and boundary conditions. While UWB is considered as being able to show accuracies of 0.5 meter, Wi-Fi, BLE and 5G are less accurate (values reported somewhere around 1-5 meter). Current commercially available Navstar GPS provides the worst accuracy with typical deviations around 2-10 meter. However, it is technically capable to be much more accurate, but the signal is actively and purposefully limited for non-defense usage. Next GPS generations like Galileo will also support higher accuracies.
- **Use of existing infrastructure** refers to synergies with existing/other non RTLS-specific infrastructure. GPS and (if available) 5G do not need a dedicated RTLS infrastructure, Wi-Fi is also often available. The other technologies need dedicated hardware components [15].
- The use of the stated RTLS technology in common **consumer devices** such as smartphones potentially enables RTLS to use these devices for RTLS related use cases. While UWB are not standard features yet in those devices, Wi-Fi, GPS, and Bluetooth are normally available. However, stronger availability of UWB

technology and also 5G in smartphones can be expected in the near future.

- **Indoor usability**: satellite-based GPS is the only technology that is not suitable for indoor positioning as it needs a clear line of view to the satellites. All other technologies are well suited for indoor use.

As indicated, the specific realisation depends on the selected technology provider and individual boundary conditions. Recent research work states that the licensed bands like Wi-Fi, Bluetooth will in future not be enough to use data originating from all IoT devices in a factory due to capacity, latency and interference [4]. Therefore, usage of 5G is proposed since it is less prone to interference and data transmitting abilities are far better than the 2.4 GHz band used in Bluetooth and Wi-Fi [4].

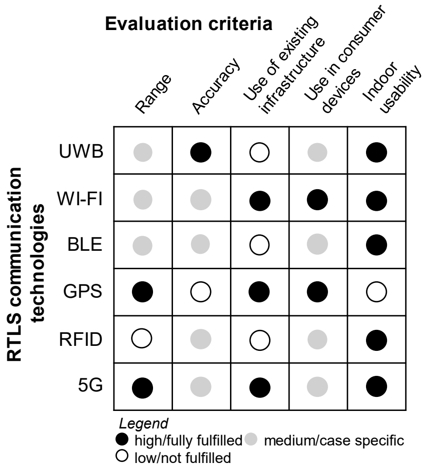

Fig. 3. Qualitative comparison of RTLS related communication protocols

2.4. RTLS Architecture Morphology

The review of the technologies and algorithms underlines the large variety of RTLS setups that actually also can be found in both research and industrial practice. To support the systematic configuration for manufacturing, Figure 4 provides a simplified RTLS morphology. In combination with the specific benefits and drawbacks of the solution elements and the requirements of the intended use case with its application environment, meaningful setups can be identified.

configuration items ▼	solutions elements (selection) ►					
Basic principle	separate tag	use of smart phones	vision based	…	…	..
Tag power supply	battery powered	external power	rechargeable	passive	..	…
Communication standard	UWB	WIFI	GPS	5G	RFID	BLE
Algorithm localization	Angle of Arrival (AoA)	Time of Flight/ Arrival (ToF / ToA)	Time Difference of Arrival (TDOA)	Receiv. Signal Strength Indicat. (RSSI)	Sym. Double Sided 2-Way (SDS-TWR)	Phase Difference of Arrival (PDoA)
data types	X,Y coordinates	X,Y,Z coordinates	coordinates and time stamps	orientation	temperature,, humidity…	…
Objects of investigation	products/ materials	logistic elements	people	machines	Tools	…

Fig. 4. Simplified morphological box for RTLS configuration

3. Use Case Definition

As described, there are manifold ways to define RTLS based solutions but of course the considered factory case finally determines the specific configuration. This includes the definition of the addressed key performance indicators (KPI, e.g., improvement of transportation time, reduction of stocks), the intended use scenario and users (e.g., planning, operation), the factory objects (see below) as well as the identification of boundary conditions and constraints (e.g., system definition, distances, reliability). Figure 5 underlines this necessary balancing of requirements and RTLS specification towards a technically feasible and beneficial solution.

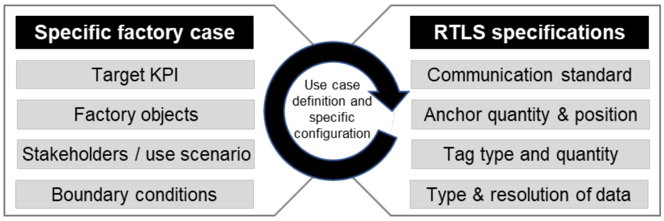

Fig. 5. Use case definition and RTLS configuration

Many examples can be found in research and industrial practice, but those tend to be quite specific and descriptive while not clearly providing an overview of involved objects, technologies, and variables. This impedes comparability and the derivation of most promising but also innovative applications. To address this challenge, a guiding framework is proposed here. Furthermore, structured interviews were conducted among research and industry in order to identify the current and future fields of actions.

3.1. Structured description of RTLS use cases

The connection matrix as shown in Figure 6 brings together the factory elements (with their respective state variables and parameters) and RTLS functionalities. Based on the time stamps, also velocities, trajectories etc. can be gathered. As a simplification of handling the detailed coordinates, an allocation of objects to defined areas of a factory is also possible and often sufficient. Furthermore, all the data points can be stored and used as a base for later analysis, for example to improve object flows within the factory. In terms of factory objects, four categories are distinguished here that all include state variables (describing state of the object) and parameters (defining behavioral/control options). All those variables and parameters might profit from combination with RTLS data:

- **People/humans**: Different stakeholders are working and interacting in factory environments, e.g., workers, maintenance personnel or managers but also visitors or third-party companies (executing certain services). Typical state variables could be operational status (e.g., working, on break) or potentially even health related information (e.g., detected collapse, heart rate). Obviously, these are very sensitive issues and need to be treated appropriately in terms of e.g., data privacy. Parameters are e.g., task allocations or directions that could be provided.
- **Logistic elements** comprise of all equipment that is responsible for transportation purposes in the factory, e.g., fork lifters, automated guided vehicles (AGV) or trucks. State variables could be again operational status (e.g., loaded/unloaded, operating/failure) or additional information like charging level (e.g., for electric AGV).

Typical parameters are related to the navigation through the factory, e.g., next target to go to and related directions.

- **Material and (semi)finished products** depict the value adding material flow through the factory. Typically, these are connected to working orders (with defined workflows and schedules) and it is of strong relevance to know about the current status. RTLS can support here through providing additional spatial information about the exact position or at least the respective factory area. Also, further information e.g., about specific temperatures and order/product properties can be very useful.
- **Machines and tools** are assets that are necessary to run or support operations. While at least larger machines are relatively stationary, tools can be in use in the whole factory and thus location information is relevant. State variables are related to operational status (e.g., in use/available) and parameters could include e.g. operational settings for the specific task.

The integrative view on both RTLS functionalities and factory elements now allows structured description of use cases (Figure 6). This includes the interaction of different factory elements among each other (indicated through color setting).

Factory elements		RTLS functionalities		
	Categories, related state variables and parameter	Provision of coordinates and speed	Allocation to defined factory areas	Analysis of flows with historic data
People	ID/Role	16	5	
	Health status	6 18		
	Directions	8	12	
	Tasks		4	10
Logistic elements	ID			10
	Status	7	14	
	Charge level			
	Directions	9	12	
Materials & (semi) finished products	ID			10
	Order status	1	13	
	Temperature		15	
	Quality status			
	Quantities		2	
Machines and tools	ID	11	17	
	Status (on/off)			
	Maintenance			
	Control Param.	3		

Fig. 6. Structured connection matrix for systematic use case derivation (numbering is referring to the text)

Figure 6 also includes some exemplary use cases derived from publicly available sources like scientific publications or websites from technology providers [19-24], those are briefly summarized here:

1. Tracking of semi-finished products/orders.
2. Monitoring of a factory buffer zone so to avoid overload of incoming material.
3. Tools (e.g. torque wrenches) are adjusted based on their location relative to a product.
4. Staff information when new materials reach assembly line.
5. Mustering of people in terms of emergency situation with checks of proper evacuation of e.g. buildings.
6. Tracking of human accidents (e.g. worker has fallen down)
7. Forklift accident avoidance (collision with worker)
8. Indoor navigation of people (e.g. visitors)
9. Indoor navigation for AGV
10. People, product, or logistic element flow analysis
11. Tracking of assets (e.g. tools) to decrease search time.
12. Virtual geofencing for locking certain areas for e.g. specific persons or logistic elements (e.g. with alarms).
13. Tracking and automatic booking of work orders based on position in factory area.
14. Replacement of paper Kanban cards to control supply
15. Monitoring of quality related timing and zoning, e.g. cold chain control.
16. Visitor tracking to ensure safety and security.
17. Automatic booking of tools when entering specific areas.
18. Pandemic control through monitoring social distancing.

While this is certainly not a comprehensive list, it underlines the manifoldness of applications and the feasibility of the overview. Besides this structuring and documenting functionality, potential new fields of action become visible and an ideation process to bring industrial needs and potential contributions through RTLS together is enabled. There is e.g., interesting potential when it comes to the combination of data from different factory objects and their respective RTLS related data into joint data platforms as base for advanced applications (see also e.g. [25]). Examples for that could be the automatic adaption of tool parameters depending on nearest operator or the automated navigation of persons/tools to critical maintenance situations. However, manifold possibilities can be identified here, and the next question is of course whether the resulting use cases are worth further developments.

3.2. Structured interviews

In order to get a better understanding about the current needs and thoughts from industry and research in the context of RTLS, structured interviews were conducted based on an online form. Two thirds of the participants came from industry (mainly from the Netherlands and Germany) with background from different sectors (with certain emphasis on automotive). With 19 people involved, results are not intended to be representative and might be rather subjective. This is even more relevant since over 90% indicate that they have no or low experience with RTLS. Still, given the share and diversity of industrial participants, the results provide interesting first insights. For more detailed questions, participants were asked to choose whether they are interested graded from 1 (not interesting) up to and 4 (very interesting). Figure 1 shows the results for asking for the most relevant objects to be tracked.

According to that, it turns out that tracking of (semi)finished products and raw materials are seen as most interesting (indicated by high average values and robust distributions), followed by tools. Machines and logistic elements like forklifts and AGVs are following behind but here the results are rather ambiguous when looking at the distributions. Tracking humans is clearly considered as less interesting by the participants.

Figure 8 illustrates the answers on the more detailed question regarding specific use cases. Here, the interest of participants is reflected in terms of which industrial challenged should be addressed through RTLS.

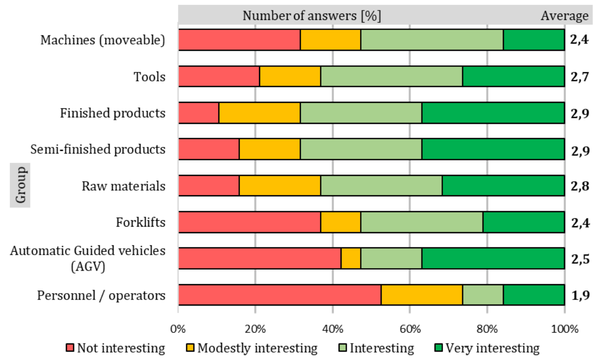

Figure 7: Results for “Which items are interesting for you to track?”

The results confirm the tendencies of Figure 7 with indicating that the tracking and also automatic booking of products/orders are considered as most interesting. But also the tracking and management of tools and other assets is valued high. Another relevant use case is the analysis of factory object flows as base for improvements. According to the results, person related RTLS use cases are not valued very high, just the support in emergency situations reaches at least average values.

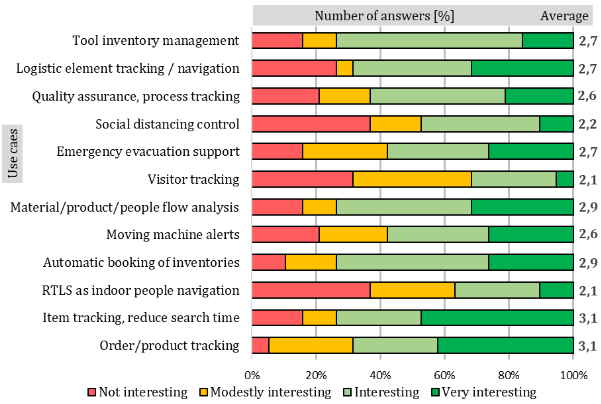

Fig. 8. Results for "What RTLS use cases do you find interesting?"

Altogether, 76% of the participants see high or even very high potential for future manufacturing. Finally, participants were also asked (as open question) what they see as main challenges for RTLS based solutions. Three main areas were indicated:

- RTLS related investment and efforts/costs are critical and need to be brought together with potential savings (does RTLS pays off?). Assessment of economic feasibility is not trivial while effects might be hard to measure.
- RTLS accuracy still needs to be improved. Some of the use cases are critical in terms of safety and operational performance so accuracy needs to be good and robust.
- Data privacy issues e.g. when tracking persons. For establishing those solutions, formalities, and close alignment with e.g. worker unions need to be considered.

4. Summary and Outlook

This paper deals with the usage of tag based real time locating systems (RTLS) in a manufacturing context. Besides giving an overview on RTLS related components, a framework is presented that supports towards common understanding, to structure existing use cases but also to derive innovative new ones. While keeping the general structure this framework could certainly be extended and more detailed in terms of more objects and related state variables and parameters. The presented list of use cases shall rather illustrate the working principle and is certainly not fully comprehensive.

Acknowledgements

The authors thank Gijs Brouwer and Corné Lunshof for their valuable support for literature review and survey preparation.

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