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Robotics – Mobile Robotics and Localization Methods

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ROBOTICS – MOBILE ROBOTICS AND LOCALIZATION METHODS

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LIST OF ABBREVIATIONS

AHRS	Attitude Heading Reference System
AMCL	Adaptive Monte Carlo Localization
AoA	Angle of Arrival
AR	Augmented Reality
B-rep	Boundary Representation
CAAP	Computer-Aided Assembly planning
CAD	Computer-Aided Design
CAEX	Computer Aided Engineering Exchange
CGI	Cell Global Identity
CoO	Cell of Origin
DBMS	Data Base Management System
DHBW	Duale Hochschule Baden-Württemberg (Baden-Wuerttemberg Cooperative State University)
DOF	Degrees of Freedom
EKF	Extended Kalman Filter
E-OTD	Enhanced Observed Time Difference
ERP	Enterprise resource planning
G20	Group of Twenty
GPS	Global Positioning System
HRI	Human-Robot Interaction
IAB	Institute for Employment Research
ICC	Instantaneous Center of Curvature
IMU	Inertial Measurement Unit
IWT	Institut für Wirtschaft und Technik GmbH (Institute for economics and technics GmbH)
LiDAR	Light Detecting And Ranging
LOS	Line-of-sight
LQE	Linear Quadratic Estimantion
PDM	Product Data Management
PID	Proportional-Integral-Derivative
PLM	Product Lifecycle Management
RF	Radio-Frequency
RFID	Radio-frequency identification
RGB	Red, Green, Blue
ROS	Robot operating system

RSSI	Received Signal Strength Indicator
RTT	Roundtrip Time
SLAM	Simultaneous localization and mapping
STEP	Standard for the Exchange of Product Model Data
TDoA	Time Difference of Arrival
ToA	Time of Arrival
VR	Virtual Reality
WiFi	Wireless Local Area Network
XML	Extensible Markup Language

An introduction to driverless robotics and selected applications

B. Eng. Kris Dalm MBA [8]

Keywords:

mobile robotics, industry 4.0, robot navigation, mobile robot application, chair robot

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1 INTRODUCTION

The first part of the paper covers the current state of *Industry 4.0* and explains its meaning. Generally, *Industry 4.0* (or *I4.0*) is an expression that is very popular in the German Industry and stands for the fourth industrial revolution [1]. Moreover, the field of *I4.0* is researched all over the world, but worldwide it is more popular as a part of digitalization and not under the expression *Industry 4.0*. Especially in Germany, the companies are looking for applications where *I4.0* can be realized. There are several reasons for that: firstly, the shortage of skills is a problem that leads to think about new approaches. Already in the year 2003 Reinberg & Hummel (2003) [2] pointed out that Germany could have a longterm lack of skilled workers in the future. Another reason for the reinvention of the industry is the globalization and the following worldwide competition. Therefore, Germany has to automate its industry more to be competitive in a longterm view with the low paid workforce in the eastern countries [3]. Mainly these two regardings force the companies to think about new approaches in case to survive and to be competitive globally. Besides, there are many other reasons like new work, silver society, and some more.

Industry 4.0 is, as mentioned, the forth-industrial revolution. Therefore, there must exist also Industry 1.0 to 3.0. The steps to the forth-industrial revolution are explained in the following part of this paper.

With the first industrial revolution, the industry was born in 1784. At this time, mechanical production machines were introduced and facilities were generated, the first kind of automated mass production was invented. Thereby, the impulsion of the machinery from steam and hydropower, as it can be seen in Figure 1. An example for a machine from this time are looms [4, p. 13].

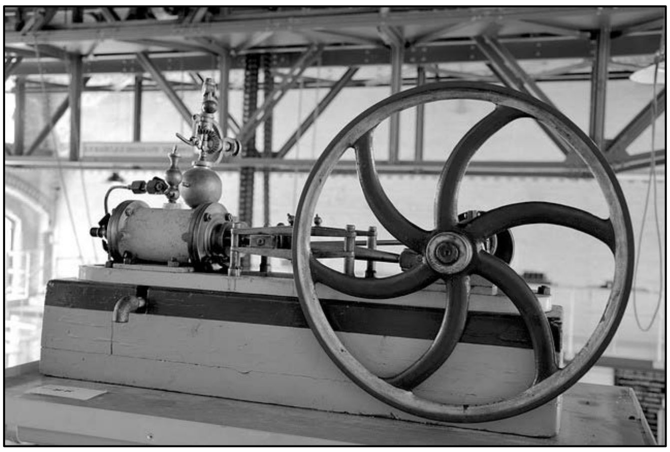

Figure 1: Steam machine[9]

[9] Source: pixabay.com

Then, the second industrial revolution was established in the year 1870. There, productions with production lines were implemented in the factories. Thereby, the impulsion was conducted by electrical energy the first time. That is why the industrial environment could start from this time to produce huge unit numbers. The sectors where *Industry 2.0* was implemented were mainly the automotive industry (see Figure 2) and the food industry, for example in slaughterhouses [4, p. 13].

Figure 2: Transfer system automotive industry[10]

Despite a mass production was already possible because of the already established second industrial revolution, humans did most of the work and machines were seldom. That is why 1969 the third industrial revolution took place in the industry. From this time on IT was a part of productions and the automation caused that more and more tasks were not done by humans, but by machines. Especially tasks where heavy pieces must be moved or monotonous jobs had to be done. This was the first time when PLCs, or programmable logic controllers, came into the production environments and started to do things automatically and to make decisions [4, p. 13]. An example can be seen in Figure 3.

[10] Source: pixabay.com

Figure 3: Electrical installation[11]

Finally, according to Huber (2018) [4, p. 159], the expression *Industry 4.0* was launched in the year 2011 at the Hannover fair in Germany. Since then, many changes happened in the industry and a shift in the kind of working and thinking occurred (see Figure 4).

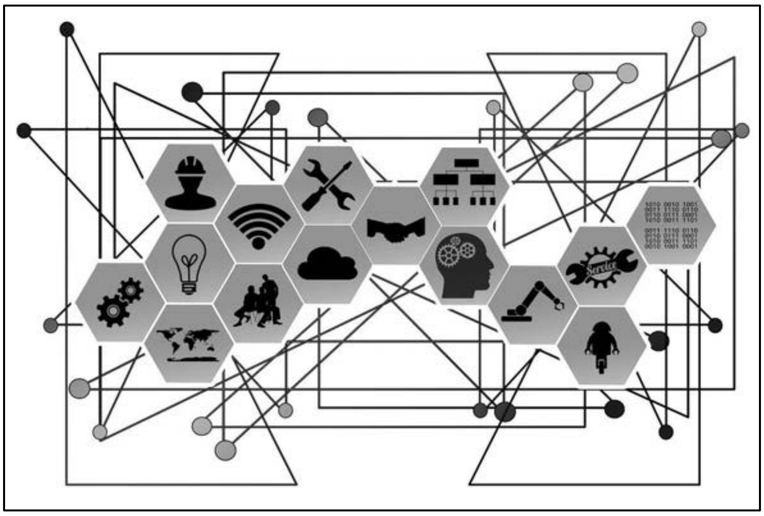

Figure 4: Industry 4.0[12]

To explain *Industry 4.0*, first it has to be said, that an official common definition does not exist. Even the tries of explanations is different from organization to organization. One explanation from a renowned institute in Germany, which is called *Steinbeis*, says that the revolution includes the connection of production technologies with intelligent systems and digital networks. Furthermore, they mention that a connection of the single steps of the value added chain and modern communication techniques play a big role. In addition, Steinbeis explains I4.0 as a combination of communications between human beings, machines and material [5, p. 38].

[11] Source: pixabay.com
[12] Source: pixabay.com

Another well-known German institute that deals with topics from the fourth-industrial revolution is the *Frauenhofer Institut*. They have several departments and one of those is the IOA, or Frauenhofer-Institut für Arbeitswirtschaft und Organisation. In the publication of Spath (2013) [6, p. 2] *Industry 4.0* is described as an area-wide exchange of information and communication techniques and their connection to the *Internet of Things*, services and data, which allows a real-time behavior of the production.

The last German institute that was regarded is *Bitkom e.V.*, which means *Bundesverband Informationswirtschaft, Telekommunikation und neue Medien*. When they talk about *Industry 4.0* in their paper they mention that it means an increasing digitalization, a company overall networking and the tendency to automation and all these topics lead to a huge amount of data [7, p. 10].

The technology of smart robots can be derived from the *Industry 4.0* approach and will be explained in the following chapters of this paper.

2 ROBOTICS

The work tasks of the modern society become more and more automated and the fields of jobs shifts constantly. While 41 percent of the US workforce was employed in the field of agriculture in 1900, the number increased to two percent in 2000. This fall was caused mainly by the introduction of automated machinery and the steady implementation of new technologies [8]. Consequently, a study of the statistics portal statista shows the estimated stock (estimated for the future numbers) of industrial robots worldwide from 2010 until 2020 (see Figure 5).

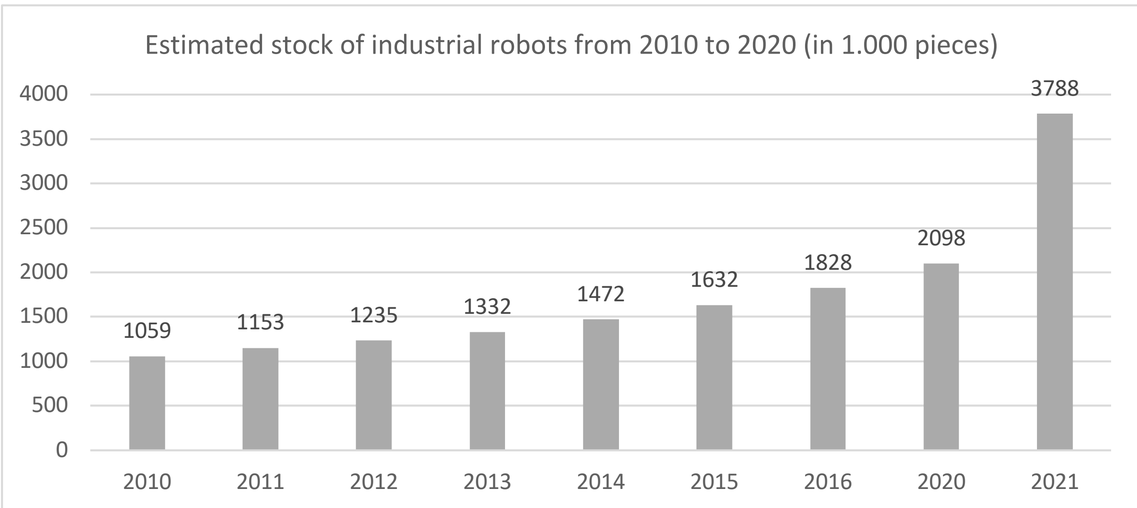

Figure 5: Estimated stock of industrial robots worldwide from 2010 to 2020[13]

[13] Source: de.statista.com/statistik/daten/studie/250212/umfrage/geschaetzter-bestand-von-industrierobotern-weltweit/

The result is that Germany had a robot density of 322 robots per 10.000 employees in 2017[14] in the industrial environment [9] and reached the third position in a comparison of the G20 countries, see Figure 6.

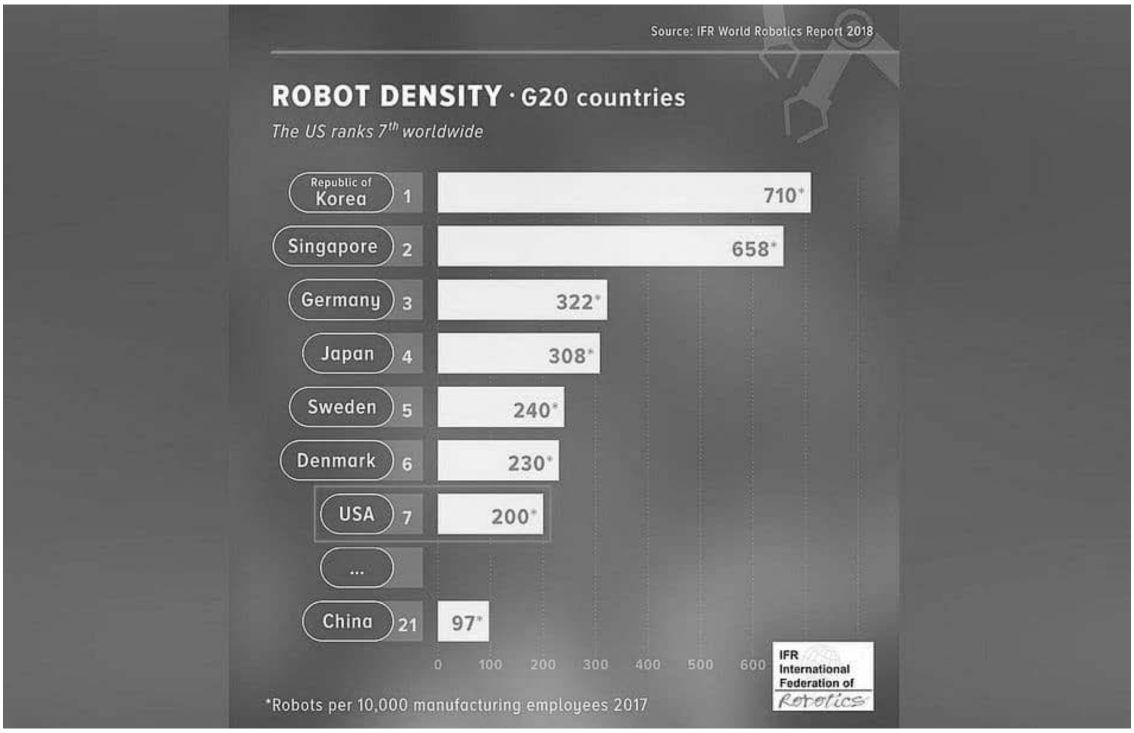

Figure 6: Robot Density of G20 Countries[15]

There are several reasons why robots become more popular. One reason is that human beings do not want to do repeating tasks the whole day; another argument is that they do not want to do awkward tasks. Besides the benefits concerning the support for humans, robots can also increase the quality of products and processes. Therefore, according to Ferraresi and Quaglia [10], the usage of robots has many advantages like high repeatability and the task performance with high accuracy. However, the high accuracy can only be reached if the system is calibrated proberly. When there is a process like gluing, the robot can repeat the process infinitely often with the same accuracy wheras a human being cannot guaranty a constant quality. Furthermore, a benefit by using robots is the flexibility, because they can be used for different task with a small investment of setup time. These arguments and the possibility of avoidance of dangerous tasks like assembling a blade or handling acid are responsible for the increase of robots. That is why robots are predestined for a wide variety of applications.

[14] https://ifr.org/
[15] IFR World Robotics Report 2018

Even now, there are many kinds of robots: drones (flying robots), mobile robots, outdoor robots, industrial arm robots, collaborative robots, human robots, and even modern autonomous cars are kinds of robots.

As the classic industrial robot can move very fast and has a fixed position within a defined area, mobile robots belong to the family of collaborative robots, have many sensors, and no fix position. Collaborative in that case means, the robot can interact with a human being without any physical protections. Thereby, the security is given by the intelligent sensor system. Because of that, the navigation of a mobile robot is always a challenge and needs some complex algorithms in the background.

In this paper, the current state of mobile robotics as well as an example application will be explained. First, the definition of mobile robots is described, followed by a state-of-the-art analysis of navigation methods for mobile robotic systems. Then, a brief comparison of the currently available mobile robots can be seen. Linked to this, a student's project is described where the most suitable mobile robots from the previous comparison are included.

3 DEFINITIONS

According to Hertzberg, Lingemann and Nüchter (2012) [11], a mobile robot is defined as a programmable machine that acts within a closed environment on the base of environmental sensor data. Thereby, during the moment of programming, those environmental parameters are not yet known. Another characteristic of a mobile robot is the fact that it can move free within defined borders. Modern mobile robots usually have no wires and can move without any obstacles on the machine site. The locating process can happen either via environmental sensors or via a digital map, which has to be recorded in advance. In addition, a combination of both approaches is common. In former times, some labels on the floor were necessary or a magnetic path directly under the floor where the mobile robot has to move.

A mobile robot has different sensors, to be able to navigate without accidents in defined areas. There are distance sensors, which simply return the value of the distance to an obstacle. The sensors may be known from cars (parking sensors) where they send a signal in the form of a light. The theory behind this sensor is the measurement of the time of the light, when it is reflected by the obstacle and returns to the sensor [12]. A further mentionable sensor is the LiDAR. With this sensor, horizontal and vertical information can be detected. Thereby, the information is provided with high vertical accuracies and at high spatial resolutions [13].

There are some more or different sensors in mobile robots, but the configuration strongly depends on the developer of the system and the usage.

4 NAVIGATION OF MOBILE ROBOTS

Navigation techniques

One of the main challenges by using mobile robots is the localization because they have to know where they are. This topic is still in a research phase and many methods have already been developed. For example, Sidi, Hudha, Kadir, and Amer (2018) [14] present the modeling of 3DOF tacked mobile robot. In that approach, the control of the mobile robot speed is conducted by a Proportional-Integral-Derivative (PID) controller. Further, MATLAB Simulink Software is used for modeling development. The result of their work is the recognition that the prediction of the tracked mobile robot responses of different parameters works within a simulation.

Another approach in the field of indoor navigation in connection to mobile robots is based on RFID. Panigrahi, Hoda, Sharma, and Goel [15] wrote a paper about wireless control and navigation issues with autonomous mobile robots. Therefore, they have tagged a robot with an RFID reader, an Arduino and ZigBee. The RFID reader has the task to read several RFID tags to recognize, if the robot has changed its direction. The Arduino is the calculator in this scenario and plans the shortest and most efficient path for the robot to move. The ZigBee interface cares about the data transfer. With that equipment on the mobile robot, several tests can be conducted.

Indeed, there are many more localization techniques for mobile robots. However, the obstacle in that area is like in many other technical disciplines: there is no standard defined. The company infsoft GmbH has prepared a document [16], where several navigation methods are listed and described. There are many approaches, with GPS, Wi-Fi, Bluetooth, object recognition via vision methods, and many more.

Use cases of indoor navigation techniques

The systems are used in different areas in several industries. One example is the usage of these technologies in railway stations. The advantages for the passengers is that they can be guided through the railway station by an interaction of their mobile phone and the installed indoor navigation system because usually a GPS signal is not available indoor. As a result, platform changes caused by delays can be handled more easily. Further, the operator of the railway station has advantages because he can evaluate the data, which comes out of the indoor navigation system. Thus, the operator knows when the customers are where in the station and so for example the placement of marketing tools can be installed very efficient.

Another use case of indoor navigation systems are shopping centers. There, the systems are used for influencing the shopping behavior of the customers. With the system, the customers cannot only see the latest offers; there is also a possibility to an indoor navigation too there. For the mall operators the advantage is again the gained data from the system. With the data it can be analyzed the customers' shopping behavior and it can be checked, how long the costumers stay in the food corner of the shopping mall. Further, an evaluation of the number of customers is possible. With that information, an efficient labor planning is possible.

Further, the technique is used already in airports, factories, and many more.

5 MOBILE ROBOT EVALUATION

Some students of the DHBW Ravensburg have done a research work during their studies to evaluate the existing models of mobile robots at this time. The request for that research work was that a mobile robot for research and educational purposes has to be purchased. Initially, they found out that there are 17 designated manufacturers (e.g. KUKA or Omron) as well as start-ups, which offer mobile robots that can be used in industrial environments. Further, it became obvious, that mobile robots are well-developed and the battery at most of the models lasts for more than eight hours, which is mostly the duration of one shift in a facility. The payload starts at 90 kilograms and goes up to 1500 kilograms. The research ended in a comparison of four mobile robots: Innok Hero from Innok Robotics [17], MiR100 from Mobile Industrial Robots [18], MPO-700 from Neobotix [19] and Omron's LD-90 [20], that can be seen in Figure 7.

Figure 7: Mobile Robot Omron LD-90

6 MOBILE ROBOT APPLICATIONS

Mobile robots have many applications in different areas, mostly in the household and in the production environment. Further, a group of students of the DHBW Ravensburg did a research project with the question, if a mobile robot can be used to place and replace chairs. This project will be introduced in the next paragraph and is based on the literature of Dalm & Zull (2018) [21].

According to a study conducted by the Institute for Employment Research (IAB), the current technology can already handle more than 70% of the work in a company. Particularly in the field of manufacturing professions or simple repetitive work, the experts see tremendous potential, which can certainly be further exploited.

However, not only in industry, but also in skilled trades and in the area of event management, the potential of automated guided vehicle systems (or mobile robots) was investigated. It was specifically about the fully automated assembly and disassembly of chairs in rooms and halls.

The first part of the study was to conduct a market analysis examining the need for automated seating. In the second part, the practical part, a modified mobile robot was realized, which automatically takes chairs from a pile and places them accordingly in the room. This scenario was realized not only in the construction, but also in the dismantling of chairs.

<u>Market analysis</u>

In addition to the technical realization of the project, also the economic consideration with the specific issue of a potential market for the application on the program was regarded. Through the research activities, the potential users of the robot could be divided into several groups and fields of application. The first group are trade fair and convention centers, which deal with the seating of visitors. The second group of potential users to be investigated are restaurateurs whose purpose is to furnish premises primarily for celebrations. As other possible users, organizers were identified who also provide rooms for customers or even offer the construction and dismantling of chairs as a service.

By a personalized survey of 350 potential customers, several data points concerning the users and possible cost and automation potentials could be recorded. The evaluation revealed that there is enormous potential for savings, especially in the measuring area, since there the number of chairs is very high, namely up to 2500 daily.

A downstream survey enabled the creation of a business case from the customer's perspective, which makes the potential for automation in euros tangible and thereby emphasizes the time saved. The main drivers for the financial profitability of a seating robot are above all the acquisition costs and the flexibility of use. Actual cost savings can

only be achieved with flexible and easy use. In addition, the depreciation resulting from the acquisition costs directly competes with the hourly rates of the trade fair staff.
Further research into the economics of the mobile robot should still be explored, as the use of the process depends on many constraints (e.g., number of chairs, personnel costs, frequency of seating, etc.).

Technical conduction

At the campus of Friedrichshafen, students of the DHBW Ravensburg have access to a fully equipped learning factory in the Industry 4.0 environment, where technologies ranging from augmented reality to human-machine collaboration are examined. The research facility is an IWT project funded by the Zeppelin Foundation in Friedrichshafen, Germany. It does not only provide equipment, but also supports with experience and expertise. In this specific case, the project was supported by IWT and the final realization of the demo setup was done there.
According to the student project manager, the project is to divide seating robots into three modules. The driverless vehicle system, the software component and the task-specific structure.
The model of the mobile robot was already mentioned (Omron LD-90). This has various sensors for localizing the robot, such as sonar and laser sensors. The mobile robot transmits its position wirelessly to an external tablet.
The support frame for the chairs was designed by the student team. It consists mainly out of square profiles and their connecting elements. One part is firmly mounted on the robot, while another part can be moved vertically in a guide rail. This moving part is moved by a screw jack, which in turn is driven by an electric motor. The electric motor draws its power directly from the mobile robot. Finally, the control unit ensures that the engine and the robot can work together. Thus, the lifting device can be moved and aligned.
The software components are partly provided by the manufacturer, partly they can be obtained from the open source pool. The positioning of the robot was implemented in this case with the software "Mobile Planner", which is a tool from the manufacturer for mobile robots navigation (see also 4). This tool also enables remote access control, which can enable future machining applications.

Figure 8: Mobile robot carrying a chair

For the Baden-Wuerttemberg Cooperative State University and the IWT, the project "Seating Robot" was one of many projects in which the application of smart mobile robot concepts for a wide variety of areas was examined. However, it remains exciting which applications will prevail in the non-industrial sector in the long term.

7 CONCLUSION

With respect to the rising number of robots, estimated up to 3.053.000 in 2021, especially mobile robots become more and more important in the future. The programmable machines that act within a closed environment on the base of environmental sensor data can be operated with different kinds of navigation techniques that were explained in chapter 4. Further, there are different use cases for mobile roboters that can be regarded. Mostly the mobile robots are used in the household, logistics and production environments, but there also possible applications in the field of event management, as a cooperative student project of the DHBW shows in chapter 6. After a market analysis was conducted, they found out, that there is some potential for mobile robots for setting up chairs for an event or a fair and developed a demonstrator. However, there is many potential in the usage of mobile roboters in the industrial environments because nowadays these kinds of robots are autonomous, affordable and flexible. Even at the Hannover Messe, the responsible manager for industrial automation mentioned that robots are an important element of industry 4.0 because they can be used as flexible automation components [22].

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A method of model-fitting with geometric constraint to improve object localization in robotic assembly tasks

M. Eng. Chihpeng Chang [16]

Keywords:

model-fitting, STEP, robotic assembly task, assembly simulation, hole alignment, extrinsic constraint, geometry extraction

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1 ABSTRACT

The trend of massive customized product urges more researches in the direction of making robots more flexible. The visual marker-based localization is a popular and cost-effective solution to make mobile robot more accurate in the indoor application. However, the setup for visual marker is not flexible and requires human to attach and configure the markers.

In this work, a model-fitting and auto-alignment method are proposed to replace visual marker-based localization in the structured industrial environment. It claims that it is unnecessary to extract accurate pose from object localization with accurate camera. Taking advantages of industrial products that there are correspondent 3D models, the geometric relations between components can be easily extracted from the corresponded 3D models in the simulation environment. The result of localization can be corrected by applying the geometric relations. This work shows the advantage of integration with 3D model and assembly expert knowledge, which can reduce the requirement of accuracy of hardware.

The correction of localization is done by structuring the pose errors from object localization in a way that the pose of the latter assembled component always depends on the former component. As a result, as long as the first component is localized accurately, which can be done by using gripper as a locating fixture, the rest of the components can be assembled without accurate camera.

The experiment is conducted in a simulation environment based on Cranfield assembly benchmark for testing the algorithm. The input of the experiment, which is the result of object localization, is generated by adding Gaussian distributed error to true pose in the simulation environment. The experiment is repeated one hundred times to evaluate the influence of error from camera and object localization. Therefore, the false geometric constraints as outliers can be removed.

However, Cranfield assembly benchmark is a simple mechanism. Many industrial assemblies are much more complicated. The proposed method of this work should be further extended with other assemblies. The further application can integrate into ERP or PLM system, where there are collections of many mechanisms.

2 RELATED WORKS

This chapter introduces some field related to robotic assembly task. A survey of object localization with point cloud is introduced in Section 2.1. As an auxiliary for object localization, some works based on extrinsic constraints are presented in Section 2.2. The works in section 2.3 give a brief idea to extract geometric information from 3D model. The section 2.4 is concerned with further extension in the field of computer aided assembly planning are presented.

2.1 VISION-BASED LOCALIZATION WITH POINT CLOUD

This work focuses on industrial environment, where the objects are usually textureless which increases the difficulty to recognize successfully. Depth camera and point cloud have drawn much attention as a potential solution to recognize the textureless and occluded object in the scene.

Hashimoto, Manabu, Shuichi Akizuki, and Shoichi Takei introduced the general concept of object recognition with 3D point cloud data [1]. Some typical works are further introduced in detail and compared. It also introduces a local reference frame, which is an essential factor for accurate pose estimation.

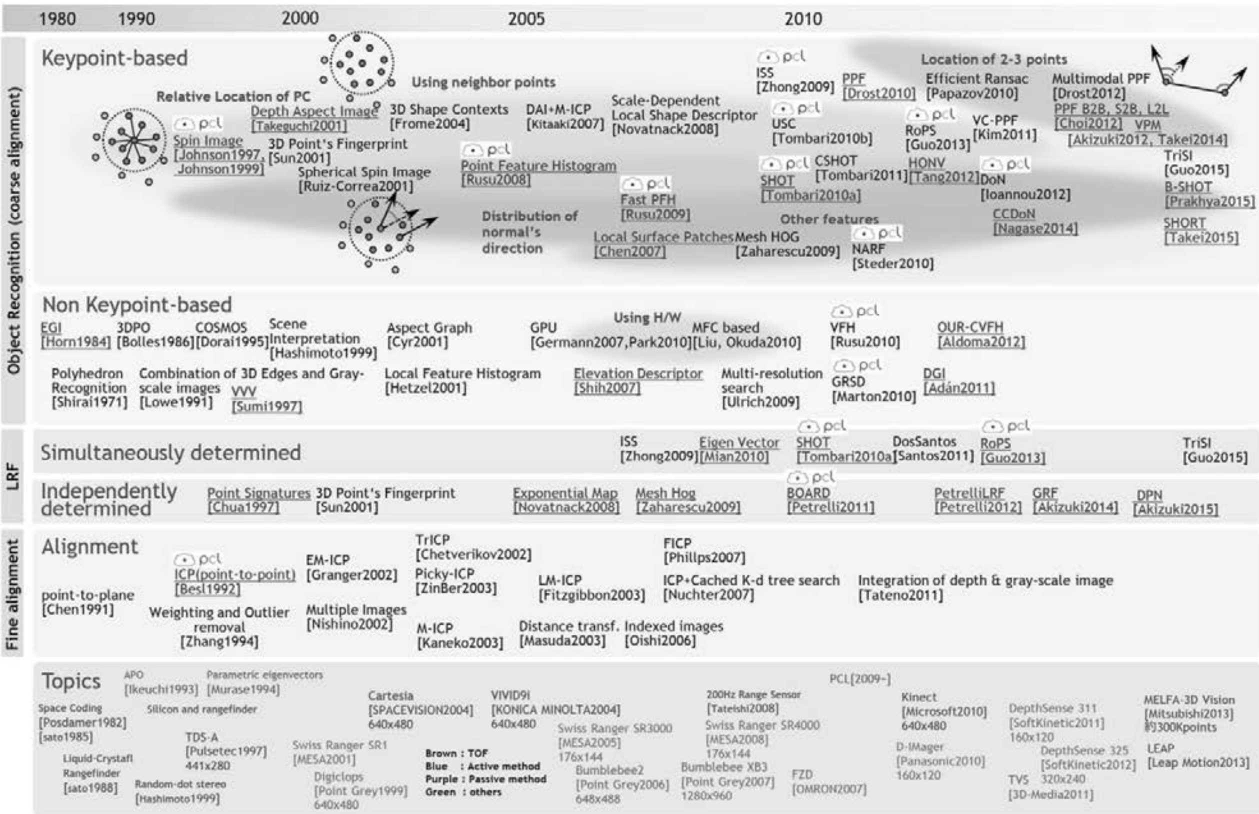


Figure 9: History of researches on 3D features and local reference frame [1]

2.2 OBJECT LOCALIZATION WITH EXTRINSIC CONTRAINTS

Extrinsic constraints are mostly used to improve result of object localization. The pose of object could also be defined by extrinsic constraints cause by adjacent functional units, such as the geometric relation between the objects and their known neighbors.

Wan, Weiwei, et al. (2017) [2] used multi-modal 3D Vision, which fuses RGB images, markers to achieve higher accuracy of object localization in teaching robotic assembly task. In the robot execution stage, it integrates point cloud and extrinsic constraints, which reduces the noise of pose by applying geometric constraints that the contact surfaces of object and table should be parallel to each other.

Wolniakowski, Adam, et al. (2018) [3] compared some methods for gripper design related to correct the error of object localization from computer vision. In other words, with a predefined shape of a gripper, it is used as the same as a fixture. As mentioned in the literature, it is also a field required expert knowledge to design gripper regarding the geometry of the objects. However, it is worthy to investigate further whether there are some commonly used shapes and correspondent grippers.

2.3 GEOMETRY EXTRATION OF 3D MODEL

Malleswari, Valli, and Sarcar (2013) [4] explained in detail how to recognize a cylindrical hole feature and its properties out of string base STEP format. Wang, Yuehong, et al. (2012) [5] proposed an efficient method to detect through both round holes and non-round holes in the mesh file. Automatic recognition of machining features using artificial neural networks (2009) [6] used an artificial neural network to recognize machining feature and transferred the detected machining features to the field of computer-aided manufacturing.

Beside traditional CAD model format, 3D point cloud has also drawn some attention from the researcher because of depth camera became popular. Extending from 2D computer vision, Hough transforms and random sampling consensus was adapted to point cloud for simple geometry shape recognition [7–9]. Aldeeb, Nader, and Hellwich (2017) [7] proposed a method to detect and classify holes in the 3D point cloud. Geometry detection and reconstruction is an expecting technology, which can be further integrated with knowledge from the field of traditional CAD.

2.4 COMPUTER-AIDED ASSEMBLY PLANNING

Computer-Aided Assembly planning (CAAP) has been developed for three decades. It started to decline since the last two decades, because expert knowledge from assembler and human interaction with assembled parts are not taken into account and was substituted by VR and AR [10].

Sierla, Seppo, et al. (2018) [11] presented a product-centric method in assembly planning, which ambitiously attempts to integrate CAD models and PDM/ PLM system. Due to internal format from each software supplier. Detailed information, such as geometric constraint and assembly information, is accessed through the Computer Aided Engineering Exchange (CAEX) by processing string in XML format.

3 THEORETICALLY BACKGROUND

This chapter begins with the introduction of STEP file format in section 3.1 and then go on to basic idea of geometry extraction in section 3.2. Last, a brief example of the hidden expert knowledge of assembling is given in section 3.3.

3.1 STEP FILE FORMAT

STEP file is a standard 3D model exchange format, which is a readable text file and the feature of the model can be easily extracted by simple text processing. It describes the shape of 3D models by defining the boundary of the shape, which is called boundary representation (B-rep).

B-rep is composed of two parts: Topology and Geometry. Topological part defines the structure of shapes and boundaries for the geometries. Geometric part defines geometries of shape with a mathematical equation, such as surface and curve. i.e., A rectangular surface can be defined with point and a normal direction in geometric part and is bound by four lines in the topological part.

With exploring the hierarchy of STEP, the specific geometric feature can be recognized by searching the similar structure that contains the same type of elements. Moreover, the related characteristics can be further extracted, i.e., the endpoints and direction of an edge (line). The structure of STEP is shown in Figure 10.

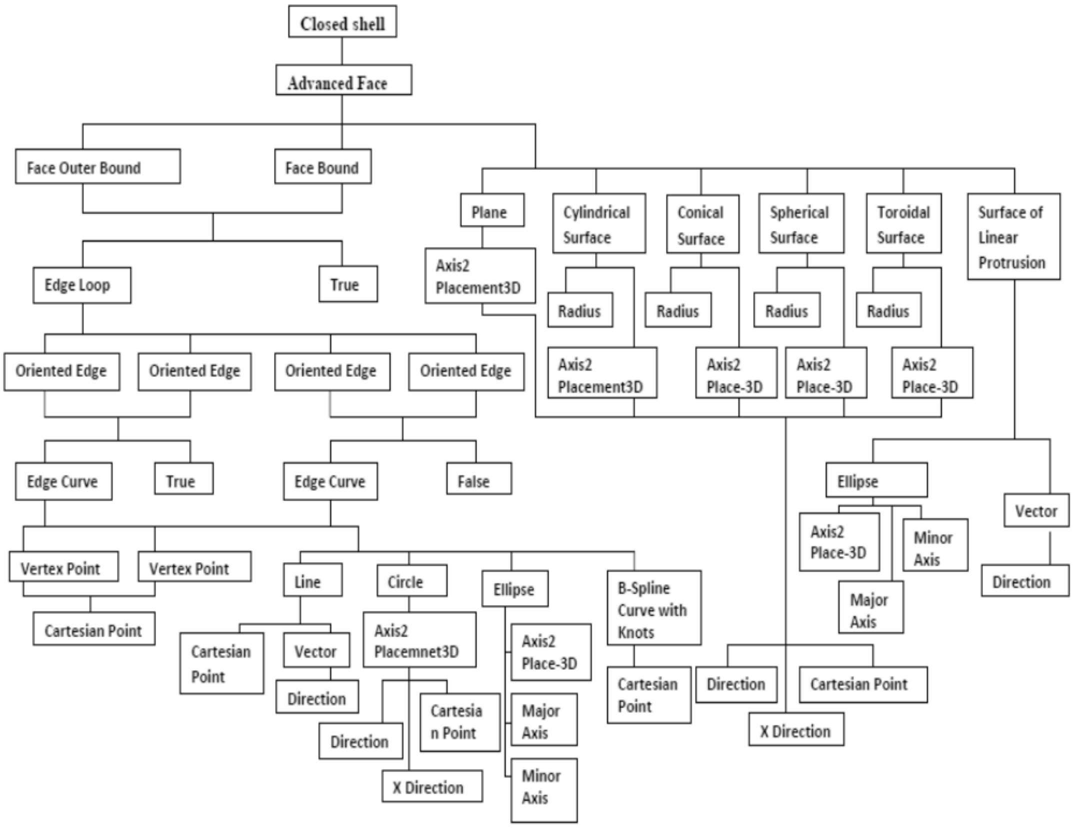


Figure 10: Hierarchy of STEP file [4]

As shown in Figure 11, each element in has its identification number (ID) and contains its properties as well as ID of child elements.

```
#35=CLOSED_SHELL('Closed shell',(#75,#92,#132,#149,#177,………………..#586)); …
#75=ADVANCED_FACE('PartBody',(#74),#40,.T.);
#40=CYLINDRICAL_SURFACE('generated cylinder',#39,50.); #74=FACE_OUTER_BOUND('',#69,.T.) ;
#69=EDGE_LOOP('',(#70,#71,#72,#73)) ;
#70=ORIENTED_EDGE('',*,*,#49,.F.) ;
#71=ORIENTED_EDGE('',*,*,#56,.T.) ;
#72=ORIENTED_EDGE('',*,*,#63,.T.) ;
#73=ORIENTED_EDGE('',*,*,#68,.F.) ;
#49=EDGE_CURVE('',#46,#48,#44,.T.) ;
#56=EDGE_CURVE('',#46,#55,#53,.F.) ;
#63=EDGE_CURVE('',#55,#62,#60,.T.) ;
#68=EDGE_CURVE('',#48,#62,#67,.F.) ;
#44=CIRCLE('generated circl',#43,50.) ;
#53=LINE('Line',#50,#52) ;
#60=CIRCLE('generated circle',#59,50.) ;
#67=LINE('Line',#64,#66) ;
#43=AXIS2_PLACEMENT_3D('Circle Axis2P3D',#41,#42,$) ;
#59=AXIS2_PLACEMENT_3D('Circle Axis2P3D',#57,#58,$) ;
#41=CARTESIAN_POINT('Axis2P3D Location',(0.,0.,0.)) ;
#57=CARTESIAN_POINT('Axis2P3D Location',(0.,20.,0.)) ;
#39=AXIS2_PLACEMENT_3D('Cylinder Axis2P3D',#93,#94,#95) ;
#93=CARTESIAN_POINT('Axis2P3D Location',(0.,30.,0.)) ;
```

Figure 11: Partial STEP file for a description of a cuboid

The elements in STEP contains at most information: ID of child elements, property name, Boolean value, the value of the property

3.2 GEOMETRY EXTRACTION

A certain type of geometry can be easily extracted from STEP file with text and structure pattern matching. For example, the fact that a straight hole contains two half-cylinderical surfaces can be used to find all the candidates of hole, which can be filter out by checking whether the vertex of surface is overlapped with the vertex of another surface that forms a round cylindrical surface.

Figure 12 Example of different description of the same geometry
Default interpretation of a hole from Creo to STEP, which contains two cylindrical surfaces

3.3 MODEL ALIGNMENT IN CAD SOFTWARE

In CAD software, aligning two models requires to assign associated geometric shapes and geometric relation. Geometric shapes could be points, lines, curves, planes, surfaces, axes, coordinate systems and so on. The geometric relations could be coincident, parallel, perpendicular, angle offset, distance, tangent, etc.
The most common assembly constraints are planar alignment and axial alignment. Planar alignment aligns two planes parallelly or coincidently. Likewise, axial alignment aligns two axes to be coaxial. Both planar alignment and axial alignment constrain the orientation of models. The position of models is later assigned with angle or distance offset.

4 METHODOLOGY AND EXPERIMENTS

This works focuses on improving the accuracy of object localization in robotic assembly task, which corrects result of object localization with vision approach by applying geometric alignments. Figure 13 shows that the difference between the scenario of application in the real world and experiment in simulation. The left flow chart is the scenario in real world, which is not implemented in this work. The right flow chart shows the scenario of experiment with fake object recognition in the simulation environment. The algorithm of alignment is independent to result of object recognition, which means if the fake detected pose is real enough, it can reflect the effectiveness of the proposed method in the real world.

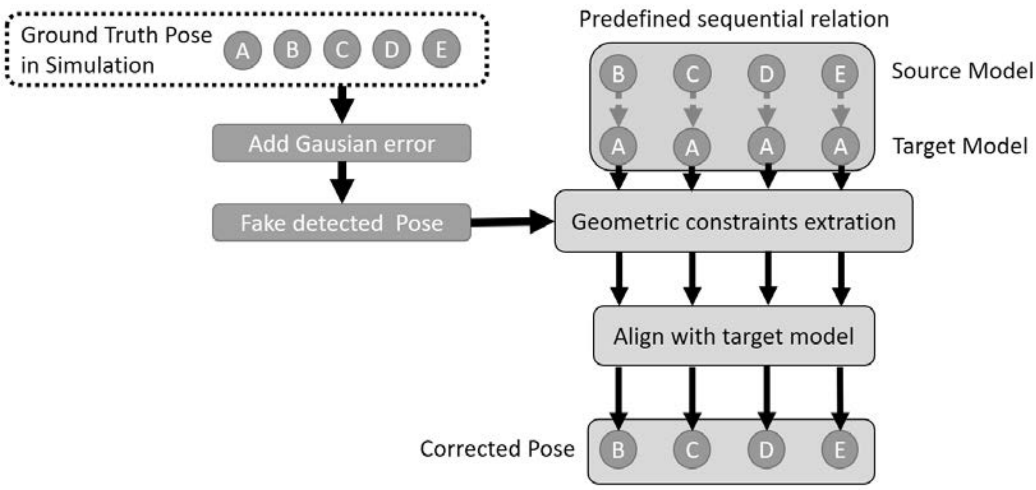


Figure 13 Flowchart of methodology and experiment

The orange blocks simulate the result of object localization by adding gaussian error to ground true pose. The sequential relations, which are CAAP concerned about but predefined in this work, indicates that the prerequisite to assemble the target model before the source model. The blocks in green illustrate the procedure of method proposed by this work, which corrects pose based on geometric constraints which are extracted from results of object localization and sequential relations.

4.1 ALIGNMENT

The procedure of assembling usually begins with restricting the orientation by aligning the planes or axes to be parallel, especially the planes perpendicular to the direction of gravity. After constraining orientation completely, the position of components is constrained by assigning distance between planes or by aligning correspondent screw holes between two components. In this work, models are aligned with the following procedure: gravity, planes and screw holes.

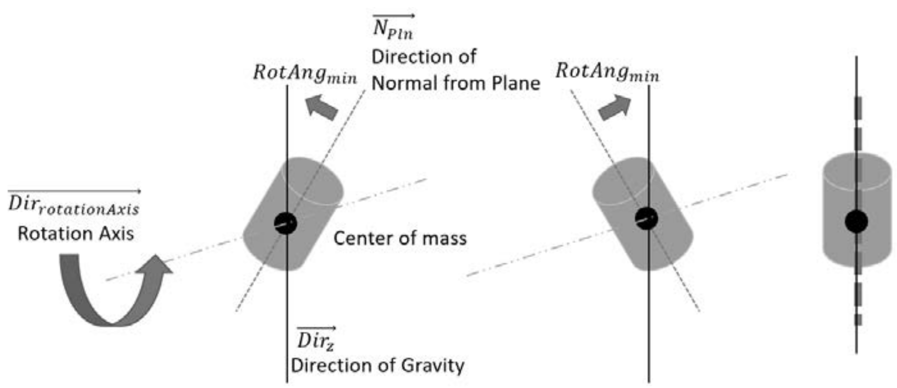


Figure 14: Gravity Alignment
(Left, Middle) Before alignment (Right) After alignment

4.2 EXPERIMENT

The object localization result is required to test the algorithm of alignment. As a substitution to a real camera and object recognition, the fake result of object localization is generated by adding error to true pose. The error is based on [2] with camera Kinect v2 and is listed in Table 1.

Table 1: Experiment configuration of Gaussian distribution error for testing data

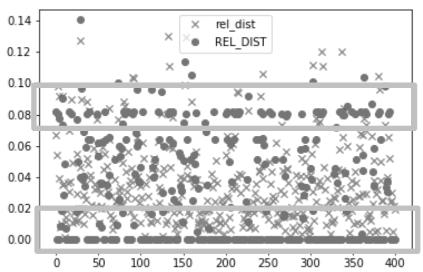
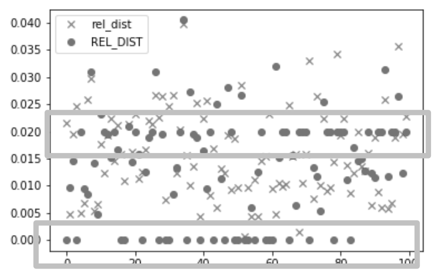
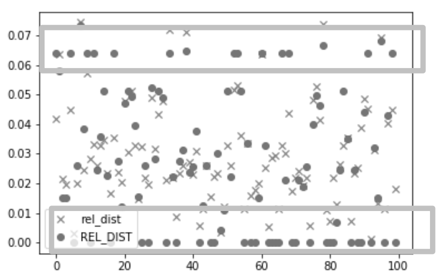
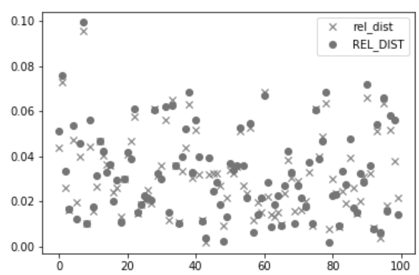
Set	Position error (mean, std) [m]	*Orientation error ((mean, std)) [deg]
1	(-0.01, 0.01)	((30,30), (20,20), (10,10))

**The orientation errors are randomly assigned to roll, yaw, pitch.*

4.3 RESULTS

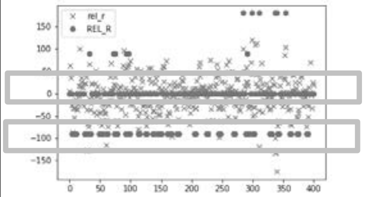
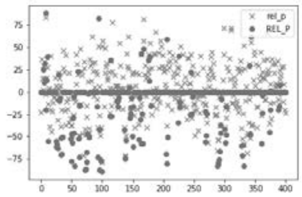
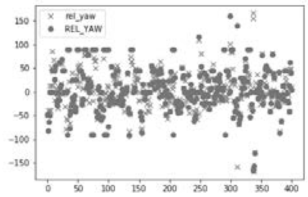
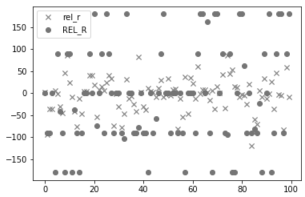
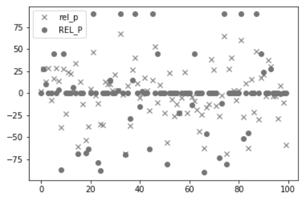
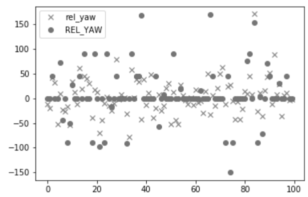
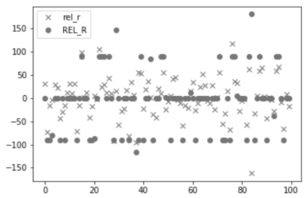
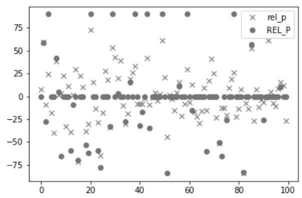
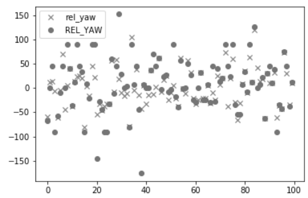
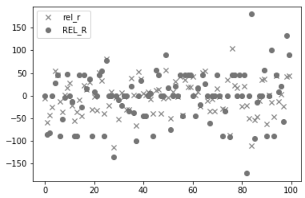
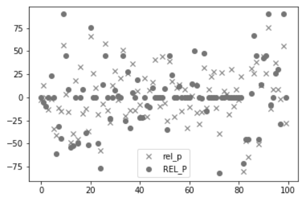
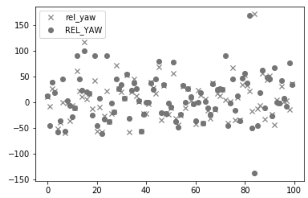
The result of pose error after correction are shown with distant error and orientation error regarding true pose based on the base part from Cranfield assembly benchmark and expressed with the local coordinate system of based part. Consequently, the error that depends on the base part due to alignment is ignored. The result shows that after alignment, the error can be reduced to zero conditionally by filtering out the data with low frequency.

Table 2 Scatter plots of distant error with auto-alignment

Support Pin	Separator
	
Shaft	Pendulum Rod
	

The y-axis stands for distant error in millimeter. The x-axis stands for the index of data. The red cross is the data error before alignment and blue dot stands for the error after alignment. The data within green rectangular has higher much frequenc. Zero error means that the component is aligned with correct geometric feature. The other value with high frequency means than the component is successfully aligned but with wrong geometric feature.

Table 3 Table of figures of scatter plots of relative angular error with auto-alignment

	Roll	Pitch	Yaw
Support Pin			
Separator			
Shaft			
Pendulum Rod			

The red cross stands for the error of orientation before alignment. The blue dots represent the error of orientation after alignment. The horizontal axis represents the index of data, and the vertical axis represents for error of either relative roll, pitch or yaw in degrees. It is obvious that in roll and pitch direction, parts are aligned with a base with certain angles such as 0, 90, 180 degrees.

5 CONCLUSION

In this work, a model-fitting and auto-alignment method are proposed to replace AR-marker in robotic assembly task. By taking advantage of model-fitting, this work follows and applies common procedures that human use to assemble new mechanism: align parts with their planes and holes.

The accurate position related to the target part can be obtained after the successful alignment. The successful alignment heavily depends on how the planes or holes are selected for alignment. On the other side, it also depends on whether position and orientation error result in misalignment.

This work shows the successful replacement of vision-marker approach and make learning stage less dependent on the error of object localization by retrieving position related to the target part after deriving from geometric constraints. With already defined geometry from the object and known error of object localization, it is possible to further eliminate the misaligned positions according to their density in the scatter plot of distance between two local coordinate systems.

However, the algorithm for alignment is only flexible for simple assembly like Cranfield assembly task. Many industrial assemblies are much more complicated. Further integration with assembly planning is required. Moreover, the proposed method of this work should be further developed and tested with other assemblies. For a more systematic solution, further integration with assembly planning and augmented reality is needed.

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Robust localization of mobile robots

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Keywords:
mobile robotics, robot localisation, differential drive robot model, pose estimation, wheel odometry, IMU, LiDAR, sensor fusion, kalman filter

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1 INTRODUCTION

With the introduction of Industry 4.0, automation and data exchange in Manufacturing technologies have reached new heights. Extensive efforts are being made towards creating a safe, ergonomic and smart working environment for the employees. Better collaboration between a human and a robot can reduce the risks and increase the productivity of an industry. To facilitate Human-Robot Interactions (HRI), the robots should drive autonomously in the facility avoiding collisions and planning paths such that they don't interfere with other running jobs. Any autonomous robot system must answer the fundamental question of where it is in the environment? What is its goal? Moreover, how to achieve it?

To answer the above question, it is necessary to understand the kinematics of the autonomous robot, which deals with the configuration of their workspace, between their geometric parameters, constraints imposed in their trajectories. [1] The kinematic equations depend on the geometrical structure of the robot. Once the robot perceives itself, it accommodates in the modelling of its environment with the help of different sensors. After the environment is known to the robot, it has to localise in this environment. For a robot to navigate autonomously toward the goal, it is a must to have an efficient localisation. Currently, localisation is being intensively researched to enhance accuracy and introduced to different sensor fusion techniques for the same. This paper presents one of the most efficient ways of sensor fusion technique to improve the robustness of the localisation.

2 STATE OF THE ART

2.1 MOBILE ROBOTICS

[2] A mobile robot is an automatic machine that is capable of locomotion. [1, 3] The mobile roboticist must understand mechanisms and kinematics, dynamics and control theory to solve locomotion problems. The fundamental conceptual and methodological element developed over the year for the nonholonomic and omnidirectional wheeled robot. Nonholonomic system in physics or mathematical system whole state of depends on the path taken to achieve it. The robot (car-like and car-trailer robots) are known as nonholonomic, i.e.; a robot is subject to nonintegrable equality nonholonomic constraints involving the velocity. In other words, the dimension of the admissible velocity space is smaller than the dimension of the configuration space. Also, the range of possible controls is usually further constrained by inequality constraints due to mechanical stops in the steering mechanism of the tractor [4]. Whereas in holonomic system number of controllable degrees of freedom is equal to the total degrees of freedom.

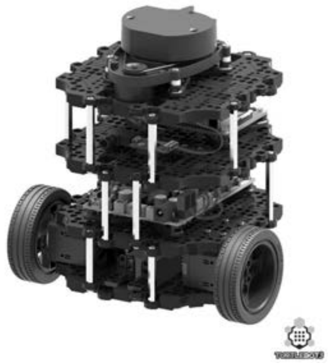

Figure 15: Differential drive robot

Figure 16: Omnidirectional wheeled robot

Differential drive robot is the nonholonomic wheeled robot whose movement is based on two separately driven wheels placed the single axis of the robot. Differential drive robot is the most commonly used robot. By changing the relative rate of motion of its wheel, the robot will change its direction, and thus it does not require an additional steering motion.

2.2 LOCALISATION

[5]Robot localisation is the process of determining where a mobile robot is located with respect to its environment. Localisation is one of the fundamental capability required by the autonomous robot to understand the robot's location in its environment to perform any future task. In the recent trends, probabilistic approaches have taken a leading role in pose estimation of mobile platform owing to its robustness and high accuracy [6, 3]. An extensive study on the use of different sets of sensors is taking place to find an optimal solution to the localisation problem. Keeping in mind the limitation on the usage of computational resources for mobile robots, robust algorithms are being developed which distributes the computational complexity in a network.
To improve localisation, various approaches are proposed in recent years. Radar-based localisation is also under extensive study. Tesla, an electronic automobile manufacturer, has found applications of a Radar based localisation instead of using more expensive laser scanners.

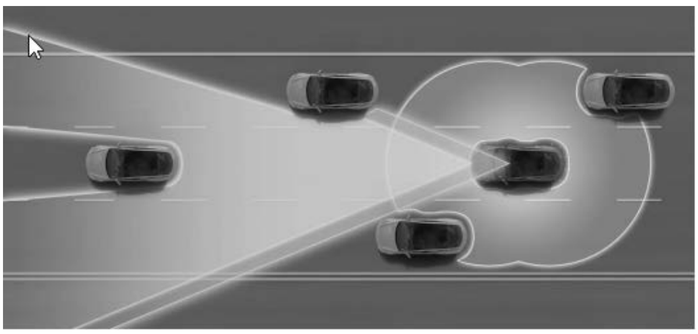

Figure 17: Tesla Smart Radar Technology

An RF (Radio frequency) based indoor localisation estimates the position based on the received signal strength (RSS) in WLAN enabled environment. Furthermore, Bluetooth positioning also uses a similar technology. However, the pose estimates obtained from them is less accurate than wheel odometry, but the data from different sources can be fused to achieve a more precise localisation. There are different sensor fusion techniques to improve the pose estimation, but the Kalman filter [7, 8] is one of the most efficient and common sensor fusion technique. It uses a Gaussian distribution to model uncertainties in the system and can also be further evolved to deal with the nonlinearities in the system.

3 THEORETICAL BACKGROUND

3.1 DIFFERENTIAL DRIVE ROBOT CONTROL

Many mobile robots use the differential drive mechanism, consisting of the two wheels mounted on the same axis and each wheel can independently drive either forward or backwards [9, 10]. It is crucial to understand how to control both wheels at the same time to drive the robot is required direction.

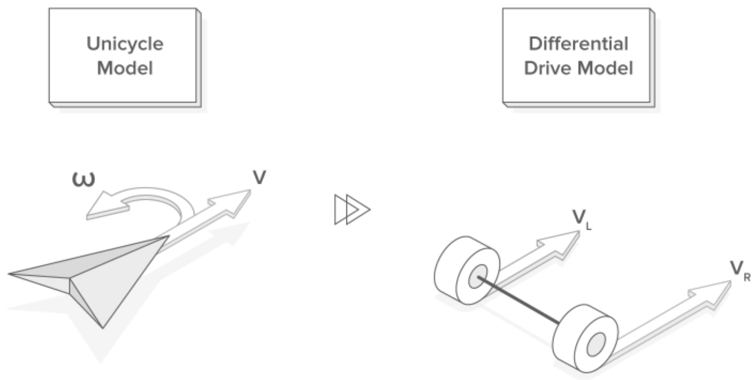

Figure 18: Mobile Robot Model

To illustrate the differential drive robot initially mobile robot is considered to be controlled only using translation velocity v and angular velocity ω this model is known as the unicycle model of the mobile robot [1, 9]. A unicycle type robot is, in general, a robot moving in a 2D world at some position (x, y) and headed in a direction making an angle ϕ with the X axis. The simple non-linear model describes the kinematic model of the unicycle robot [11].

$$\begin{cases} \dot{x} = v \ \cos\phi \\ \dot{y} = v \ \sin\phi \\ \quad \dot{\phi} = \ \omega \end{cases} \qquad (1)$$

For a robot with differential drive, a pair of wheels is mounted on a common axis, and the position (x, y) and heading (ϕ) of the robot are calculated at the centre between the two wheels. In the presence of Angular velocity ω, wheels rotate on the ground (i.e. no slipping) with different velocity form Instantaneous Center of Curvature (ICC). The kinematic equation is derived by considering this condition.

Consider a differential drive robot with the distance between two wheels, L and radius of the wheels are R. The simple non-linear model describes the kinematic model differential drive robot.

$$\begin{cases} \dot{x} = \frac{R}{2}(Vr + Vl)\cos\phi \\ \dot{y} = \frac{R}{2}(Vr + Vl)\sin\phi \\ \dot{\phi} = \frac{R}{L}(Vr - Vl) \end{cases} \tag{2}$$

By solving the equation of both kinematic model of unicycle robot and differential drive robot, right velocity Vr and left velocity Vl are found. v and ω are the control signals.

$$Vr = \frac{2v + \omega L}{2R} \tag{3}$$

$$Vl = \frac{2v - \omega L}{2R} \tag{4}$$

By giving linear and angular velocity, we calculate the respective wheel velocities to control the differential drive robot.

3.2 POSE ESTIMATION

3.2.1 ODOMETRY

Odometry is the most widely used method for determining the momentary position of a mobile robot [12]. This uses the data from motion sensors to estimate a change in position over time. However, pose estimation mainly get affected by three dominant error sources in differential-drive mobile robots: (a) uncertainty about the effective wheelbase (b) unequal wheel diameters and (c) wheel slippage.

The pose calculation is performed by utilising the data from wheel encoders. The starting point is taken as the initial position of the robot and in a differential drive robot, the motion is controlled by two wheels of the robot.

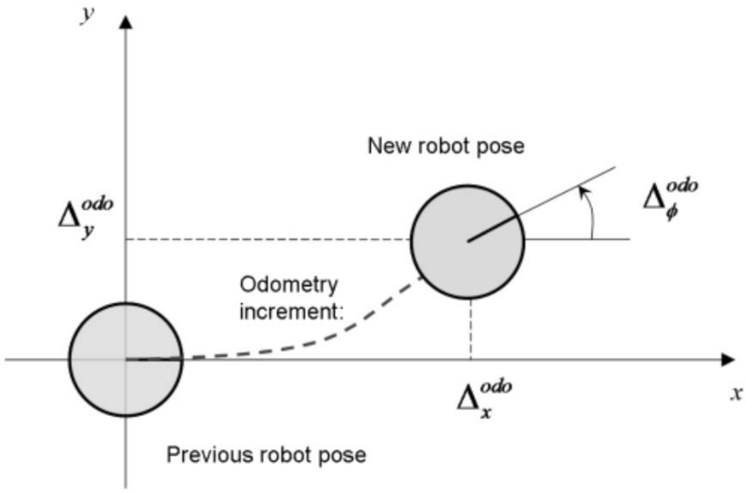

Figure 19: Robot Pose

The two wheels of the differential drive robot mounted on the single coordinate. To steer each wheel is separate power, hence during steering two wheels will rotate at a different speed. The encoder of each wheel will have different values. Differential drive model will give the position of the robot by taking the counter values of each wheel.

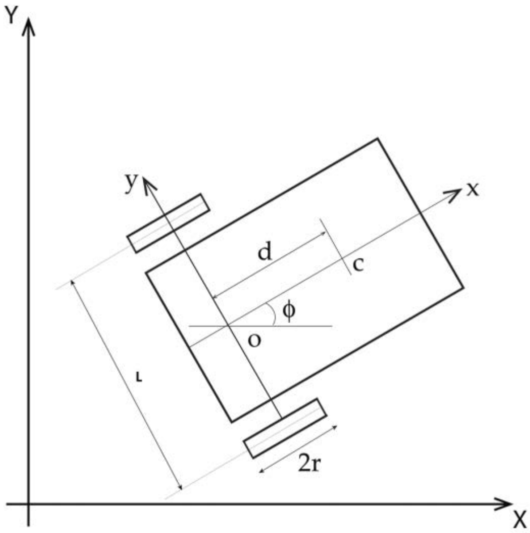

Figure 20: Differential Drive Robot Model

Considering the robot motion is constraints to a 2D plane as shown in the figure. Center of the robot O lies in $x - y$ axis, where L is the distance between two wheels and r is the radius of the wheel. Encoder count for one complete rotation of both wheels is N.

$$D_l = 2\pi r \frac{\Delta tick_l}{N} \tag{5}$$

$$D_r = 2\pi r \frac{\Delta tick_r}{N} \tag{6}$$

D_l and D_r are displacements of the left and right wheel in $\Delta tick_l$ and $\Delta tick_r$ tick in Δt time interval. The ticks are the number of counts obtained from wheel encoder in a time interval Δt. D_c the displacement of the robot and it is given by the equation,

$$D_c = \frac{D_r + D_l}{2} \tag{7}$$

The new pose of the robot in the coordinate system in the given time interval is calculated and updated previous pose.

$$\acute{x} = x + D_c \cos \phi \tag{8}$$

$$\acute{y} = y + D_c \sin \phi \tag{9}$$

$$\acute{\phi} = \frac{D_r + D_l}{L} \tag{10}$$

3.2.2 INERTIAL MEASUREMENT UNIT

An Inertial Measurement Unit (IMU) is a Micro-Electro-Mechanical System (MEMS), which converts the physical changes into the digital data. The module comprising of typically an accelerometer, gyroscope and a magnetometer to measure a body's specific force and angular rate. The 3-axis accelerometer in the IMU is responsible for measuring the linear acceleration in the xyz-direction. The 3-axis gyroscope measures the angular velocities or rotational rates as the pitch-roll-yaw of the body. Some IMU also include a magnetometer which is commonly used as a heading reference. Often this magnetometer needs to be calibrated to justify the magnetic declension in the region. Also, in the presence of external magnetic fields like those from the motors and battery, the measurements from a magnetometer become noisy.

Frequently, an IMU finds its applications in a navigation system to calculate the system's attitude, velocity and position. The data from the accelerometer, gyroscope and magnetometer are fused to estimate the attitude using an Attitude Heading Reference System (AHRS). The attitude estimates are then used to transform the acceleration measurements into an inertial reference frame where they are integrated once to obtain the linear velocity and twice to obtain the position.

The method of integrating the acceleration twice to obtain position has its major disadvantage of introducing a drift in the position. This means that a constant error in the acceleration results in a linear error in the calculation of velocity and quadratic error growth in the position.

The drift can be reduced by utilising Attitude Heading Reference System (AHRS), which is an efficient orientation filter for inertial sensor arrays to determine the attitude and orientation of the body [13]. This filter uses a gradient-descent algorithm by fusing the data from an accelerometer and gyroscope to compute the direction as a quaternion. The benefits of using such a filter are that this filter is computationally inexpensive and effective at a low sampling rate.

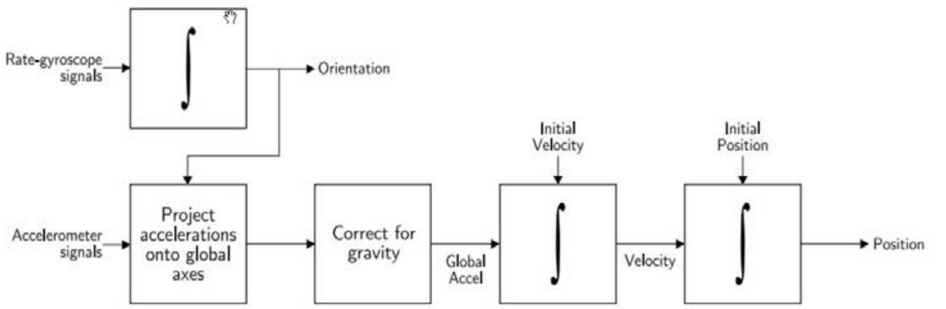

Figure 21: Pose calculation

From the accelerometer, the magnitude and direction of the field of gravity are obtained in the sensor frame along with the linear accelerations from the motion of the sensor. To calculate the orientation of the sensor in the earth's frame, it is assumed that accelerometer will only measure the gravity. To define the orientation, quaternion representation is used than the Euler angles to obtain a complete solution. Since it is an optimisation problem, the gradient descent algorithm is used to estimate the orientation based on an initial guess.

The zero bias for the gyroscope drifts over time because of the temperature and motion. Simple orientation filters can compensate this drift through the integral feedback of the error in the rate of change of the orientation.

Once the orientation of the sensor is found in the earth's frame, the directional acceleration is calculated. The measurements obtained from the accelerometer are rotated with the orientation so obtained from the AHRS resulting in the directional acceleration. The acceleration in the z-axis corresponds to the absolute gravity which can be subtracted. The final values are pure acceleration values across the xyz axes. The acceleration values can be then integrated to obtain the position. Before the acceleration is integrated twice, it is necessary to detect when the object is stationary. This step reduces the drift in the calculation of position by a huge margin because the cumulative integral error becomes significantly less.

3.2.3 DISTANCE SENSOR

LiDAR (Light Detection and Ranging) is the wildly use distance sensor, which utilises the time of flight principle to measure the distance. [14] Ranging information is essential for the robot to navigate. Even if the path of the robot is preplanned, in a dynamic world, it important to consider the obstacle that interferes with the travel of the robot. Obstacle detection is also concerned with the location of the obstruction in the robot's future paths, so that robot can decelerate from a high speed to a stop before it collides with the obstacle. Collision avoidance is also involved with the navigating the robot around the detected obstacle to reach the goal.

Algorithms such as Simultaneous Localisation and Mapping (SLAM) and Adaptive Monte Carlo Localisation (AMCL) [7] utilise the laser scanner data to build the map of the environment and localise its self in the environment by matching the scanned data with the map and will reduce the drift in the odometry pose estimation. Moreover, laser scanner data used alone for pose estimation of the autonomous robot by matching them with a map. However, this method fails when there too my dynamically changing obstacles in the environment.

3.2.4 VISUAL ODOMETRY

Visual Odometry is a well-known process of determining the position and orientation of the robot by analysing the camera images. Extensive research is happening to optimise the process so that the algorithm can be robust and less resource intensive.
Pose estimation using visual aids is based on finding the correspondences between points in the real environment and their 2D image projection. With the use of external landmarks and fiducial markers, the problem becomes less complicated.
A recent studies [15, 16, 17] has shown that with binary square fiducial markers, a single marker can provide enough such correspondences to determine the camera pose.Also, the inner binary codification makes them robust, allowing the possibility for error detection and correction techniques. ArUco marker is the most commonly used fiducial marker for pose estimation. The camera on the robot detects its pose concerning the particular marker, which intern transformed into robots pose in the environment.

3.3 SENSOR FUSION

It is necessary to understand the dominant technique to fuse the positional information from multiple sensor sources to increase the robustness of the pose estimation. Various sensor fusion algorithms are available; however, the Kalman filter is the most commonly used.

Kalman filter algorithm uses mathematical models to estimate unknown state variables despite inaccurate real-time measurements. Kalman filter is broadly a two-step process - Prediction step and an update step.

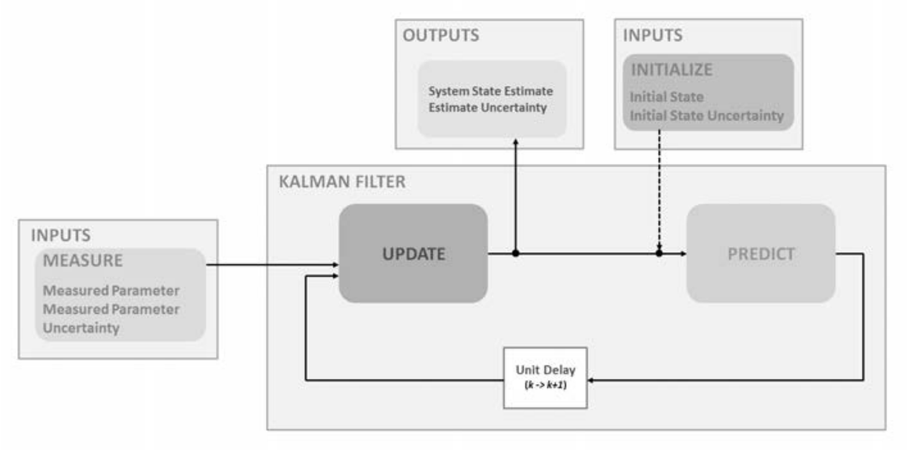

Figure 22: Schematic description of the algorithm

The system model is required to use a Kalman filter for estimating the internal state of the process. The mathematical model of the system is made from state matrices and control matrices. The covariance of the process noise is also needed to be defined. An initial estimate is given to the model, and the filter progresses in estimating the state variables.

A realistic mathematical model for a Kalman filter looks like below:

$$x_k = \boldsymbol{A}x_{k-1} + \boldsymbol{B}u_k + Q \tag{11}$$

$$z_k = \boldsymbol{C}x_k + v_k \tag{12}$$

Where, x_k: state vector at time step k

$\boldsymbol{A}$: State transition matrix

$\boldsymbol{B}$: Control Matrix

u_k: Control vector at time step k

Q : Process noise covariance

$\boldsymbol{C}$: Observation matrix

v_k : Observation noise covariance

Kalman filter is a recursive estimator; the current estimate of the state variable is done based on the estimated previous state and the current measurement. This means that no history of observations or estimates is required. The estimation progresses in two phases - Predict and Update.

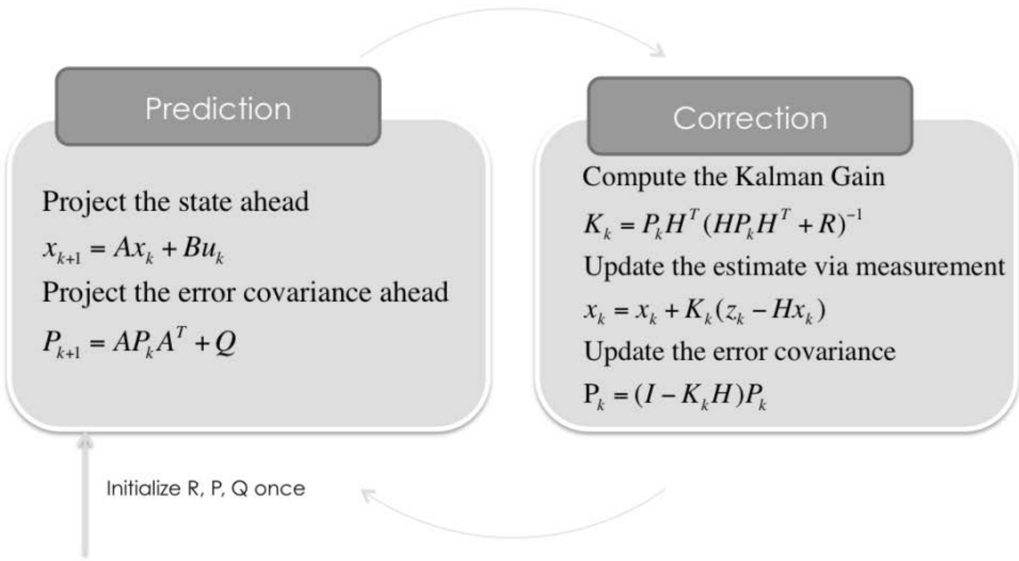

Figure 23: Predict and update

Predict phase: During the predict phase of the filter, a prediction of the state at the current time step is made based on the previous estimate. This is known as an *a priori* state estimate. This prediction does not include the observations made during the current time step.

$$\hat{x}_k = \boldsymbol{A}\hat{x}_{k-1} + \boldsymbol{B}u_k \quad (13)$$

$$\boldsymbol{P}_k = \boldsymbol{A}\boldsymbol{P}_{k-1}\boldsymbol{A}^T \quad (14)$$

Where, $\boldsymbol{P}_k$: predition error covariance.

The prediction error covariance denotes the square mean error in the prediction of the state variable. This error act as feedback to the filter which is corrected in the update phase.

Update phase: After a prediction of the current state is made, the information from the current observations is matched, and the error difference is moderated to refine the prediction previously made. This estimate is then updated, and the process continues with further observations. The improved estimate from the update step is called a *posteriori estimate*.

$$\boldsymbol{G}_k = \boldsymbol{P}_k\boldsymbol{C}^T(\boldsymbol{C}\boldsymbol{P}_k\boldsymbol{C}^T + R)^{-1} \quad (15)$$

$$\hat{x}_k = \hat{x}_k + \boldsymbol{G}_k(z_k - \hat{x}_k) \quad (16)$$

$$\boldsymbol{P}_k = (\boldsymbol{I} - \boldsymbol{G}_k\boldsymbol{C})\boldsymbol{P}_k \quad (17)$$

Where, $\boldsymbol{G}_k$: prediction gain covariance, R : measurement noise covariance.

During this step, the prediction error is corrected with weights. These weights are defined as Kalman gain which is based on the uncertainties from the predictions and measurements. As the filter progresses, the prediction error matches the reduction in covariance from the update step and the filter is considered converged.

For the optimum functioning of the filter, the observation noise and process noise needs to be modelled as accurately as possible. Various methods have been proposed to model the error covariance.

3.3.1 EXTENDED KALMAN FILTER

[8] Kalman filtering, also known as linear quadratic estimation (LQE), the algorithm uses the mathematical model to predict the unknown state variable from noisy measurements.

However, Kalman filter for a nonlinear system is ineffective, to solve this problem of nonlinearities in the system, Extended Kalman Filter (EKF) [7] is introduced. The governing equations for an Extended Kalman filter are similar to the linear Kalman Filter, but to account for the non-linearities, the transition and the measurement matrix are linearised by using the Jacobian of the time derivative.

4 CONCLUSION

Localisation is a vital factor in the autonomous mobile robot to navigate in the environment and perform any tasks. Therefore, the robot must perceive perfect pose by utilising the sensor information. But it is unsafe to rely on a single sensor because they restrained with their drawback for providing more reliable pose estimation. Nonetheless, by fusing the pose estimations from different sensors will increase in the accuracy and reliability in the measurement. EKF will facilitate the sensor fusion for the non-linear system to enhance the robust localisation of the mobile robot in a given environment.

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Discussion of a hybrid method for passive localization of moving emitters

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ABSTRACT

The position of a transmitter, emitting electromagnetic waves, can be estimated by analyzing the arrival time and angle of arrival at a receiver. For example, the transmitter may be a robot in an indoor environment or an active outdoor radar station to be localized. This paper considers the estimation error of the transmitter position when a hybrid localization method in a multipath environment is applied. Hereby, the scenario is generated by a Markoff chain and the propagation paths are modelled by a 2D channel model. In reality, relevant angular and temporal information of the incident propagation paths at the receiver side can be affected by noise which degrades the estimated transmitter position, which is also considered by dedicated simulations.

1 INTRODUCTION

The propagation of electromagnetic waves in the Gigahertz range is affected by the interaction with objects in the environment due to physical effects such as diffraction, scattering or reflection. At the receiver side, the superposition of incident waves from different directions leads to a resulting power. Hereby, the individual radiant power of different propagation paths is weighted by the angle dependent radiation patterns of the transmitting and the receiving antenna. As the receive power depends on the propagation scenario, a channel model is typically used to predict the receive power. Channel models can be based on an empirical, a deterministic or a stochastical approach. Other approaches use the theory of diffraction, or a combination of the above mentioned methods [1-3].

Localization by electromagnetic waves

As already mentioned, multipath propagation occurs when electromagnetic waves emitted by a transmitter interact with objects. Vice-versa, by analyzing these paths at the receiver side, it is possible to estimate the position of the transmitter. This paper considers the estimation of the transmitter position. There are different methods for this purpose [2, 4]. Figure 1 presents a possible classification of selected Radio-Frequency (RF) localization techniques:

- At the left hand side of Figure 1 methods are shown, which involve the analysis of field strengths. Known methods are Beacon and Received Signal Strength Indicator (RSSI).
- A second possibility is based on the analysis of path delays to obtain distances. The figure shows some established methods together with the relevant abbreviations (e.g. ToA, OTD).
- Furthermore, incident angles of the received propagation paths can be used for an analysis. Corresponding methods are Angle of Arrival (AoA) or Triangulation.
- Finally, a combined approach involves both, the estimation distances and angles as a hybrid method.

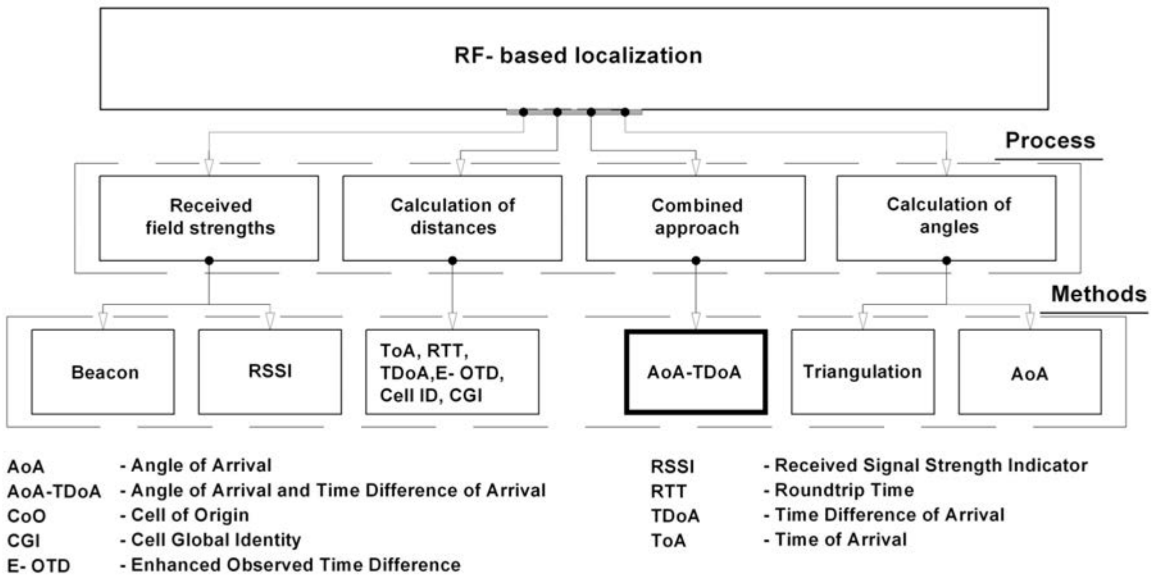

Figure 1: Classification of RF-based localization

Goal of this paper and approach

This paper applies a two-dimensional, geometric-stochastical channel model which has been developed at Tomsk State University of Control Systems and Radioelectronics and at Baden Wuerttemberg Cooperative State University. In a first step, a scenario with random objects is created using a homogeneous, one-step Markov chain. Then, the transmitter and receiver position is defined in a line-of-sight (LOS) scenario, and possible propagation paths based on single reflections are determined. The goal is to localize the transmitter position based on the angular and temporal information of the incident waves at the receiver using a dedicated hybrid method which is presented in more detail in the next section. To consider realistic scenarios, relevant information is affected by noise which reduces the accuracy of the estimation. The results show the proper operation of the analysed localization method. Furthermore, limitations of the approach are shown and an outlook for future work is given.

2 MATHEMATICAL FORMALIZATION AND DERIVATION OF A HYBRID METHOD

This section considers the mathematical background of a hybrid localization method whereas the method can also be used for radiomonitoring. Before presenting the details, a brief overview of its advantages compared to other methods is given:
Localiaztion systems typically use the following principles: a) measurement of delays, b) measurement of incident angle (Angle of Arrival) or c) combination of these methods. To meet given system requirements (e.g., Allen deviation: accuracy, α- error, β- error, calculability, etc.), a well-established approach is the usage of two or three base stations in receive mode for localization purposes. Hereby, certain distances between the base stations are required to meet the specified accuracy. Distances may vary up to several kilometres depending on the application. This requires some dedicated requirements regarding the communication link between the base stations (e.g., secure data transfer). A reduction of the number of receivers would hence be favourable, which would also relax maintenance effort. In the best case, only one base station in passive receiving mode is required.

Such an approach with only one receiver is now considered in more detail: The applied method for localization of the transmitter will be hybrid, hence using information on path delays relative to LOS and incident angles of the electromagnetic waves. The considered scenario is two-dimensional with reflecting objects and LOS between transmitter and receiver. To apply the hybrid method, a) LOS condition, b) an a-priori knowledge of the reflecting objects and c) at least one reflecting path are required. The investigation considered in this paper assumes random objects based on a rectangular grid. An ongoing analysis involving different shapes of objects could be investigated in future works.

The hybrid localization method is explained in Figure 2.

In a first step, the propagation scenario is defined. The reflecting objects in the 2D scenario and the receiver position are given. The upper part of Figure 2 shows a scenario with multiple objects (e.g., called O_{II}, O_{III}, O_{IV}) and all object edges. The lower part of Figure 2 visualizes an extract of the upper part, but tailored to one chosen reflection path at object O_{II} (only one reflecting object is considered). The relevant reflected path is called "2". The dimension of the lengths in Figure 2 is explained in more detail in chapter 3.

The figure also gives the definition of relevant angles and lengths relevant for the hybrid algorithm. The line between the points *M* and *N* represents the relevant edge of a reflecting object based on a rectangular grid. Point *A* shows the transmitter position (to be estimated) and point *B* the receiver position. Antenna patterns are assumed to be omnidirectional in the considered two-dimensional scenario. The lower part of the figure shows two propagation paths between transmitter and receiver: the LoS path and a path based on a single reflection. It is assumed that the transmitter position can be estimated by two parameters:

- α_2 (incidence angle of the reflected path with respect to reference North direction). This corresponds to the angular relationship of the reflected path
- τ_i (delay between the reflecting path and the LOS path)

Figure 2: The upper part shows a digital map with a-priori known objects and relevant propagation paths based on single reflections. The lower part shows an extract of the above figure tailored to the reflection path 2, together with definition of angles and lengths relevant for the hybrid algorithm

The following consideration derives the equations for localization based on the lower part of Figure 2:

Two propagation paths are considered: The LoS path between point *A* and *B* as well as the reflected path (reflected at object O_{II}) from point *A* to point *B* via reflection point *C* (which is positioned on the straight line $\left(\overline{MN}\right)$).

Application of cosine theorem gives:

$$\left(\overline{AC}\right)^2 = \left(\overline{CB}\right)^2 + \left(\overline{AB}\right)^2 - 2 \cdot \overline{AB} \cdot \overline{CB} \cdot \cos\left(\measuredangle\delta_2\right) \tag{1}$$

Where $\sphericalangle\delta_2 = \measuredangle\alpha_2 - \measuredangle\alpha_0$ corresponds to the angular difference between the reflected path at object P_2 (therefore index 2) and the LOS path (occurring at an angle $\sphericalangle\delta_0$) as shown in Figure 2.

Figure 2 indicates $\left(\overline{AC}\right) = l$, $\left(\overline{CB}\right) = d$, $\left(\overline{AB}\right) = r$, so that equation (1) can be written as:

$$l^2 = d^2 + r^2 - 2rd \cdot \cos\left(\measuredangle\delta_2\right) \tag{2}$$

The difference of the path lengths between reflected and LOS path is

$$\Delta r = \left(d + l\right) - r = d + l - r$$

Solving for l gives:

$$l = \Delta r + r - d$$

Substituting l in equation (2) gives:

$$\left(\Delta r + r - d\right)^2 = d^2 + r^2 - 2rd \cdot \cos\left(\measuredangle\delta_2\right) \tag{3}$$

This equation is solved for r by the following calculation steps:

$$\Delta r^2 + 2r\Delta r + r^2 - 2rd - 2\Delta rd + d^2 = d^2 + r^2 - 2rd \cdot \cos\left(\measuredangle\delta_2\right)$$

$$\Delta r^2 + 2r\Delta r - 2rd - 2\Delta rd = -2rd \cdot \cos\left(\measuredangle\delta_2\right)$$

$$2r\Delta r - 2rd - 2\Delta rd + \Delta r^2 = -2rd \cdot \cos\left(\measuredangle\delta_2\right)$$

$$2r\Delta r - 2rd + 2rd \cdot \cos\left(\measuredangle\delta_2\right) = 2\Delta rd - \Delta r^2$$

$$2r \cdot \left(\Delta r - d + d \cdot \cos\left(\measuredangle\delta_2\right)\right) = 2\Delta rd - \Delta r^2$$

$$2r = \frac{2\Delta rd - \Delta r^2}{\left(\Delta r - d + d \cdot \cos\left(\measuredangle\delta_2\right)\right)}$$

This leads to:

$$r = \frac{2\Delta rd - \Delta r^2}{2 \cdot \left(\Delta r - d \cdot \left(1 - \cos\left(\measuredangle\delta_2\right)\right)\right)} \tag{4}$$

where Δr is given (as already introduced) by $\Delta r = d + l - r$, but also by $\Delta r = \tau_i \cdot c$ where τ_i corresponds to the delay between the reflected path "2" and the LOS path "0" and c is speed of light.

In general, if a reflection occurs at an object O_i , the angle $\measuredangle\delta_i$ is defined by

$\measuredangle\delta_i = \measuredangle\alpha_i - \measuredangle\alpha_0$.

According to [5], equation (4) can then be written as

$$r_i = \frac{2\Delta r d - \Delta r^2}{2 \cdot \left(\Delta r - d \cdot \left(1 - \cos\left(\measuredangle\delta_i\right)\right)\right)} \tag{5}$$

which corresponds to the estimated distance between transmitter and receiver calculated with the information on path i. When the coordinates of the receiver are given by (x_B ; y_B) based on the coordinate system of the Figure 2, the coordinates of the transmitter can then be calculated by:

$$\begin{cases} x_i = x_B + r_i \cdot \sin\left(\measuredangle\alpha_0\right) \\ y_i = y_B - r_i \cdot \cos\left(\measuredangle\alpha_0\right) \end{cases} \tag{6}$$

In case of a multipath propagation with several reflection paths resulting from several objects, the estimation of the transmitter position using equation (6) can be done separately for each combination of LoS and reflection path. In the ideal case assuming perfect reflection and exact information on both the incidence angle of the reflected path and the delta delay between the two paths, the individual estimations will be identical as geometry leads to the same intersection point of the paths. This intersection point corresponds to the transmitter position. Furthermore, the estimated position will be identical with the actual position. Basically, the individual results can then be combined to get a single position. Hereby, it is not favourable to apply an arithmetic average of the results due to the following effect: Some of the individual estimates of the transmitter position may be of poor-quality, e.g., when the LOS direction and the direction of the incident angle of the reflected path are nearly parallel to each other. Any small angular deviation will have a large impact on the interception point (which is the transmitter position). Therefore, the combination of the individual results in case of multipath propagation should be done in an intelligent way, e.g. by special weighting. Very strong variations of the estimated positions could even be ignored. This may be a topic for future investigation.

The presented hybrid method for passive localization [6] has been proposed by Professor Dr. habil. Vadim Denisov from Tomsk State University of Control Systems and Radioelectronics in Russia. Further elaboration of the topic, supported by post-doctoral staff, has lead to the patent as described in [7].

3 RESULTS

Simulations based on the hybrid method are performed to study the accuracy of the estimated transmitter position. The software package used for the stochastic simulation is described in more detail in [8]. As required by the hybrid method, indicent angles and path delays at receiver side are the relevant input measures to estimate the transmitter position relative to the receiver. The investigated scenario corresponds to mesh type "D" of [9] as a result of using a homogeneous, one-step Markov chain. The idea of using a Markov chain has been described in [10].

The map with the objects in Figure 2 is based on pixels and involves 270 x 270 pixels. Note that the dimensions in the map are in pixels and not in metres. Depending on scaling factor, the map could hence describe indoor or outdoor applications as well. Due to the consideration of pixels, the investigations in the paper are independent of wavelength or frequency. However far field conditions are assumed as a prerequisite to model incident waves as transverse electromagnetic waves. Since pixels are used, all lengths based on the map are in pixels as well (such as $r, r_i, \Delta r$ etc.). For simplification, only one object has been used for the calculations. This helps to investigate the behaviour and effects of the hybrid method.

For the simulation both, the angular and the temporal information are modulated by additional noise to model uncertainties in a real world measurement setup as described above. The disturbance variables are based on Gaussian distributions (μ=0, $\sigma_{\measuredangle\delta, N} = 0..1,5°$ for incident angles and $\sigma_{\tau, N} = 0..0,5\,pixel$ for delays). Figure 3 shows the setup of the simulation. 10 000 simulations are performed to study the statistics of the localization error.

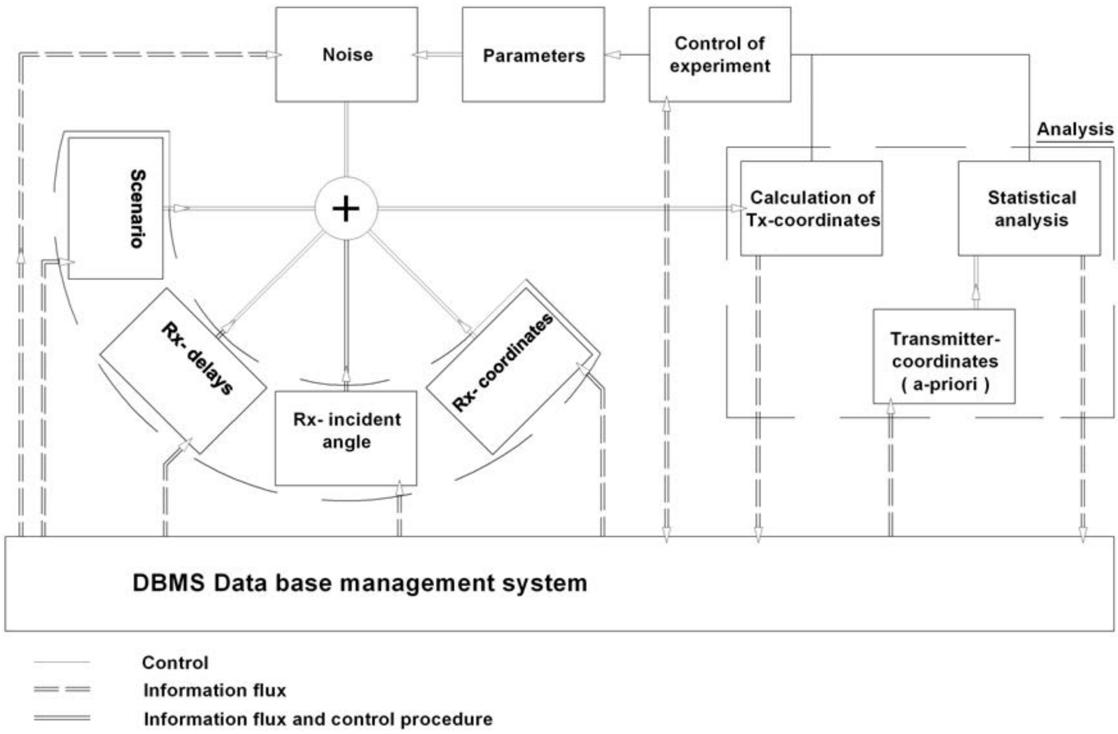

Figure 3: Overview of the simulation setup

For the analysis, equation (5) is applied in case of noisy information to estimate the distance r_i between transmitter and receiver. This means that both $\sigma_{\measuredangle\delta, N}$ and $\sigma_{\tau, N}$ are present in the ranges as already described. The value r_i is then compared to the actual distance (called *R*, a-priori known for statistical analysis), leading to the standard deviation σ_r as a measure to describe the distance error. In a second step, a relative distance error is defined by the following equation:

$$\delta_r = \frac{\sigma_r}{R} \tag{7}$$

The definition in (7) is an established measure to describe a relative distance error [5, 11]. For the analysis, δ_r is determined as a function of $\sigma_{\measuredangle\delta, N}$ for different cases of $\sigma_{\tau, N}$ (see legend in Figure 4). The figure shows how the relative distance error increases when the disturbance $\sigma_{\measuredangle\delta, N}$ increases. The function is nearly linear, but depends on $\sigma_{\tau, N}$ (in pixel). It can be seen that an increasing product $\sigma_{\measuredangle\delta, N}$ leads to an increasing relative distance error whereas this influence is stronger in for small values of $\sigma_{\measuredangle\delta, N}$. For the special case without any noise ($\sigma_{\measuredangle\delta, N} = 0$ and $\sigma_{\tau, N} = 0$) there is no relative distance error, hence the estimation is perfect as already predicted by considerations on geometry as presented before. The hybrid method proves its functionality.

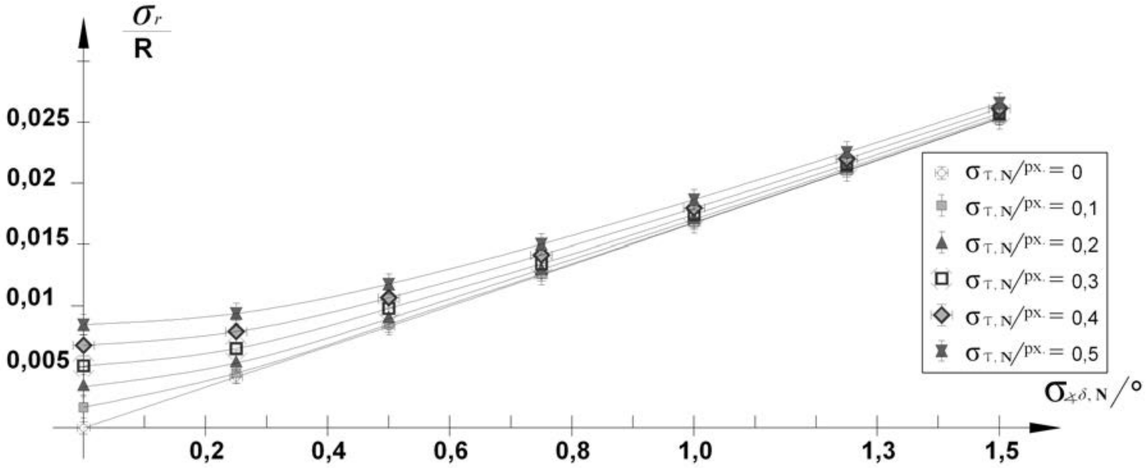

Figure 4: Relative distance error in dependence on $\sigma_{\measuredangle\delta,\,N}$

4 CONCLUSION AND OUTLOOK

The investigated hybrid localization method shows a passive localization of RF emitters by only one receive station as an alternative, favourable approach compared to classical methods involving several stations. Hence, there is no spatial distribution of the localization system. This minimizes maintenance effort, because there is non need to establish communication links between the elements. A further advantage is the fact that localization is done in a passive way, which means no radiating elements are required at receiver side.

The paper derives the hybrid method including the relevant mathematical background and gives the relevant references to the original work. The method is then applied to study estimation errors of the transmitter position for cases with noisy input information. Relative errors are studied as a function of noise, revealing the associated impacts and proving the functionality of the method.

Future work may comprise the following aspects:

- Intelligent weighting of estimated distances in case of multipath propagation
- Inclusion of antenna patterns

- Implementation of scattering properties instead of ideal reflection
- Extension of the map from two dimensions to three dimensions: Beside azimuthal angles, also elevation angles will have to be considered; furthermore, the effect of ground reflections has to be investigated.
- Influence of angular and temporal resolution at the receiver side
- Influence of the number of reflected propagation paths
- Classification of errors and understanding the associated influence on the estimation

Finally, field tests are possible to prove the predictions obtained by simulation.

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