TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

MOBILE ROBOTS IN INDOOR LOGISTICS

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Bachelor of science thesis

Examiner: Prof. Jose L. Martinez Lastra

ABSTRACT

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Robotics is a field capturing a large interest within the academia and the industrialist, during last years the interest has also spread to the general audience.

Traditionally, the sector of robot manipulators has been the one capturing the largest share of markets and the general audience. However, the latest advances on perception and cognition have paved the way for the wide use of mobile robots in general, and in industrial systems in particular.

The thesis presents a survey of the main components to take into account at the time of deciding to implement mobile robots for indoor logistics in automation systems. In particular, the work presents different locomotion methods, navigation systems, technologies for implementing path panning of the robots and some solutions for the fleet management in case of large population of robots at the factory floor. In addition, the thesis also introduces some of the most promising commercial products and, when possible, presents the application in real industrial use cases. Understanding the initial stage of the current market situation, this survey is complemented with a patent analysis of the field, providing a landscape of some 500 patents. A few of the most relevant patents have been also studied and presented in great detail.

The concluding chapter of the thesis summarizes the main findings and proved the original perception of the author regarding the availability of new technological solutions, solution that will allow mobile robots to stress their presence at the factory floor becoming essential component for future indoor logistics systems.

PREFACE

The topic for this paper was a result of a meeting with professor Lastra. The meeting was on 30 of August 2017 but the actual writing happened mostly during October and November. The topic of this paper is very wide and most of September was used to gather information, setting guidelines and overcoming the fear of the blank paper.

Once the writing prosses had been started I found a genuine interest in many specific areas like neural networks, fuzzy logic and task based robot programming. These are areas I will definitely include in my future studies. This thesis has also verified that my choice for the master phase (factory automation and industrial informatics) was the right choice.

Overall the writing prosses has been very motivating, interesting and I have learned a lot. A very motivating feature was to see and recognize things from my studies and see them in practice or in scientific test setups.

I want to thank the examiner of this thesis, professor Lastra. I am very grateful that he had the time to guide and evaluate my work. I want to thank my friends at TUT for all the support, peer evaluations and genuine interest, without it the work would not have been so motivating and I would not have learned as much. Lastly, I want to thank my girlfriend Sonja for the support when it really counted and all the motivational speeches at times where the words did not find their place on the paper.

Markus Kasurinen
10.1.2018, Tampere

CONTENTS

1. INTRODUCTION

Robots have been a part of the manufacturing industry for over 50 years. The tasks robots can complete have gotten more complex over the years. 50 years ago, robots were usually fixed to a base and had limited working spaces due to small amounts of degrees of freedom. During the development of robots, mobile robots have evolved and lost the guiding wires and reflective tapes on the floor and transitioned to more intelligent navigation systems and path planning methods.

This thesis is written as a bachelor thesis for the laboratory of factory automation and industrial informatics at Tampere university of technology. The purpose of this thesis is to survey the field of mobile robots that are used in indoor applications. Due to the focus of this paper, I have left the technologies used in outdoor applications out and focused on the technologies used in indoor logistics. I have based my research on up to date literature and the patent analysis in chapter seven is based on an analysis of the patents at Derwent Innovations Index database.

This paper is divided into eight sections, this introduction being the first one. In the second section I introduce two nature-inspired locomotion methods and showcase my research outcomes in traditional methods, these include but are not limited to omni wheel locomotion and different wheel configurations. In the navigation section my focus is not on the technologies used, it focuses more on the principles of navigation. These include maples-, map-building-, and maples navigation systems. In the fourth section I again do not focus on the hardware, I showcase my research outcomes about the methods of path planning, what are the systems used and what kind of principles they rely on. The fifth section is about fleet management. In this section I have gathered information about methods of task allocation and communication. These include an auction based method and an improved protocol for it. I have also included a section about robots that can merge into one if the task requires it.

The section titled "Companies" is a survey of the companies that sell robotic warehouse solutions. It also has some use cases that illustrate the ability of these kind of systems. In this section I have also included a documentation of the teardown of a KIVA robot.

The last section before the conclusion is a patent analysis. It includes a landscape analysis of the patents in the field of mobile robotics. I have also researched the patents from the companies I have introduced in the company section. With this I am able to identify the areas where the progress is fast and what are the areas that have not been so attractive to develop.

2. LOCOMOTION

A robot is mobile when it has the ability to move in its environment without any fixed structure. This can be achieved with multiple different technologies and configurations.

Locomotion can be achieved with traditional methods like wheels or tracks. There are also nature inspired technologies such as snake like movement, legged robots and configurations that mimic the movement of fishes.

2.1 Traditional methods

In traditional methods the locomotion is mostly achieved in the same fashion as in human operated vehicles. These include wheels in different configurations, caterpillar tracks or propellers. These technologies work in many different environments and have not changed significantly in the last years. The need for alternative locomotion technologies has risen due to the widening of the field robots are used.

A traditional and very effective drive system is the omnidirectional wheel, such include the omni wheel and mecanum wheel. Omnidirectional wheels have the advantage that they have more than one axis that they can spin around, this enables a robot with omnidirectional wheels to do zero radius turns and change the direction the robot is travelling without changing its orientation. The omni wheel has small discs in the place where traditional wheels have a rubber contact surface. This allows the robot to move in four directions without changing the orientation of the robot in the environment. A mecanum wheel has rolling cylinders that are on an angle in the place of the rubber surface on a traditional wheel. These wheel types are very useful in indoor applications due to the freedom regarding the orientation in respect of the travelling direction. [1]

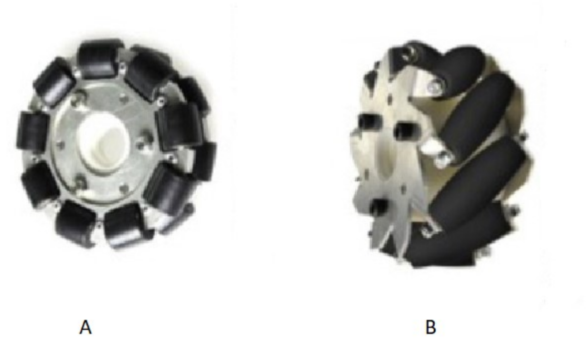

Figure 1. Two types of omnidirectional wheels, A) a omni wheel, B) a mecanum wheel [2]

An option for heavy duty indoor logistics is to utilize a traditional wheel based locomotion technology in tandem with air bearings. The bearings create a thin air film under the mover which lifts the load 10-27mm of the floor. This changes the requirements for the wheels a lot. The wheels do not need to carry the weight of the load and this means they do not need to be as heavy duty as without the air bearings. With air bearings it is possible to bear the load of the transported goods, this leaves only the locomotion and steering to the wheels. The problem with air bearings is the need of high pressure air, the flow has to be constant and the high-volume of the flow can also be problematic. The needed air volume is determined by the load and the quality of the surface on which the mover is being used. If the surface is high quality (polished concrete for example) the air flow needed can be 75% lower as with a low-quality surface. The mover can have metal stilts for a situation where there is no air flow. This way the pressure of the load is not resting on the wheels. [3]

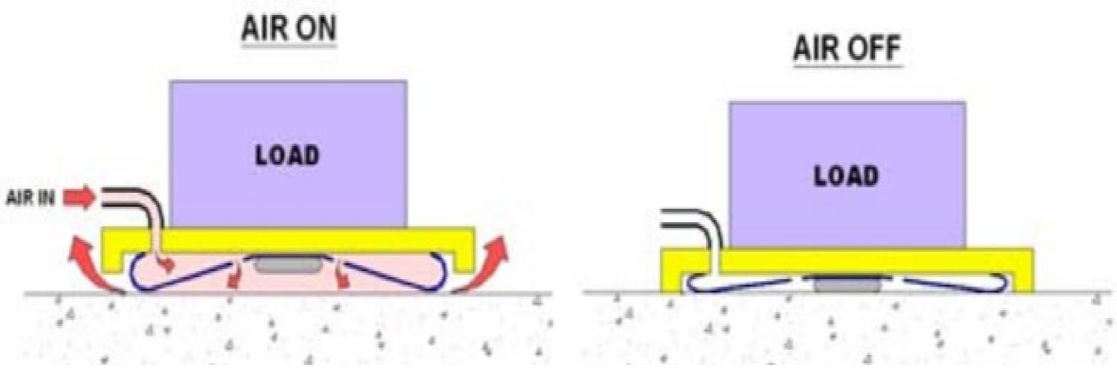

Figure 2. On the left an air mover with the air flow on and on the right without the air flow [3]

2.1 Nature inspired methods

One nature inspired technology is a multi-segment robot that mimics the movement of an earthworm. The robot has five segments, each equipped with two solenoids. The locomotion sequence is five stepped. In each step the solenoids activate a pulling and/or a pushing motion between the segments. This generates a linear locomotion much like the one of an earthworm. For an angular movement only one of the two solenoids in a segment activate. With the help of a third solenoid in each segment the robot could be able to move not only horizontal but also vertical. [4]

Another form of nature inspired locomotion is one that mimics the movement of a snake. The setup was a multilink system where each joint has a motor that can generate torque to the links. Depending on the desired movement the actuators generate torque to one (in slow movements) or multiple (fast movements) links at a time. [5]

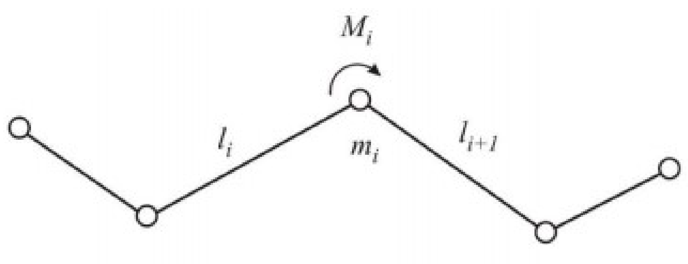

Figure 3. *A multilink nature inspired mobile robot. [5, p. 614]*

As we see in figure 3 a snake like mobile robot has actuators which generate torque to the links between them.

The two locomotion systems established above could be a great alternative for rough terrain locomotion. This could be useful in rescue robots and other tough terrain applications. If the utilization area is water, there are also locomotion technologies that mimic the movement of a fish or a frog. [5] But these are not relevant to the topic of this paper.

3. NAVIGATION

A vital task for a robot is to be able to locate itself in an environment and navigate to a goal position. The environment can be static but unknown or a dynamic known environment. Early Automated Guided Vehicles (AGV) had to have some sort of guideline which they followed. This has been done with guidewires that are embedded in the floor and with reflecting tape that the AGV follows. These approaches are viable options for continual tasks such as moving a product from the production line to a warehouse. But they lack the intelligence to make new path decisions, encircle obstacles and perform multiple tasks.

The systems used in indoor applications can be divided in to three main categories, depending on how they compose a map of their surroundings. The three categories are map based navigation, map building navigation and maples navigation. [6]

3.1 Map based systems

In map based navigation the system is dependent on having a detailed map that is created by a user. This leaves the robot the task of locating itself in the environment and navigating with the help of the map to its goal position. For the locating task the robot can use vision based methods, RFID-tags, QR-tags etc. In vision based systems the robot gathers information about its environment with the help of cameras. The information is gathered from the images with the help of software that detects landmarks from the environment, these can be walls edges, colors, poles etc. The landmarks are then identified and compared to the given map, after this the robot calculates the position of its self. [6]

One option for map based local navigation is to use radio frequency identification (RFID) tags. The robot is given a topology map of the tags and set in a known environment, but the location is unknown to the robot. In this configuration the tags were placed on the left-hand side of hallways, so the robot moves around to find a wall. To interpret the environment the robot has a laser based range finder. After the robot has found a wall it follows the wall blindly until it finds a RFID tag. The navigation proses proceeds with the robot moving right, left or forward depending on the position of the RFID tag relative to the goal. After the decision has been made the process continues until the RFID tags id matches the goal id. [7]

One other form of map based indoor navigation is to use an array of magnetic beacons as landmarks. The concept by A.Sheinker et al. was built for personal indoor navigation. [8] It used smartphones as the receiver, but the same technology could be used for mobile robots.

3.2 Map building systems

Map-building-based navigation is a system where the robot creates a map of the environment. The robot has systems (sonar, laser or cameras) which gather information and the information is reduced so the algorithm can extract distinctive features of the environment.[6]

Moravec and elfes proposed an occupancy grid type of information structure. The environment is divided into cells and each cell has an individual probability to be occupied. [9] In today's robots the occupancy-grid technology is much more effective due to multiple and more accurate censors.

An occupancy grid can deliver a map that is high in geometrical detail but in large environments it can be inefficient to compute path plans or locate the robot. Therefore occupancy-grid based systems are usually used in tandem with topology-grid based systems. [10]

3.3 Maples systems

The third type of indoor navigation is maples navigation. In this, the robot does not need a map of the environment because it resorts on object recognition and visual observations. The techniques for gathering and reducing information are the same as in a map-building-systems. The key difference is that in a maples system the exact position of landmarks or elements does not have to be known. The navigation is based on the distance and position of the object in respect to the goal. Vision based maples navigation can use either optical flow or appearance based technologies.[6]

Optical flow based technologies use the comparison of a right and a left camera to stay on the correct path. The technique mimics the navigation of bees. The technique is to compare two images, a right one and a left one. If the robot moves strait in a corridor the speed calculated from the different camera images is the same on both sides. This way the robot knows that it is on a straight path without knowing its exact position in the environment. [11]

Appearance based technologies use images that are taken from slightly different angles and merge them together. These images are then processed and that defines a specific place in the environment. The places are then associated with a direction relative to another place. A neuro network is then able to navigate the robot from an unknown location to a goal location by recognizing the places and the knowledge of the relative direction associated with them. [12]

The accuracy of a robot can be defined as the difference between the goal position and the actual position of a robot. The lack of landmarks can reduce the accuracy of a robot dramatically especially in dynamic environment where the landmarks cannot be detected from long distances. To solve this problem artificial landmarks can be created. These can be used as an aid for navigation (the robot uses artificial and native landmarks in tandem) or on its own. [13]

There are many configurations for map based navigation systems. They vary in terms of the map the robot is given and technology used for localization in other words how the landmarks of the map are recognized. The same applies to the map building and maples navigation. In map building navigation systems, the robot makes notes of the environment with some technology and builds a map out of the notes. Maples navigation relies on the relative position of the robot to features of the environment. The robot can recognize these features with help of cameras, sonar, RDIF or some other technology. This could be a possible application for Internet of things (Iot) too; things that are stationary in the environment could identify the robot and transmit the location of itself to the robot. The robot then identifies the object, and this gives the robot the information where it is.

4 PATH PLANNING

Path planning is the function of a robot to move itself from a location A to a location B. The process includes obstacle avoidance, navigation and optimizing the path.

Most important elements for efficient path planning are: Perception, localization, cognition, path planning and motion control. Path planning algorithms can be divided in *global path planning* and *local path planning.* In global path planning the planer needs to have an accurate knowledge of the environment and with that it is able to plan a detailed route. Traditional methods are for example: cell decomposition, sub goal methods and potential field method. [14]

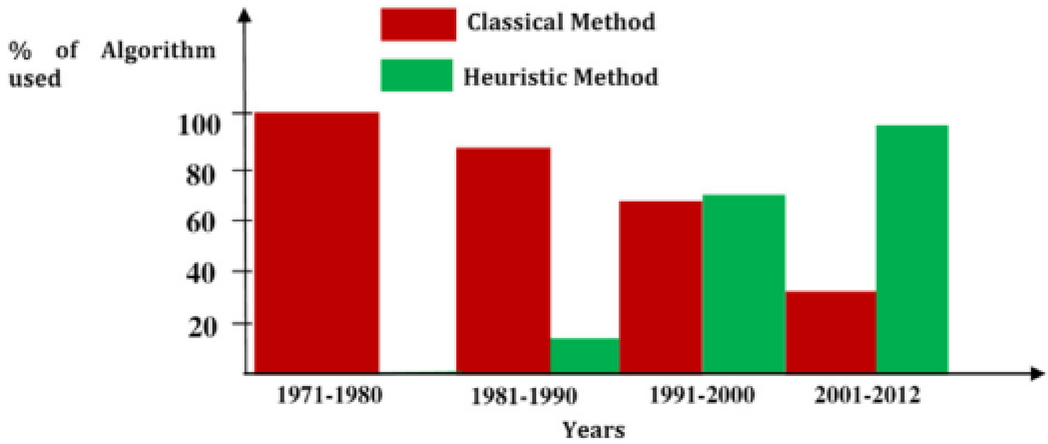

Figure 4. *The use of classical and heuristic methods in mobile robotics [14, p. 15]*

As we see in figure 4, the use of heuristic algorithms has been increasing after 1990. This shows that adaptation for dynamic environments and complex task management are needed, now more than ever.

The traditional methods for path planning require detailed knowledge of the environment. That makes them very hard to implement in indoor logistics. In indoor logistics, the environment is often dynamic and without constantly updating the path planer it cannot plan a suitable path.

The lack of adaptation in global path planning has been approached with different solutions. One is to present the environment as a point cloud and if changes occur, update the changed cloud to the robots that are affected by the change. This is not very efficient, nor has the method a theoretical guarantee for reaching a goal by using an optimal path.

Local path planning methods include heuristic-based algorithms, for example: Hybrid algorithms, Nature Inspired Algorithms and Fuzzy logic. Local path planning is not dependent on prior information of the environment; it gathers the needed information with onboard sensors. This has the effect that the planer can work efficient even in dynamic environments.

Heuristic-based algorithms are a much more efficient way to navigate robots in dynamic environments. Heuristic methods have several advantages compared to classic path planning. One huge advantage is the ability to learn which can be done with a neural network. One largely studied method is to merge fuzzy logic (IF-THEN logic) and a neural network. This combination could give the robot a human like ability to think and learn. [14]

Nature inspired methods have been developed for over fifty years. The principle is to imitate the behavior of certain animals or colonies. The results are algorithms such as genetic algorithm and ant colony optimization algorithm. [14]

4.1 Neural Networks

Robots need to function in dynamic environments and they need to gather information, process it, interpreter it, make decisions based on the information and learn from the outcome. This kind of adaptive process mimics the thinking of a human and it is very hard to achieve. With neural networks there is potential of achieving an artificial intelligence level that is capable of achieving these requirements.

Neural networks are a group of processing units, so called neurons. The neurons are arranged in multiple rows, the rows are called layers. A neuro network works and learns by receiving inputs, processing them in multiple layers and composing an error function. An error function is simply the difference of the goal and the output of the network. The learning is process where the network weights different neurons differently and then checks if the error function is going to zero. The network modifies the emphasize of each neuron and optimizes the result. To enhance the learning capabilities the learning can be supervised. In practice this means the network is given classified pattern information. This shortens the learning process drastically. But in real life applications it is not always possible. The neuron count is always a compromise, with more neurons in a layer the accuracy increases but the learning process takes longer and vice versa. [15]

In mobile robot's path planning tasks, the task of the neuro networks can be divided in two separate tasks. The first is to find a free space in the environment. For this the neuro network needs to interpreter the information flow of cameras or sonar and conclude if a space is free or not. The second part is the actual path planning. This task can require information about the current position and orientation and the goal position. [15] As examined in the navigation section of this paper the navigation systems vary largely and the information needed can also vary.

A survey of a test setup where a robot followed a moving target in a non-static environment resulted in a smooth movement of the robot and perfect obstacle avoidance. The stability was guaranteed with a combination of Lyapunows stability theory and qualitative analysis.[14]

D. Janglova developed a path planer that uses two neural networks. The first was a principal component analysis (PCA) and the second was a multilayer perceptron. PCA is a data reduction system that reduces the input data to its basic components. Hebbian rule is used for these components and by that the robot generates save spaces in the environment. These spaces and the goal location are used as the inputs for the multilayer perceptron. The output of the second network is the direction in which the robot should move. [15]

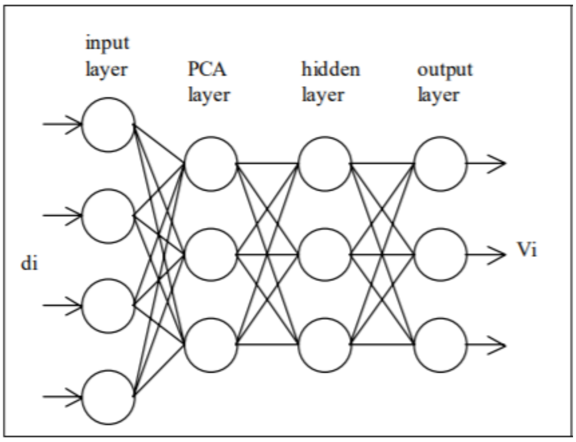

Figure 5. *The system proposed by Janglova [15, p. 17]*

4.2 Fuzzy logic

Fuzzy logics goal is to mimic the navigation process of humans. Humans have the ability to navigate without any exact measurements of the environment. In fuzzy logistics all tasks are divided to the key elements and then a series of IF-THEN-rules are employed to these elements. The outputs from the fuzzy controller are then transformed into valid inputs for the motors. In path planning fuzzy logistics have three main tasks: seek goal, avoid obstacles and keep the right orientation. These three components are included in a cost function which will give a target steering angle to the robot.[14, 16]

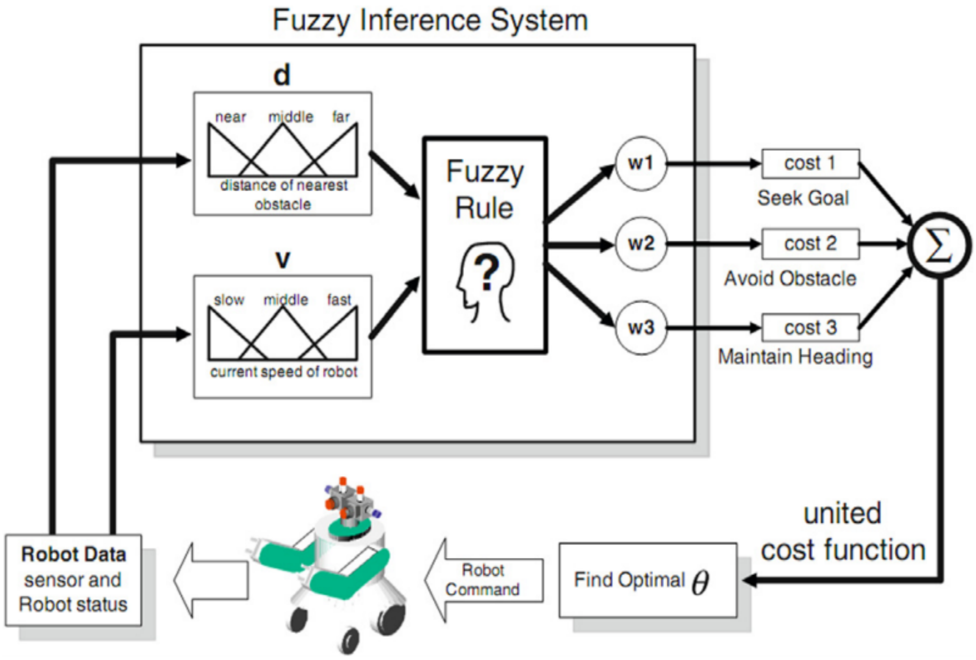

Figure 6. *A model of the decision making of a fuzzy logic path planning [16, p.14]*

Fuzzy logistic systems solve many problems but the issue with them is the prioritization of the IF-THEN rules. This is why a robot with a path planning system that uses fuzzy logistic will not make optimal path planning decisions in every situation. [16]

4.3 Natural inspired algorithms

The nature is full of fleet management and path planning, and that is why nature has inspired many path planning algorithms. Genetic algorithms mimic the genetic processes found in nature, such as natural selection, mutation and crossovers. With the information from the on-board sensors of the robot, the algorithm selects paths that have been proven successful and eliminates unsuccessful paths. If the robot uses occupancy-grid navigation, it can also merge two cells together if they are connected. [14]

Ant colony optimization algorithm mimics the process in which ants find the shortest route from their colony to the food source. In nature the ants are randomly wandering in the environment of the nest. If they find a food source they head back to the nest leaving a trail of pheromones on the path they use. Pheromones evaporate over time, so the attractiveness of the path decreases over time. This leads to the situation that the path that is the shortest, has the strongest pheromone smell. When an ant comes out of the nest it takes the path which has the most pheromones on it. After the food source is used the path is no longer used and the pheromones evaporate. [17]

In robotics the robots do not wander around, they simply communicate if they find a route between two places. This way more and more robots use the shorter route. In practice this kind of algorithm gives a smooth path, but it takes time to reduce many possible paths to one optimal path.[14]

All the path planning algorithms and methods above have disadvantages. By combining them in to a multilayer system, it is possible to impair some of the disadvantages to a moderate level. The most promising developments are in the field of neuro networks and fuzzy logic. The vision that robots would have a human like learning and decision-making capabilities would make many applications for robots possible. The idea of a hybrid configuration is that the fuzzy logic would be the decision-making part and a neuro network would have the part of learning. This way the fuzzy logic controller could be used as an input for the neuro network and the training time would be reduced and accuracy increased without a large number of neurons.

5 FLEET MANAGEMENT

Fleet management is a vital part of the use of mobile robots in indoor logistics. The term fleet management contains aspects from task management, communication, life time cost of a fleet to the servicing of a fleet. For this paper focuses at task allocation and communication aspects.

Robots communicate with each other and can make path planning and task allocation decision that result in optimal performance. For it to work the robots need to know the position of each other, the position of the item that they need to transport, and which robots are available. Task allocation can be peer-to-peer based or have a centralized architecture.

5.1 Centralized systems

One possible solution for task management is to decompose the environment into sections, that way each robot has a separated area or "a cell". The system uses a centralized operation software that allocates the task to the robot which has the operation cell suitable for the task. The problem with this are tasks that spread over multiple robot specific work cells. To solve this problem an algorithm was generated that used a customized version of a Voronoi diagram for the decomposing of the area. The outcome is a list of cells that have a specific task which can be completed within that cell. If the fleet is heterogeneous i.e. the robots have different recourses in terms of capabilities, location etc. The robots may need to switch cells, this is done by a software named Semantic MozardSpaces. Sematic MozardSpaces uses parameters to match the task with the right robot. The match is evaluated with a four-stage evaluation: exact (task and the capabilities of the robot match perfectly), subsume (the robot has more capabilities than the task requires), plugin (the opposite of subsume) and fail (if none of the above match). After the evaluation the task is given to the robot that is the best mach. [18]

In indoor logistics applications the fleet is usually homogeneous, for example the KIVA system. In this case the task allocation software has to optimize not the capabilities but the distance between the robot and the task. In centralized systems this creates a lot of communication, which generates high demands for the communication system.

Communication between robots and the central system should be minimized for several reasons. It applies a load on the network which can cause delays on the system and on the other hand large and efficient systems are expensive. Unnecessary communication will be an issue for large fleets in particular.

5.2 Robot to robot systems

One solution for efficient task management is a robot-to-robot system. In peer-to-peer based systems the information is not broadcasted to the entire fleet but to one robot. This robot can send the information about the task to another robot which sends it to another, this is called multi-hopping. [19]

In task allocation, multi-hopping can be used for example in tandem with an auction based task allocation protocol. In practice it means that a robot gets the information about a task, it makes its own bid and transmits the task information forward to another robot. This action is repeated and after the auction is closed the task is given to the best bidder. In the case of large fleets this method will have long delays. The unnecessary bids make this method´s cost efficiency in the field of communication costs very low. [19]

A solution to minimize the unnecessary communication is to limit the area where the bids can be made or to limit the range the task information is transmitted. If the initial information of the auction and about the task are send to a robot near the task itself this method does not lower the possibility of an optimal bid wining the auction. The communication costs can be limited also with an auction protocol where all the information is transmitted in one message. In practice it would look like this: The first robot gets the information about an auction and the task, it makes its own bid and sends this to the next robot. The second robot will attach its own bid to the end of the message only if it can make a better offer. This is repeated until all the robots in the area of the task have had the opportunity to make a bid or until the forwarding limit is exceeded.[19]

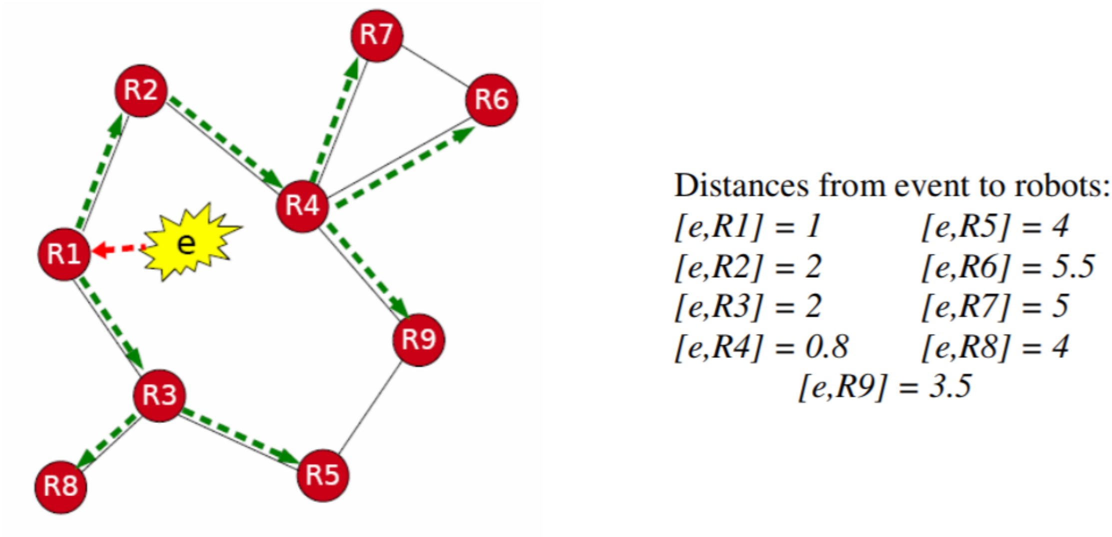

Figure 7. *Auction based task management system [19, p.186]*

As we see in figure 7 if the hops are limited to one, only the bids from robots R1, R2, R3 are in the auction. This shows the problem with simple auction protocol: the best bid of R4 is ignored because it is two hops away.

To improve the possibility of an optimal solution being found a subauction can be held. This means in a situation where a robot wins the auction it will ask the robots near it if they can complete the task more efficient. If the main auction had a bid limit (the forwarding of the message is limited to N times) or only robots in a certain area can bid, then this kind of an subauction can improve the efficiency greatly. If we take the situation in figure seven as an example, with a subauction the best bid would be considered if R2, R3 and R4 would be near each other.[19]

Robot-to-robot communication is necessary and lowers the communication costs, compared to a centralized system, but it has disadvantages too. For the best performance of a fleet the task should be showcased for the whole fleet, but as explained above, in large fleets this is not possible. In homogenous fleets the best option could be a combination of the decomposing of the work area into cells and a simple auction method. The centralized task management software would transmit the task to all the robots that are working in the cell where the task is located. This way it would keep unnecessary communication to a minimum (if the decomposition is done correctly the bids from robots in other cells would be unnecessary) but every robot that has a possibility to make a good bid would have the chance to do so.

5.3 Mergeable robots

A new approach to fleet management are robots that can work as one if needed. They are called mergeable robots. The idea behind it is that if a task requires recourses a robot does not have, for example the payload is too low, it can complete a task with the help of a second robot. There have been systems where the robots are controlled central and configurations where the robots work as a group each as an individual. But neither of these configurations work efficient in both scenarios, as individual robots and when doing team work.

One possible solution is provided by M Nithin et al [20]. The robots are individuals and have their own sensors and processors but at the same time the robots are a module of a merged robot. In practice, the robots work as individuals as long as a merge is not needed. When the merge is initialized the robots form a new robot. The physical connection is established with the help of grippers and the communication via wi-fi. The initializer becomes the brain of the robot and all the other modules become the nervous system of the new robot. This way the robots become a new robot which has individual decision-making capabilities and can perform a task efficiently. When the merge is no more needed the modules separate and become smaller individual robots again. [20]

The modularity of robots opens new possibilities in indoor logistics. Perhaps a product cannot be picked because it is too high on the shelf or the environment is a e-comers warehouse where most of the products are small and light but sometimes there is a need to transport a heavier load? These are problems that a fleet that has the possibility to form new robots with the suitable capabilities could solve.

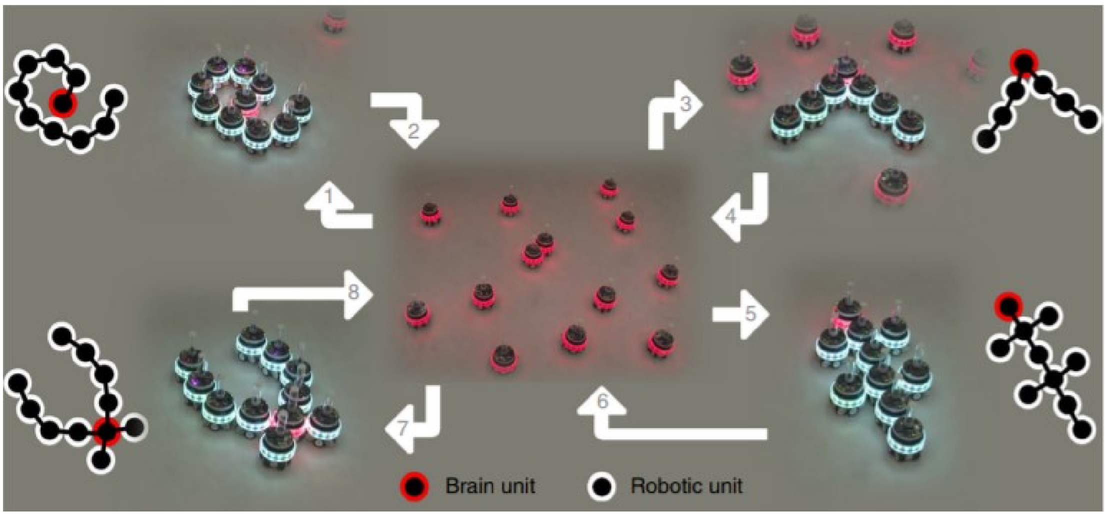

Figure 8. *A fleet of robots that have a ability to merge [20, p. 2]*

In figure eight we see a fleet of robots that have the ability to merge. The robots work as individuals as long as the merge is not initialized. If one robot initializes the merge it becomes the brain unit (in the picture it shows as a red robot). Every robot has its own brain before the merge. After the merge the rest of the robots form the nervous system of the robot. All the motors, sensors and actuator of the nervous system are in use for the brain unit. The already ones merged robot can merge again if needed, in this situation the initializer robot brain unit stays as the brain unit of the new robot.[20]

6 COMPANIES

The field of mobile robots designed for indoor logistics is very wide and there are many companies competing for market share. This chapter introduces some of the companies in this field and the solutions they offer. The specifications of the robots are based on the claims of the companies and have to examined critically. All the companies offer a system that includes the robots and a monitoring software, the KIVA system and Hikvision robots also need a central software for task allocation and path planning.

6.1 Amazon technologies (former KIVA systems)

The KIVA-system is a parts-to-picker system. It is suitable for logistics that involve relative small products that can be stored in pods. E-commerce distribution centres are a good example of such environment. Amazon bought the company in 2012 and Amazon probably made some minor modifications to the robot. KIVA or Amazon have not published the exact details of the robot, but Ben Einstein the founder of BOLt (a venture capital company that invests in companies that operate in the intersection of hardware and software) has dissembled a KIVA robot and documented the process in a blog post. The information below is from the post and should be read critically.

The KIVA system is composed of robots, pods, picking stations and software. The robots use a QR/datamatrix to navigate the route the “brain“ gives it. The robot has two cameras, one pointing up and one pointing on the floor. The down-wards pointed camera reads the QR- codes that are placed every 40” on the floor. Given that the robots use only right angle turns this is enough information for the robot to stay on the path. This is a map based navigation system and the QR-codes are the landmarks which are for the means of self-localization. The upwards angled camera reads the QR-codes that are placed on the bottom of every pod. This makes sure the right pod is moved to the picker.
In terms of obstacle avoidance, the robots have infrared sensors on each side. This enables the robot to stop if a product has been dropped on the path or if there is another robot in the way. As a backup there are multiple pressure sensors attached on the outer shell of the robot. If the pressure changes (the robot hits an object) all movement is automatically stopped.[21]
The robots in KIVA-system do not make path planning decisions, they only navigate with help of the QR-codes. A centralized software in the cloud or on a local server does the actual path planning. [21]

KIVA robots use four 12v 28Ah-lead-acid rechargeable batteries as their power source. These are wired in series to achieve the needed 48V DC. The batteries need to be charged regularly, for this there are charging docs in the facility. The robots return automatically to the docs when the battery level falls under a certain limit.

For the locomotion, there are two drive wheels, one on each side of the robot. This configuration gives the robot the ability to do zero radius turns. For stability there are four small wheels, two on the front side and to in the back. These wheels turn 360 degrees and they have no drive possibility, they are only for stability. To lift the pods that can whey up to 500kg, a second motor and a ball screw are used. [21]

The robots are only a part of the system, the picking stations are a vital part of the system too, they detect when the picker has picked a part and which of the stations are available. The whole system operates with the help of a highly intelligent software that is responsible for the path planning of the robots, keeping track of the pods and tasks which need to be completed. [21]

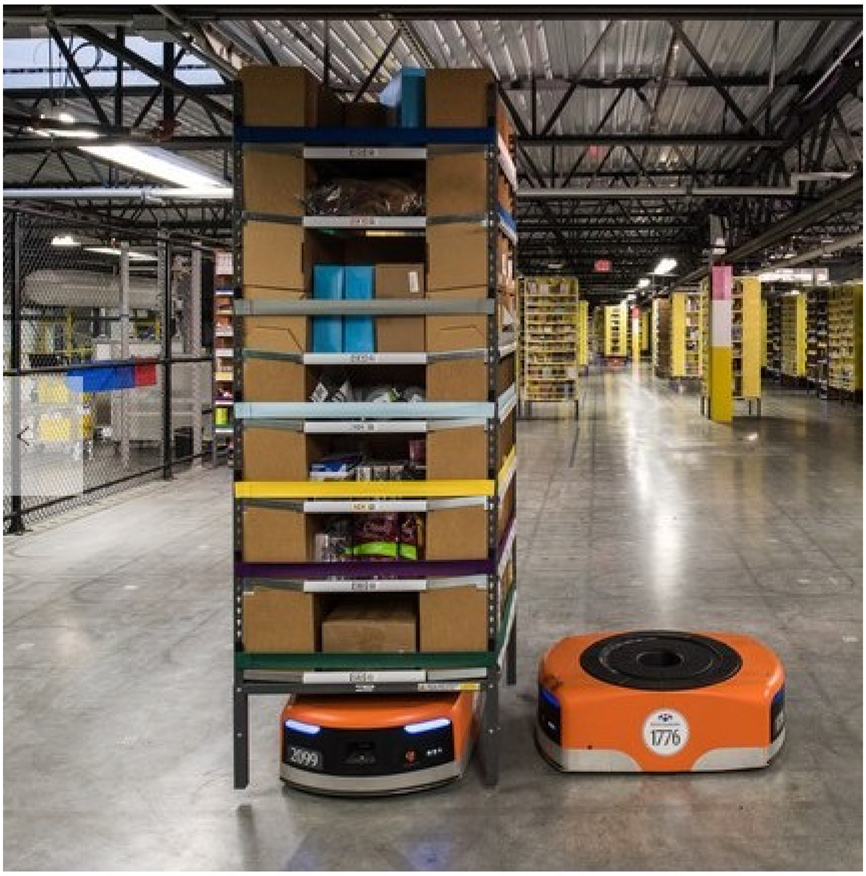

Figure 9. *A warehouse robot and a pod from amazon [22]*

Amazon is also a very good use case company. It has converted many of its warehouses into semi-automatic configurations. In 2016 amazon reported it has now 45 000 robots working in over 20 fulfillment centers around the world. One fulfillment center can have a fleet of hundreds of KIVA robots. The increase of robots was over 50% in the last year, this shows the economic benefits of the robots. [23]

6.2 Hikvision

Hikvision is a China based company that offers a large repertory of different mobile robots. They range from a small 460*380*190mm sorting robots to parking robots with a payload of 3000kg. Their mid-range mobile robots are very close to the robots in the KIVA system. They are designed to work on their own in an area where there is no human interference, but they still have basic obstacle avoidance systems. The robots also have the ability to do zero radius turns and they navigate much like the KIVA robots- with help of QR-code stickers on the floor. [24]

6.3 Fetch Robotics

Fetch Robotics robots are similar to the KIVAsystem robots at least on a hardware level. But there is a difference in the application of the robots. Where the KIVA system is designed to have a pod area where there are no humans working, the fetch system is designed to work with humans. The robots are designed be used as carriers (the human loads products on them and they transport them to a location) and have a payload of 75-1500kg. Because the robots are designed to work in collaboration with humans, the collision avoidance systems are more complex as in the robots of the KIVA system. They are able to stop, slowdown and even move around an obstacle. The robots do their own path planning and can navigate with help of recognizing landmarks. So I assume the robots use a map-based navigation system. Task management is done with a centralized software that controls the tasks given to robots. [25]

6.4 Locus Robotics

The products of Locus Robotics are transporting robots, much like Fetch Robotics offers. They have a touchscreen to interact with the operator and can transport the loaded products autonomously to the destination. The payload is between 18kg and 45kg, so Locus is definitely targeting the E-commerce market. The cruising speeds is 2m/s which is about the same as the robots of fetch robotics have. [26]

Figure 10. *A LocusBot from Locus Robotics [27]*

As seen in figure , the main product of locus Robotics has a basked in which the piker can put the products. It has also a touchscreen that allows the robot to interact with the piker. The screen can show what products the order has and after the pick has been completed it can be checked out and the robot can move to the next ail or go to the packing station.

Locus Robotics has taken a slightly different aspect to the robot human relationship. In the KIVA system the robots bring the products to a picker station where a human picks the products needed for an order. The solution of locus requires the picker to be in the ail where the product is. This increases the area of the warehouse (there have to be ails for the pikers to work in) but it is still effective. A major customer for Locus Robotics is DHL. It has implemented LocusBots in its warehouse in Memphis. A clear improvement is the distance the pickers walk in a day, before the LocusBots the pikers walked in average 14 miles in a day, now the distance is only 5 miles. [28]

7 PATENTS

In this chapter I review a patent analysis of patents listed in Derwent Innovations Index database. The analysis includes a landscape and some data about the assignees. After that there are a couple examples of the patents of the companies mentioned in the sixth chapter.

7.1 Landscape

Figure 11. *A patent landscape*

In figure 11 we see a patent landscape that is the result of a search for “mobile robot” OR “mobile robotics” in Derwent Innovations Index database. This landscape includes over 4000 patent families, not all of them are exactly for indoor logistics applications but some of them can be used in that field too. The landscape can be interpreted as a topology map. The higher the ground, the more patents have been applied in that area. For example, in the top left corner there is an area titled “Legged” this area includes many patents and that is why it forms a high ground.

There are a couple high grounds regarding locomotion. The biggest is the segment titled “legged”. This was to be expected, but it is not that relevant to the topic of this paper. The more interesting area is the area next to it, titled “wheel drive”. Most of the time the environment in indoor logistics applications is a warehouse or a factory, this means the surface where the robot moves is smooth and flat. That is why most of the robots used today are wheel driven and that technology will develop in the future too.

The landscape supports the chapter titled “navigation” in many ways. On the right of the landscape there is a high ground titled “reference image” this area contains patent families regarding vision based systems and is directly linked to maples and map building navigation systems. There is also an area for estimated localization, it is a direct link to maples navigation.

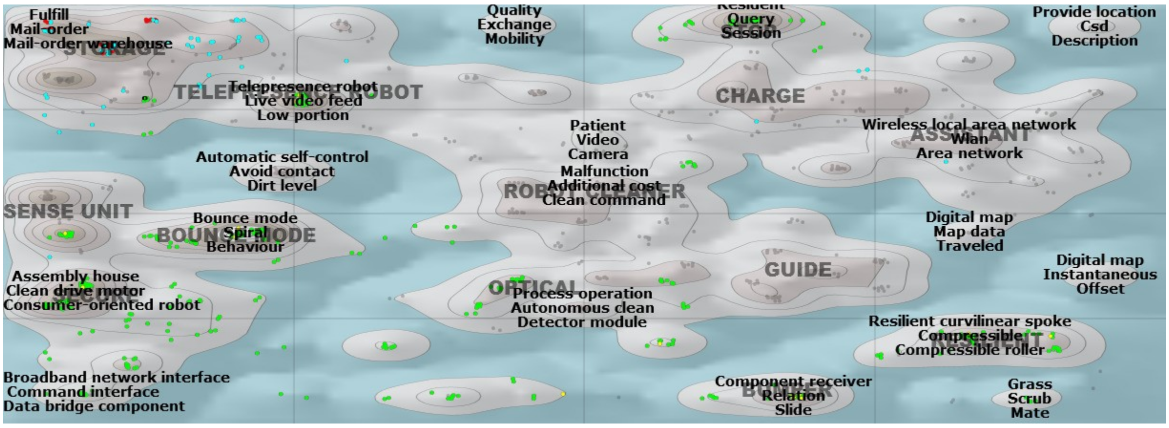

Figure 12. *A landscape with a more focused search*

In figure 12 we see a highly focused patent landscape with about 500 patent families. In the top left there is a large area containing patents regarding warehouses and mail-orders. The cyan dots are patent families where the assignee “Amazon technologies” was. The red dots represent paten families from KIVA-systems. The green spots are patent families where the assignee iRobot is. IRobot focuses on cleaning robots and some of the technologies are used also in logistic solutions.

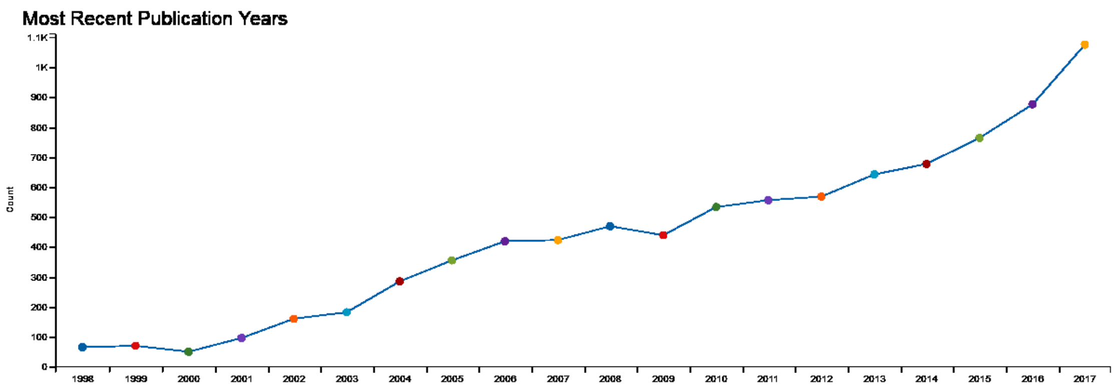

Figure 13. *Publications in specific years*

In figure 13 we see the number of individual patents filed through the years 1998 to 2017. It is apparent that mobile robots as a segment is growing very fast. Amazon alone has over 150 patents in this field.

As seen from figure 12 the mail-order segment of the mobile robot market is largely developed by KIVA systems and later Amazon technologies. Other companies established in the sixth chapter have also some patents and in the sections 7.2 and 7.3 are examples of them.

7.2 Fetch Robotics

Fetch Robotics own four patents regarding mobile robotics. One of them is a patent for a task allocation method.

Patent US2017252926-A1 claims a method of load balancing. The method separates the work area into regions in a manner where every task allocation server has its own area. The tasks are given to the first server by a central management software, the first task server evaluates if it has a suitable robot for the given task, if not, the task is send to the next task server. The first server will send the task to the second task server also if it has a long queue. Otherwise the first server will give the task to a robot in its area. This sequence is continued by the second task server doing the same evaluation: does it have a suitable robot and a short task queue, if yes it takes the task, if not it sends the task to the third task server. [29]

The patent US9744667-B1 claims a system that prevents the robots appendage from completing a task that would draw the battery under a certain power limit. The system estimates the energy consumption of a trajectory, if the trajectory needs too much energy it will be modified to match the capabilities of the battery. If there is no alternative trajectory the task will not be continued. This increases the safety of the appendage and as a consequence the whole systems safety is increased.[30]

The third patent of Fetch Robotics claims an end effector locking system. This system makes it possible to change the end effector on a manipulator very quickly. The system has wireless power transfer and information flow from the manipulator to the end effector. The actual locking mechanism which holds the end effector on the manipulator is magnetic. [31]

The last patent from Fetch robotics claims a system, which enables the charging connector of the charging doc to move in a plane that is perpendicular to the floor. This lowers the precision requirements for the robot when it docs itself to the charger. The patent claims the method of a floating mating connector and the actual charging dock that includes the floating mating connector. [32]

7.3 Locus Robotics

I wound four patents that Locus Robotics own in the field of mobile robots. The patent US2017261992-A1 is owned by Locus Robotics and claims a navigation method. The method is used to find a product in a space. To achieve that the space is divided in to sections using fiducial markers and each marker has a set of coordinates linked to it. The information of the marker is given to the robot as a fiducial marker ID. Every id has a set of products linked to it. When the robot receives a task to collect a product it actually receives a marker ID and navigates to the coordinates where it finds the marker. [33]

The warehouse system of Locus Robotics is designed to handle the transportation of the products. The actual picking is left to a person. This is why the robot does not need to navigate to a specific product. It can navigate to a marker, which marks a shelf for example, and then the employee brings the product to the robot.

The second patent claims a method for tracking the employee's performance. The robot has a proximity sensor which detects the operator coming close to the robot after it has parked at a marker. The robot has a display on which the operator interacts with the robot. For the interaction the robot first identifies the operator (this can be done with a RFID-tag) then retrieves the interface preferences of the individual operator from its memory. This way every operator can interact with the robot as efficient as possible. After the operator has fulfilled the task the robot sends the information of the time spend for the task to a management server. [34]

The patent US2017032306-A1 is an addition for the patent explained above. Its ads a camera to the robot, this enables contactless identification of the operator. The rest of the patent claims a similar method is the patent above. The robot parks near a marker, detects and identifies the operator and interacts with the operator. After the task is completed the robot sends the performance data of the operator to a server. [35]

8 CONCLUTION

In this chapter I review the findings of this thesis. This paper handles a wide subject and I have tried to keep everything as streamlined as possible. Every chapter introduces a couple of principles or technologies for that specific task of a robot.

Locomotion is essential for a mobile robot, it can be achieved with many different technics but for indoor applications omni directional movement is a clear advantage. This can be achieved with the help of omni- or mecanum wheels. The air bearings can provide a significant advantage in heavy duty applications. In my opinion natural inspired locomotion principles will not have a significant role in indoor applications because they do not bring additional value to the processes.

The ability to navigate is critical for a mobile robot. In this paper I categorized the navigation methods based on map creation. Map-based navigation methods need a detailed map of the environments and most of the time landmarks are artificial. This is a problem especially in dynamic environments. This problem can be avoided by using maples navigation systems. In maples systems the information gathering process seems to be heading into vision based technologies.

The need for intelligent robots that have the possibility to adapt to the environment and this can be seen in the rise of heuristic path planning algorithms. The most promising results have been with a combination of a neural network and a fuzzy logic controller. This supports the trend for maples navigation systems. Fleet management and especially task allocation are also moving away from the traditional centralized systems and the research leans more into adaptive peer-to-peer systems.

A scenario where a low level mobile robot could be used are basic factory logistics. A roll of paper needs to be transported from the paper machine to a warehouse. This is the kind of task that will not change in the near future and the requirements for the robot are low. It will need a basic map-based navigation system, a traditional path planning algorithm and some sort of obstacle avoidance system. This is the lowest level of mobile robot there is and for this kind of simple task that happens in a rather static environment it is good enough.

A scenario where the most advanced technologies could really show their performance would be a distribution center where the robots would be working alongside humans, in a dynamic environment and the communication would be a peer-to-peer system that would have the shipping details of the orders that are processed. This scenario would need a robot fleet with a peer-to-peer task allocation system that utilizes the information of the orders, it could be auction based or cell based system. For the navigation a maples vision based system could provide the best performance. Path planning would need a neural network – fuzzy controller hybrid, this is just to ensure the robot could handle the changes in the environment, make efficient path planning decisions and have an intelligent obstacle avoidance algorithm.

All the areas of development I have surveyed show a similar direction. Robots get more intelligent, they need to adapt their movement to the environment, the tasks robots are performing are getting more complex and they will need to work as individuals without centralized control systems. This is also the direction future research should be heading. Todays robots are largely working with instructions that a human has written, in the future robots will work as individual units that are able to complete tasks rather than execute a line of code. The elements that have the most potential in my opinion are: navigation, it will become more and more vision based and a map is no more needed, for this to happen neural networks and fuzzy logic controllers have to develop more. Task allocation inside the fleet has to involve more peer-to-peer communication. So future work is needed but with this rate of development and implementation of robots in a wide range of environments the evolution of robots is guaranteed.

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