Budapest University of Technology and Economics

Thesis Booklet

Intelligent Range Sensing and Modeling Methods in Mobile Machine Automation

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1 Introduction

The aim of the dissertation is to optimize machine transport; this is presented in the work in several steps, in a comprehensive sense: first, management and logistics problems are discussed, then in the second part the tracking / recognition tasks are analyzed, from the side of the sensors, taking into account the special and safety needs of the machines.

The significant advancement of automation and autonomous transport has brought significant advances in both remote sensors and intelligent methods supporting them. Construction processes are complex, each process is considered to be unique due to the different quality and quantity of resources, different circumstances and tasks. However, in the field of construction automation, there are many analogues on the topic of transport (e.g. construction vehicles, mobile machinery). Due to the similarity of the areas, it is worth to use methods which are well-proven in autonomous vehicle researches for mobile machine automation problems. In construction areas, it is at least as important to optimize the paths of the machines to optimize the processes as the paths of the vehicles on the roads. The first prerequisites for this in the construction industry are the existence of an optimal layout of the construction site and the knowledge of the position of construction vehicles. In order for the autonomous machines to travel safely and to react in a more reliable way to different (even unforeseeable) situations, we need to increase their intelligence with remote sensors and methods that support them. Mapping and recognizing the environment can allow machines to be completely autonomous in traffic and work. The purpose of my research was to investigate how mobile machine automation could utilize methods and sensors that have already been successfully applied in other industries, and explore the development possibilities of these technologies. In addition, I have also developed new environmental sensing methods for special sensors for case of industrial automated guided vehicles, which also allow the benefits of autonomous transport. Moreover, the developed methods can be used partly on public roads as well, as industrial utilization shows. Among the sensors I mainly dealt with the applicability of LIDAR (Light Detection and Ranging) technology. Different disciplines such as decision support and machine vision have been used and combined to optimize the processes that uses mobile machines.

I am currently an assistant researcher at Department of Material Handling and Logistic Systems of the Budapest University of Technology and Economics. I started my PhD studies in this department in 2014. My researches concerning construction processes started with the research project 'Investigating construction processes to improve logistics and information technology'. I am also a research assistant as MTA Young Researcher in the Machine Perception Research Laboratory of The Hungarian Academy of Sciences Institute for Computer Science and Control since 2016. Here, I deal with research and industrial development projects. We are in contact with several automotive suppliers (eg. Bosch, Knorr-Bremse), and some of the theses are partly related to the developments within these collaborations.

My first thesis deals with planning and uncertainties of construction transport. This is realized in two sub-theses in which decision support system and criterion system are proposed. In the field of environment perception the challenges are aroused from the novelty of LIDAR technology, point cloud processing and recognition from partial information. The second thesis proposes an obstacle prediction method for autonomous vehicles in industry. Finally, the third thesis is a method proposition for object classification of high speed autonomous vehicles with different sensor installation.

2 Related Works

In this section, I briefly introduce the currently applied methods and ongoing researches in construction projects and mobile machinery related to themes of the dissertation, they are in the same order as the subsequent theses discuss the topics.

A good review about Multiple-criteria Decision Making (MCDM) methods in constructions can be found in [Jato-Espino et al., 2014]. Decision making, support and its applications have been part of construction management from the beginning, it is still an active research area [Erdogan et al., 2017]. Construction logistics requires decision making in many levels. One of the first ones is the equipment selection. In [Temiz and Calis, 2017] the proper excavator is selected by using Analytical Hierarchy Process (AHP) and The Preference Ranking Organization Method for Enrichment of Evaluation (PROMETHEE). The author of the present dissertation is also a co-author of an equipment selection publication. In this publication a Fuzzy-based expert system was developed for crane and earthmoving equipment selection [Bohacs et al., 2013]. This was a good basis for the development of the hybrid MCDM method, part of the dissertation. Another important part of construction logistics which frequently utilize decision support is material supply ([Jakowski et al., 2018], [Cengiz et al., 2017]), and last but not least it can be useful in the design ([Moghtadernejad et al., 2018]) phase as well. The method in the dissertation is also used in the design phase to choose among layouts (thesis of section 4.1.1).

The localization problem is present in construction sites in more than one form. It is a demand to know the position of the workers [Park and Brilakis, 2016], materials, tools [Cheng et al., 2011] and equipment [Ibrahim and Moselhi, 2016]. The position monitoring of the different resources can reduce the time loss, by avoiding shortage of materials, malfunction or any unnecessary stops. It can be an outdoor or indoor problem [Ibrahim and Moselhi, 2015] with different difficulties. Detailed investigation on the topic and evaluation of different technologies in case of construction sites is the topic of thesis of section 4.1.2.

Machine vision can help the optimal going of construction processes and transport etc. in many ways. It can enhance safety by predicting the movement of workers and equipment [Zhu et al., 2016], being used for action recognition

[Yang et al., 2016], guiding autonomous robotic assembly [Feng et al., 2015], surveying the construction process [Siebert and Teizer, 2014] or structural health monitoring of bridges [Riveiro et al., 2016]. The most important applications in point of view of the dissertation (theses of section 4.2 and 4.3) are the ones related to object recognition. Like the one in [Kim et al., 2016] where high number of category were recognized or in [Fang et al., 2018] where Convolutional Neural Network (CNN) was used to detect workers. 3D vision applications are especially important even within this topic e.g. [Xu et al., 2018] where the authors achieve voxel-based segmentation of construction site point cloud, or [Chen et al., 2018] where well-known point cloud descriptors were evaluated for object recognition in construction applications.

Camera systems are standard factory equipment on construction machinery. Applying radars is also a common practice for machines and vehicles to move in a more secure and efficient way and increase the field of view of the operator. Nowadays, autonomous hauling systems have been operating over a decade (the first one was started by Komatsu) and these require various Obstacle Detection Systems (ODS). Beside that, there is a very little application of active safety technology in construction machinery, despite the hazardous equipment. Volvo has just recently started a development about using LIDAR for increase safety. This shows that construction industry has a great potential to accept range-sensing technology and intelligent methods based on that.

In industrial environment applying 2D LIDARs on automated guided vehicles is common practice for decades. These sensors operate as safety equipment (stopping the vehicle in dangerous situation), warn the vehicle about hanging crane hooks or objects jutting out of the shelving (based on their installation pose) and used for navigation purposes. However, they are rarely used to increase the vehicle intelligence for example with object recognition.

3 Methodology

First, I developed a new Multi-criteria Decision Making (MCDM) Method. This is based on the KIPA (Kindler and Papp) decision making method and fuzzy logic. Fuzzy logic is a frequently applied tool for dealing with uncertainties, within that topic I applied the theory of hesitant fuzzy sets to consider multiple decision makers.

In the second sub-thesis of the first thesis I analyzed available fleet tracking methods. In order to do that I used the Guilford method to determine criteria weights and KIPA method for establishing preference order between some of the most popular vehicle localization and data transfer types in different scenarios.

In the areas of image processing and 3D image processing the corresponding literature is extensive. In case of 3D image processing more and more depth sensors are appearing inspired by autonomous driving (e.g. high resolution Velodyne VLS-128[1] or solid state LIDARs like Quanergy S3[2]) and new types of data like point clouds have to be processed. There are numerous, publicly available databases and algorithms. The most known database is the KITTI [Geiger et al., 2012] and library is the Point Cloud Library (PCL) [Rusu and Cousins, 2011] in case of 3D image processing. The availability of these can be an advantage, because newcomers can acquire knowledge quickly, the ownership of expensive sensors are not necessary and the available algorithms can be easily extended. However, this results this field to be a very competitive area. The correct evaluation of an innovation at least as important as the idea itself. The methods has to be reproducible and comparable to other ones on public data; the scientific result has to properly presented to reach significance.

In case of theses related to 3D image processing, I developed methods for the recognition of partial point clouds of varying degrees and situation. To do this, beside the own developments, I applied and extended point cloud processing methods, known from the literature. Including, but not limited

[1] https://velodynelidar.com/vls-128.htm
[2] https://quanergy.com/s3/

to: Random Sample Consensus (RANSAC) variant based ground plane detection [Torr and Zisserman, 2000], Iterative Closest Point (ICP) for frame registration [Besl and McKay, 1992], Euclidean clustering for object segmentation [Rusu, 2009] or 3D Harris for key point extraction [Sipiran and Bustos, 2011]. Naturally, the evaluation was done in public databases ([Veltkamp and Haar, 2007], [Geiger et al., 2012], [Borcs et al., 2017]) as well. In case of both systems prototypes were prepared in Matlab programming language and environment, later C++ implementations were done as well. These have been partly introduced into industry, and the conditions of operation are determined by real environmental factors and requirements.

4 New scientific results

4.1 Thesis: Applying and developing decision support for route optimization of mobile machinery

I developed a new decision support system and method for the sub-tasks of route optimization (layout determination, tracking). I applied them for construction automation tasks.

The automation level of mobile machines and related processes (eg. selection, map design) is not high enough yet in the practice. Exploiting this potential has been targeted by the research summarized in this thesis (and sub-theses) on decision support.

4.1.1 Sub-thesis: Application of Hybrid MCDM Method in Construction Logistics

I have developed a new MCDM method that combines KIPA method and fuzzy logic. The method is able to take into account the uncertainties and the plurality of decision makers as well, in contrast to those who were previously available. This method was tested in a layout selection problem from the literature.

Optimization of building processes due to their versatility means objective function optimization with many variables. One of the decisive factors is optimizing delivery routes, but this can only be useful if another determining element, the layout is optimized (optimized paths on a poor layout will never be sufficiently effective).

To solve this decision problem, I developed a new method that can be applied to other general decision problems. The method is based on fuzzy logic [Zadeh and Bellman, 1970] and KIPA method [Kindler and Papp, 1975], which have proven to be successful in decision-support separately as well, and my hybrid method has succeeded in combining the benefits of these (mature method, multi-decision making, hesitant fuzzy sets).

In the layout design decision problem, I used ten criteria based on the principles of lean construction, determined by co-author of related publications. The method was shown by a problem from the literature.

Close related, own publications:

- [Rozsa and Sztrapkovics, 2015]
- [Sztrapkovics and Rozsa, 2015]
- [Sztrapkovics and Rozsa, 2016]

4.1.2 Sub-thesis: Analysis and Evaluation of Fleet Tracking Methods in Construction and Transport Industries

I defined a criteria system that evaluated fleet tracking methods. This assessment was done by separating traffic and the construction industry, so I helped to choose the optimal system for a specific task. Previously there was no decision support criteria system specified for this task.

In order to optimize logistic processes, it is essential to provide the optimum routes for our vehicles, and for this vehicle tracking is essential.

I examined the literature on vehicle and fleet tracking both in the construction industry [Pradhananga and Teizer, 2013] and in case of transportation [Jain and Goel, 2012]. Based on this, I developed a system of criteria that was used to compare different technologies (Global Positioning System - GPS, Sign-Post - SP, Ground Based Radio - GBR, Dead-Reckoning - DR) and propose the best for different tasks.

This comparison was made on the basis of the KIPA [Kindler and Papp, 1975] method, and finally, based on the results obtained, I proposed a preference order of application for different cases (urban transport, long distance transport, construction) for the different technologies.

Close related, own publications:

- [Kovacs and Rozsa, 2015]

4.2 Thesis: Developing a 3D Recognition System for Partial Point Clouds

I have developed a complete system that can detect partial shapes from point clouds. This methodology introduces a new scale definition based on local microstructure of point clouds, key point search procedure, local and semi-global descriptors. The method solves a so far unresolved problem of the literature, recognizing partial 3D shapes, but also gives a good result compared to State of the Art in the common measurement range.

After studying the literature, it turned out that although there are well-established pattern-recognition methods, there is no successful attempt in case of 3D partial recognition. Despite the fact, in environmental mapping of any robot, the decision as soon as possible is indispensable.

4.2.1 Sub-thesis: Local Scale Definition, and Developing a Key Point Search Method for 3D Image Recognition

I introduced a new local scale definition that is independent of the full size. This metric was successfully applied to both the key point search and the description of the local environment, what are subprocesses of our 3D image recognition.

Shape recognition can base on local or global descriptors. Since the application of global descriptors requires the knowledge of the full 3D shape (which is not possible in practice), local descriptors are used in case of 2.5D point clouds. Shape recognition systems are mostly composed of the following steps [Guo et al., 2014]:

- Key Points Search
- Description of Key Point and Local Environment
- Descriptor matching
- Hypothesis Verification

By examining the key point searching methods, I found that they lack of a very important feature: repeatability (finding the same key points in the same shape, and similar ones on similar shapes). Therefore, I have been suggesting a Harris [Sipiran and Bustos, 2011] keypoint search which is acknowledged method in image processing. Since previously it was used only for mesh models, I first developed a version of it applicable for point clouds.

The problem of partial recognition has not been solved before because of the lack of a proper local scale definition. In the absence of the absolute scales, we can not estimate how big the overall shape will be.

Starting from the measurements of the modified Harris method based on local curvature, I defined a new local scale definition; this helped both (as a part of the descriptor) of the partial point cloud recognition and the improvement of the repeatability of the Harris method. We assign an environment to a particular type of keypoint within which we no longer find new key points.

4.2.2 Sub-thesis: Local Pattern Definition Suitable for 3D Partial Recognition

I introduced a new local pattern definition, whose basis is built on subgraphs constructed from heterogeneous keypoints. This pattern was used for sequential recognition of partial point clouds. The efficiency of the method was verified with artificial and real tests.

Recognition of the shape, such as environmental objects of vehicles and machinery, plays a very important role in safe transport, whether it is an autonomous or conventional vehicle. The decision must be done as quickly as possible. Therefore, I have developed a method for detecting the partial point clouds, which continuously improves recognition accuracy through 3D recon-strution of the sequenced environment. Among others, AGVs have the option of 3D reconstruction and sequential recognition, with availabe both locating system and LIDAR sensors.

In the literature, previously, the recognition of partial clouds is not addressed, it proved to be too difficult. So the Bag of Features [Csurka et al., 2004] method of 2D image processing, was the starting point for my method. With my previously developed keypoint finder method, I found stable keypoints with a well defined environment based on the scale definition. Thus, it extends an environment (forming a heterogeneous graph from 3 closest neighbors) to a semi-global descriptor that no longer describes only one surface but not yet characterize a complete shape either. Thus, it could be well applied for partial recognition, e.g. for the description of body parts and parts.

The effectiveness of the developed method was first tested in public databases and then experimentally proved in real-time cloud sequences in several steps, in different environments, in different shapes.

Close related, own publications:

- [Rozsa and Sziranyi, 2016a]

- [Sziranyi and Rozsa, 2016]
- [Rozsa and Sziranyi, 2016b]
- [Rozsa and Sziranyi, 2016c]
- [Rozsa and Sziranyi, 2017]
- [Rozsa and Sziranyi, 2018a]

4.3 Thesis: Developing a Shape Recognition Method for Planar Scans

I have developed a shape recognition algorithm that can detect even in instances does not satisfy the 3D sampling theorem in vertical direction. I have developed a shape recognition algorithm that can detect objects from one plane of LIDAR scanner. If multiple scanned plane information is available, the method can also consider this. I proved the effectiveness of the method on a large public database.

Vehicles, mobile machines are very often equipped with 2D or occasionally 3D LIDAR sensors. On the one hand for safety considerations, and on the other hand to increase the intelligence of the machines. In case of 2D LIDARs, a very small amount of information can be obtained from 2D contour points recorded in a plane, which is hardly usable for recognition. For 3D LIDARs [Maturana and Scherer, 2015] there is similar situation, if the object is far from the LIDAR, the shape we want to recognize can be visible in only one plane.

By examining the literature [Beyer et al., 2017] [Kurnianggoro and Jo, 2017] - in case of recognition from contour points -, I found that the available methods do not take into account that if a particular object is examined at a certain height (this is not a criterion for my method) or the fact due to the movement of the object, the image scene changes continuously. Thus, my method beside of using a descriptor not yet used for this problem (Fourier [Cooley et al., 1969]) is also novel in taking into account how the shape changes in consecutive frames.

In addition to the above, I suggested a simple maximum likelihood scheme in case there might be more than one scanned plane of the object. I tested the performance of the method on tens of thousands of samples that came from a public database and own measurements; also investigated its performance as a function of how many frames we track. Compared to the previous literature, it proved to be even more successful already in the most basic cases.

Close related, own publications:

- [Sziranyi and Rozsa, 2018]

- [Rozsa and Sziranyi, 2018b]
- [Rozsa and Sziranyi, 2019b]
- [Rozsa and Sziranyi, 2019a]

5 Practicional applicapiblity of the results

Many of the research results have been included into various teaching materials taught by BME-ALRT (Construction Logistics, Image Processing). This demonstrates the theoretical significance of research. I summarize the practical applications as follows.

Using the criteria that take into account the principles of lean construction in the first thesis, professionals in the construction industry can make a thorough decision about the layout design problem. The decision support algorithm can be applied to any general decision problem.

The second sub-thesis of the first thesis provides guidance to fleet trackers on the question of what kind of method to use, and the article containing the thesis is a thorough comparison that helps new entrants to the area.

The second thesis aims to increase the mobility, the autonomy and the intelligence of mobile machines, vehicles. The methods presented, contribute to real-time operation so that, even without modification, methods can be applied to autonomous machines. Real scenarios are tested on Automated Guided Vehicles.

The third thesis helps the recognition task of high speed (e.g. construction transport vehicles) intelligent vehicles. The developed framework was handed over to an automotive supplier. The method is currently being tested in different situations occuring in case of an autonomous truck.

In case of both environment perception systems (subjects of second and third theses) real-time applicability was a requirement.

In the dissertation I report numerous results. Most of them are aimed at developing construction and mobile machine automation, but without exception all results can be applied in other areas as well.

6 Future research plans

The promise of the achieved results and the actuality of the research topic foresees that I will continue to pursue the research that has begun in the same direction in the future. I would also like to look at the applicability of the method of supporting the developed decision to other problems with construction automation. In addition, I would like to put more emphasis on the practical application side in the future. I plan to track the machines and analyze their environment to a level where even the automatic assignment of different machines can take place by focusing on environment perception.

More specifically, I would like test the developed object representation by applying it to other type of neural networks. I plan to extend my investigations to different sensor modalities (e.g. camera), new localization algorithms (e.g. SLAM) and new problems (e.g. change detection). This will require measurements in diverse scenarios and environments. The theme of the dissertation can be the basis of a future subject on the topic 3D image processing applications in autonomous driving and intelligent transportation.

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