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Introduction and the history of the research

Different sensors and sensor-systems are often used in robotics so that a robot can (to some extent) explore its surroundings (the obstacles and the objects that characterize its environment) and react to the presence of these characteristics, if needed. The computer vision-based systems have a key role in these devices, because – with their help –, a great amount of information can be obtained. I have been developing robotic systems based on image processing and other sensors since the nineties. My first results appeared in the topic of an automatized classifying system with learning capabilities, and visual route planning using a neural network [VZ4], [VZ22], [VZ23], [VZ24].

Later, several mobile robots were developed under my leadership, and almost all of them used (near other sensors) traditional and omnidirectional cameras as well. This thesis focuses on the results I achieved on this field during ten years of research. So the dissertation concludes the achievements of a longer development process, and during this period, many new technologies and devices appeared, became widespread, and brought different approaches and methods. This process can be demonstrated using simple examples: firstly, at the start of the nineties, live camera pictures could only be analysed using expensive digitalizing cards, while nowadays, cheap and excellent quality web cameras that can be connected using a USB interface are very widespread. Secondly, the increasing spread of different GPS devices and software components provide us with totally different possibilities than what we had around 2000, when the accuracy of the GPS system was artificially distorted. At that time, the OEM GPS receivers only provided us with the basic data, without any supplying software components. The continuous change and improvement supplied us with numerous new tasks and possibilities.

I involved some of my inquisitive students into the researching and resolving of different sub-problems. This co-operative works (where I was their supervisor) have had excellent results in the National Scientific Conferences of Students (8 first, 5 second, 6 third prizes, and special prizes), in different national and international exhibitions, and they were published as well. In these publications I identified the student co-authors, and here I would like to thank them once again for their persistent work.

Sight is the most powerful human sense. Sensing the environment around us allows us to do several movements that are limited by our world. Humans usually perform these high-performance movements without specifically understanding how this process works. Lots of researchers, from psychologists to engineers, work on the complex problem of visual perception. Our common goal is to develop an artificial vision system that allows us to investigate how a robot could efficiently, in a robust way, use the visual information that is really only two dimensional to aid its operation in the three dimensional space. The developed sensor system can allow the robot to do simple everyday tasks like “go to the end of the corridor, and then turn right”.

In every sensor system, should it be human or artificial, the critical component is the perception itself, which is the way that we use to collect the environmental information. It is an important observation in the field of biology that the geometry of the optical lenses varies a lot amongst different species. Most of the insects and the primates obtain visual information from a relatively wide field of view, and their eyes are capable of depth-variant segmentation and focusing. The perception capacity of these species can be explained with the specially adapting geometric changes in their eyes. Similarly to this, in this thesis we study the advantages of a very wide field of view solution that is achieved by an omnidirectional camera, so the horizontal field of view is 360 degrees [1].

Every time we receive an image from an omnidirectional camera, we have the problem of processing it. The main question is how should we process the image? Should we use it to form an internal model or representation of the outside environment? Can these pictures provide us information about the environment without detailed internal representation [2]? This basic question has been a long-standing problem for computer vision specialists and it has also been one of the central questions for the understanding of visual perception.

In the middle of the twentieth century, Gibson [3] introduced a new approach of the field of vision. He emphasised the importance of the optical array, saying that its invariant properties determine every information of the environment (structures and events as well). According to his theory, the information can simply be “picked up” by the observer as soon as the observer moves in the environment. Because of this, Gibson stated that the perception is *direct*: the perception and the intervention are strongly related, without the need of an internal representation. The complexity of the environment is a given factor, it is impossible to process everything at once, so the theory emphasizes that perception is based on selective attention mechanisms.

In 1982, Marr’s work [4] introduced the computerized approach of the vision, establishing the bases of modern computer vision. In this work, he

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described the sequential and modular synthesis of the visual perception, where the internal representation, the internal model was the starting point. This *indirect* approach is fundamentally different than Gibson’s approach. According to this computerized method, first he starts with a preliminary scheme that has information about regions and boundaries of the picture. Starting from this representation, he continuously builds up a scheme with 2½ dimensions that is determined by the position of the observer and the position (distance) and orientation of the object. At the end, he prepares the 3D model of the environment where the perception is independent from the observer.

In the visual perception, my approach follows the indirect technique in building the model of the environment. In this meaning, I follow Marr’s method, but unlike his approach, I do not create a detailed internal representation continuously for every state. Instead, I focus on creating a representation that is suitable to complete the task. For example, if we are moving on a street, then it is sufficient if we know our position by the accuracy of one house block. But if we want to enter into one of the buildings through the door, then we need a substantially bigger precision. The internal representation of the environment must be customized for every navigational task, and we have to collect the necessary information according to that task. For example, in numerous cases, animals alternate the “milestone” or “signal”-based navigation with integration methods for an approximation path, if necessary [5].

When the robot must make long distance movements, then for the perception of the world we use an appearance-based environmental representation. For tasks that require greater precision (like approaching the docking position, or going through doors) the perception switches from the appearance-based technique to a technique where there are bigger emphasis on the image features. These two different operations can be described using two separate models, and they are named topological navigation and visual road tracking.

The long-distance (less precise) and short-distance (more precise) sensor modules play an important role in the efficient and robust solution of the robot navigation problem. This approach is important, because many times the important thing is not the usage efficiency of these models, but the emphasis is rather on making the world model itself.

In my thesis, using self-made mobile robots usually equipped with image processing sensors, I examine the solutions of sub-problems that occurred during the navigation because of different working environment conditions.

1 Research goals

In the dissertation, with the help of self-made mobile robots, I examine the solutions of sub-problems that occurred during the navigation and that should be solved on the base of some (micro or macro) working environment condition. The research activity and the thesis aim at describing the navigational sub-problems (avoiding obstacles, mapping the environment, path planning and navigation) and the examined possible solutions as well.

1st goal

First I study the possible solutions for indoor navigation and avoiding obstacles using different sensors and PAL optics. I search for solutions for avoiding obstacles, route planning, occupancy grid representation, and vector-based environment mapping.

1st sub-goal: I examine the route planning algorithms in the aspect of their usability with signals from a simple sensor-group, assuming small – microcontroller-like – computational possibilities. Then I compare these in the case of occupancy grid map-representation. I plan to use the solution for the navigation of a four-legged robot using the signals from its retro-reflective optical sensor group. I will work out an image processing method using PAL optics that will be capable of the real-time processing of the mobile robot's field of view, and using this, it will be capable of avoiding obstacles.

2nd sub-goal: I search solution for an obstacle detection and environmental mapping method, where data can be represented in a very compact form. I examine image processing with structured lighting and its usage using a self-developed laser sensor, and the fusion of other data from sensors with different principles. My aim is a general solution, where data from different sensor sources can be merged easily.

2nd goal

I develop methods for outdoor localization tasks; I examine the use of OEM GPS, the different ways of increasing the precision of localization data in known environment, and the environmental mapping using a sequence of images created with an omnidirectional camera.

1st sub-goal: I search for solution for an outdoor coarse localization using a GPS. I study different GPS sensors, and run tests to determine

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how precise I can determine the position of the robot with the different sensors. I investigate different ways to increase the accuracy of the location given by the GPS sensor in a known environment using images taken by an omnidirectional camera.

2nd sub-goal: In the form of a computer software I implement a method that (by transforming the central part of omnidirectional images taken from above the robot) can build a topological map for navigating mobile robots. Using the prepared map, I plan a route for the robot, and I test the results using a self-made wheeled mobile robot.

3rd goal

The third goal is to find solutions for specific problems in the field of robotics. Problems like the method of developing stepping strategies for walking robots, and practical implementation of mobile robot navigation and obstacle avoidance. The last problem is the real and effective improvement of the resolution and the quality of the used omnidirectional images, so that as many details can be taken into account by the previous tasks as it is possible.

1st sub-goal: I develop a statically stable stepping strategy for a self-made four-legged walking robot, and I examine the possibilities of developing a stepping sequence that will give the robot some dynamic stability and a faster forward speed. I develop a movement-editor software that makes it possible to easily develop stepping strategies for the self-made six-legged robot.

2nd sub-goal: Using self-made and self-developed wheeled and walking robots I introduce the physical implementation of the previously mentioned goals, I point out the usage possibilities for the algorithms and methods developed for navigation and environmental mapping. On a traditional camera picture I examine the possibility of using optical flow calculations for detecting obstacles.

3rd sub-goal: As a specific solution, I show how to improve the quality of the picture of PAL optics and omnidirectional sensors, enhancing their usability in complex navigational tasks.

2.1 Optical flow techniques

Under optical flow [6] we mean that the movements of picture intensities are shown on the consecutive images. Let *I(x, y, t)* mean the intensity of a picture at a given time. The picture must be the part of a picture series that must change over the time. We can make two assumptions:

- on the bigger part of the picture, the $I(x, y, t)$ intensity is hardly dependent on the x, y coordinates;
- the intensity of the points of the moving or stationary objects are (essentially) unchanged over the time.

Let us suppose that there are some objects on the picture (or only some pixels) that during dt time (practically this means that between the times when the two images were taken) move a distance of (dx, dy). By calculating the $I(x, y, t)$ intensity values into Taylor series and using the second assumption, we get to:

$$-\frac{\partial I}{\partial t} = \frac{\partial I}{\partial x}\frac{dx}{dt} + \frac{\partial I}{\partial y}\frac{dy}{dt}. \qquad (2.1)$$

This expression is usually called the conditional equation of optical flow (or simply the optical flow restriction), where $dx/dt=u$ and $dy/dt=v$ are the optical flow's two components in the x and y directions.

For different types of image inputs, different optical flow algorithms can give different results [7], so it is advised to choose from the available algorithms based on the type of the input data, so that the resulting vector field is the closest possible approximation to the real physical movements of the actual objects on the images. Usually, two close video frames are used as input images.

To find the matching pixels, the optical flow algorithms expect that the intensity of matching pixels is almost the same. Almost all methods are based on this assumption, which is called *optical flow restriction* [7], and which was described in the previous point. The equation contains two unknowns (u, v), and to solve the equation, the following techniques are the most widespread [7]:

- Differential methods: Older technologies, but they are reliable, even the newer methods could not bring significantly better

The * character marks the students who were involved in the research, and who received a prize in the National Scientific Conference for Students, and for whom I am thankful for their work. The (*Ref. n.*) stands for an independent citation for my given publication.

Journal publications

[VZ1] Nagy, A.*, Vámossy, Z., „Super-resolution for Traditional and Omnidirectional Image Sequences", *Acta Polytechnica Hungarica*, Vol. 6/1, Budapest Tech, 2009. pp. 117–130, ISSN 1785 8860

[VZ2] Vámossy, Z., „Map Building and Localization of a Robot Using Omnidirectional Image Sequences", *Acta Polytechnica Hungarica*, Vol. 4/3, Budapest Tech, 2007. pp. 103–112, ISSN 1785 8860

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Publications in international conferences' proceedings

[VZ5] Nagy, A.*, Vámossy, Z., „OpenCV C# Wrapper Based Video Enhancement Using Different Optical Flow Methods in the Super-Resolution" In: *Proc. of 6th International Symposium on Intelligent Systems and Informatics*, Subotica, Serbia, September 26-27, 2008, ISBN 978-1-4244-2407-8

[VZ6] Vámossy, Z., „Topological Map Building from PAL Images with Navigation Purpose", in *Proc. 6th International Symposium on Applied Machine Intelligence and Informatics*, Herl'any, Slovakia 2008, pp. 217–220., ISBN 978-1-4244-2106-0, IEEE C. N.: CFP0808E-CDR

[VZ7] Vámossy, Z., „Map Building and Localization of a Robot Using Omnidirectional Image Sequences", in. *Proc. 4th International Symposium on Applied Computational Intelligence and Informatics*,

4 Utilization possibilities and further research plans

Utilization possibilities for the achieved results

The achieved results are not only usable in the presented research tasks, but some of them resulted in a more general solution. The image processing library developed for the PAL-optics camera positioned on the lower side of the walking robot can (with minimal amount of modifications) even function as a security software. By placing the camera to the ceiling, even a large area can easily be supervised. The developed GPS system was successfully tested on vehicles as well, and the results displayed on the map were correct. The system that implements the super-resolution technique uses a generalized solution, so it is capable of transforming a small-resolution image sequence (e.g. an old-fashioned TV broadcast) into a nowadays expected higher resolution (HD quality) images.

Improvement possibilities

Naturally, many other development requests can be formed. When transforming the PAL images, right now only the virtual top-view images are used to generate the maps. In an indoor environment, the panoramic area of the images contains well identifiable parts of some objects that could be easily used for creating topological maps and for appearance-based navigation as well. These features could be for example the vertical edges of doors, which can be seen as radial lines in the ring image.

During the movement of the robot, different navigational properties could be obtained from the optical flow. For example, if the robot is moving forward in a corridor, then we could generate a control signal from the difference of the two optical flows on the sides to stay in the centre line.

Figure 4.1. CCExplorer with forward looking traditional camera and with omnidirectional system

quality results. As for their motion model, they belong to the parameter-less algorithms;

  - Horn–Schunck method [6];
  - Lucas–Kanade method and its pyramid variant [8]
- Correlation methods (block matching) [9].

2.2 Neural networks

The neural network is a multi-processor computer capable of parallel data processing [10]. The single processors are called neurons (or cell processors); they have the task of implementing a transfer function that is relatively very simple compared to the processing power of the combined system. These neurons can be interconnected in different ways, and these connections determine the topology. The network has three main characteristics: the processors, the topology, and the training method.

The processors first calculate the weighted sum of the signals on their input pins (W_{ij} is the weight for the connection between processors *i* and *j*), then they calculate their output using a transfer function. The most common transfer functions are step functions and the sigmoid functions.

The topology means the connection system of the cell processors, which in the simplest case can be simply feedforward, feedback, or the combination of the two. In case of a feedforward neural network, the signals always move from the input to the output, while in the case of a feedback network, in more or less cases, the signals can move backwards as well.

The main types for the training method are the supervised learning and the unsupervised learning. The most common learning rules are the so-called Hebb rule and the Delta rule.

3 New results, theses

From the mid-nineties, I created several mobile robots – with the help of students involved in the research –, and almost all of these robots had (in addition to other sensors) traditional and omnidirectional cameras as well. The thesis presents the achieved results and solutions on the area of building robots. The dissertation concludes the achievements of a longer development process, and during this period, the connecting technologies and used methods had improved, and they offered new and different approaches.

In my dissertation I examined the solutions of sub-problems that occurred during the navigation and that should be solved on the base of some working environment condition. My results can be divided into three groups and can be summarized as the following.

Details about the solutions in the mobile robot navigation in *indoor environment*, using different sensors and PAL optics area:

Theses I.: My results in connection with obstacle avoidance, route planning, occupancy grid representation, and vector-based environment mapping:

Thesis I.1.: *I implemented and compared route planning algorithms in case of occupancy grid representation. I developed an image processing based method for real-time monitoring of the leg surroundings of a four-legged walking robot and for obstacle avoidance using PAL optics.*

In the developed EXPLORATORES II. robot system [VZ19], [VZ21] I used maps created with retro-reflective optical sensor group and occupancy grid representation to compare different ruleset-based, neural network and potential field calculation supported route planning methods with learning capabilities. I pointed out the usability of different techniques, along with the advantages and disadvantages, thought some of the disadvantages occurred partly because of the representation's and the implementation's high memory requirements. I improved the wave-propagation based algorithm so that it can produce a correct result even in a previously unknown environment [VZ20].

I gave a solution for a problem that occurs with walking robots using image processing for pictures taken with PAL optics. I created an image processing library that (when incorporated with a four-legged robot [VZ16], [VZ17]) can process the pictures of the omnidirectional camera positioned at the bottom of the robot in a real-time way. Using the camera picture, the library

Thesis III.3.: *Using a self-made robot, I presented a method to significantly improve the quality of the image of the PAL optics and the omnidirectional sensors, and this way I presented a more efficient applicability of those in complex navigational tasks.*

I examined techniques to improve the quality and the detail of PAL optics image sequences using the super-resolution technique. Using this opportunity, we could further improve the accuracy of the easily accessible location and orientation data that allows us to obtain even more precise environment maps and obstacle positions. I implemented different optical flow techniques (section 2.1.) and I compared them in the aspect of quality improvement [VZ5]. The developed super-resolution system can process any kinds of video sequence and – in the case of PAL images – it creates a detailed omnidirectional image sequence [VZ1].

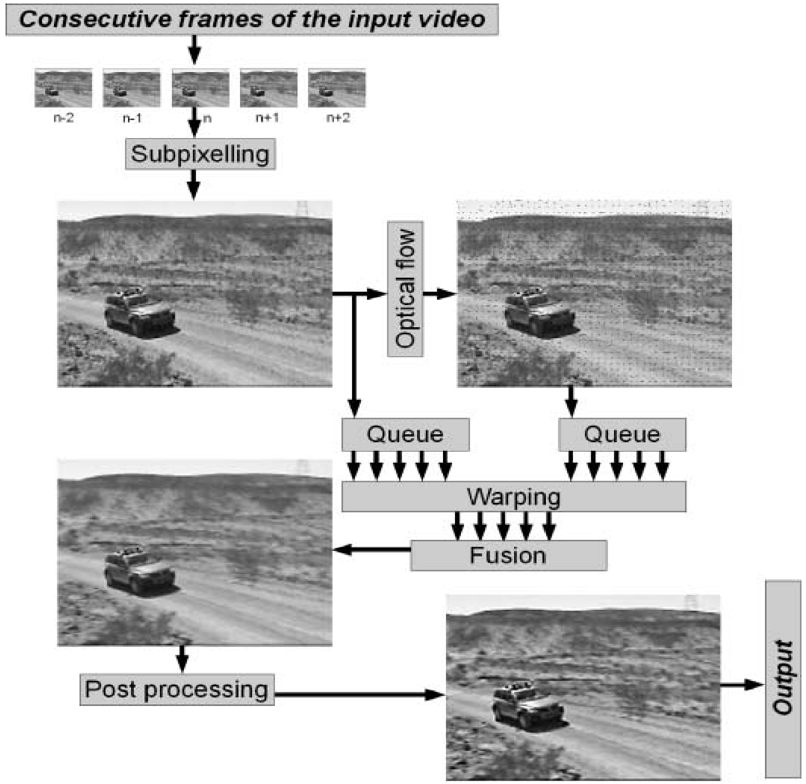

Figure 3.13. The schematics of the implemented system [VZ5]

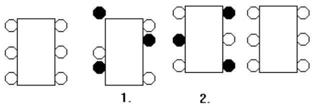

Figure 3.10. Tripod movement

Thesis III. 2.: *In the case of self-made wheeled and walking robots, through the physical implementation of the previous theses I presented the operation of the developed navigational and environment mapping methods.*

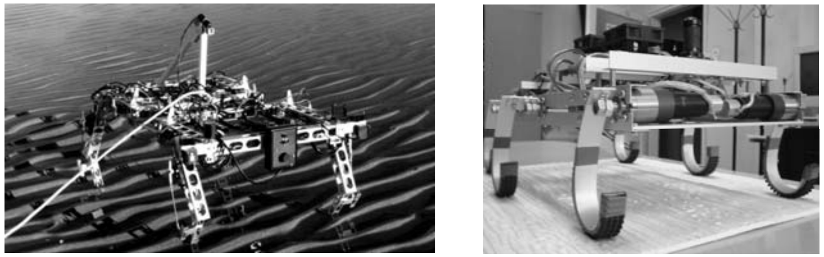

Figure 3.11. EXPLORATORES II. quadruped FOBOT the six legged robot

Amongst the developed wheeled mobile robots and navigational systems, it was the CCExplorer that I presented in details [VZ15]. The robot detected its working environment using optical flows (Figure 3.12.), it localized its position using GPS and later it refined its position in a known environment using the omnidirectional PAL optics image [VZ9].

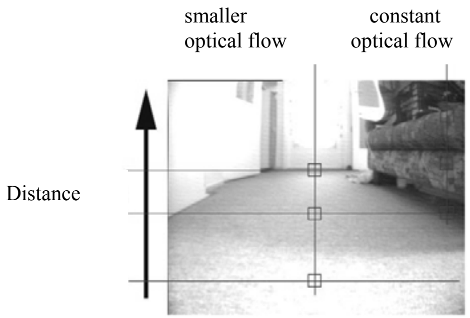

Figure 3.12. The principle of measuring depth data in a two-dimensional image

could detect the local position of the legs, so it made the collision-free, safe movements possible.

Method (*algorithm*)	*Environmental condition*	*Advantage* (a) / *Disadvantage* (d)	*Improvement suggestions, remarks*
Rule-based	Unknown	a: Can be implemented in a microcontroller => autonomous d: Must be prepared for all conditions, small efficiency, not always finds the exit	Can be improved by storing the last step
Neural networks	Unknown	a: Some conditions can be left out, d: the learning process must be tested, not always finds the exit	Can be improved by storing the last step
Observation collector	Unknown	a: Can be efficient in a known environment, d: Not always finds the solution	Self-made method
Wave-propagation based method	Known	a: If there is an exit, then it will find the shortest path, d: Big memory requirements	Improvement: Better computational efficiency in case of 8-neighbourhood
Improved wave-propagation based method	Unknown	a: It finds the solution, d: Not globally optimal	Own results
Graph search based	Known	d: Very high computational demand	
Image processing based	Unknown	a: Real-time operation, d: Sensitive to illumination, local technique	Own result

Table 3.1. Summary of the examined route planning algorithms

Thesis I.2.: *I presented a method of obstacle detection using structured illumination and image processing that can be used in robot navigation.*

I also investigated other approaches for integrating sensor data with maps. I defined a more compact, vector-based representation that is also capable of generalization [VZ12] and handling several sensors' data at once. I successfully tested the system using a self-developed laser sensor with structured light and ultrasound sensors [VZ10] (Figure 3.2).

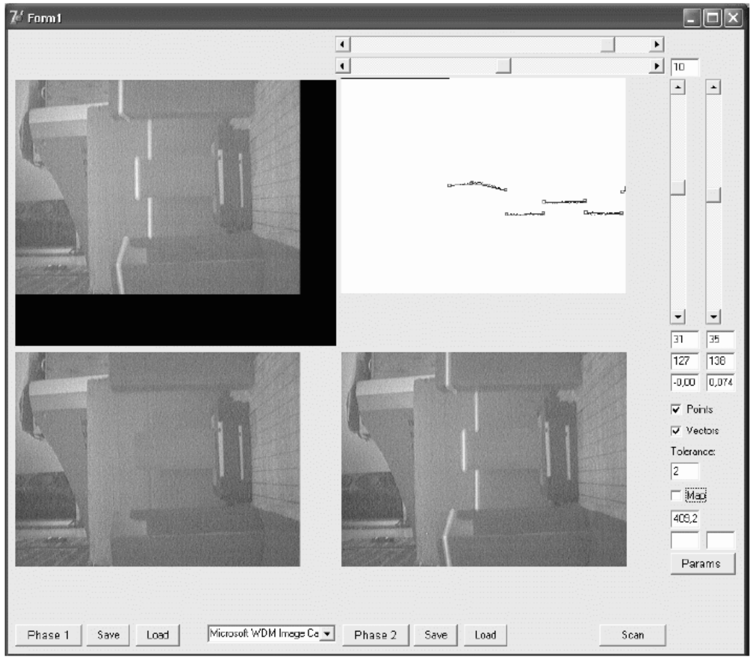

Figure 3.1. The user interface of the system. Input image with and without laser light on the bottom, blurred image on the top-left, the (rotated) result of the vectorization on the top-right

The main principle of the laser sensor is the following: the projector shoots a laser beam onto the observed object, and then the beam is reflected back to the sensor. According to the structured light method, we can make estimations on the shape of the object shape and distance based on the distortion. After calibration, we can definitively determine the distance of the object from the position of a reflected line segment. The measurement method can be seen on figure 3.2. On the figure, *d* is the focal length (the distance between the CCD and the focal point), *z* is the distance between the object and the focal point, *h* is the length of the laser line segment, *h’* is the length of the line segment we see on the camera picture, and h_{max} is the maximal length. Because of the similar triangles rule:

$$d / h' = z / h, \qquad (3.1)$$

The example (Figure 3.8) shows the phases of a step forward. The filled circles (●) represent the legs that are currently touching the ground (they are the supporting points), and the empty circles (○) represent the lifted legs. Arrows mark the movements of the legs and the body.

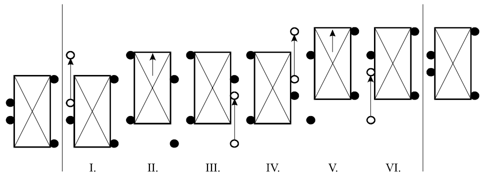

Figure 3.8. Movement strategy for one step forward, four-legged robot [VZ21]

The FOBOT six-legged robot has legs that perform rotating movements, and these rotations had to be properly synchronised to move forward. To achieve the accurate timing, I developed a movement editor program (Figure 3.9.), that (after successful simulation tests) sends the properly set and timed command sequence to the robot. The movement of the legs can be tested separately or together. In the latter case, it is possible to create stepping strategies – strategies tripod (Figure 3.10.), quadropod, and „caterpillar” were developed –, and it is also possible to watch the change of leg-positions in a numerical and in a graphical representation as well [VZ14].

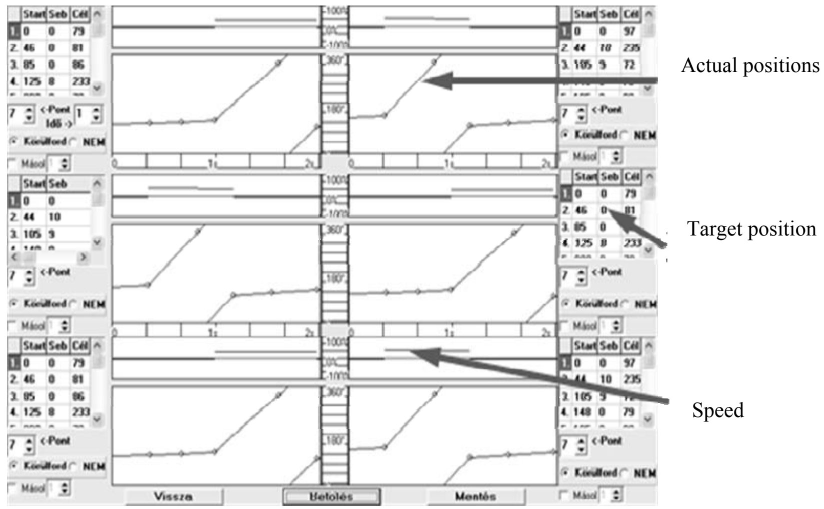

Figure 3.9. Movement editor

previously mentioned specially trained neural network (Figure 3.7.). During the search for the road or line or path, the free parts on the map are determined using adaptive binarization and the required route to the finish is determined using the wave-propagation based algorithm.

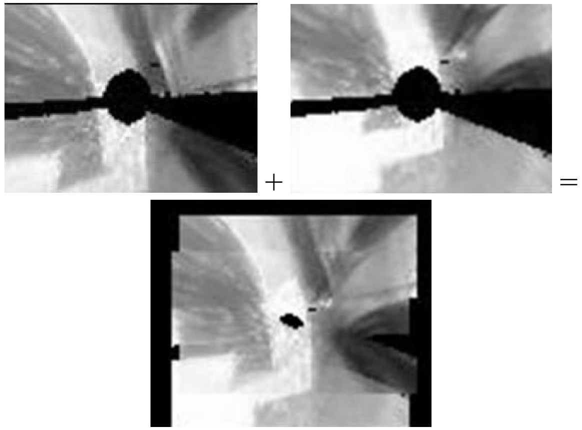

Figure 3.7. Merging virtual top-view PAL pictures [VZ2], [VZ6]

After this, I presented solutions to *specific problems in the field of robotics*, such as the method of developing stepping strategies for walking robots, and practical implementation of mobile robot navigation and obstacle avoidance. The last problem is the real and effective improvement of the resolution and the quality of the used omnidirectional images, so that as many details can be taken into account by the previous tasks as it is possible.

Theses III.: Results achieved in implementing and navigating profession-specific mobile robots:

Thesis III.1.: *I examined the stepping strategies on self-made four-legged and six-legged robots and developed a movement-editor software tool that makes it possible to easily develop stepping strategies.*

In case of walking robots, one of the basic tasks is the development of a properly aligned and stable stepping strategy. With the four-legged robot, I developed a statically stable movement sequence for forward and backward walking, rotation, and sidling. Then, to achieve a faster walk speed, I developed a variant where the forward movement itself was the dynamic stabilizer [VZ3], [VZ19], [VZ21].

from this, taking the pitch angle (α) of the camera into consideration, we get:

$$z = \frac{d\,h_{\max}}{h' + d\,tg\alpha}\,. \qquad (3.2)$$

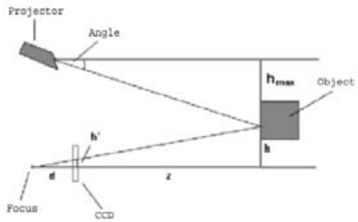

Figure 3.2. Measurement using structured light

In *outdoor environment* I presented solutions for the localization task (usage of GPS, making the GPS location more accurate in a known environment), and for the map generation task. I also presented a solution for the omnidirectional based localization.

Theses II.: My results in connection with outdoor navigation and omnidirectional based environmental mapping:

Thesis II.1.: *I gave solution for the outdoor coarse localization of a mobile robot using GPS. I developed and implemented a method to refine the GPS location in a known environment using omnidirectional images.*

In outdoor environment, it is preferred to combine the vision-based techniques with other sensor data. Following this suggestion, I examined GPS-aided coarse localization in the developed system (Figure 3.3.) [VZ11], [VZ13], [VZ14].

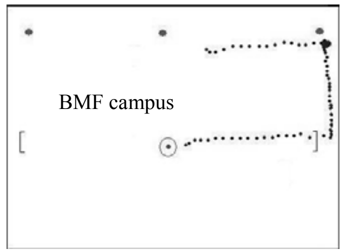

Figure 3.3. Test of the navigational system with a robot [VZ14] (Marks: handball goals: [, centre field: circle, light posts: 3 big dots at the top, waypoints: smaller dots)

I presented that assuming a known environment, how to improve the localization of our CCExplorer robot [VZ14] using an omnidirectional camera. As a few known features appeared on the ring image of the omnidirectional camera, with analyzing these features and some 3D geometrical calculations, it was possible to refine the mobile robot's position, and decrease the GPS error with about 50%. In addition to the localization information, the image helped us to determine the orientation of the robot as well [VZ9].

The feature points were found using the Harris method, and the feature tracking was done using the Lucas-Kanade technique. The localization was corrected with at least half of the error, depending on the robot's relative position to the known feature points.

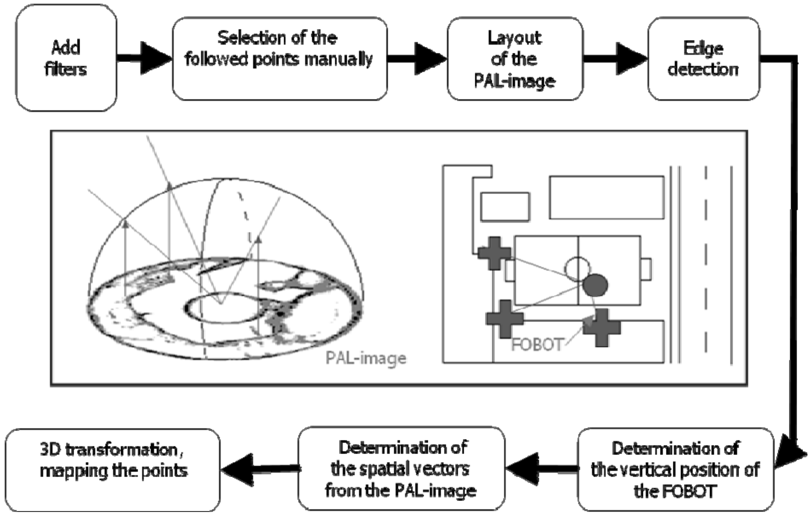

Figure 3.4. The main steps of the localization and the sketch of the testing environment (the football field at the former campus of Budapest Tech) [VZ9]

Thesis II.2.: *To aid the navigation of mobile robots, I developed and implemented a method to create topological and top-view maps.*

I presented the planning and development of a PAL optics equipped mobile robot (Figure 3.5) that is capable of autonomous navigation [VZ8]. By "autonomous", I mean the capability to perform different tasks without help, tasks like following a line, avoiding obstacles, and mainly independent localization, environmental mapping, and route following based on a known

map. The main characteristics of the developed system (Figure 3.6) is that in addition to the basic line and object following tasks, the robot is also capable of mapping its unknown environment using a hybrid method (genetic algorithm and backpropagation neural network) [VZ2], [VZ6], [VZ7]. Using this feature, the robot is capable of going to any user-defined position without any collision.


Figure 3.5. PALCOM mobile robot with PAL optics

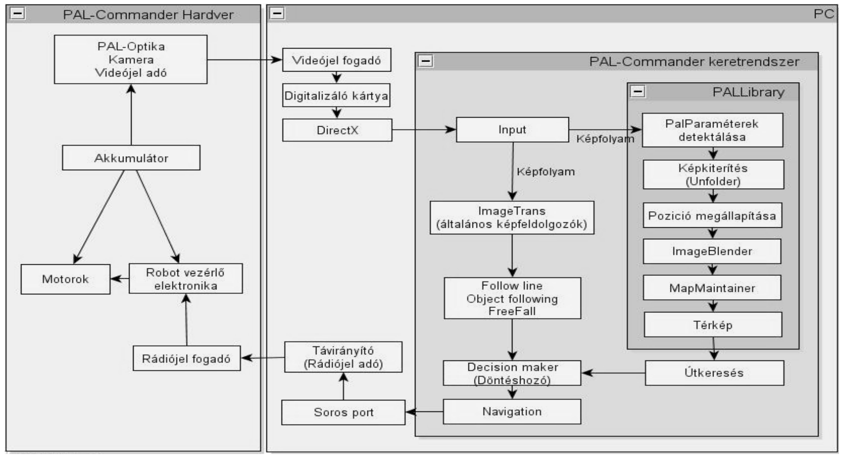

Figure 3.6. The PALCOM-system's modules and their relations

The map generation starts with transforming the omnidirectional ring-shaped image of the camera into a virtual top-view image by modifying the centre part of the camera picture so that the straight lines on the source image will stay straight lines on the transformed result as well. The resulting image parts are then merged using the so-called blending filter and the