Optimal Location and Motion of Autonomous Unmanned Ground Vehicles

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Abstract: This paper deals with an optimal location and path-finding algorithm in a real general environment. This algorithm is designed for autonomous motion of unmanned ground vehicles. Importance of this problem solution is connected with the wide application of unmanned vehicles in the modern world. The article is divided into three basic parts and covers a general discussion of the problem, definition of basic principles of our optimal path-finding algorithm, an issue of optimum maneuver in a general environment on a local and global level, and a mathematical design for our algorithm.

Key words: optimal path-finding algorithm, unmanned vehicles, autonomous motion, area reconstruction

1 Introduction

The sense and utilization of unmanned vehicles is increasing steadily all the time; these vehicles are used in many various applications, both in the civil and military area. Unmanned aerial vehicles (UAV) are used most frequently; however, unmanned vehicles are also seen operating in a different type of media: unmanned space vehicles, unmanned ground vehicles (UGV), unmanned surface vehicles (SUV), or unmanned underwater vehicles (UUV, AUV).

Development of unmanned vehicles goes in two general directions; the development of hardware, electronic equipment, sensorial, weapon and communication systems, keeps up with software innovations, particularly in the area of decision processes automation. Vehicles, which had originally been controlled by the operator from a control center, gradually became semiautonomous and autonomous devices which are able to fulfill their tasks independently on their operators.

This paper results from the long-term research in the area of unmanned aerial and ground vehicles carried out at the University of Defence in the Czech Republic. The research priorities consist not only in developing unmanned systems but also in designing and implementing the algorithms for decision process automation support, optimizing tactical tasks, automatic searching and monitoring targets, etc. [4], [5].

2 Optimal path-finding task

The task of optimal movement of an unmanned vehicle in a general environment is not a trivial one. Although it cannot be classified as an entirely new and already unsolved issue, the only possibility how to achieve some progress in this area consists just in designing and creating mathematical models and algorithms of our own since there cannot be expected that somebody else is willing to provide us with his/her results. It is obvious that such know-how is carefully protected.

In general, there can be found several different attitudes and approaches how to solve this issue. The two most frequently used are as follows:

- Environment analysis in the infrared and visible light spectrum via passive sensorial devices (cameras).
- Environment analysis via laser scanning devices.

Our project considers implementing both above mentioned approaches in the future. Currently, however, our optimal path-finding algorithm applies just the second principle when a laser scanner for the environment reconstruction process is used. This device is able to scan surrounding environment at a visual angle of 360°. As a result of the scanning process, there is acquired a two-dimensional distance map serving as the input to our path-finding algorithm. During motion of the vehicle, the map is unceasingly elaborated and supplied with the missing parts of the environment.

Currently, this project is still in the making. We are working on the development of an experimental vehicle, which is supposed to move in a general environment autonomously. In the first stage of our research, a limiting condition was determined: the scanning process is conducted only in two-dimensional space. The reason of that condition does not consist in our algorithm but in the laser scanner providing the objects distances in one plane. In the future, the full three-dimensional environment reconstruction is expected.

There are wide application possibilities, particularly in the military area. Successful and sophisticated solution will be of great benefit to all modern armies since they use unmanned vehicles in order to fulfill their tasks. Practical utilization can be seen by using in foreign missions and operations (Afghanistan, Iraq, etc.) for automatic reconnaissance, target surveillance, following persons, transportation of wounded soldiers, etc. In addition, there are various further applications in the civil area as well.

3 Optimal path-finding algorithm

Design and implementation of a general optimal path-finding algorithm [3] is a fundamental prerequisite for a problem solution of this task.

Real time path optimization in a general environment is solved in two layers: a higher and a lower layer, where the high layer is independent of level of automation of local element control and determines rough (in terms of high model resolution) path configuration on the digital terrain model. Results of that algorithm are establishment of a motion vector configuration on the particular model in available resolution and based on general tactical and geographical information.

The key point of solution consists in particular ability of parallel execution of that solution and implementation of the GPGPU concept to element processing (NVIDIA-CUDA, AMD-Stream). In these areas, there are certain possibilities that there is not possible to avoid serialization of particular phases since iteration steps of algorithm is previous result dependent; nevertheless, process solution of each phase is possible to parallelize. Here is another small complication of global memory share of particular threads of phase solution resulting in small latency in the final solution. General effectiveness is dependent on parallel process count, which can be executed in each phase of the iteration process; this number is variable to calculation process and in general point of view it is trapezoid or triangle trend, as illustrated in figure 1.

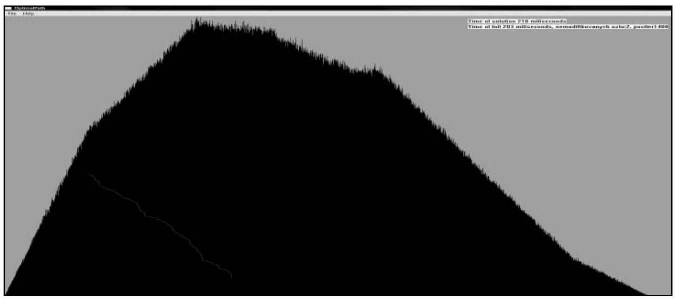

Fig. 1 Graph of number of executed threads in each phase of solution

There is an example of model containing 1 million elements and 4 millions connections, where final solution was achieved in 1,400 iterations phases, where in each phase it was possible to execute 1 to 1,286 parallel threads operating over elements as shown on a graph. Parallel solution in that case could speed up the final solution more than 100 times.

Regarding the fact that a detailed description of the algorithm or extract of its program code would exceed the scope of this article, bellow there is outlined a sequence of individual steps aggregating individual processes ensuring implementation of mainly trivial and routine sub-processes:

1. Input or creation of initiatory data mode (chart) of a traffic network, especially initiation of weight coefficients, for links of individual nodes.
2. Initiation of starting positions of individual elements and determination of destinations for each of the elements.
3. Sequencing elements in the queue for solution.
4. Calculation of an optimum path for the first element to its destination.
5. Extrapolation of timetable of the path being solved and determination of probability coefficients for a given element in given time and given segment.
6. Inserting this calculation in a table of paths and inclusion of an indicator in transit segments of the chart for this item of the table of paths.
7. Solution of path optimization for the next element (in the queue). Prior to partial summation of individual links starting from the given node, expected time of arrival to the node (and middle of the link) is being calculated as well as spatiotemporal component of each link from the table of paths colliding with anticipated time of (the center of) the link is being integrated (separate algorithm).
8. Until the end of the queue of elements is reached, the algorithm continues with the step 5, after that it continues with step 9.
9. Should any of the elements reach its destination, it is excluded from the queue; should there be a requirement to add a new element, it is included at the end of the queue.
10. Update of positions of all elements in the model, setting of given element indicator at the beginning of the queue and continuation with the step 4.

Maneuver optimization of a large number of elements in the time resulting in effective exploitation of distribution network is a relatively new phenomenon, being in the initial phase of its development.

The main issue in the commercial sector is the need to equip end elements (vehicles) with adequate communication and imaging technology. However, the situation differs in the military. The trend of gradual implementation of C4I systems even at the lowest levels of command frankly calls for this application. At the beginning it is very difficult to estimate the extent of effective enhancement. Nevertheless, intuitively it is possible to assume that it will be substantial, particularly with increasing density of traffic and growing incidence of critical events (accidents, blocking, path overload, etc.).

Corresponding detailed method dealing with given problem mathematically would substantially exceed the scope of this article and take attention from the general primary principle to computing details of the algorithm.

The detailed algorithm is elaborated by this article authors in the C/C++ code. The text bellow describes its generalized variant including explanation of key moments of the solution process where the starting structure is represented by a chart of a traffic network with initial weight configuration of individual nodes that in the basic version determine traffic-carrying capacity of a given segment.

In this respect it is possible to consider also quality of a given road, which eventually affects maximum speed in a given segment and therefore its capacity. Relation between these variables can be derived from results gained in experiments. General relations can be often resolvable only with substantial difficulties and therefore it is necessary to determine given parameters empirically and individually. Influence of individual elements in real time present in a given segment of traffic network is to be taken into account.

Again, in order to apply efficient optimization calculation to a real-life situation, these factors have to be analyzed in detail based on data resulting from experiments. In other words, after starting up the entire system, it is necessary to continue the adaptive modification of quantified criteria of effects and conditions reflecting real response of attributes of these elements (velocity, position etc).

Fine-tuning of given criteria approximates iterative process of a solution, where some parameters randomly oscillate in certain intervals around their mean value, which is based on statistic assessment of predicted actual states continuously refined to bring extrapolated position configurations of most elements into consonance with actual situation.

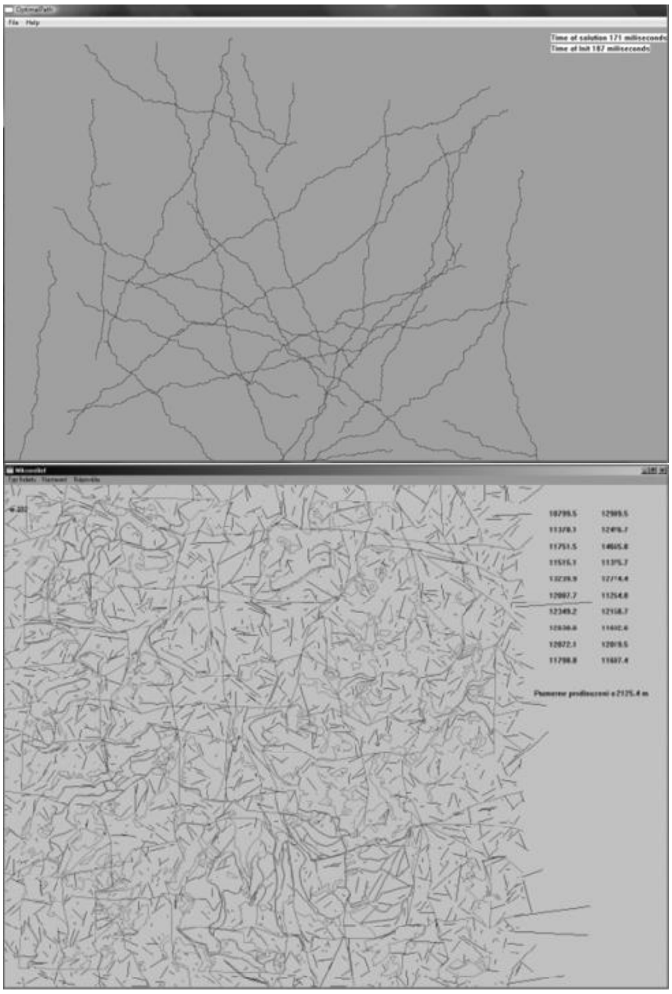

Fig. 2 Samples of the optimum path output

Path search automation and optimization is a topical issue and in the future its importance will be on increase. Wide implementation of fully or semi autonomous vehicles is undisputable, mostly in military applications, same as time optimization of traffic overload on communications.

4 Mathematical model

There is a flow diagram presenting a fundamental work scheme of our algorithm in figure 3. At the beginning, we are in the initial point whose exact position we know. The goal is to reach the target point; again we know its exact position. All blocks of the diagram are described in the following chapters in detail.

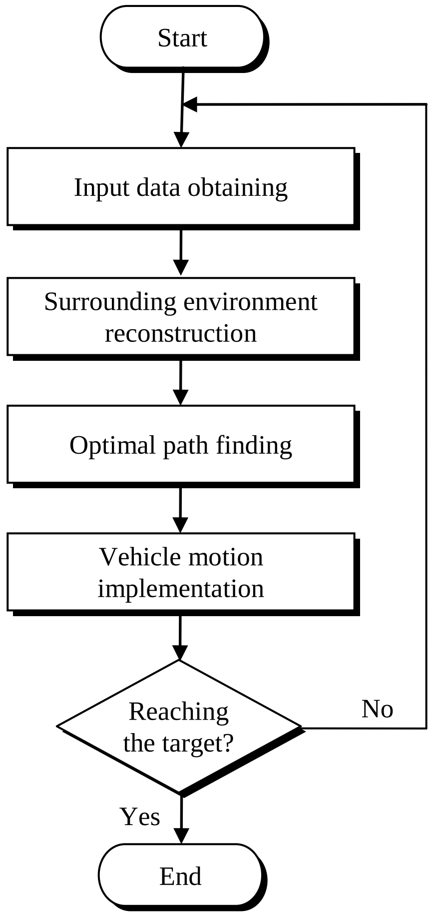

Fig. 3 Flow diagram of our algorithm of unmanned vehicle autonomous motion

4.1 Input data obtaining

We use a laser scanning device LD-LRS1000 made by Sick company in order to obtain input data (see figure 4). This device can scan the surrounding area at the visual angle of 360° at speed up to 10 Hz with precision 0.25°. Operational range of measured distances is from 0.5 m to 250 m [6].

Fig. 4 Laser scanning device LD-LSR1000

As a result of the scanning process within one revolution of the rotation head, we acquire the distance map of the area which is composed of a data set of distances from the rotation head to the nearest object within a particular angle. The whole process is graphically presented in figure 5. The gray surface in the picture expresses the scanned area in the horizontal plane.

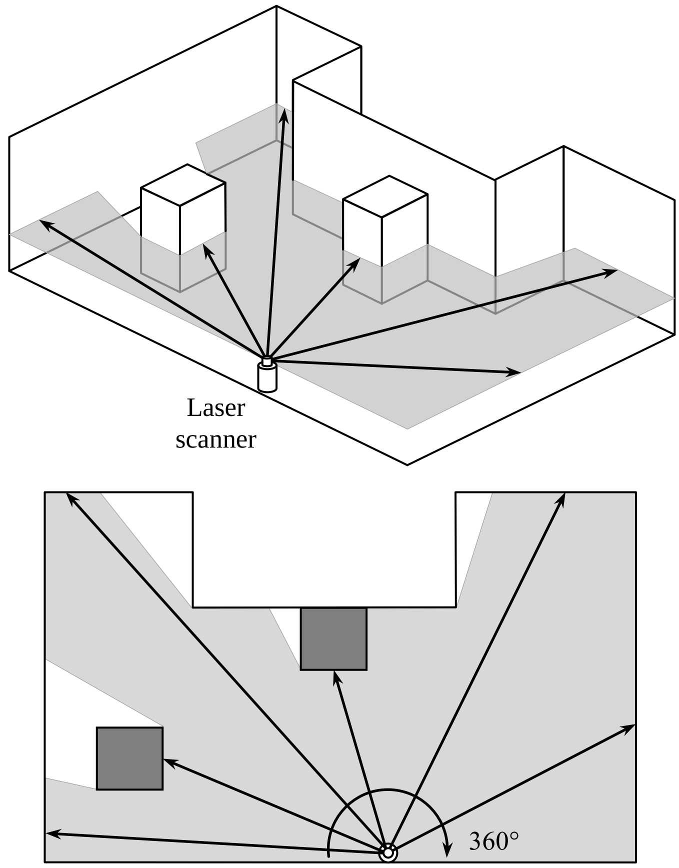

Fig. 5 Principle of the laser scanner LD-LRS1000

4.2 Surrounding environment reconstruction

Within each turn of the rotation head of the laser scanner, we gain the preview of the surrounding area. In many cases, the whole configuration of the area is not known since objects in the area restrain from direct visibility; hence the laser scanner is not able to scan the area which is located behind those objects (see figure 5).

Therefore during motion of a vehicle, it is necessary to supply and update the digital image of the surrounding environment. At the moment of a small change of a vehicle position in the area, we obtain new information about distribution of the obstructions there. A different angle of view ensures exposing of the areas that were so far hidden behind objects. The new information is integrated into the whole map of the area.

The described principle is presented in figure 6. In figures 6a and 6b, there are two independent maps of the same area, however, they are taken from a different position of the scanner. Figure 6c shows the principle of the surrounding area reconstruction which is conducted by unification of the both distance maps. Supplying of missing parts of the digital image of the area is carried out continuously during the whole vehicle motion.

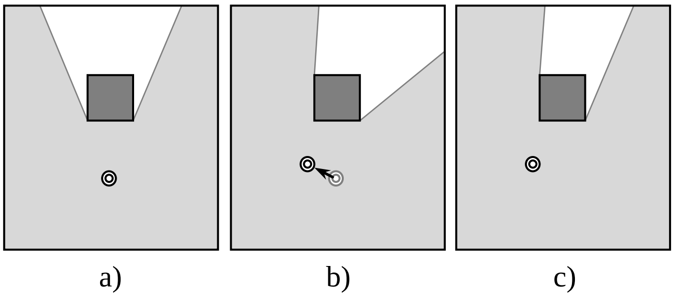

Fig. 6 Principle of surrounding area reconstruction

We need to know the position of the laser scanner at the moment of the measurement to be able to unify two different distance maps. However, it is not a simple task. The precise vehicle position is known only at the beginning. There are several approaches how to compute the vehicle position during its movement:

- Applying a software analysis to every new distance map and determining its best position in the reconstructed area.
- Keeping an estimated vehicle position via motion measurement of its motive parts (e.g. measurement of driving wheels revolution and their steer angle).
- Keeping an estimated vehicle position via a digital magnetometer and accelerometer.

Each of the approaches mentioned above has some positives and drawbacks, which will be briefly analyzed in the following text.

4.2.1 Software analysis

The advantage of the first approach is that we do not need any special measuring devices or instruments for its implementation. The whole method requires only distance maps to fulfill its functionality; every new map is compared with old ones in order to find as many as possible common features. The drawback of this method is relatively significant computational requirement and higher probability of an error in case of substantial dynamic changes in an obstacles configuration.

Figure 7 presents the principle of this method. Figures 7a and 7b show two independent distance maps computed from the output data from a laser scanning device positioned in two different locations in the area. Considering the first distance map, our vehicle is located in a point whose exact position is known; it is either the initial (starting) point or the point whose position was determined in a previous step. Using thorough comparison we find the best location of the last distance map towards the previous one in the coordinate system (see figure 7c). Distance maps for the comparing process are acquired in regular time intervals.

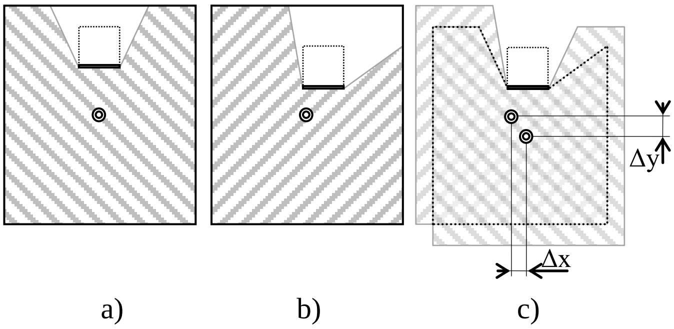

Fig. 7 Principle of determination of the new vehicle position via software analysis

When locating the best place of the new distance map, our method compares free known space and particularly firm known objects and obstacles in the area. Having determined the position of the new distance map and reconstructed the surrounding environment, we gain values Δx and Δy representing a relative shift of the vehicle in the area according to the formula (1).

$$\begin{aligned} x &= x + \Delta x \\ y &= y + \Delta y \end{aligned} \tag{1}$$

As already mentioned, the drawback of this method consists in a big computational complexity of the entire process. The reason of this is that the comparison is necessary to conduct not only in the coordinate axes x and y but also within the turning angle φ of the laser scanning device. An objective function expressing the comparison quality of the two distance maps is then the function of the three independent variables – see the formula (2). Thus the whole process is advisable to implement on a graphical processor which is able to compare a vast amount of data in parallel.

$$f(\Delta x, \Delta y, \varphi) = \max \tag{2}$$

The presented approach has a big positive feature. Errors and inaccuracies in determination of the vehicle position during the whole vehicle motion do not accumulate; a new independent distance map is processed in each step.

4.2.2 Measurement of vehicle motive parts

The second way how to follow the position of the vehicle in the area is to measure its motive parts. This method is strongly dependent on the way the vehicle moves. Thus the drawback consists in necessity for creation of a corresponding conversion model of output data into the new vehicle position and also relatively big inaccuracy of the result.

When using wheeled vehicles, the principle consists in measurement of the driving wheels revolution and their steer angle within short time periods. This information is used for determination of the shift of the vehicle in the area (Δx and Δy) and computation of its new position according to the formula (1).

Inaccuracy of this method is caused by an imprecise calculation of the distance and (particularly) the direction the vehicle moved; the direction is computed from the steer angle of driving wheels. The whole process is strongly dependent on the results from previous steps; errors in each step are added up and they can dramatically affect accuracy of results particularly in later phases of the vehicle motion.

4.2.3 Using digital accelerometer and magnetometer

The last principle mentioned above consists in computing the vehicle position in the area via a digital accelerometer and magnetometer. This method requires having both the mentioned measuring instruments, which are in the constant position and angle toward a laser scanning device. The position of the vehicle is computed according to the formula (3) where s is the position of the vehicle in the area, and a is its acceleration.

$$s = \iint a \tag{3}$$

Digital accelerometers provide acceleration usually in three coordinate axes as $\vec{a} = (a_x; a_y; a_z)$ in constant time periods (up to 1000 samples per second). Acquired values are composed of two different independent components: static and dynamic acceleration. Static acceleration is caused by gravitational acceleration in every axis of an accelerometer; dynamic acceleration represents acceleration caused by the motion of the vehicle.

It is necessary to compute the position only from dynamic acceleration a_d without an impact of static (gravitational) acceleration a_s. Thus we need to subtract static acceleration from the output values in each step according to formula (4).

$$\vec{a}_d = \vec{a} - \vec{a}_s \tag{4}$$

To do that, we need to know the turning angle of our digital accelerometer in each step to be able to subtract an impact of gravitational acceleration in all coordinate axes of the device. This is possible to implement via a digital magnetometer (integrated with the accelerometer in the best case).

The digital magnetometer provides Euler angles (roll θ, pitch ϕ, yaw ψ) from which we are able to calculate particular components of static acceleration according to the formula (5). Then static acceleration is subtracted from total acceleration and as a result we acquire dynamic acceleration we are interested in; we can use it to compute the vehicle position in the area according to the formula (3).

$$\begin{aligned} a_{sx} &= -\sin(\theta) \\ a_{sy} &= \cos(\theta) \cdot \sin(\phi) \\ a_{sz} &= \cos(\theta) \cdot \cos(\phi) \end{aligned} \tag{5}$$

There is a drawback of this method – accumulation of errors during the whole process. The slightest error in each step results in substantial inaccuracy at the end of the process. Continuous uncontrollable shakes of the accelerometer during the motion of the vehicle and low sampling frequency are also a huge source of errors. Relatively major errors are also caused when computing dynamic acceleration as subtracted static acceleration is calculated based on data from different independent sensors from those in acceleration and usually with different sampling frequency. All these factors implicate short-period utilization of this method.

In practice, this principle is being used in connection with the satellite system GPS when there is unceasing refinement of the current position from the GPS system and data from the accelerometer only elaborates the result in short time periods. Nonetheless, this does not work inside buildings because there is no GPS signal available.

4.2.4 Combination of presented methods

In our project, we take an advantage of the combination of three mentioned above methods; it ensures very precise results even within the long-period motion of the vehicle in the surrounding environment. The whole process is as follows:

1. Using a digital magnetometer for determination of the accurate direction of the vehicle.
2. Measurement of revolutions of vehicle motive wheels to determine the distance of the motion.
3. Refinement of the estimation of the vehicle location via the software analysis of distance maps.

At first, we read the direction of the vehicle motion φ from the digital magnetometer. Particularly, we use the type 3DM-GX3-25 made by MicroStrain company [7] (see figure 8).

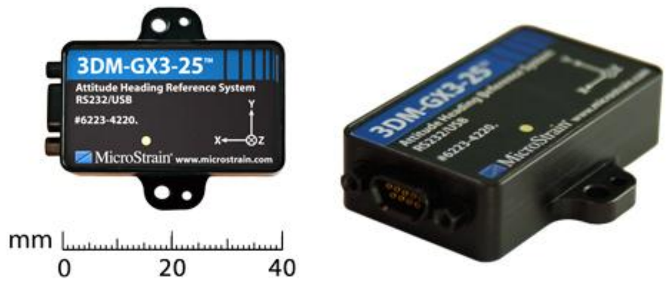

Fig. 8 Digital accelerometer and magnetometer 3DM-GX3-25

Then, we are able to determine very accurately the distance d, which the vehicle covered within a short-period time interval via measurement of vehicle motive wheels revolutions. In our case, we measure (very accurately) revolutions of servomechanism which rotates the motive wheels. We can estimate the new position of the vehicle from those two independent pieces of information according to the formula (6).

$$
\begin{aligned}
x &= x + |d| \cdot \sin(\varphi) \\
y &= y + |d| \cdot \cos(\varphi)
\end{aligned}
\tag{6}
$$

Figures 9 and 10 present a model example of the time characteristic of the vehicle motion and visualization of the trajectory of its movement in two-dimensional space.

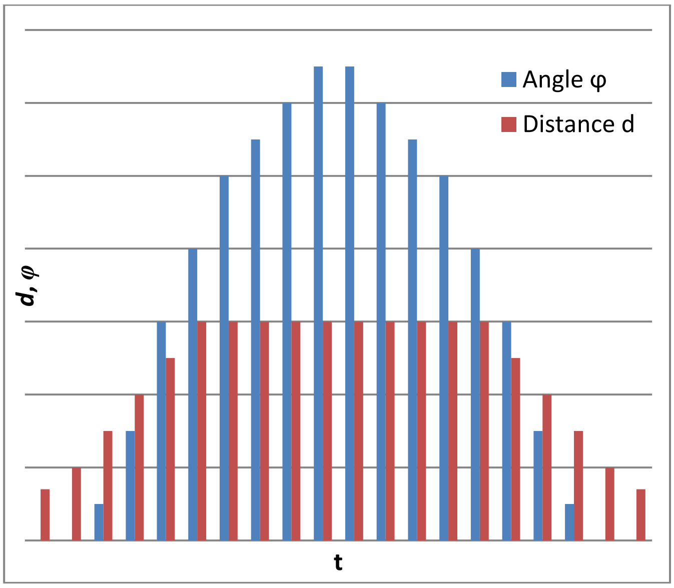

Fig. 9 Model example of the time characteristic of the vehicle motion

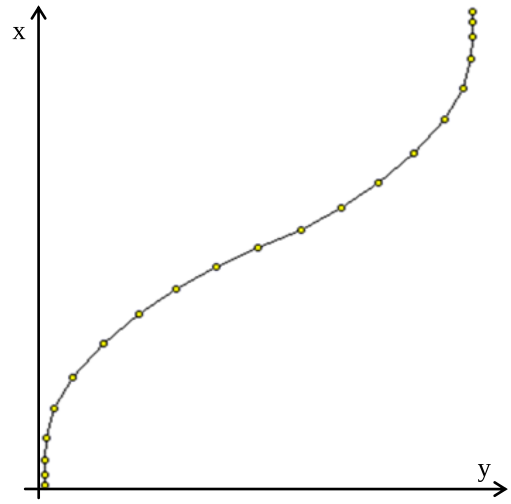

Fig. 10 Visualization of the vehicle trajectory according figure 9

Finally, we launch the software analysis of a previous and a current distance map to elaborate the position of the vehicle in the area. The big advantage is that the angle φ is eradicated from the objective function in the formula (2) as its value is known from the digital magnetometer. The objective function thus becomes function of only two variables Δx and Δy according to formula (7). In addition, distance maps are compared in both coordinate axes only within small distances given by the maximum estimation error; we only need to elaborate the result slightly, not to find it on the entire surface of the distance map.

$$
\vec{a}_d = \vec{a} - \vec{a}_s \tag{7}
$$

The combination of the methods mentioned above is very precise because there is no accumulation of errors within individual steps. Therefore we can utilize the whole process in the long term without a necessity of result corrections.

4.3 Optimal path finding

At the moment of a surrounding environment update, the optimal path-finding algorithm is accomplished (see chapter 3); hence there is a new route from a current point to a target point. Our algorithm sets corresponding weights to all points of the reconstructed area.

Small weights are set to points through which the transport can be conducted. Vice versa, very high weights are set to points representing known obstacles; it is so because we need to omit those points as possible variants. The area which is still hidden deserves a special attention. All points in this area are set to middle weights; our algorithm tries to find the route through free known space firstly, and only in case when it is not possible, through unknown space. In case of uncovering new information, the route update takes place again.

The above mentioned principle is shown in figure 11. On the left, there is a reconstructed area; the right picture presents weights as an input to our algorithm. The value of weights corresponds to the gray color scale. We can see that the solid object (in this case only one visible edge of the object) is encapsulated in gradually decreasing weights of high values in order to respect the size of the vehicle and its turning radius.

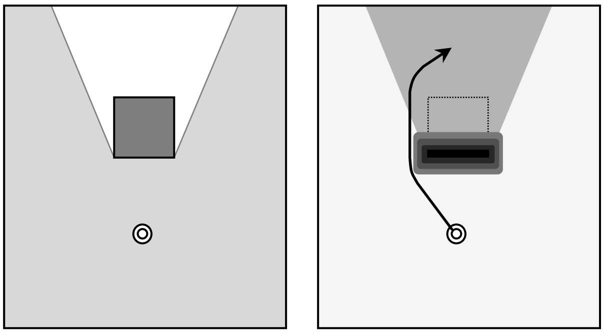

Fig. 11 Principle of assigning weights to the area

4.4 Vehicle motion implementation

Motion of a vehicle is conducted immediately after a new trajectory (route) is found (provided it exists). The whole process of the environment reconstruction and optimal path finding is repeated unceasingly during the vehicle motion. In case of dynamic changes in the environment, the instantaneous update of the route takes place. The algorithm ends at the moment of reaching the target point.

In figure 12, there is an example of the key fragments of the vehicle motion on our designed simulator which we had developed in order to verify our theoretical designs and conclusions. The top left picture shows the configuration of the environment including initial and target points. The successive pictures present the progress of the vehicle motion. The red line shows the optimal path from the current point; the blue line preserves the path through which the vehicle moved.

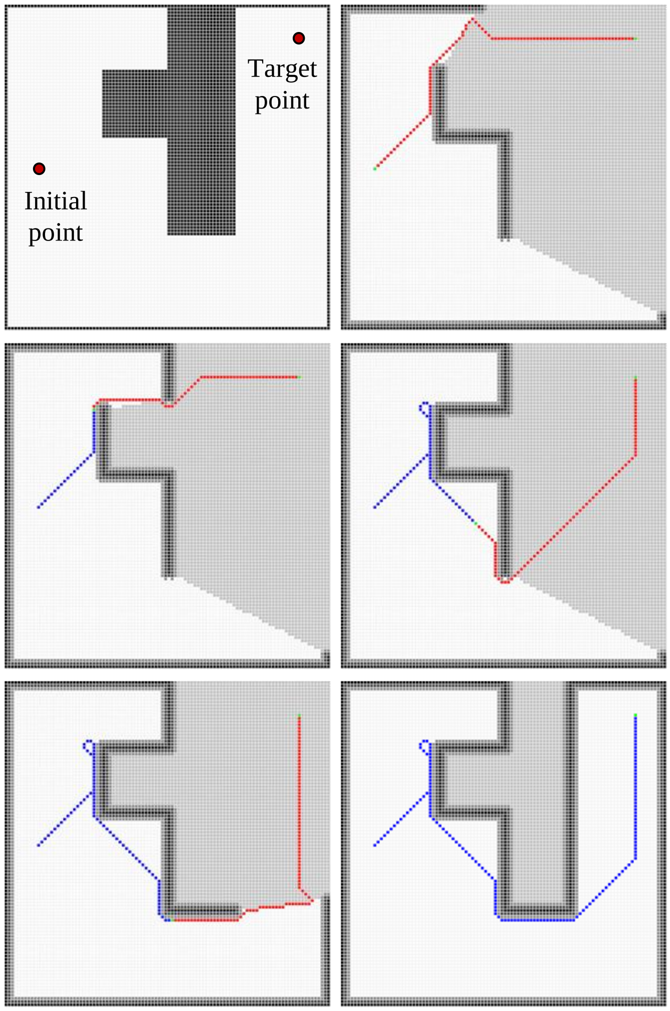

Fig. 12 Verification of our designed model on the simulator

We verified the process of autonomous vehicle motion also in practice on a simple example via our designed experimental vehicle. In figure 13, there is, analogously as in the previous case, the succession of the vehicle motion in the real environment.

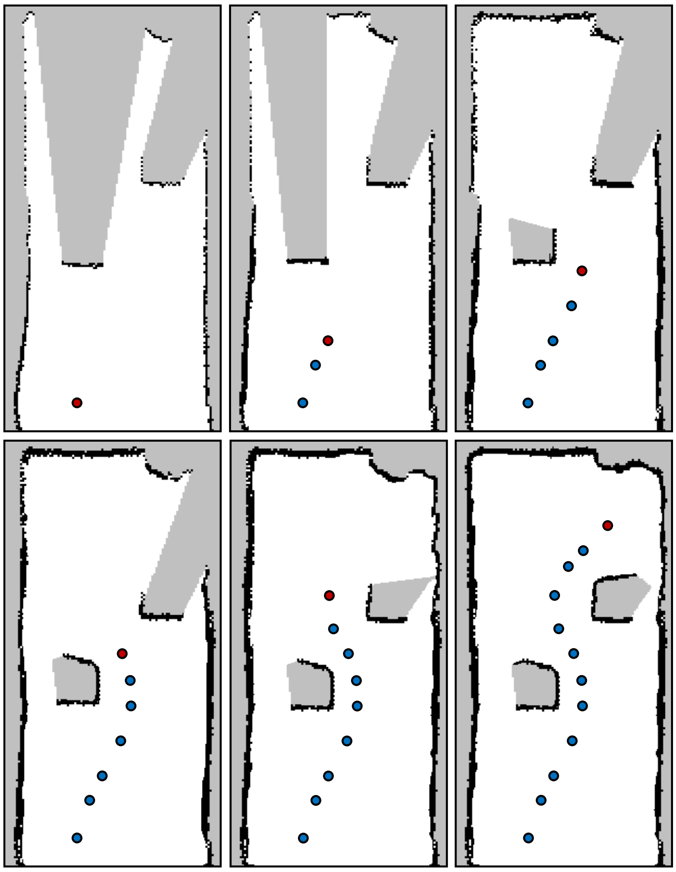

Fig. 13 Verification of our designed model in the real environment

5 Conclusion

As already mentioned, the paper was created within the research at University of Defence in the Czech Republic. We deal with development of autonomous unmanned systems and also with development of the software equipment for the system of the soldier of the 21st century. Figures 14 and 15 present some results of our research.

Our key project remains in the development of the autonomous unmanned ground vehicle (see figure 14). This vehicle is used especially for reconnaissance purposes offering the possibility of targets destruction. The vehicle is based on the chassis of a four-wheeled vehicle YAMAHA YFM400. On the top of the chassis, there is a robotic platform fitted with the sensorial, communication and weapon system.

Fig. 14 Unmanned ground vehicle

Nowadays, we are developing control software, particularly units for decision process automation support. In the future, we are planning to implement the described optimal path-finding algorithm into this vehicle. We are also working on the system of automatic searching and monitoring targets.

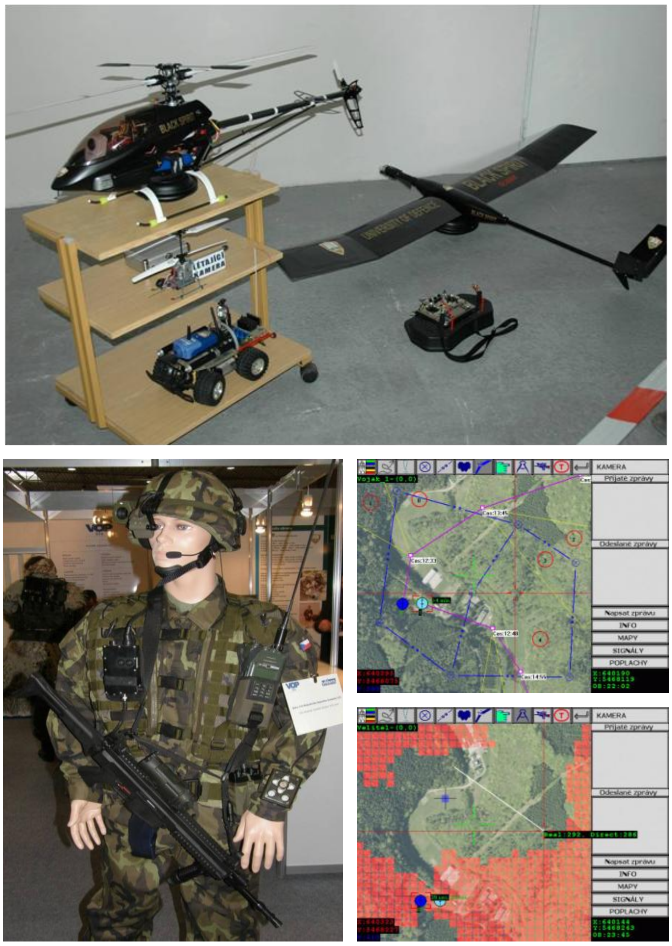

Fig. 15 Further results of our research

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