Using Diagnostic Information for Planning an Energy-Optimal Path of an Autonomous Vehicle

Przemysław Szulim
Warsaw University of Technology, Poland

The article has presented a general idea for an algorithm that would allow for determining the optimal parameters of vehicle movement. The sources of energy dissipation have been assumed as follows: damage to the engine and the drive. In addition, the mathematical basis have been presented for assessing the impact of damage resulting from problems such as axial misalignment on the dissipated energy. In the second part of the paper, the concept of the algorithm has been detailed, paying special attention to certain problems that have arisen, and an algorithm has been proposed that determines the optimal movement parameters for a simplified case, when the vehicle is moving along a path determined in advance. In addition, the results of applying the algorithm for a simple case have been presented, as well as the impact of the particular energy dissipation parameters of the model on the optimal velocity profile of the vehicle. The plans for further research include estimating the impact of other damages, such as damaged bearings or demagnetising, on the energy dissipation. Further work on an algorithm is also planned that would allow for simultaneous determining of an optimal path as well as an optimal velocity profile.
Keywords: path planning, bldc motor, diagnosis.

1. INTRODUCTION

The idea of building autonomous vehicles has existed for a very long time. In numerous research centres, research teams explore this issue in increasingly complex ways. Today, autonomisation in an average person's life is a commonplace and takes many forms. Nothing about this process indicates any signs of stopping, either. On the contrary – new competitions and research programmes are announced regularly, making people ever so more comfortable with this issue. This is well exemplified by automobile industry and market, where the largest producers introduce more and more advanced systems aiding the driver in the cars they manufacture. This ranges from assisted steering, through assisted parking, to experiments in unassisted, autonomous navigation of roads.

Although the areas where autonomous vehicles are used are still strictly connected to specialised tasks and the term „autonomous" in many cases means, in practice, operator-assisted work, use of autonomous vehicles is growing dynamically both in the scientific and practical sense. This paper discusses the possibilities of using algorithms for optimising the trajectory of an autonomous electric vehicle, where the main goal of the optimisation is to minimise the energy spent. Similar research goals are being pursued in multiple research centres. In papers 1*,2* the authors have presented the solution for the problem of minimising energy use for a small, three-wheeled mobile robot. The goal has been divided into two stages: in the first one, a global path has been set up by using a graph algorithm, while in the second stage the path has been smoothed. The paper assumes that energy losses during operation result from rolling resistance. In the paper 3* the authors have focused on the issue of local optimisation of the robot's trajectory. To this end, a simple mathematical model has been used, focusing mainly on solving the issue of the presence of nonholonomic connections. To that end, a sun exposure map for the area of robot operation has been created; the robot would be powered by batteries as well as photovoltaic cells. This was done by creating a sun exposure map of the area where the robot would move; subsequently, a solution has been presented to the problem of energy and time minimisation during operation. In the presented paper, an attempt has been made to find an energetically optimal trajectory for a mobile robot. It has been assumed that the goal is to find an optimal global trajectory. This means that an important aspect has been ignored concerning the kinematic limitations of the vehicle. This subject shall receive more thorough attention in the later stages of the project. In the proposed solution, the source of energy losses is the electrical engine powering the robot. Due to specific defects, the properties of the engine change, and with them the ability to transform energy. According to Cempel's model, the energy resulting from damages is partly dispersed in the form of heat, and partly contributes to further development of the damages. Further work is needed to determine whether a proper method of steering the autonomous vehicle allows the possibility of lower energy dissipation, which in turn means a slower development of the damages. The processes that occur in a BLDC electrical engine as a result of specific errors are the subject of research currently conducted by the research team, while this paper presents the examples of modelling the impact of selected defects on energy transformation efficiency. In later sections of the paper, an algorithm is suggested that solves a simplified optimisation problem, as well as the results of the operation.

2. ENERGY DISSIPATION IN DAMAGED AREAS

One of the several types of damages the occur in brushless motors is axial misalignment. This effect occurs when the axis of the rotor is not aligned with the axis of the engine's stator. This is presented in the below figure 1.

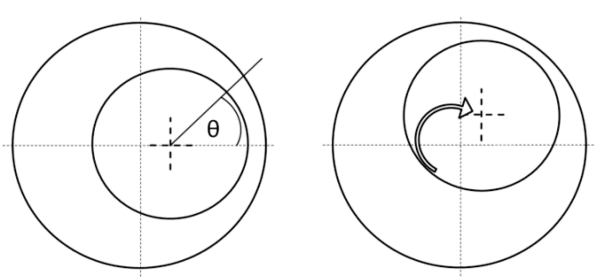

Fig. 1. Static and dynamic misalignment

In addition, two kinds of axial misalignment can be specified – static and dynamic. This distinction is connected to keeping the characteristic gap between the rotor and the stator. It may be motionless, when the axis of the rotor does not change its position in relation to the axis of the stator. In this case, we can talk about static axial misalignment. When the axis of the rotor rotates around the axis of the stator, the air gap rotates as well. We can, then, talk of dynamic axial misalignment. As a result of the misalignment, the gap between the rotor and the stator is deformed. If the nominal width of the air gap is d0, then – as a result of dynamic axial misalignment, the resulting width of the gap can be expressed with the following formula:

$$d_{de} \cong d_0\big(1 - \delta_d cos(\theta - \omega_r t)\big) \qquad (1)$$

while in the case of static axial misalignment, the resulting width of an air gap can be modelled using the following formula:

$$d_{se} \cong d_0\big(1 - \delta_s cos(\theta)\big) \qquad (2)$$

where ωr is the angular velocity of the rotor, δ_d, δ_s – the displacement of the rotor and stator axes, θ – the angle for which the width of the gap is measured. The changes in the width of the gap result in a change of magnetic field reluctance which is directly proportional to the length of the air gap. The permeance, which is the inverse of the reluctance, may be expressed via the following equation:

$$\Lambda_{de} = \Lambda_0 + \sum_{i_{ecc}=1}^{\infty} \Lambda_{i_{ecc}} cos(i_{ecc}\theta - i_{ecc}\omega_r t) \quad (3)$$

where:

$$\Lambda_{i_{ecc}} = \frac{2\mu_0\left(1-\sqrt{1-\delta^2}\right)^{i_{ecc}}}{d_0\delta_d^{i_{ecc}}\sqrt{1-\delta^2}} \qquad (4)$$

$$\Lambda_0 = \frac{\mu_0}{d_0} \qquad (5)$$

In the paper [1] it has been shown that for δd<40% the impact of the elements of the sequence for >2 is negligibly small, therefore in order to simplify calculations it is henceforth ignored. An uneven gap results in the changes of magnetomotive force and, furthermore, to changes in magnetic induction, which can be approximated using the following formulas for the case with a static gap (7) and a rotating gap (6):

$$B_{de} = B_1[1 + \delta_d cos(\theta - \omega_r t)]cos(p\theta - \omega_s t - \varphi_t) \quad (6)$$

$$B_{se} = B_1[1 + \delta_s cos(\theta)]cos(p\theta - \omega_s t - \varphi_t) \qquad (7)$$

where p – the number of pairs of poles, ωs – angular velocity of the stator's field, ωr – angular velocity of the rotor.

It should be noted here that the derived formulas apply to a case with an asynchronous induction motor. BLDC synchronous motor, the angular velocities of the shaft and the rotating field are rigidly connected to each other. It should also be noted that the formula (6) presents the description of an amplitude modulation, where is the parameter describing the modulation depth. Such modulation does not result in the case of static axial misalignment. The current input for an BLDC motor with damages resulting from a dynamic axial misalignment may be expressed using the following formula:

$$I_{de} = I_1[1 + \alpha cos(\omega_r t)]cos(\omega_s t - \varphi_i) \quad (8)$$

The factor α is a parameter connected to, expressing the offset of the axes of the rotor and the stator. It is also known that the average value is constant and does not depend on the modulation depth parameter. This means that the average power drawn by the engine remains unchanged. What is change, on the other hand, is the power dissipated by the engine, connected to the losses due to resistance of the electrical circuit. If we express it using the following formula:

$$E_S = \int R * {I_{de}}^2 dt \quad (9)$$

then the average value of the power dissipated by the engine equals:

$$E_S = (0.5 + 0.25\alpha^2)R{I_{de}}^2 \quad (10)$$

As we can see, the presence of damage such as dynamic axial misalignment results in an increased loss in the electric circuit of the engine. It is important to estimate the losses not merely because it allows for actions that would increase the efficiency of the energy spent, but also due to the danger of resulting demagnetisation due to temperature. This is a significant problem for electric motor with permanent magnets. Depending on the elemental composition of the magnets, the acceptable temperature of operation may be, for many applications, highly important. For some magnets created from rare earth elements, the acceptable temperature of operation may be as high as about 80^{O}C. Exceeding this temperature may result in a permanent loss of magnetic properties of permanent magnets and, as a result, decrease the engine's operational performance. This implies that an important factors is such a method of control the drive of an electric vehicle that does not result in exceeding the acceptable work conditions. Since there are many possible causes of demagnetisation, it is also important to monitor any such damages in order to estimate their impact on efficiency of energy transformation.

3. MOTION PLANNING

Rational energy management requires a lot of information, notably in two main areas: information about the causes of energy dissipation and information about limitations. The first type of information may be used to update the model of the object representing the autonomous vehicle. The second type provides information about the existing limitations to the model. With such information at our disposal, it is possible to create a model tying all significant parameters to the amount of energy dissipated. An analytical solution of such a problem would be very difficult or impossible, due to numerous non-linear dependencies as well as the character of input data. It has been assumed that the surface that the vehicle travels is described via a two-dimensional matrix. However, similar problems have been solved in another way before, which might be adopted for the solution of the presented problem.

The task of searching for shortest paths has been thoroughly described in numerous publications and the problem is efficiently solved for many applications. There exist many methods of finding optimal paths, which can be divided into analytical and field methods, as well as the so-called grid-based class of models. The relatively good parameters of the latter models make them suitable for using it for solving the path-finding problem as well as determining the optimal parameters of operation of the vehicle – which is to say parameters which would minimise the consumption of energy.

Grid-based methods make the whole search area discrete. The search area may be the configuration area of the robot. In the case of movement optimisation, the search area may introduce completely different dimensions, connected to the mathematical model describing the dissipation of energy. An additional dimension of space may be e.g. the control of the robot. The path-creating algorithm analyses the points of the grid by determining the cost of traversing the unit sections from point to point. There exist many modifications for this general method. Many tools from the areas of mathematics concerned with graphs have been used in solving this problem. Among a few algorithms whose purpose is to find the shortest paths and which have been created for the purpose of searching through graphs, there exist two algorithms named Dijkstra and A*. Both of these algorithms are capable of finding the shortest path, while A* - thanks to some additional information – is capable of determining such a path faster. Further analysis of the algorithms shall henceforth use elements of the Graph Theory. The solution of any problem connected to the search for an optimal path may therefore, for this class of problems, be abstracted into finding the correct path in a graph. A graph is an abstract structure, tightly bound to the area map (for this class of problem). It consists of points and edges.

Each edge is assigned a weight that, in this case, represents the energy required to traverse the path between two points of the path. Let us analyse a simple path-finding scenario for any two points in a city. The grid approach requires superimposing the grid on a city map and the subsequent creation of a graph from the points that ended up on the streets. The points of the grid selected in such a manner will correspond to the specific points in the city map, which in turn will be reflected in the points of the graph. The edges will connect the points adjacent to one another. In addition, each edge will be assigned a weight, a parameter reflecting the cost of traversing from one point of the graph to its neighbour. In this case, the weight may be assumed to be the distance between two points on the map. Based on such a representation, using the two aforementioned algorithm, it is possible to find the shortest path between any two points. An example solution of this problem for a maze has been presented in figure 2. An important feature of a graph-based representation is the possibility of solving an arbitrarily complex problem. In Figure 3, a solution has been presented for path-finding in a three-dimensional map. In Figure 4, by contrast, a solution has been presented to the so-called „piano problem", which is to say the transfer of an object with a complicated geometry. This is also a problem with a three-dimensional search area, because – in addition to manipulating two coordinates, it was necessary to manipulate the rotation of the object. It is therefore possible to solve many interesting problems by representing them with graphs, including the problem of finding an optimal path and movement parameters for a vehicle.

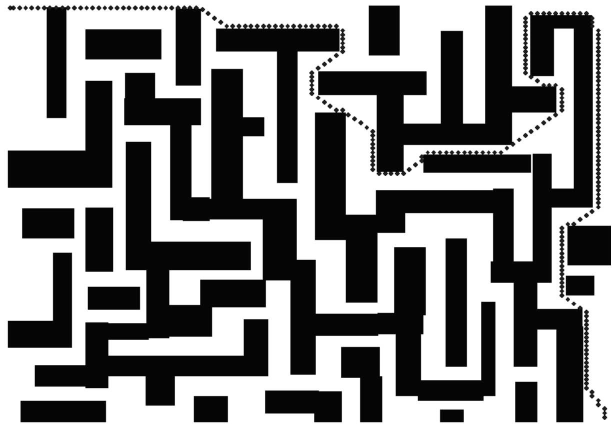

Fig. 2. Two dimension problem

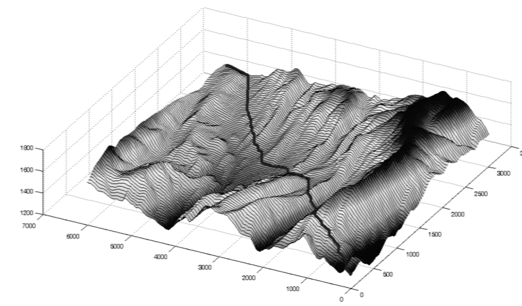

Fig. 3. Three dimension problem

Fig. 4. Piano problem

In order to simplify a problem, it has been usually assumed that the vehicle is a single point, so that the properties of many vehicles connected to nonholonomic connections may be ignored. The model of a vehicle has been simplified to a specific point with a finite mass of m, aerodynamic coefficient C, and rolling resistance factor of f.

A vehicle is powered by an electric motor rigidly connected with a gear system. The movement formula describing the vehicle can be expressed as follows:

$$\dot{v} + \xi_1 v = \xi_2 \qquad (11)$$

where:

$$\xi_1 = \frac{C}{m} + \frac{i^2 k_\omega^2 \eta}{r^2 R m} \qquad (12)$$

$$\xi_2 = \frac{i\eta k_\omega}{rRm} u - g\big(f cos(\alpha) + sin(\alpha)\big) \qquad (13)$$

C - air resistance factor;
m – mass of the vehicle;
i – reduced ratio;
kω – electric engine parameter;
η – efficiency of the mechanical layout;
r – radius of the vehicle's wheels;
R – engine resistance;
f – rolling resistance factor;
g – Earth gravity's acceleration;
α – angle of the slope that the vehicle is traversing.

U – is the controlling input that, for this model, reflects the voltage applied to the motor. In the first stage, the value controlling the movement of the vehicle will be assumed to be the voltage. In such a case, it is expected that the algorithm find a path that allows for minimised energy consumption in the path section Δs from a specific starting point s to a final point t:

$$E = \int_s^t u(t) i(t) ds \qquad (14)$$

The algorithm should search the three-dimensional space, where two dimensions reflect the physical position, while the third dimension reflects the controlling voltage. The first problem consists in determining the specific correspondence to the energy drawn from the power source. For a selected section of the path Δs (a section of the path connecting two adjacent points on the map), with the angle α and the starting velocity of the vehicle v0, the energy drawn from the energy source is expressed by the following formula:

$$E = \left(\frac{u}{R} - \frac{uc\xi_2}{\xi}\right) t + \frac{uc}{\xi}\left(\frac{\xi_2}{\xi} - v_0\right)\left(1 - e^{-\xi_1 t}\right) \qquad (15)$$

- The first problem is that the drawn energy from the source may be negative. This may happen e.g. when the vehicle is braking. Negative energy implies that the cost of traversing between two points may be negative. None of the proposed algorithms correctly solves the problem of correctly determining the path with the lowest sum of weights with the introduction of negative weights. This means that the algorithm needs to be altered;
- The formula includes the dependency on time. The traversing time between the two selected points on the map, with a given controlling method, may be determined using a differential equation, but it may not be applied to the analytical model. It is necessary to determine the approximate solution using one of the several established methods, which complicates the solution.
- The energy drawn from the energy sources depends also on the initial velocity v0. This is the velocity that the vehicle has acquired by moving from a certain earlier point to the point being analysed. This means that the energy, and therefore the cost of traversing as well, between two nodes is not constant – in the sense that it depends not only on the selected section of the path and the assumed control method, but also on how the movement in the earlier sections of the path was selected. By applying this to a graph method, the resulting graph has edges whose weights are a function of the weights of previous edges of the path, which is presented in figure 5 in simplified form.

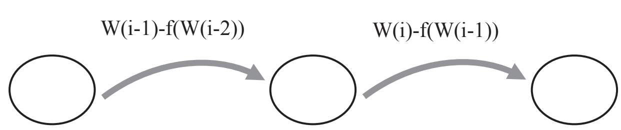

Fig. 5. Relative weight of graph problem

For such a problem, no known algorithm is able to determine an optimal solution. In order to solve this problem, a number of simplified assumptions need to be made. Let the task of finding the optimal path and control method consist only of finding the optimal control method for a given path. In this way, the three-dimensional problem can be reduced to a two-dimensional problem. Another assumption is the ability to move in only one direction from the starting point to the end point. This results in a directed graph.

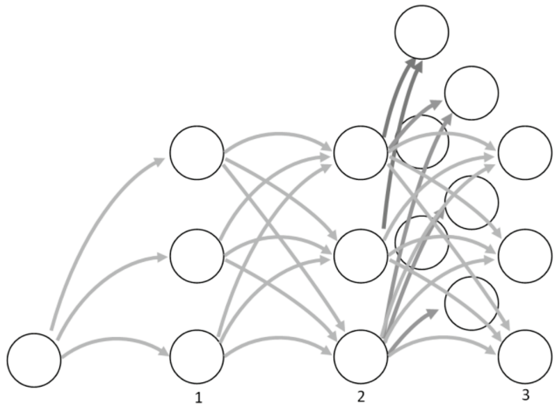

Fig. 6. Modification of graph

Figure 6 presents an example graph like this. Its characteristic feature is that it is not possible to move between points above and below the point being analysed. This has a physical justification, as it is not possible to change the controlling level without moving from place. The resulting graph is built like a matrix. In order to solve the problem of non-constant weights in the graph, it may be used in a modified form (fig. 7).

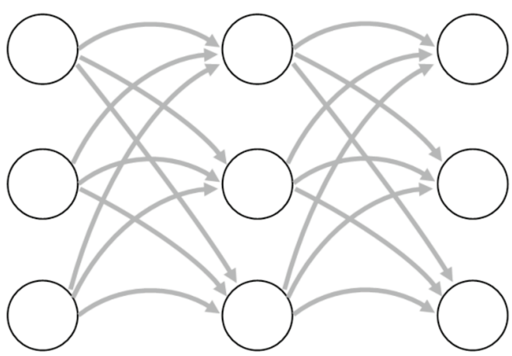
Fig. 7. Graph modification for non-constant weight problem

It should be noted that reaching the second column of the graph from the first column is non-ambiguous, because the initial conditions are constant and may not be changed. The problem noted earlier does not therefore apply here. On the other hand, moving from the second column to the third column is no longer non-ambiguous, because when analyzing any pair of points, where the first point belongs to column 2 while the second belongs to column 3, it is necessary, for the purpose of calculating costs, to account for the velocity at which the vehicle reached the initial point. There are as many such possibilities as the number of R rows in the graph. Therefore, when analysing any pair from columns 2,3 – with the total number of such pairs being R^2 -it should additionally be analysed for R cases. This observation may be presented in the form of a graph, by adding (R-1) columns in parallel to column 3. Now, when analysing column 3 and the columns added to it, it should be noted that they all correspond to only one point on the map. Similarly, when analysing column 4, R columns should be added for every column from the 3rd row. The number of edges between column 1 and 2 is R^2, between columns 2 and 3 – $R^{3,}$ and between columns 3 and 4 – R^4. If one were to determine the total number of edges L in such a graph, then assuming that the number of points being analysed is N (which corresponds to the initial number of columns in the graph), the formula may be presented as follows:

$$L = R^2 + R^3 + R^4 + R^5 + \cdots = \sum_{i=2}^{N} R^i = \sum_{i=1}^{N-1} R^2 R^{i-1} = R^2 \frac{1-R^{N-1}}{1-R} \approx R^N \quad (16)$$

This is a very significant problem, because even with relatively small dimensions of the initial graph, e.g. 10x10, after using the method presented, it grows so that the total number of edges in the graph will be 10^{10}. The problem, in practical terms, is therefore insolvable in this form. Another solution is to choose the parameter controlling the movement of the vehicle in a way than ensure that the weights of the edges remain constant. A control method based on the current or the momentum does not solve this problem. It is control based on the velocity that yields the needed results. In order to implement such a control scheme, an interpretation needs to be found for the transition from a point in one column to a point in another. In this paper, a variant is proposed with linearly changing velocity from v_C to v_{C+1} , where C is the number of the column being analysed. This assumption, although not necessary energy-optimal, significantly simplifies the problem of controlling the voltage applied to the engine. It is due to the fact that, in this case, the basic motion formula remains in force (11). It is necessary to add a regulating mechanism that ensures that the required velocity be reached. The assumption made regarding the linearly rising velocity during the traversing of a path section between two adjacent points implies assuming a constant acceleration on a path section Δs, according to the following formula:

$$a = \frac{v_{c+1} - v_c}{t_{c+1} - t_c} = \frac{\Delta v}{\Delta t} \tag{17}$$

where:

$$\Delta t = \frac{2\Delta s}{v_c + v_{c+1}} \tag{18}$$

Therefore, by substituting into the formula (11) and transforming (11) in order to determine u(t), the resulting formula determines the voltage that needs to be applied to the engine terminals, so that for the given model, with the defined parameters of the path section (length, slope) we achieve the necessary increase in velocity from v_C to v_{C+1} , which are the parameters being optimised by the algorithm.

$$u(t) = \frac{rRm}{i\eta k_\omega}\left[\xi_1 \frac{\Delta v}{\Delta t} t + \xi_1 v_c + \frac{\Delta v}{\Delta t} + g\big(f cos(\alpha) + sin(\alpha)\big)\right] \tag{19}$$

It should be added that, for simplicity, the limitations resulting from the acceptable values of the controlling voltage have been ignored. The energy drawn from the power source for controlling purposes (19) can be expressed as follows:

$$i(t) = \frac{rm}{i\eta k_\omega}\left[\xi_1 \frac{\Delta v}{\Delta t} t + \xi_1 v_c + \frac{\Delta v}{\Delta t} + g\big(f cos(\alpha) + sin(\alpha)\big)\right] - \frac{ik_\omega}{rR}\left(v_c + \frac{\Delta v}{\Delta t} t\right) \tag{20}$$

The energy drawn from the powers source for controlling purposes (19) will be equal to:

$$E = \int_0^{\Delta t} u(t)i(t)dt = \frac{1}{3}\frac{rRm}{i\eta k_\omega}\frac{\Delta v^2}{\Delta t^2}\xi_1\left(\frac{rm}{i\eta k_\omega}\xi_1 - \frac{ik_\omega}{rR}\right)\Delta t^3 + \frac{1}{2}\frac{rRm}{i\eta k_\omega}\frac{\Delta v}{\Delta t}\left(\frac{rm}{i\eta k_\omega}\xi_1\left(\xi_1 v_c + \frac{\Delta v}{\Delta t} + g\big(f cos(\alpha) + sin(\alpha)\big)\right) - \xi_1\frac{ik_\omega}{rR}v_c - \left(\xi_1 v_c + \frac{\Delta v}{\Delta t} + g\big(f cos(\alpha) + sin(\alpha)\big)\right)\frac{ik_\omega}{rR}\right)\Delta t^2 + \frac{rRm}{i\eta k_\omega}\left(\xi_1 v_c + \frac{\Delta v}{\Delta t} + g\big(f cos(\alpha) + sin(\alpha)\big)\right)\left(\frac{rm}{i\eta k_\omega}\left(\xi_1 v_c + \frac{\Delta v}{\Delta t} + g\big(f cos(\alpha) + sin(\alpha)\big)\right) - \frac{ik_\omega}{rR}v_c\right)\Delta t \tag{21}$$

The energy determined on the basis of formula (21), describing the cost of traversing between two points of the graph is characterised by the fact that it depends solely on the parametres connected to the point of the graph in question, and specifically – with the pair of points connected by the edge being analysed. Since the graph is a directed graph, with weights that may be negative, the Bellman-Forda algorithm has been used in order to determine the path with the lowest weight, and consequently the optimal velocities on the particular sections of the path that result in the minimum energy consumption. It should be noted that in formula (21), the only parametres that is being optimised is the velocity at which the section in question is traversed. In paper 1,2* the robots traversed a flat area and, as a result, time was an additional factor to be optimised, because otherwise the problem became trivial (minimum energy expenditure results from minimum speed). In the case where the area analysed is not flat the issue of time optimisation may, but does not need to be taken into consideration. This effect is discussed in the following section.

4. RESULTS

In this section of the paper, the results are presented that show the implementation of the algorithm. The only sources of energy dissipation are the ones included in the model, i.e. losses due to resistance in the engine, losses due to air resistance, losses due to rolling resistance.

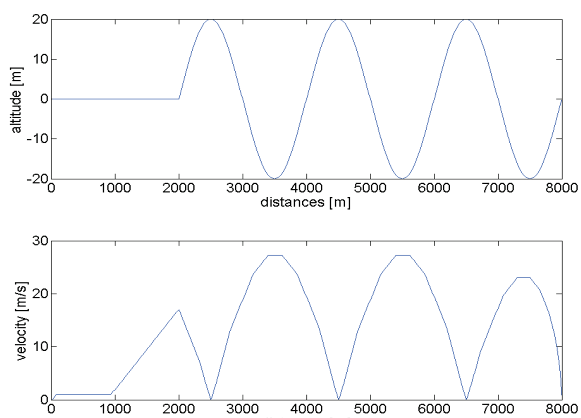

Fig. 8. Effect of performing the algorithm

In the figure 8, the result of using the algorithm for a theoretical segment of the path is presented. The segment's profile has been presented in the first diagram. This profile has been assumed deliberately, due to its regularity. It can be expected that the shape of such a profile should at least partially be reflected in the controlling profile. The lower diagram presents the speed profile that has been determined for the given path profile as well as the specific model parameters. The path segment has been divided into 400 equal parts. The algorithm was used to determine the velocity for the specific segments of the path. The velocity was allowed to change within the range of 0.1-30 m/s. The area of velocity change has been divided into 100 equal segments, which gave velocity resolution at the level of approximately 0.3 m/s, for path segments equalling 20 m. It is characteristic that, according to the movement plan determined by the algorithm, the vehicle should start linearly accelerating at around 1000 m. This fits fairly well with the intuitive prediction, which suggests that, due to the presence of obstacles, the vehicle should have reacted at an earlier time. The algorithm has created a solution for performing the movement in an energetically optimal manner. The last phase of the movement is characteristic as well. Although the shape of the terrain profile starting at 2000 m is sinusoidal, the algorithm takes into account the fact that at 8000 m the vehicle has to stop. As a result, for the last 1000 m the movement of the vehicle is directed differently, taking into consideration the necessity to finally stop the vehicle. In the following part of the paper, the impact of the specific parameters connected to energy dispersion on the optimal velocity profile will be presented.

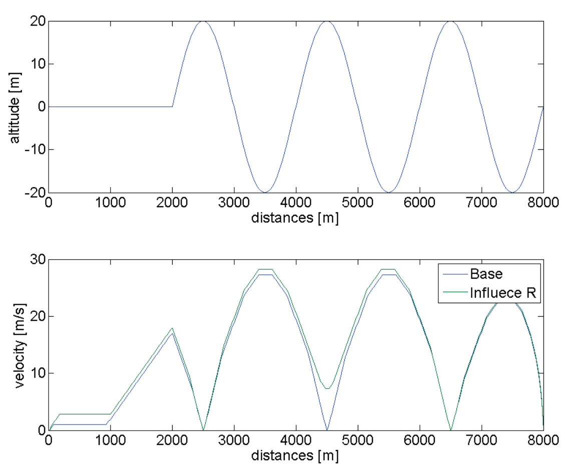

Fig. 9. Impact of resistance on the velocity profile

In Figure 9, the impact of the change in resistance on the resulting velocity profile has been presented. The blue colour shows the basic profile, as presented in Figure 8.

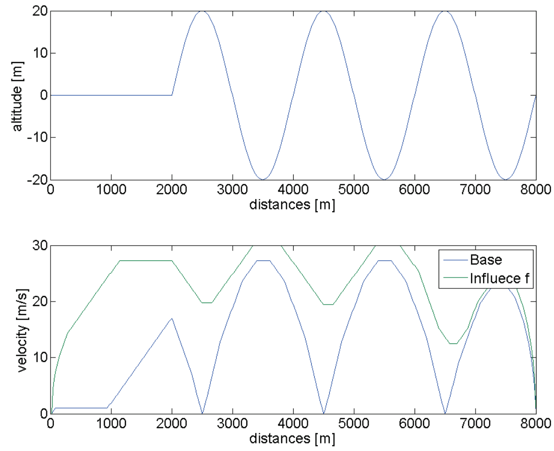

Fig. 10. Impact of rolling resistance on the velocity profile

In Figure 10, the impact of an increased rolling resistance factor on the resulting optimised velocity profile has been presented. It is clearly seen that for the segments of the path placed the lowest, the algorithm has chosen the highest possible velocity. In such situations, it is clear that an increase in the permitted velocity could result in an increase in the energy efficiency of the vehicle.

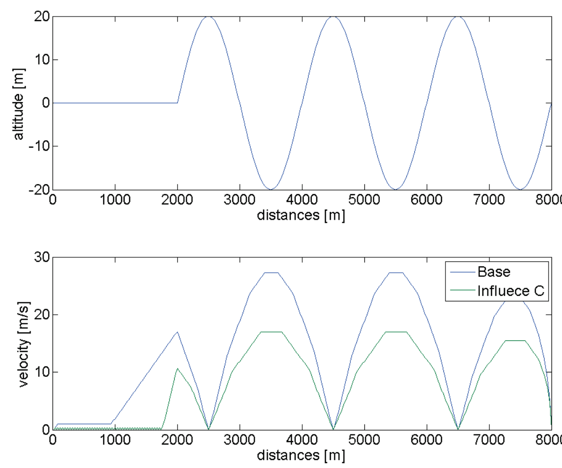

Fig. 11. Impact of air resistance on the velocity profile

In figure 11, the impact of increased air resistance of the vehicle on the optimised velocity profile has been presented. As might be intuitively guessed, the vehicle will move at lower velocities in such situations.

5. SUMMARY

The article has presented a general idea for an algorithm that would allow for determining the optimal parameters of vehicle movement. The sources of energy dissipation have been assumed as follows: damage to the engine and the drive. In addition, the mathematical basis have been presented for assessing the impact of damage resulting from problems such as axial misalignment on the dissipated energy. In the second part of the paper, the concept of the algorithm has been detailed, paying special attention to certain problems that have arisen, and an algorithm has been proposed that determines the optimal movement parameters for a simplified case, when the vehicle is moving along a path determined in advance. In addition, the results of applying the algorithm for a simple case have been presented, as well as the impact of the particular energy dissipation parameters of the model on the optimal velocity profile of the vehicle. The plans for further research include estimating the impact of other damages, such as damaged bearings or demagnetising, on the energy dissipation. Further work on an algorithm is also planned that would allow for simultaneous determining of an optimal path as well as an optimal velocity profile.

REFERENCES

[1] Liu S., Sun D., Optimal Motion Planning of a Mobile Robot with Minimum Energy Consumption, IEEE/ASME International Conference on Advenced Inteligent Mechatronics, s. 43-48, 2011

[2] Weigo W., Huitang C., Peng-Yung W., Optimal Motion Planning for a Wheeled Mobile Robot, Proceedings of the IEEE International Conference on Robotic & Automation, s. 41-46, 1999

[3] Weigo W., Huitang C., Peng-Yung W., Time OptimalPath Planning for a Wheeled Mobile Robot, Jurnal of Robotic Systems 17(11), 585-591, 2000

[4] Plonski P. A., Tokekar P., Isler V., Energy Efficient Path Planning for Solar-Powered Mobile Robots

[5] Kim H., Kim B., Minimum-Energy Translational Trajectory Planning for Battery-Powered Three Wheeled Omni-Directional Mobile Robots, 10th Int. Conf. on Control, Automation, Robotics and Vision, p.1730-1735, 2008,

[6] Cameron J., Thomson W.: Vibration and current monitoring for detecting airgap eccentricities in large induction motors, IEEE Proceedings 133(3):155-163,

[7] Blodt M., Granjon P., Regnier J.: Mechanical Fault detection in induction motor drives through stator current monitoring - Theory and application examples, Fault Detection (2010), 451-488,

[8] LaValle S. M., Planning Algorithm, Cambridge University Press

[9] Wilson R. L., Wprowadzenie do teorii grafów,

Przemysław Szulim
Warsaw University of Technology, Poland
p.szulim@mechatronika.net.pl