Modelling of the UAV Safety Manoeuvre for the Air Insertion Operations

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Abstract. Tempo and complexity of the contemporary asymmetric battlefield is on the increase and time for a certain component delivery (ammunition, medical kit, vaccine and so on), for instance in the special operations, could be critical. Usually, the only way in these situations is a fast air delivery of concrete material to the "hot" destination zone. Contemporary air insertion in that case is usually performed by manned or unmanned (if available) system with human intuitive manoeuvre planning supported by information from ISR systems. In this case, there is almost impossible to achieve a fast, detailed and mathematically optimal solution with the real time implementation to the UAV control system (autopilot). The article describes a modelling approach which leads to high automation and optimal (autonomous) reasoning in case of 3D UAV path planning, respecting the operational situation in the area, manoeuvre limits of the UAV and potential threat in the operational area. The solution is based on detailed operational area 3D modelling, known and unknown probabilistic threat simulation and its capability estimation, quantification of safety area parameters and large 3D (multi-criteria) safety matrix development, criterial function and boundary condition specification, UAV air manoeuvre and constraints algorithm development, optimal UAV path search and operational evaluation.

Keywords: UAV · Safety manoeuvre modelling · ISR · Optimization · Air insertion

1 Introduction

In many branches, especially technically or technologically oriented, the approach of successful modelling as well as finding inverse solutions to generally set output requirements, is common and successful (with accuracy corresponding up to 95 % to real tests – statics, aerodynamics, hydrodynamics etc.). It is possible due to high level of exactness and little uncertainty in the model. Uncertainty is unfortunately presented in socio-economical domains, where military operational-tactical processes belong.

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Therefore it is difficult to model a process of combat activities with accuracy corresponding to technological processes, nevertheless it is possible to model conditions accompanying a specific tactical situation successfully. After optimization of solution to these conditions we can use the results as a starting point for selection of variants of friendly or enemy forces activities (courses of actions). This approach is commonly used in the process of an operational task solution, where aspects of this problem should create a backbone of commander's and staff's decision making process [1].

A solutions of an operational-tactical task is realized through an initial mathematical model (operational environment) of the task that is an object of an application of additional methods and procedures, usually aggregated in partial geographical-tactical tasks in a way leading to the solution to the given task. A character of operational-tactical tasks is usually pragmatic-statistical or probabilistic, related to its solution assignment and its goals, setting ideal conditions, position, maneuver, reaction etc. for a specific task accomplishment. Thus, solutions to operational-tactical tasks support commander's decision making process during preparation and execution of military operations. Geographical-tactical analyses can be considered as basic building blocks of operational-tactical tasks solutions [2], aggregating military-geographical battlefield assessment into thematically unified algorithmic processes applicable to tactics, namely decomposition of operational-tactical tasks, which is the aim of the paper.

2 Analyses

The importance of automation of an optimal manoeuvre selection is crucial in actual dynamic conditions of digitalized battlefield. Automation is also possible in conditions of communication and computing infrastructure. In an actual command and control process architecture arrangement, automation of optimal manoeuvre selection belongs so far to support of a commander's or an operator's decision making process. Nevertheless, due to algorithmic character of the task and the need for continuous re-computing, based on operational space changes, i.e. due to changes in the state graph of a manoeuvre during an operation, we can suppose that full integration of the process into an automated low-level UAV control process under an operator supervision will take place in near future – Man on the Loop [3].

There can be more approaches to the solutions and they can give different results. Our approach to optimization is based on approximation of a 3D safety space of a manoeuvre that is transformed into a 3D non-oriented graph, where the minimal path is evaluated by the sum of all safety coefficients of all individual intersected subareas. The path topology is subordinated to another criteria, which have to be met. In general, these criteria are related to constraints of manoeuver capabilities of the UAV.

3 State of the Art

Relatively a lot of work has been done and published in the area of UAV manoeuvre optimization recently and it is undoubtedly an actual topic. Based on a literature research it can be stated that most of publications deals with UAW swarm optimization or UAV reconnaissance optimization, where the objective function is usually set on time or fuel consumption minimization during a selected manoeuvre type accomplishment (trajectory planning [4], safe trajectory [5], cooperative path planning [6], Ant colony approach [7, 9], heuristic and genetic algorithms [8]).

In many cases the third dimension of the air space (a fixed altitude operation) [4] and possibly other flight or aircraft parameters and options are omitted, as a velocity variation etc. An integration of given parameters significantly increases complexity of calculation models and these parameters are often approximated or neglected during modelling and simulation.

From the terminology point of view, a safe manoeuvre or path planning are usually defined as trajectories respecting selected criteria and integrating a collision avoidance features at the same time [10]. The presented concept of a operational safe manoeuvre or its equivalent considering a complex 3D model of a battlefield including variable and dynamical threats has not been found within a literature research yet and it represents a substantial innovation [11–13].

4 Solution

Taking into account main criteria, factors influencing the solving process and the context of the approach described above, O_{UAV} criterial function was constructed. We suppose optimization by minimizing the sum of all possible safety threats that the UAV faces during task accomplishment. The task accomplishment means a flight through a 3D operation space, from an issuing point to a specified destination point. The Fig. 1 demonstrates the "experimental displacement" of the operational area.

The trajectory can be evaluated by the purpose function:

$$UAV_{path} = \min \rightarrow \sum\nolimits_{i=1}^{M} K_{I_i,J_i,K_i}; \quad (1)$$

where:

$K_{x,y,z}$ – 3D safety matrix of operational area, derived from the set of analyses (3)
I_i, J_i, K_i – are the mathematical progressions coding the individual components/axes of the 3D path

The condition:

$$\forall i \in (1\ldots M) = \; > (|I_{i+1} - I_i| + |J_{i+1} - J_i| + |K_{i+1} - K_i|) < 3, \quad (2)$$

means that that two following elements of K matrix are adjacent and:

$K_{I_i,J_i,K_i}; i = 1$ – starting point of the UAV flight, represented by a particular matrix element
$K_{I_i,J_i,K_i}; i = M$ – destination point of the UAV flight, represented by a particular matrix element

A calculation of the 3D safety space should consider an actual situation in the operation space – COP – and it can be fully or mostly automated by means of C4ISR

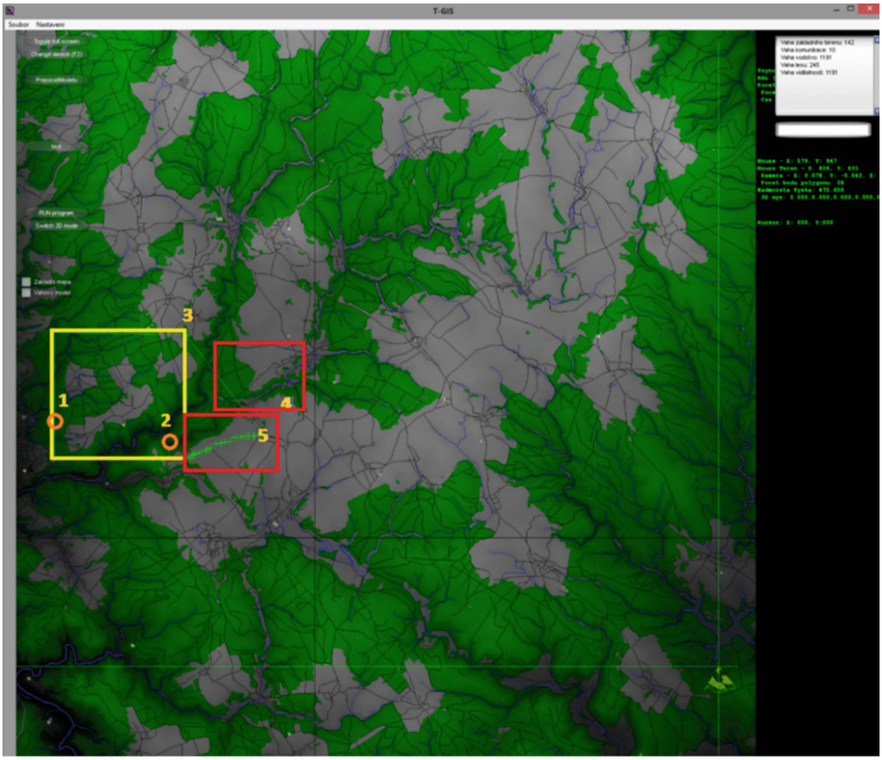

Fig. 1. Operational area, 1-issuing point of the UAV flight, 2-destination point of the UAV flight, 3-desired area of safety evaluation, 4-operational area of enemy – 2 option, 5-operational area of enemy – 1 option, from application developed by the authors. (Color figure online)

systems. Criteria definitions and a system of operational-tactical analyses, from which the target safety coefficient of operational space 3D matrix can be derived, are crucial for the task solutions:

$$K_{i,j,k} = \sum\nolimits_{l=1}^{N} \left(TV_l \cdot An_l(i,j,k) \right) \tag{3}$$

$K_{x,y,z}$ – 3D safety matrix of operational area
$An_l(i,j,k)$ – geo-tactical or operational analyses
TV_l – tactical weights defining the priorities in particular case of operational task solution

The number of analyses influencing coefficients of the safety matrix is not limited, nevertheless it is necessary to set rates among A_i weight coefficients. Setting key parameters and requirements on the task is usually commander's or operator's decision. Setting A_i coefficients is an operational task and it is based on manoeuvre requirements and a supposed threat character. The sum of the A_i weight coefficients is normalized, i.e.

$$\sum_i A_i = 1. \tag{4}$$

To demonstrate the chosen approach we suppose following scenario. Tactical enemy entities are equipped by two type of weapons that can engage UAV, namely heavy and light weapons. The entities equipped by heavy weapons are mounted on vehicles that can move only on roads. Positions of the entities equipped by light weapons are not limited, so we can suppose them to be in the operation area, with respect to tactical rules influencing a threat probability in a point of operational space.

So for this purpose we suppose:

- Defined space for the threat matrix computing, denoted by D_{OR}, see Fig. 1 - *for the first demonstration (Figs. 4 and 5) we took in account area 5.*
- Defined area of enemy entities movement, denoted by S_{OR}.
- Analysis of visibility from the area of enemy entities occurrence, denoted by S_{OR}.
- Analysis of the threat for the area of interest D_{OR} from the S_{OR} area by light weapons.
- Analysis of the threat for the D_{OR} area from selected positions in the S_{OR} area by heavy weapons.
- Definition of UAV manoeuvre limitations.

The following algorithm, Fig. 2, describes schema of sequence of individual processes:

For calculations of individual analyses following relations were derived:

Analysis of D_{OR} (area of interest) threat from S_{OR} area by "light weapons" A_{lk}:

$$A_{lk} = C_{alk} \cdot F_v(S, D) \cdot P_{zlk}(\mathrm{S}, \mathrm{D}), \tag{5}$$

analysis of D_{OR} threat from selected positions in S_{OR} area by "heavy weapons" A_{tk}:

$$A_{tk} = C_{atk} \cdot F_v(S, D) \cdot P_{ztk}(\mathrm{S}, \mathrm{D}) \tag{6}$$

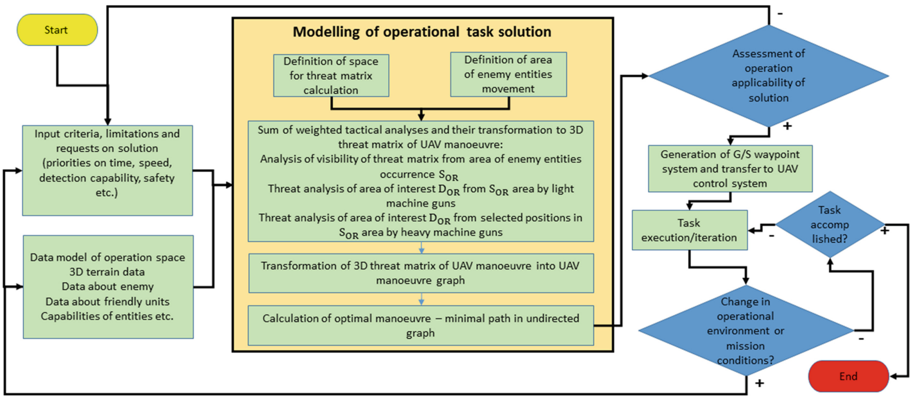

Fig. 2. General algorithm of the solution.

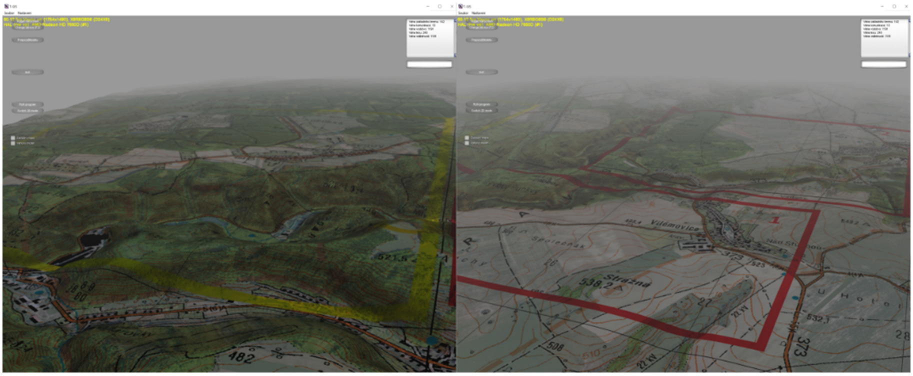

Fig. 3. 3D visualization of operational area, application developed by the authors.

where:

- C_{alk} is a tactical (pragmatic) coefficient of a multi-criteria evaluation defined for A_{lk} analysis.
- C_{atk} is a tactical (pragmatic) coefficient of a multi-criteria evaluation defined for A_{tk},
- $F_v(S,D)$ is a visibility function from the S point to the D point in a digital terrain model, $0 \leq F_v(S,D) \leq 1$. This function can reflect also level of clouds, fog or daylight.

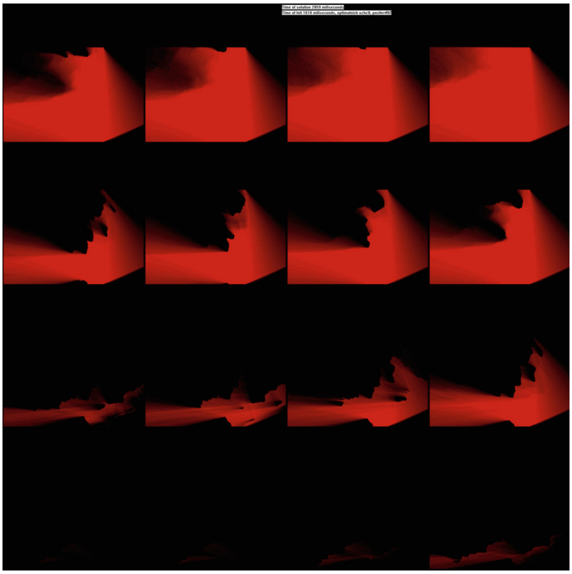

Fig. 4. Illustration of 16 cuts of the 3D safety matrix, individual slides represent development of the safety coefficient in each altitudes (rise up about 10 m on each slide, lowest slide stars at 80 m), from application developed by the authors.

- $P_{zlk}(S, D)$ is a hit probability of a slowly flying target at the position of $D(x, y, z)$ by a "light weapon" from the point of $S(x, y, z)$ in a digital terrain model (in ideal conditions).
- $P_{ztk}(S, D)$ is a hit probability of a slowly flying target at the position of $D(x, y, z)$ by a "heavy weapon" from the point of $S(x, y, z)$ in a digital terrain model (in ideal conditions).
- $S(x, y, z)$ is the initial point in a digital terrain model.
- $D(x, y, z)$ is the target point in a digital terrain model.

To demonstrate solution of the task, a standalone application was programmed in C++, where algorithms explained above were implemented and terrain data of the Czech Republic were used for digital terrain model creation. Virtual 3D look on operational area is demonstrated in the following picture (Fig. 3):

The results of operational analyses, supporting the 3D safety matrix development, are visible in the next Fig. 4.

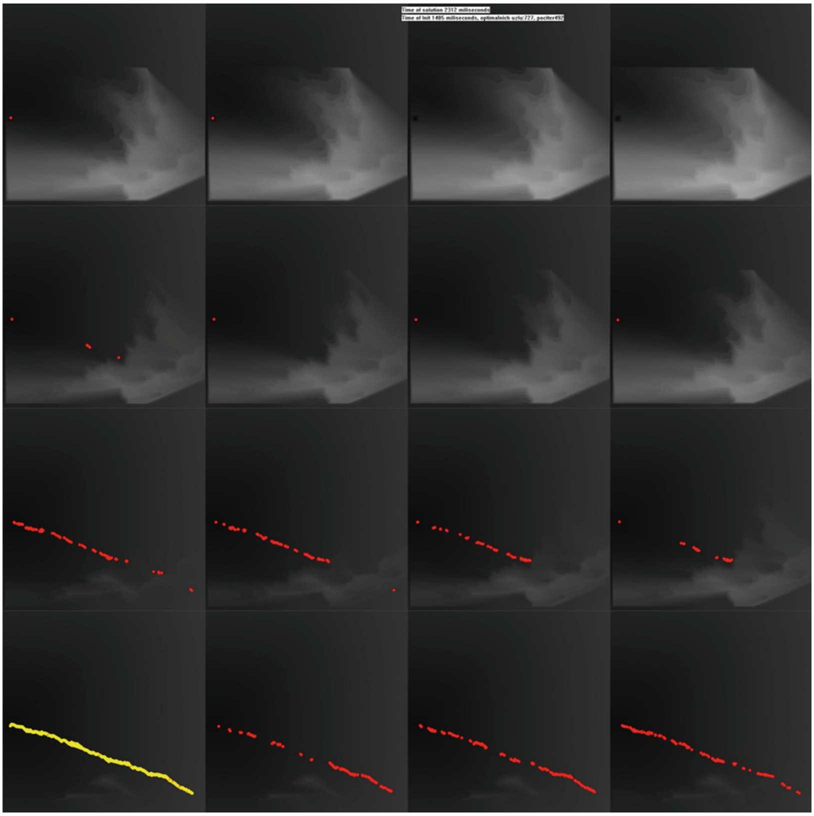

Fig. 5. Illustration of 16 cuts of the 3D safety **MANEUVER** matrix, with the best UAV route highlight in each layers/altitudes, integration of all waypoint from all slides (red dots), creates the continuous path as it is demonstrated in the left corner (yellow) individual slides represent of the safety **MANEUVER** coefficient distribution in each altitudes (rise up about 10 m on each slide, lowest slide stars at 80 m), from application developed by the authors. (Color figure online)

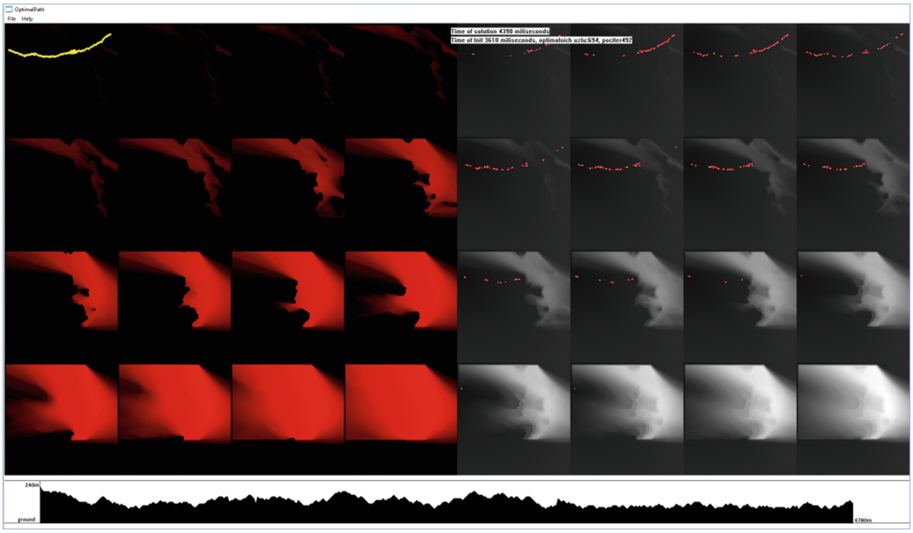

Fig. 6. Illustration of 16 cuts of the 3D safety matrix and safe **MANEUVER** matrix, with the best UAV route highlight in each layers/altitudes, this analyses took in an account enemy operational area 2 - Fig. 1 – red rectangle no. 4, (rise up about 10 m on each slide, lowest slide stars at 80 m), altitude flight profile – 240 m top line, 4780 - flight “horizontal” length, from application developed by the authors. (Color figure online)

Taking into account the previous analyses and criteria, the 3D threat matrix was constructed. From this matrix a 3D maneuver space graph was derived and a minimal path calculation in a non-oriented weighted graph was applied on it (26-direction topology of connecting neighbouring cells was chosen - in 3D). After computing, the value of the best possible safety/cost maneuver (to that point) is stored in every node of the graph (total of 512 × 512 × 16 nodes). Choosing a target point and by running a back search, a concrete path is found, that is demonstrated in Fig. 5.

The approach explained above and the algorithms demonstrate a possible way to solve the discussed problem. It is possible to develop the solution with regard to completeness and adaptation to a concrete application. The calculations were performed on a PC with AMD A10-5800 K (3.8 GHz) processor and the whole task solution, including geo-tactical analyses, took approximately 10 min.

The same processes were executed also for enemy operational area 2 (Fig. 1 – red rectangle no. 4) with identical criteria and constrains. The result is presented on Fig. 6 including altitude profile of the flight. Optimal path change is apparent at the first look.

5 Conclusion

In many cases an algorithm schema can be applied to pragmatic aspects of tactical activities, so the decision making process of their execution can be automated at a quite high level. Taking into account this fact, it is possible to formulate a generic starting point, based on a new philosophical perspective on a computer support tactical decision making process and a system approach to operational-tactical tasks solutions. This topic is related to a mathematical solution to problems dealing with modelling, algorithm development, automation and optimization of decision making problems of command and control bodies (commanders) in uncertain operational environment.

Issues of a decision making process rationalization based on solution to complex operational-tactical tasks are very broad and they include sets of sub-problems concerning multi-criterial decisions, game theory, probability theory, operation research, graph theory, linear algebra, mathematical analysis etc. Ways of solutions are usually not trivial and final results require further analysis from a stability point of view and assessment of their practical usability. Anyway, this innovative approach shifts a static concept of commander's decision support at a tactical level, incoming only from a technological-distribution platform, to a higher level and it provides a powerful tool for planning and execution of a combat activity.

Presented approach differs from other optimization ways based on seeking the highest probability (for instance given in [5]) of a variant task accomplishment, while the matter of the suggested approach is seeking for a system of the best conditions, within which the given task can be accomplished. In this regard, there is a connection between these approaches at a philosophical level (both of them seek for the best accomplishment of the task), but the approach based on the highest probability usually faces reality problem of key parameters, used for probability computing concerning operational activities realization, including sociological, physiological and psychological factors. The presented solution is related to exact parameters of a battlefield and individual tactical entities and it represents an approach providing better preconditions for real implementation in C4ISR systems or in direct control systems of end systems (i.e. UAV in our case). Some ideas and inspirations concerning the algorithmic approaches were also taken from [14–16].

Growing need for military information systems (C4ISR), which actually reach their limits determined by current technologies, stimulate continuous development and implementation of methods and tools using modelling and simulation support to decisions processes. Optimization of tactical activities in an area of a combat operation, especially operational UAV path optimization, which is merit of this paper, becomes integral part of it. This is a presumable trend to the tactical-technological future of the 21st century battlefield. This concept creates prerequisites for effective involvement of automatic and robotic systems into command and control processes and it contributes to time, force and equipment economy during military operations. Further development of this concept and its application and operational deployment will enable to gather adequate amount of necessary information for realization of fully autonomous and robotic operational-tactic systems, towards which technologically advanced armies aim.

References

1. Hodicky, J., Frantis, P.: Decision support system for a commander at the operational level. In: Dietz J.L.G. (ed.) KEOD 2009 - Proceedings of International Conference on Knowledge Engineering and Ontology Development, Funchal - Madeira, October 2009, pp. 359–362. INSTICC Press (2009). ISBN 978-989-674-012-2

2. Hodicky, J., Frantis, P.: Using simulation for prediction of units movements in case of communication failure. World Acad. Sci. Eng. Technol. Int. J. Electr. Comput. Energ. Electr. Commun. Eng. **5**(7), 796–798 (2011)
3. Hodicky, J.: Modelling and simulation in the autonomous systems' domain- current status and way ahead. In: Hodicky, J. (ed.) MESAS 2015. Lecture Notes in Computer Science, vol. 9055, pp. 17–23. Springer, Heidelberg (2015)
4. Geiger, B.: Unmanned aerial vehicle trajectory planning with direct methods. A dissertation in Aerospace Engineering, The Pennsylvania State University, Pennsylvania, USA (2009)
5. Kamal, W.A.: Safe trajectory planning techniques for autonomous air vehicles. A dissertation work, University of Leicester, United Kingdom (2005)
6. Tsourdos, A., White, B., Shanmugavel, M.: Cooperative Path Planning of Unmanned Aerial Vehicles, pp. 1–214. Wiley, Hoboken (2010). ISBN 978-0-470-74129-0
7. Duan, H.B., Ma, G.J., Wang, D.B., Yu, X.F.: An improved ant colony algorithm for solving continuous space optimization problems. J. Syst. Simul. **19**(5), 974–977 (2007)
8. Yao, H.Q., Quan P., Jian, G.Y.: Flight path planning of UAV based on heuristically search and genetic algorithms. In: Proceedings of IEEE 32nd Annual Conference, pp. 45–50 (2005)
9. Liu, C.A., Li, W.J., Wang, H.P.: Path planning for UAVs based on ant colony. J. Air Force Eng. Univ. **2**(5), 9–12 (2004)
10. Kress, M.: Operational Logistics: The Art and Science of Sustaining Military Operations. Springer, Berlin (2002)
11. Rybar, M.: Modelovanie a simulacia vo vojenstve. Ministerstvo obrany Slovenskej republiky, Bratislava (2000)
12. Washburn, A., Kress, M.: Combat Modeling. International Series in Operations Research & Management Science. Springer, Berlin (2009)
13. Mokrá, I.: Modelový přístup k rozhodovacím aktivitám velitelů jednotek v bojvých operacích. Disertační práce. Univerzita obrany v Brně, Fakulta ekonomiky a managementu, Brno (2012). 120 s
14. Binar, T., Sukáč, J., Šilinger, K., Zatloukal, M., Rolc, S.: The steel ballistic resistance directly affecting logistics-related expenditures. In: 16th International Conference on Advanced Batteries, Accumulators and Fuel Cells, ABAF 2015, pp. 187–196. Electrochemical Society Inc., USA (2015). ISSN 1938-5862. ISBN 978-1-60768-539-5
15. Binar, T., Dvořák, I., Kadlec, J., Sukáč, J., Rolc, S., Křesťan, J.: Material characteristics of plastic deformation in high-strength steel. Adv. Mil. Technol. **9**(2), 33–39 (2014). ISSN 1802-2308
16. Michálek, J., Sedlačík, M., Doudová, L.: A comparison of two parametric ROC curves estimators in binormal model. In: Proceedings of 23rd International Conference Mathematical methods in Economics 2005. : GAUDEAMUS Univerzita Hradec Králové, Hradec Králové, pp. 256–261 (2005). 11 s, ISBN 80-7041-53