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# Analysis of the existing approaches to in-flight aircraft rerouting

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**Abstract:** Currently, the large number of aircraft accidents is associated with the loss of control in flight and a controlled flight into terrain. It frequently occurs due to a change of flight conditions, relatively which a preparation for departure was carried out, and involves the necessity to reroute efficiently in the conditions of increased psychophysiological load and time constraint for decision-making. Generated thunderstorm cells on route, artificial or natural obstacles, not considered while planning a route, can result in amending a flight plan, which was earlier accepted and implemented in the automatic, flight director or manual modes of control. The lack of comprehensive situational awareness is fairly a frequent cause of aviation accidents for general aviation aircraft. Aviation accidents of transport category aircraft are typically associated with incorrect crew actions when dangerous flight zones are detected along the route. The article represents an overview and analyzes modern onboard facilities to detect obstacles, as well as required pilot actions to reroute a flight for in-flight detected obstacle avoidance. The current level of avionics development provides situational awareness necessary for obstacles avoidance but requires timely, correct and sometimes non-obvious flight crew rerouting decisions. The algorithms used with robotic packages of various applications in related fields ensure the automatic rerouting for obstacle avoidance. They cannot be directly used or adapted for the implementation on board an aircraft due to the lack of consideration for aircraft specific features when obstacle avoidance routing, i.e., restrictions of control parameters (an angle of attack, overload, roll angle), capabilities of a control system (available rate of overload, available and maximally allowable angular rolling velocity, etc.). Therefore, the issue to develop a system to support pilot decisions for obstacle avoidance is relevant. It encompasses the synthesis of safe alternatives for obstacle avoidance which are optimal by a pilot-assigned criterion (minimum loss of time, minimum additional fuel consumption, etc.).

**Key words:** flight on route, obstacle avoidance, algorithms of obstacle avoidance, construction of motion trajectories, flight automation**.**

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# Анализ существующих подходов к перестроению маршрута полета воздушного судна в процессе его выполнения

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**Аннотация:** В настоящее время большое количество авиационных происшествий связано с потерей управления в полете и столкновением с землей в управляемом полете. Зачастую это происходит вследствие изменения условий полета, относительно которых происходила подготовка к вылету, и связано с необходимостью оперативного перестроения маршрута полета в условиях повышенной психофизиологической нагрузки и дефицита времени на принятие решения. Причинами перестроения ранее принятого и реализуемого в автоматическом, директорном или ручном режимах управления плана полета может стать, например, возникновение на пути следования грозовых очагов или появление не учтенных при планировании искусственных или естественных препятствий. Отсутствие полной ситуационной осведомленности является достаточно частой причиной авиационных происшествий для воздушных судов малой авиации. Авиационные происшествия самолетов транспортной категории, как правило, связаны с неправильными действиями экипажа при обнаружении на пути следования опасных зон полета. В статье, носящей обзорный характер, анализируются современные бортовые средства обнаружения препятствий, а также необходимые действия пилота, связанные с изменением маршрута полета с целью облета препятствий, обнаруженных в ходе полета. Показано, что современный уровень развития авионики обеспечивает необходимую для облета препятствий ситуационную осведомленность, но требует принятия своевременных, правильных и зачастую неочевидных решений экипажем по перестроению маршрута полета. Используемые же в смежных областях робототехническими комплексами различного назначения алгоритмы, обеспечивающие автоматическое перестроение маршрута движения с целью обхода препятствий, не могут быть напрямую использованы или адаптированы для реализации на борту воздушного судна в силу отсутствия учета при построении маршрутов обхода препятствий специфических особенностей воздушных судов – ограничений на управляющие параметры (угол атаки, перегрузка, угол крена); возможности системы управления (располагаемые темп создания перегрузки, располагаемая и максимально допустимая угловая скорость крена и др.). Следовательно, актуальной представляется задача разработки системы поддержки принятия решения пилота по облету препятствий, обеспечивающей синтез альтернативных безопасных маршрутов облета препятствий, оптимальных по заданному пилотом критерию (минимальные потери времени, минимальные дополнительные затраты топлива и т. п.).

**Ключевые слова:** полет по маршруту, облет препятствий, алгоритмы облета препятствий, построение траекторий движения, автоматизация полета.

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## Introduction

The analysis of aviation accidents (AA) statistics, which occurred over a span of 2011–2020s[1] in the Russian Federation, shows that a significant part of AA as during commercial operations as while conducting general aviation flights (GAF) is associated with the following groups of events (fig. 1–4):

- collision with obstacles during the low-level operation (LALT);
- loss of control in flight (LOC-1);
- controlled flight into terrain (CFIT);
- encountering instrument meteorological conditions for which a flight crew is not permitted to operate (UIMC);
- encountering severe thunderstorm activity (WSTRW).

The results of investigations of the given AA revealed that the significant part of AA is caused by the lack of comprehensive situational awareness and wrong actions of a flight crew in the environment of increased psychophysiological load and time constraint for decision-making.

A Mi-8 helicopter crashed on April 28th, 2002, which caused 8 fatalities including a Governor of Krasnoyarsk Region Alexander Lebed. The helicopter performed a flight in the mountainous area at the altitude lower than safe, and in the conditions of reduced visibility at an altitude of 35 m. it collided with thunderstorm protection wires of power lines, lost controllability and collided with the snowy ground surface sustaining substantial types of damage. It is obvious that available information about the relative position of the manned helicopter and power lines could have averted that crash.

Furthermore, crew notification about an obstacle on a flight route is not adequate to avert AA, e.g., Tu-154M aircraft of “Pulkovo” Airline crashed in the vicinity of Donetsk on August 22d, 2006. During the flight close to the ceiling, the crew assessed improperly meteorological conditions, took an afterthought decision for leftward weather deviation climbing to the altitude of thunderstorm cells and after entering a band of hazardous phenomena exceeded the stalling angle of attack which resulted in stall configuring for a mode of flat-attitude spin. Eventually, the aircraft collided with terrain at a high vertical speed. One can claim that the timely providing one or several safe alternatives with the crew to continue a flight could have prevented the accident.

[1] The analysis of the RF civil aviation flight safety in 2020. Federal Air Transport Agency, Flight Safety Inspection Directorate, 2021, 97 p. Available at: https://aviaforum.ams3.cdn.digitaloceanspaces.com/data/attachment-files/2021/04/1598384_a3450354b90aa72fe5588472bb4eedfc.pdf (accessed: 08.10.2022).

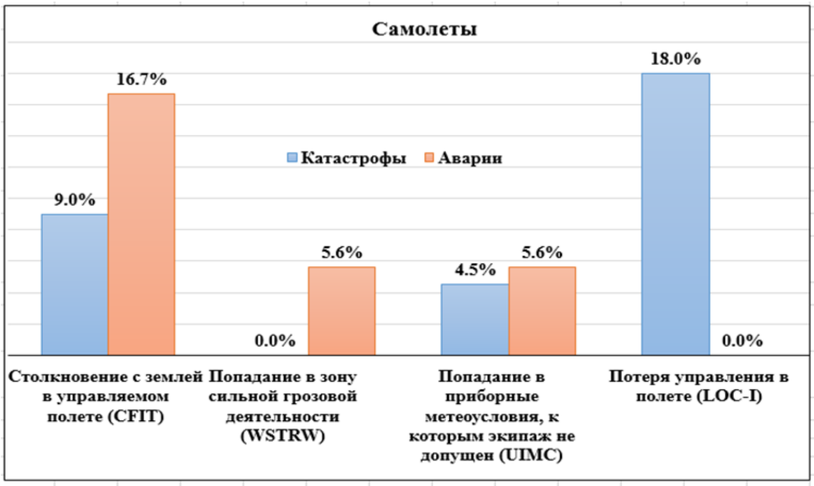



**Fig. 1.** Types of events that caused aviation accidents with commercial aircraft in 2011–2020s

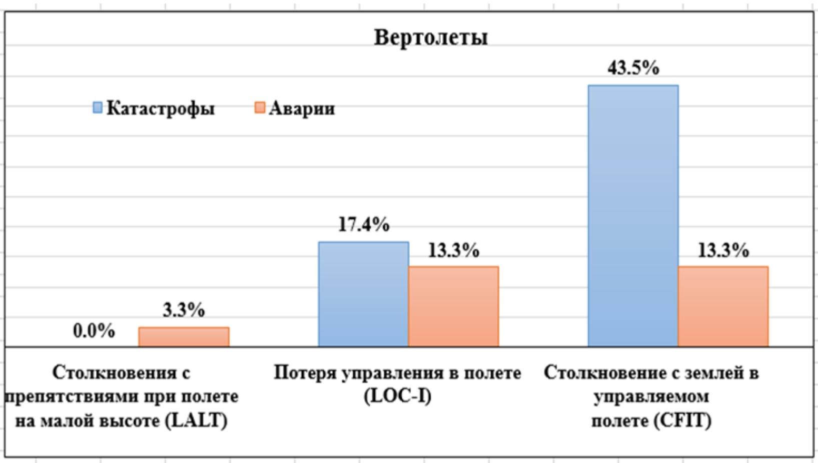



**Fig. 2.** Types of events that caused aviation accidents with commercial helicopters in 2011–2020s

Thus, an issue to identify potentially hazardous scenarios of flight and to form safe alternatives of its continuation is relevant in the broad sense. A task of operational, reconfiguration of a flight planned route in terms of the occurrence of obstacle threatening a flight safety, e.g., a terrestrial natural or artificial object, hazardous space area, etc., is particularly unequivocally of practical interest.

## Analysis of the existing approaches to avoid obstacles

Modern aircraft can make a flight in the automatic or flight director mode in compliance with the onboard computer-assigned flight route. The assignment method and the content of a flight plan depend on the aircraft type. At this rate, a long-haul aircraft flight plan comprises not only a flight via airways but also Standard Instrument Departure Routes (SID), Standard Arrival Route (STAR) and APPROACH procedures developed for each airport. However, with reference to a flight route, there are no critical differences between aircraft, as a rule, and a route is assigned by means of waypoints in airspace containing the original, turning, and terminal significant points of route. A flight route can be developed and input into the onboard computer by a pilot himself or computed in ground computers using special software and then downloaded onboard. Figure 5, as an example,

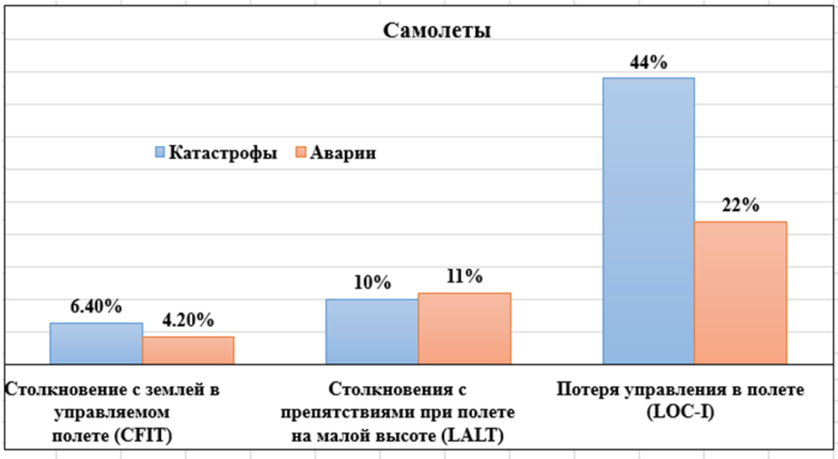



**Fig. 3.** Types of events that caused aviation accidents with general aviation aircraft in 2011–2020s

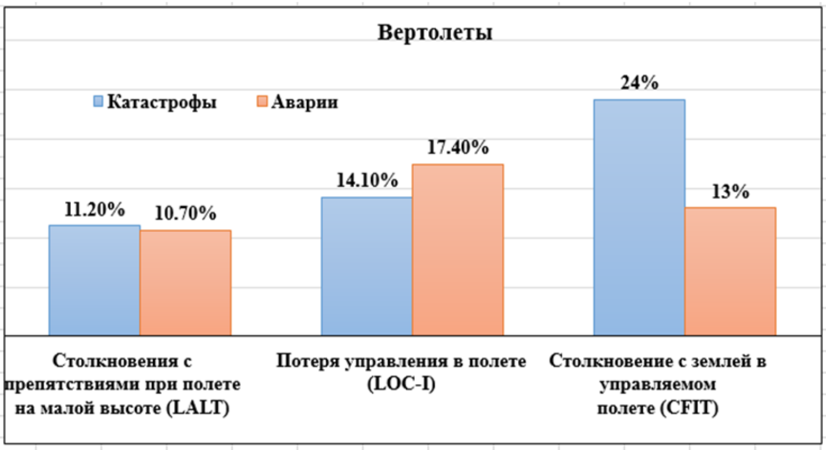



**Fig. 4.** Types of events that caused aviation accidents with general aviation helicopters in 2011–2020s

represents the screen of G3000 Garmin system developed for light aircraft with gas turbine engines, a user-assigned flight route in the form of a curve, connecting standard or user-assigned points of the route selected from the database. However, after takeoff rerouting, diversion can be carried out only by a pilot in the automatic (e.g., by adding new waypoints or assigning a new course of flight) or manual mode.

It should be noted that crews of modern aircraft possess sufficient situational awareness for a flight safety.

For example, information about marginal weather conditions can be obtained by a pilot from onboard meteorological radars or storm scopes as well as via broadcast channels of communication. Figure 6 illustrates an example of a line squall in two scales on a multi-purpose indicator of the Airbus-type aircraft. Figure 7 illustrates the weather map obtained via a satellite communication channel of G1000 Garmin suite[2]. To be based on the figures, a pilot can identify a type of a meteorological phenomenon (by color), a hazard degree of a meteorological phenomenon (by color intensity) and explore in detail the sizes and outlines of an area, changing the image scale as well [1].

[2] Pilot`s Guide G1000 integrated flight deck Cessna citation mustang. Garmin.com, 2007, 508 p. Available at: https://static.garmin.com/pumac/G1000: CessnaMustang_PilotsGuide.pdf (accessed: 08.10.2022).

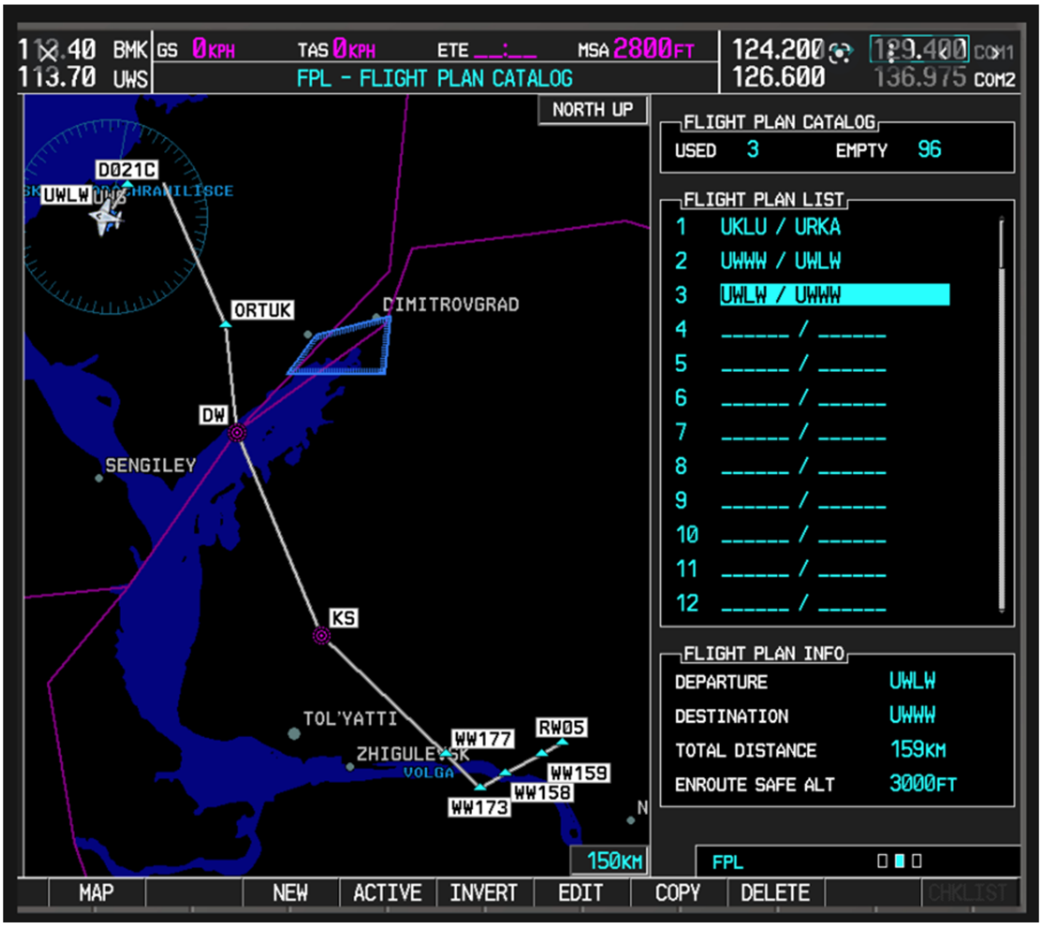



**Fig. 5.** Example of a flight route displayed on the G3000 Garmin screen

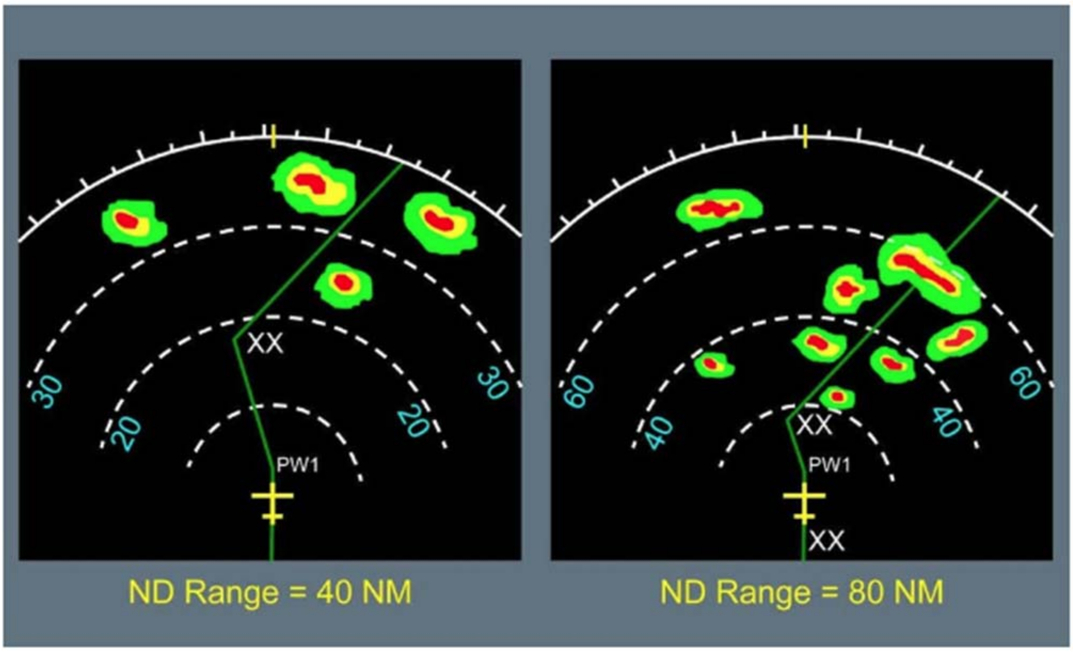



**Fig. 6.** Example of a line squall on a scale of 40 and 80 nautical miles

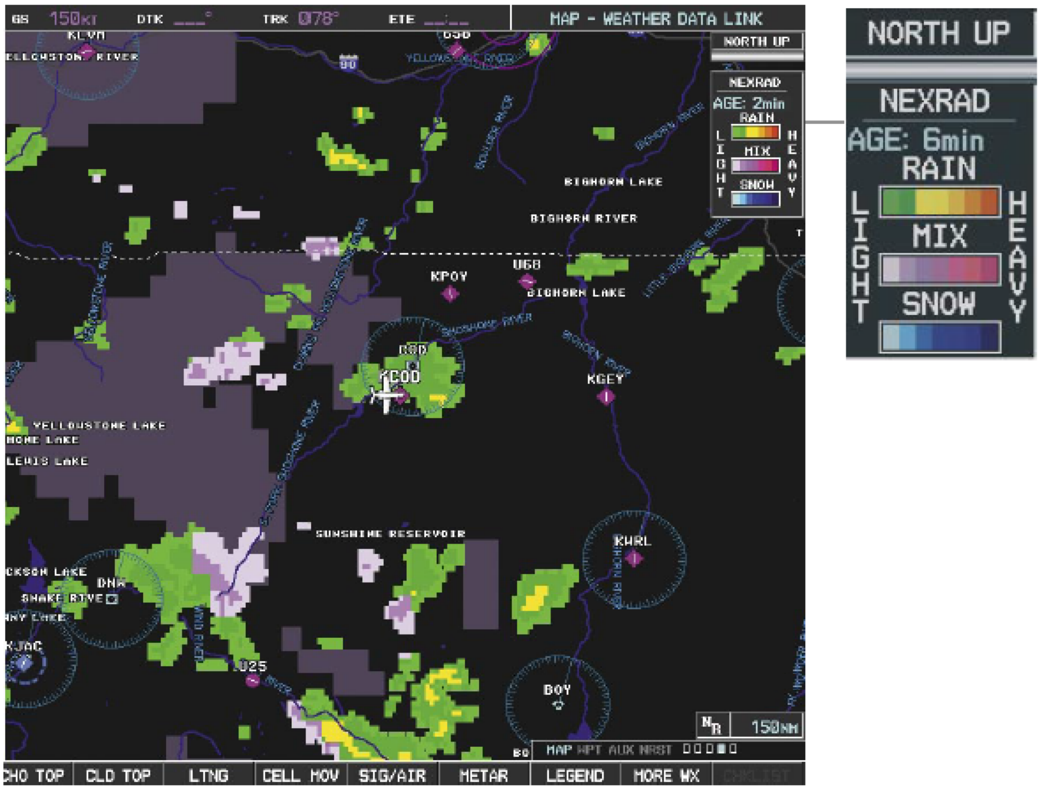



**Fig. 7.** Example of a weather map display in the Garmin suite

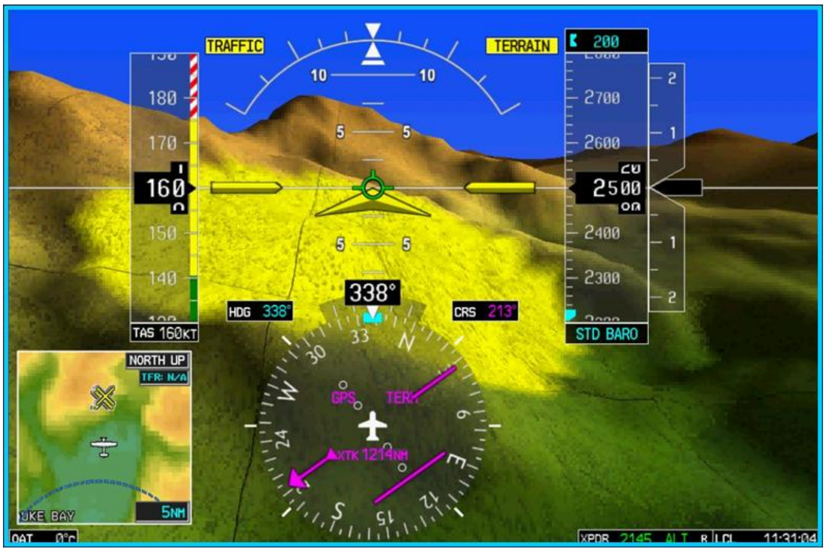



**Fig. 8.** Example a synthetic vision system display in the Garmin suite

During flights at low altitudes, information about artificial obstacles and terrain profile is critical. The information is stored on board aircraft in the form of digital terrain maps. As a rule, they are updated once a week or two weeks. Notably, digital maps use the systems of Synthetic Vision (CV) and the Terrain Awareness and Warning Systems (TAWS) [2]. Figure 9 illustrates the display of the background synthesized on the Garmin suite screen. It is apparent that the synthetic image is distinguished with realism and provides a flight crew with required

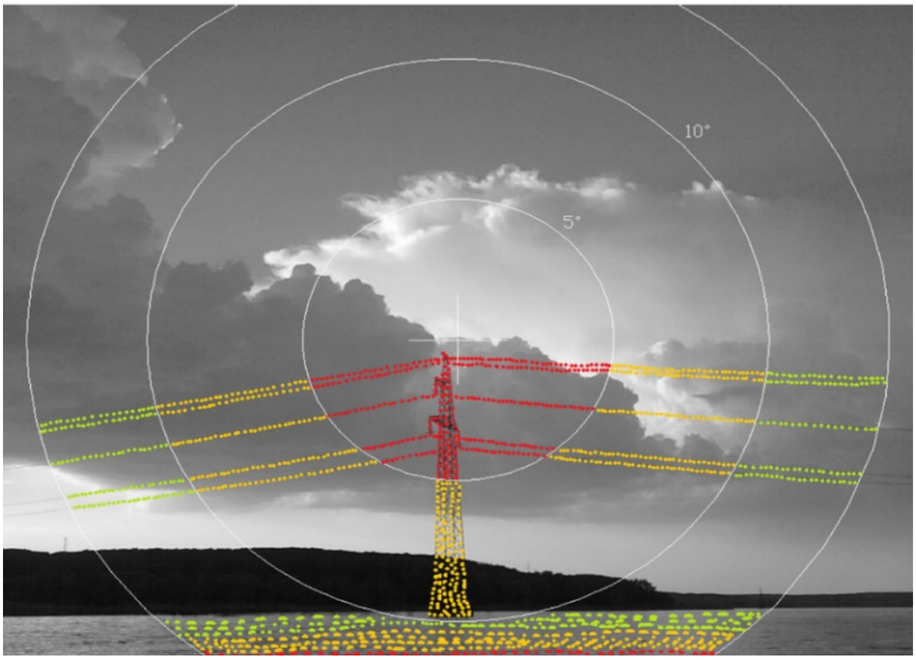



**Fig. 9.** Example of an obstacle detection display

information about the configuration of the terrain profile along the flight route in any conditions.

Moreover, aircraft can be fitted with cameras of different bands (visible and infrared), georadars and DME to detect obstacles on route. Lidars [3] have become widespread lately. An example of a complex image, obtained from cameras of visible and infrared bands combined with lidar data, is illustrated in Figure 9. It is apparent that the given image allows for an artificial obstacle on route of flight to be detected and identified.

General for all the stated above technical facilities is that all of them are informational. In essence, they only visualize information about an approaching obstacle, allowing a pilot to deal with all the arsenal of actions to avoid obstacles safely:

- obstacle detection on the screen;
- obstacle identification;
- assessment of its hazard degree;
- decision-making how to avoid an obstacle;
- implementing a decision.

Let us know that depending on a flight mode and a range of obstacle detection, the time available for a pilot to initiate the stated above actions can significantly differ. But, mostly common, these actions are accomplished by a pilot within a short span of time in the circumstances of increased psycho-emotional tension, which, as the represented above AA analysis as well as the research results [4], can lead to errors even in sufficiently simple situations. Subsequently, a tool which, within a short span of time, can calculate and propose a pilot one or several safe and aircraft-implemented alternatives of the flight continuation to fly round an obstacle, is prioritized.

For efficient flight rerouting, there is a whole set of time-tested algorithms to avoid obstacles [5], used by various robotic packages such as unmanned utility tug and trailers, automobiles, robotic vacuum cleaners, etc. Let us consider some of the algorithms:

- Voronoi diagram;
- visibility graph;
- method of Rapidly Exploring Random Trees, RRT;
- Bug-algorithm.

The algorithm, based on Voronoi diagram [3], represents the architecture of alternatives consisting of segments the points of which are equally spaced from the points comprising the geometry of obstacle avoidance. Figure 10

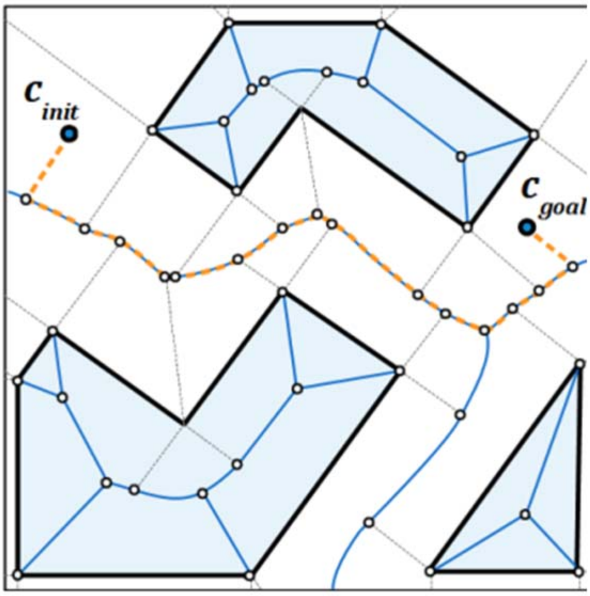



**Fig. 10.** Voronoi Diagram example

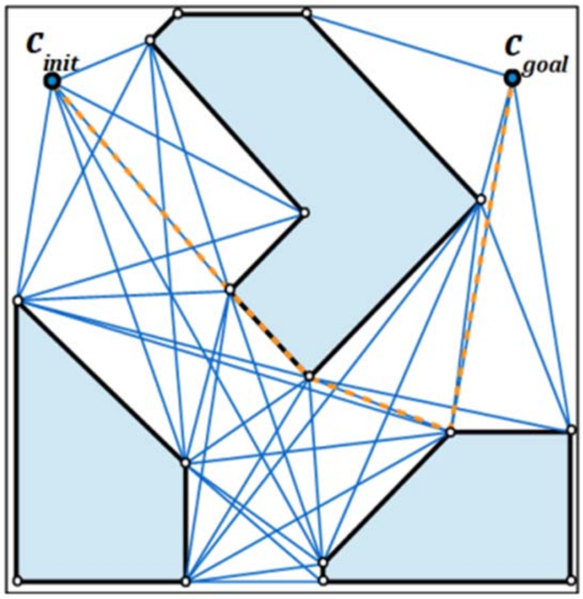



**Fig. 11.** Visibility Diagram example

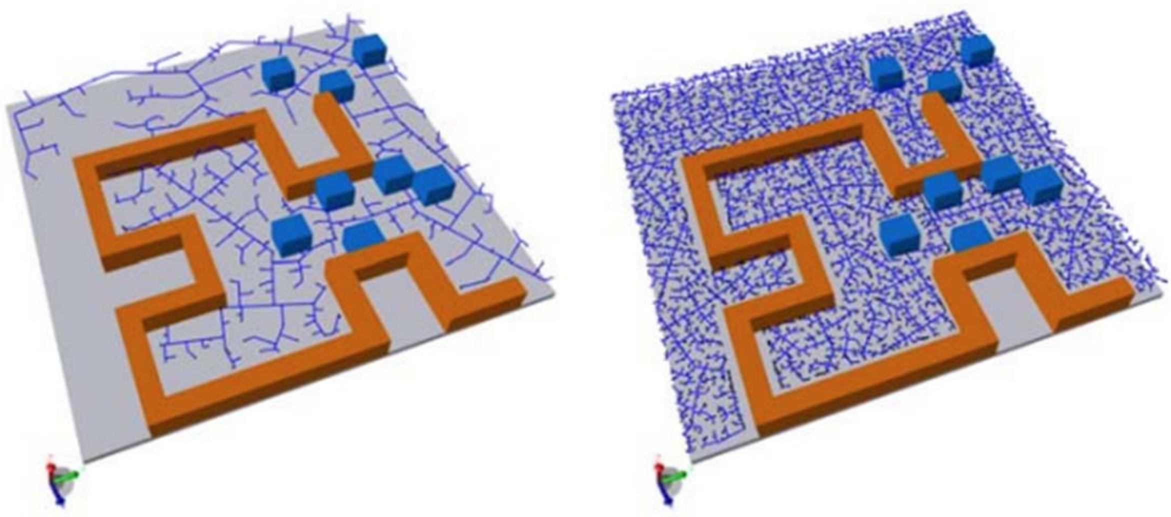
illustrates the example of such a route. The algorithm can build several alternatives simultaneously to avoid obstacles from which the shortest route can be defined using, for example, Dijkstra's algorithm [6, 7]. The disadvantage of the algorithm, based on Voronoi diagram, represents a substantial deceleration of computations as the number of obstacles increases.

The visibility graph-based method [8] handles defining transitional pairs of points between the original and terminal points of the flown-around route which can be connected with a straight line without crossing assigned obstacles. The disadvantage of the method is restrictions in the form of requirements for the obstacle shape - the algorithm operates merely with obstacles of a polyhedron or polygon shape. An example of routing by means of the visibility diagram is given in Figure 11.

The RRT method [9] is attributed to the techniques of random sampling. The method deals with building up a tree of double points from random positions located as closer as possible to the required terminal aircraft position with the subsequent erasing of two possible positions which when connected cross forbidden regions. An example of building a search tree by means of the RRT algorithm is illustrated in Figure 12. The figure shows two solutions with the different number of iterations: a – 1000 iterations, b – 2000 iterations. The advantage of the given method is relatively slight time increase required for the computation with the increase in the obstacle number. The drawback of the given method is that the algorithm issues merely a single alternative to avoid an obstacle which can be not optimal in terms of a route length.

A bug-algorithm [10] is used in self-contained and self-propelled robots. As input data, the algorithm takes advantage of obtained information about obstacles and the target of motion during the robot operation. The key point of the algorithm is that a robot moves to the target, and encountering an obstacle in front, it commences to move it around until rejoining an original route. The algorithm has several varieties. In this respect, obstacle avoidance can continue until a robot joins a point which is the closest to the target (fig. 13). In another algorithm version, while moving a robot tends to fly heading towards the target and complete obstacle avoidance when the present heading equals the original one (fig. 14). The disadvantage of the algorithm is that merely a single route of obstacle avoidance is built which can be not the shortest.

The general drawback of the considered algorithms is that all of them cannot be directly



а б

**Fig. 12.** Example of building a search tree using the RRT algorithm
a – 1000 iterations, b – 2000 iterations

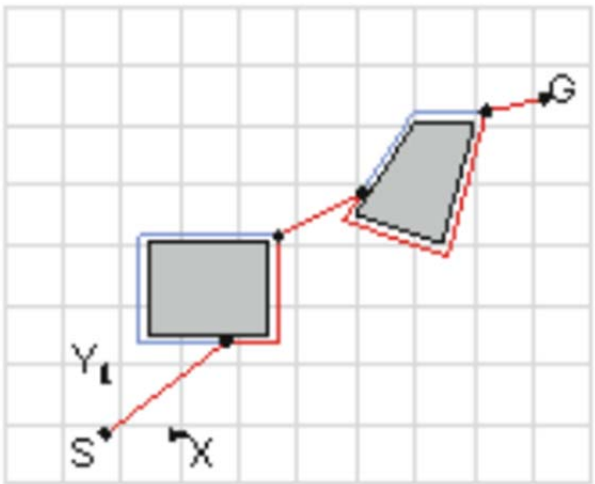



**Fig. 13.** Example of a Bug-variant algorithm
with entering the nearest point to the target

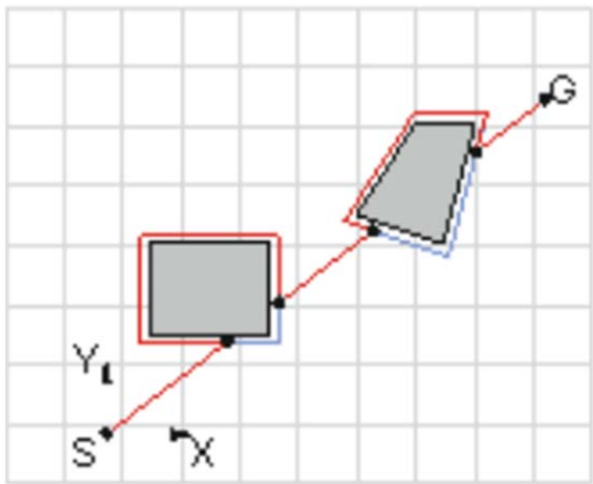



**Fig. 14.** Example of a Bug-variant algorithm
with maintaining the inclination of a straight line
to the target

used on board aircraft to build obstacle avoidance routes as the identified route represents a trajectory synthesized without taking into consideration the current limitations on control parameters of the aircraft such as lift-to-weight ratio, an angle of attack, etc. [11].

The current approaches to develop trajectories, implemented on board aircraft, can be classified into two groups on a provisional basis.

The first-group research [12] involves the probability-based approach and addresses problem solutions to overcome a defense system. This approach supposes the capability to penetrate a defense system zone, therefore, cannot be directly used to solve the stated above problems for obstacle avoidance.

The second-group research [13–17] focuses on the solution of a local problem to take the aircraft from the collision with an obstacle and does not suppose a further continuation of an original route of flight.

## Conclusion

The represented above analysis of AA emphasizes the relevancy to generate algorithms providing an efficient review of a flight plan (route) during the process of its completion. We can assert that similar algorithms on board aircraft would contribute to preventing a series of different-type AA.

The cutting-edge airborne hardware ensures sufficient situational awareness of the pilot to identify obstacles and determine the extent of their hazard. At the same time, increased psychophysiological load and time constraint to take a decision makes it difficult to search an own right decision to avoid obstacles.

The algorithms used to avoid obstacles in the related fields cannot be used on board aircraft because of significant aircraft features as an object of control.

Thus, the current relevant objective is the development of problem-oriented onboard algorithms ensuring flight rerouting. The key requirements for the alike algorithms are as follows:

1. Determination of an array of alternatives ensuring obstacle avoidance maintaining a safe distance in an automatic or flight director modes of aircraft control with due regard for the aircraft capabilities and performance.
2. Automatic arrangement of an array of alternatives by assigned criteria (minimization of additional time expenditure required to avoid obstacles, minimization of additional fuel consumption to avoid obstacles, minimum lateral diversion from the original route of flight, minimum diversion from the original route by the flight altitude, etc.) with identifying optimal routes based on each of the assigned criteria.

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