Вычислительные технологии, 2023, том 28, № 1, с. 23–32. © ФИЦ ИВТ, 2023 ISSN 1560-7534
Computational Technologies, 2023, vol. 28, no. 1, pp. 23–32. © FRC ICT, 2023 eISSN 2313-691X

DOI:10.25743/ICT.2023.28.1.003

UAV 3D path planning methodology for building health monitoring

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Received April 30, 2022, accepted May 16, 2022.

Nowadays the unmanned aerial vehicles (UAVs) become popular and are increasingly used in a wide range of applications. The UAVs are used as flying-based station to enable communication services to a ground station and are referred to as UAVs-assisted communication. Also, UAVs are used for a multitude of applications from cargo delivery to surveillance referred to as cellular-connected UAVs. This paper presents the methodology for 3D path planning for building health monitoring. The result of this study gives an optimal path for UAV which should be taken during the supervision of the building to detect the cracks on the surface of the building. The methodology combines the application of Dijkstra's, Floyd – Warshall's algorithms, travelling salesman problem (TSP), and hybrid particle swarm optimization algorithm (HPSO) for finding an optimized path in UAV moving around building for surveillance in the structural health monitoring.

Keywords: UAV path planning, structural health monitoring (SHM), critical infrastructure monitoring, photogrammetry.

Citation: Dobrilovic D., Mazalica M., Popov S. UAV 3D path planning methodology for building health monitoring. Computational Technologies. 2023; 28(1):23–32. DOI:10.25743/ICT.2023.28.1.003.

Introduction

The development of information technology in the last few years brought a revolution in this area. Nowadays the unmanned aerial vehicles (UAVs) become popular and increasingly used in a wide range of applications. The UAV is used as a flying station to enable communications with a ground station and is referred to as UAV-assisted communication, also UAVs are used for a multitude of applications from cargo delivery to surveillance referred to as cellular-connected UAVs. Drones, as smart devices, are defined as the type of aircraft which operate without human pilot interaction and are used for air and ground operations (such as navigation, surveillance, and reconnaissance). The components of unmanned aircraft systems are ground-based controllers, UAVs, and a platform that provides communication between UAVs and the controller itself. UAVs use cameras and sensors to capture heterogeneous data such as thermal images, audio, and videos for many various applications such as precision agriculture, smart transportation, crowd management, etc. Also, UAVs are widely used for military and civilian applications such as climate monitoring, environmental research, rescue and search operations, and weather forecasting [1].

The most significant problem for UAVs is finding the optimal path between the starting point and the destination. For solving these problems and find the optimal or the shortest path for UAVs we use path planning algorithms such as Dijkstra, A-star D-star, Voronoi, artificial potential, ant colony optimization, etc. The key barriers in UAV path planning are path optimization, path completeness, optimality, efficiency, and achieving robustness.

This paper presents the methodology for UAV path planning for critical infrastructure monitoring in urban environments. In this research for finding an optimal path between nodes that present coordinate of buildings is used Dijkstra's shortest path algorithm with adjacency matrix mapped in 3D space in combination with Floyd−Warshall, hybrid swarm optimization and travelling salesman problem solved with genetic algorithm. The results of this method are presented with the 3D UAV path visualization. This paper is structured as follows: the introduction gives a brief description of UAVs and path planning, the next section provides a brief review of path planning problem for UAV and their use in orthophotography. Section three shows a methodology for finding the shortest path for a drone tour of a building. The results, discussion, and concluding remarks are given at the end of this paper.

1. Related works

Path planning is one of the most important problems in the development of UAVs as city management tools. Path planning techniques aim to determine the best route or path that an UAV will follow to reach its goal from its starting point. The proper path planning depends on the operations such as remote sensing, communication, and computations. Path planning is needed for UAVs to provide them with the ability to launch and travel from point to point without the risk of collision with objects in their path. Modern technology such as big data and cloud computing didn't improve path planning techniques, so this problem is still tricky for UAVs. This difficulty arises due to the UAVs' inability to take critical decisions such as trajectory planning, task allocation, task scheduling, and path planning in real-time, particularly in a complex environment such as smart cities [2]. Path planning includes several calculations and steps which enable the UAV to overcome physical and kinetic constraints in its path. Navigation, trajectory, and motion planning are the key terms and planning steps involved in path planning. All these calculations regard flight kinetics, velocity, and time. 3D (three-dimensional) view is used for path planning in complex environments as 2D (two-dimensional) methods can not find the obstacles and objects in this environment. Paper [1] gives a systematic review of path planning algorithms for UAVs. According to this research UAV, path planning's key barriers include optimizing the system, determining the optimum path length, path completeness, optimality, efficiency, energy consumption, and achieving robustness. The paper [2] represents a comprehensive survey of UAVs' path planning techniques. This research includes critical analysis of existing proposals, and a comparison table using various parameters such as path length, optimality, completeness, cost efficiency, time efficiency, energy efficiency, robustness, and collision avoidance. Research [3] presents multi-objective evolutionary approach for offline flight plans computing for a fleet of unmanned aerial vehicles to perform exploration and surveillance missions. The method finds a set of routes for UAVs in the fleet to simultaneously maximize the explored area and maximize the surveillance. The method is based on the NSGA-II algorithm, a traditional multi-objective evolutionary algorithm (MOEA) for solving real-world problems in different application areas.

1.1. Application UAVs in infrastructure monitoring

Structural health monitoring (SHM) offers attractive strategies for preserving public safety by rapidly managing infrastructure and recovering structure from its critical state with ease. This system offers robust diagnostic and prognostic tools that can detect critical responses of a structure and evaluate any unusual symptoms, serviceability, and safety concerns. UAVs are used in SHM to inspect critical infrastructure because they carry optical or thermal cameras. Paper [4] presents an automatic inspection method of building surfaces. In this paper, the path planning is solved using a genetic algorithm (GA), in this way the minimization of the length of UAV flight while collecting complete and high-quality image data considering the limited capacity is achieved. In this research, this method is tested on real buildings in the Shenzhen University campus, and the results show that this method leads to time-efficient, accurate, and high-quality inspection data collection for building surfaces.

For next-generation smart cities, UAVs (also known as drones) are very important to incorporate in airspace for advancing the transportation systems. The paper [5] presents a review of the recent development concerning the application of UAVs in road safety, traffic monitoring, and highway infrastructure. The authors used a small UAV (QuadRotors, Phantom 3 Pro) for engineering surveys to develop a small-scale map that can be used for road design. The UAV images are processed using the UAV Agisoft PhotoScan, which finally generates the x, y, and z coordinates of the entire areas of interest. Vision algorithms and image processing is found as the key element where progress is being made leading to the advanced application of UAVs in damage assessment for bridges and roads.

1.2. Application of UAVs in photogrammetric (ortho-photography)

During their flight UAVs made the images by digital, calibrated, and integrated camera. The images made by UAVs during the flight are acquired and processed by applying the methods of photogrammetric. UAV photogrammetry describes photogrammetric measurement platforms which operate either remotely controlled, semi-autonomously, or autonomously [6]. Nowadays, UAV technologies and photogrammetry can be used for close-range areas and also as an alternative way for large area mapping. The main photogrammetric workflow UAVs project stages with include photogrammetric project parameters, flight project, and quality of the image, image processing by photogrammetric or other special software, orthophoto image generalization, and application of the acquired data. The captured orthophoto image by UAV is used to analyze visible modifications in nature and occurring economic changes by comparing the available information on the site with the possessed latest cartographic material. At present, the orthophoto images are widely applied in compiling the geographic information systems (GIS) databases for foresters, for collecting data on forest taxation, for determining forest species status and areas damaged by diseases, for planning the lumbering of the forest, and so forth [7]. The paper [6] gives a study that investigates the performance of multirotor UAVs for road design, and this study is focused on the UAV as a tool to capture data of the ground from a certain altitude. The result of the study shows that UAVs can be used to provide data from road design with reliable accuracy. The paper [7] presents the results of project calculations concerning the UAV flights and the analysis of the terrestrial images acquired during the field-testing flights. Also the results of calculation of the project values of the UAV flights taking the images by digital camera Canon S100 and the analysis of the possibilities of the UAV orthophoto images' mode are presented. The paper [8] proposes a travelling salesperson problem (TSP) solving approach in the programming flight path of

UAVs in the urban pollution monitoring system. Research presented in [9] gives a novel two-steps computational method for finding near-optimal views to cover the surface of a target set of buildings using voxel dilation, medial objects (MO), and random-key genetic algorithm (RKGA). The results demonstrate that the proposed method outperforms the previously proposed methods by finding a better solution with fewer viewpoints and a higher coverage ratio according to the authors.

2. Methodology

The methodology of the research presented in this paper consists of the following steps:
1) creation of 3D path matrix for Dijkstra's shortest path algorithm;
2) application of Floyd – Warshall's algorithm to find the shortest path between all vertices;
3) application of hybrid particle swarm optimization algorithm (HPSO) to find TSP path with a defined set of viewpoints;
4) application of Dijkstra's shortest path algorithm to find the path between nodes in TSP defined viewpoints, and 3D UAV path visualization.

The methodology is inspired by the methods of UAV path planning presented in [8]. The methodology is presented in Fig. 1.

2.1. Dijkstra's shortest path 3D adjacency matrix

The methodology will be evaluated in the following example. The first step is the creation of a 3D path matrix that represents the mapping of places of potential UAV positions in monitoring buildings as critical infrastructure. The UAV positions are connected with the paths between, as it is represented in Fig. 2. The 3D adjacency matrix has a dimension 32×32 and contains 32 nodes with its relative coordinate (stared from $(0, 0, 0)$, located at a distance of 10 m horizontally (x axis) and 5 m vertically (y axis). Every node is connected on average with 3 or 4 adjacent nodes. This 3D matrix represents the graph connectivity of

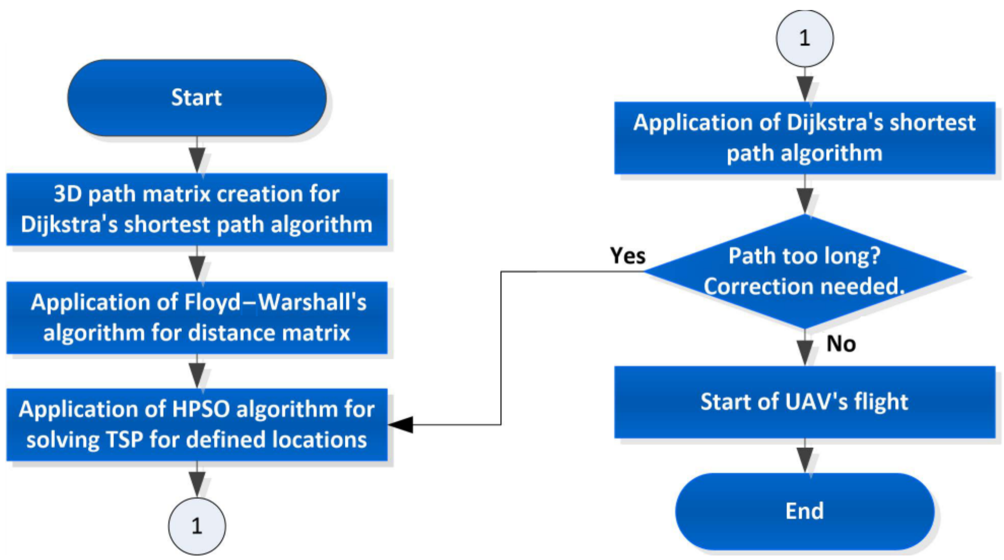

Fig. 1. Methodology of UAV path planning for structural health monitoring

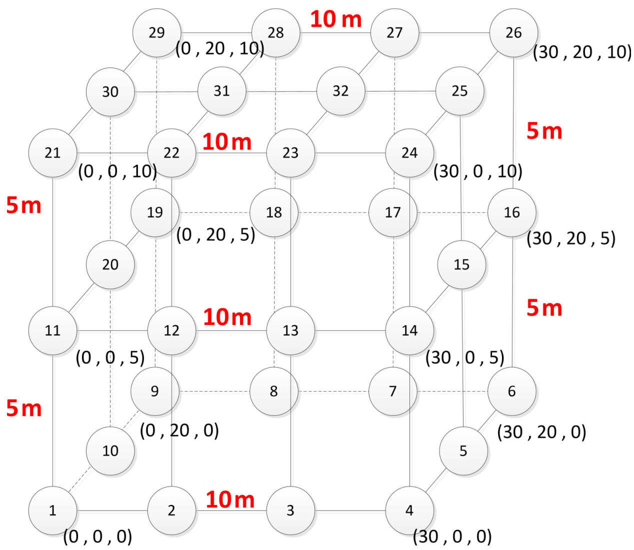

Fig. 2. UAV locations (viewpoints) and paths presented as 3D mesh

nodes that are located around the building. This graph gives the locations for the recording building (infrastructure monitoring of building) as well as the associated path which drones use during the camerawork. The nodes in the graph are vertices or UAV viewpoint or "crossroads" needed for planning UAV paths.

2.2. Application of Floyd – Warshall's algorithm for finding the shortest path between all vertices

The second step is to apply the Floyd – Warshall's algorithm to find the shortest path between all vertices. This step results in the creation of a distance matrix. Floyd – Warshall's algorithm is an algorithm for finding the shortest paths in a directed weighted graph with positive or negative edge weights. This algorithm finds the shortest path between all pairs of nodes just in one execution of this algorithm. Floyd – Warshall's algorithm is an example of dynamic programming. This algorithm compares all possible paths through the graph between each pair of vertices and repeats the cycle until the improving estimate on the shortest path between two vertices is optimal. Application of this algorithm in this methodology results in the creation of a distance matrix. The distance matrix is needed for further steps in the methodology and will be used with the TSP solution algorithm.

2.3. Application of hybrid particle swarm optimization algorithm finding TSP path with the selected set of viewpoints

The particle swarm optimization is one of the most frequently used evolutionary variants in hybrid techniques due to its capability of searching global optimum, convergence speed, and simplicity [10–12]. This algorithm was inspired by the social behavior of animals; the major advantage of this algorithm is its ability to solve a variety of difficult optimization problems and also to show a faster convergence rate than other evolutionary algorithms on the same problems. The paper [13] shows the method for the inspection path planning problem for UAVs as an extended TSP in which both the coverage and obstacle avoidance were taken into account. The results of this experiment are included in datasets obtained from UAV inspection of an office building and a bridge. In our study, this algorithm finds the order of the defined viewpoints UAV should visit using the optimal and the shortest path, considering the distance between the nodes, and the total distance needed for moving around all locations.

2.4. Application of Dijkstra's shortest path algorithm for finding the path between nodes in TSP defined locations to visit

Dijkstra algorithm is one of the well-known approaches for finding the shortest path using a graph consisting of nodes and edges. The edge represents the different paths to be followed by an UAV. Each edge is associated with the value representing its cost. Path cost is the distance in meters between locations (graph vertices). Dijkstra's algorithm has a broad area of application, and it is presented in UAV path planning as well. The paper [14] gives an experiment of using Dijkstra and A-star algorithm for a UAV path optimization and obstacle avoidance. The experiments were conducted using multiple UAVs in both static and dynamic environments, and the result showed that both methods performed equally well in minimizing the distance. In this research, this algorithm is used for finding the shortest path between nodes in the TSP path where the locations to visit are defined.

2.5. 3D UAV path visualization

In this study, 3D path visualization has been done in GNU Octave. This is the last step in this methodology for 3D UAV path planning. Together with the visualized path, the data such as path length in meters, the defined nodes to visit, and the order of visited nodes on the path are presented. The time needed for calculating the optimal path is also presented. The optimal path shows UAV movement needed during the surveillance of the building.

3. Results

The application of the presented methodology gives the following optimized path for the UAV to go around the building. The path is planned following the set of locations marked with numbers 1, 12, 15, 17, 18, 20, 31, and 32. Location No. 1 is starting and ending location and the rest are the locations that should be visited during the surveillance. These locations are targeted as locations where UAV will take images. The calculated path is as follows: $1-11-20-19-18-17-16-15-25-32-31-22-12-2-1$, end total distance is 120 m. The initially calculated UAV path was 140 m but was reduced to 120 m, after the TSP optimization. The reduction in path length is around 15 percent. The calculated UAV path is represented in Fig. 3.

The methodology is additionally tested with the more complex type of building. The additional building model and its associated graph are given in Fig. 4. The model has 144 vertices, with 3 to 4, and in two cases 5 links (edges) per node. The building has three sections, three levels with 2D dimension 10×6, one level with dimension 6×5, and one with 4×3. Measuring in meters, the first level has a 90×50 meters base, second level 40×50 meters base, and third-level 20×30-meter base.

The calculated 3D UAV path model is presented in Fig. 5.

The summarization of the results is as follows. The initial TSP calculated path length is 830 m. After 100 iterations distance is reduced to 440 m, to 53 percent of initial size.

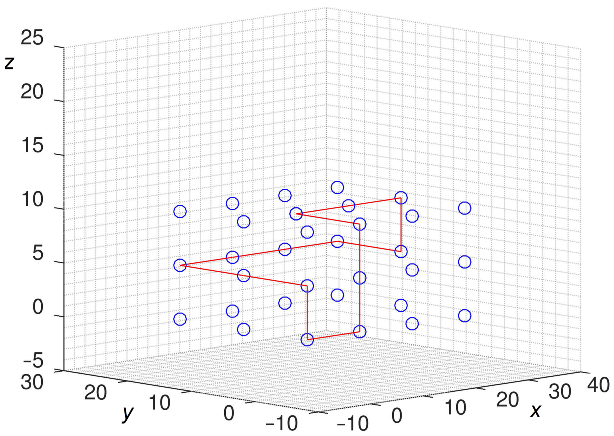

Fig. 3. Visualized 3D UAV path

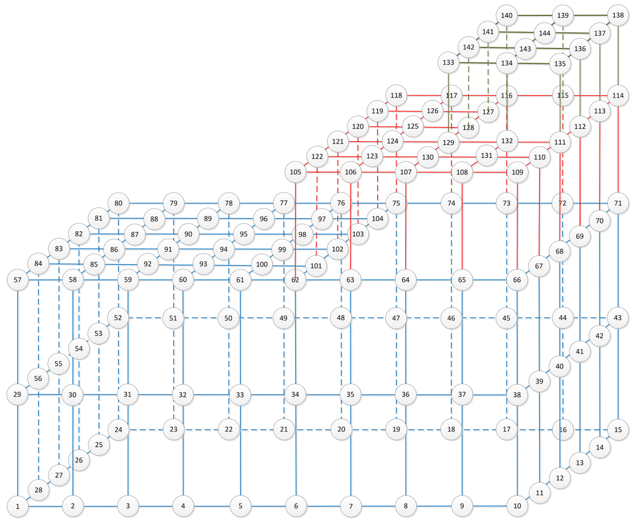

Fig. 4. UAV viewpoints (locations) presented as 3D mesh for the larger building

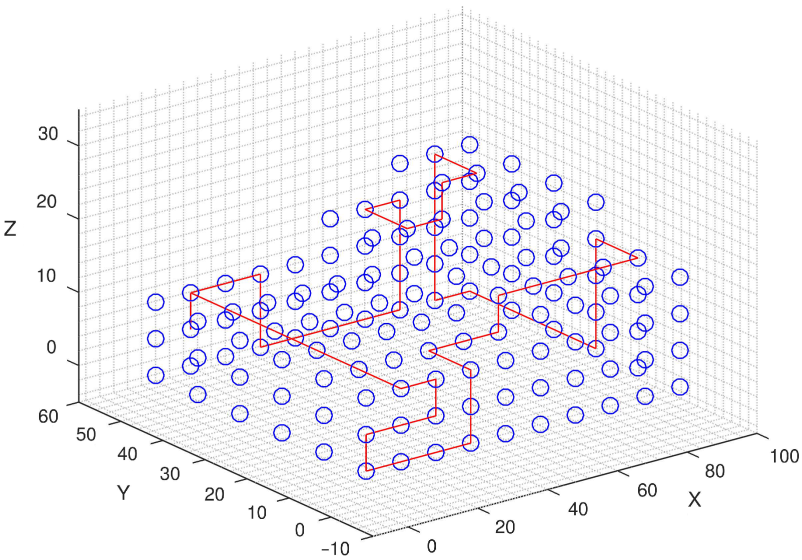

Fig. 5. Visualized 3D UAV path

The defined set of locations is: 1, 12, 15, 17, 18, 20, 31, 32, 45, 51, 72, 77, 87, 93, 123, 126, 131, and 144. The defined path is: 1 – 29 – 30 – 31 – 59 – 58 – 85 – 86 – 87 – 88 – 79 – 51 – 79 – 78 – 77 – 49 – 21 – 20 – 19 – 18 – 17 – 45 – 73 – 116 – 117 – 126 – 127 – 141 – 144 – 139 – 115 – 72 – 44 – 16 – 15 – 14 – 13 – 12 – 40 – 68 – 111 – 110 – 131 – 130 – 123 – 122 – 101 – 100 – 93 – 60 – 32 – 4 – 3 – 2 – 1.

The application of the presented model to the more complex structures and buildings the tool for modelling 3D graph that corresponds to the building shape is needed to make this process easier. For this stage of research, we can conclude that the simpler form of graphs presented in this paper are applicable for the majority of buildings in the region where this research took place. The tool for modelling 3D graphs will be useful for more complex shape structures, such as bridges, tunnels, etc.

Conclusion

The paper is focused on UAVs' path planning for a building inspection in the infrastructure monitoring process. This paper aims to give the optimal path for an UAV to move around the building on its way while using its camera for detecting the cracks on the surface of the building. Thus, avoiding deficient movements around the building, and only visiting the key places (defined viewpoints).

The methodology in this paper consists of the following steps:
1) creation of 3D path matrix for Dijkstra's shortest path algorithm;
2) application of Floyd – Warshall's algorithm to find the shortest path between all vertices;
3) application of HPSO to find TSP path with a defined set of viewpoints;
4) application of Dijkstra's shortest path algorithm to find the path between nodes in TSP defined viewpoints, and 3D UAV path visualization.

The methodology evaluation in this research is made with 3D UAV path planning for one simple and one larger and more complex shape building with three levels. The result shows that this methodology for finding the optimal path for the UAV during building inspection and crack detection is applicable for small and large buildings with different shapes. The larger building gives more reduction in optimizing path length.

The further work will include further development of the methodology with the possible inclusion of other algorithms and evaluation of dependency between the number of visited locations, 3D graph complexity, and path length reduction, as well as the computation time needed for given scenarios. The methodology will be further expanded with the parameters to help in calculating UAV operational time and time duration of the flight.

Acknowledgements. Ministry of Education, Science and Technological Development of the Republic of Serbia supports this research under the project No TR32044 "The development of software tools for business process analysis and improvement".

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Вычислительные технологии, 2023, том 28, № 1, с. 23–32. © ФИЦ ИВТ, 2023 ISSN 1560-7534
Computational Technologies, 2023, vol. 28, no. 1, pp. 23–32. © FRC ICT, 2023 eISSN 2313-691X

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ

DOI:10.25743/ICT.2023.28.1.003

Методология трехмерного планирования траектории БПЛА для мониторинга состояния зданий

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Поступила 30 апреля 2022 г., принята в печать 16 мая 2022 г.

Аннотация

Беспилотные летательные аппараты (БПЛА) становятся все более популярными и все чаще применяются в широком спектре приложений: от доставки грузов до наблюдения. Они также используются в качестве базовой станции для предоставления услуг связи с наземной станцией, и есть упоминания коммуникации на основе БПЛА. В статье представлена методология трехмерного планирования пути для мониторинга состояния здания. Результат этого исследования дает оптимальный путь для БПЛА, который следует использовать при осмотре здания для обнаружения трещин на его поверхности. Методика сочетает в себе применение алгоритмов Дейкстры, Флойда – Уоршалла, задачи коммивояжера и алгоритма оптимизации гибридного роя частиц для поиска оптимального пути движения БПЛА вокруг здания для наблюдения при мониторинге состояния конструкции.

Ключевые слова: планирование маршрута БПЛА, мониторинг состояния конструкций (SHM), мониторинг критической инфраструктуры, фотограмметрия.

Цитирование: Добрилович Д., Мазалица М., Попов С. Методология трехмерного планирования траектории БПЛА для мониторинга состояния зданий. Вычислительные технологии. 2023; 28(1):23–32. DOI:10.25743/ICT.2023.28.1.003. (на английском)

Благодарности. Министерство образования, науки и технологического развития Республики Сербия поддерживает это исследование в рамках проекта № TR32044 “Разработка программных инструментов для анализа и улучшения бизнес-процессов”.