UDC 007.52; 629.3.05; 004.021
https://doi.org/10.32362/2500-316X-2023-11-6-16-27

RESEARCH ARTICLE

Features and perspectives of application of the rapidly exploring random tree method for motion planning of autonomous robotic manipulators

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Abstract
Objectives. The work analyzes features of one of the most promising approaches to solve the problems for motion planning of autonomous robotic manipulators of various types and purposes using the rapidly exploring random tree (RRT) method. The development of modern robotics is shown to be inextricably linked with the improvement of the designs of the created samples, for which the placement of a manipulator on platform becomes a typical layout option. Prospects for using the RRT method as a constructive basis for creating a universal motion planner are evaluated for mobile and robotic manipulators, including autonomous robotic systems with a manipulator on a moving platform.
Methods. The object of the research is the RRT method and its well-known modifications RRT* and RRT-Connect. The effectiveness of applying such methods for solving problems associated with planning the motions of robotic manipulators of various types was evaluated using computer and natural simulation methods.
Results. Based on a review of the literature and the results of the research, the wide possibilities of the RRT method can be used for solving motion planning problems not only for mobile and robotic manipulators, but also for robotic systems on whose transport platform an onboard manipulator has been installed (including those having a redundant or reconfigurable structure). The effectiveness of the applied application of the RRT method is confirmed by examples of modeling a mobile platform with an onboard manipulator and the results of full-scale experiments with a prototype of the ARAKS reconfigurable mechatronic-modular robotic manipulators (RTU MIREA, Russia). It can be experimentally demonstrated and theoretically substantiated that the final dimension of the exploring tree, and hence the time of its construction up to reaching a given target state, is largely determined by the value of the growth factor.
Conclusions. The generalization of the results obtained opens up real prospects for using the RRT method as a constructive basis not only for creating universal means for motion planning mobile robotic systems with an onboard manipulator, but also for solving the problems of automating the docking of autonomous mobile platforms.

Keywords: autonomous robotic manipulator, intelligent control, reconfigurable robotic manipulator, variable kinematic structure, rapidly exploring random tree method

• **Submitted:** 17.02.2023 • **Revised:** 29.03.2023 • **Accepted:** 05.09.2023

For citation: Golubov V.V., Manko S.V. Features and perspectives of application of the rapidly exploring random tree method for motion planning of autonomous robotic manipulators. *Russ. Technol. J.* 2023;11(6):16–27. https://doi.org/10.32362/2500-316X-2023-11-6-16-27

Financial disclosure: The authors have no a financial or property interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

Особенности и перспективы применения метода поисковых случайных деревьев для планирования перемещений автономных роботов

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Резюме
Цели. Статья посвящена анализу особенностей одного из наиболее многообещающих подходов к решению задач планирования перемещений автономных роботов различных типов и назначения с помощью метода поисковых случайных деревьев. Показано, что развитие современной робототехники неразрывно сопряжено с совершенствованием конструкций создаваемых образцов, для которых размещение манипулятора на подвижной платформе становится типовым вариантом компоновки. Целью работы является оценка перспектив использования метода поисковых случайных деревьев в качестве конструктивной основы для создания универсального планировщика перемещений мобильных и манипуляционных роботов, включая автономные робототехнические системы с манипулятором на подвижной платформе.
Методы. Объектом проводимых исследований является метод поисковых случайных деревьев RRT (rapidly exploring random trees) и его известные модификации RRT* и RRT-Connect. Оценка эффективности их прикладного применения для решения задач планирования перемещений роботов различных типов проводилась с помощью методов компьютерного и натурного моделирования.
Результаты. На основе обзора литературы и по итогам проведенных исследований показано, что широкие возможности метода поисковых случайных деревьев позволяют обеспечить решение задач планирования перемещений не только для мобильных и манипуляционных роботов, но и для робототехнических систем с размещением бортового манипулятора (в т.ч. с избыточной или реконфигурируемой структурой) на транспортной платформе. Эффективность прикладного применения метода поисковых случайных деревьев подтверждается примерами моделирования мобильной платформы с бортовым манипулятором и результатами натурных экспериментов с опытным образцом реконфигурируемого мехатронно-модульного робота «АРАКС» (РТУ МИРЭА, Россия). Экспериментально установлено и теоретически обосновано, что конечная размерность дерева поиска, а, следовательно, и время его построения, вплоть до достижения заданного целевого состояния, во многом определяются величиной фактора роста.
Выводы. Обобщение полученных результатов открывает реальные перспективы использования метода поисковых случайных деревьев в качестве конструктивной основы не только для создания универсальных средств планирования перемещений мобильных робототехнических систем с бортовым манипулятором, но и для решения задач автоматизации стыковки автономных подвижных платформ.

Ключевые слова: автономный робот, интеллектуальное управление, реконфигурируемый робот, изменяемая кинематическая структура, метод поисковых случайных деревьев

• **Поступила:** 17.02.2023 • **Доработана:** 29.03.2023 • **Принята к опубликованию:** 05.09.2023

Для цитирования: Голубов В.В., Манько С.В. Особенности и перспективы применения метода поисковых случайных деревьев для планирования перемещений автономных роботов. *Russ. Technol. J.* 2023;11(6):16−27. https://doi.org/10.32362/2500-316X-2023-11-6-16-27

Прозрачность финансовой деятельности: Авторы не имеют финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

Prospective models of semi-automatic and autonomous robotic manipulators designed to work under conditions of uncertainty should offer a wide range of functional capabilities for analyzing sensory information, assessing the environment, as well as planning appropriate actions and their subsequent elaboration.

Among problems that arise, one of the most acute is related to the development of principles of construction and composition of software and algorithmic tools for solving the tasks of motion planning and motion control of manipulators of various types and layouts, taking into account a variety of constraints determined by the type of trajectories to be formed, the nature of the external environment, the peculiarities of the working scenario, and other factors. Research actively conducted in this area since the early 1960s represents a consistent accumulation of theoretical and applied achievements, which in one or another combination find their practical application in modern robotic control systems.

Nevertheless, the search for ways to improve the efficiency of software-algorithmic means of constructing routes of purposeful movement and motion planning of autonomous manipulators continues to remain relevant.

It should be noted that the steady development of robotics technologies, as well as the expansion of their areas of applications and the range of tasks to be solved, are inextricably linked with the improvement of the created samples, increasing the level of their functional capabilities and consequent complication of design layouts.

Thus, in particular, for manipulators of special and industrial purposes, the placement of a multifunctional manipulator on a mobile platform has become one of the typical construction schemes (Fig. 1).

Another type of robotic manipulators can be illustrated by the mechatronic modular ones capable of automatically transforming their structure from a mobile platform configuration to a mobile manipulator configuration as shown in Fig. 2.

In this regard, rapidly exploring random tree (RRT) method [1, 2] is of particular interest. Its specific features open up the prospects of creating a universal motion planner for mobile and robotic manipulators, including robotic systems with manipulator layout on a transportation platform.

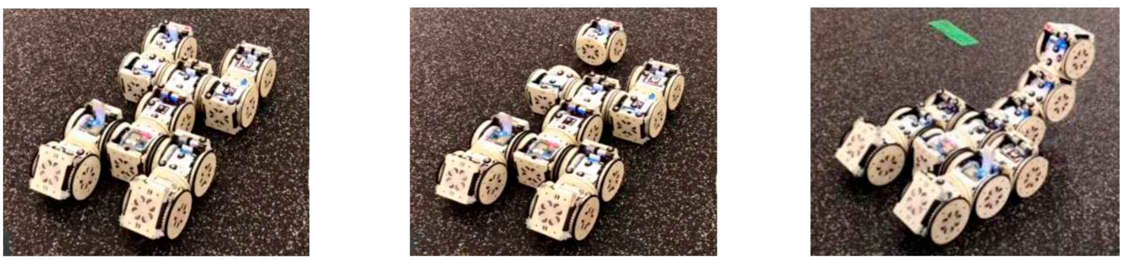
ANALYSIS OF FEATURES AND EVALUATION OF PROSPECTS FOR APPLICATION OF THE RRT METHOD FOR MOTION PLANNING OF MOBILE AND ROBOTIC MANIPULATORS

Use of the RRT method [3, 4] implies the construction of a route of purposeful robotic motion on the set of operatively generated examples from the number of admissible states in the configuration space. The generated tree, which acts as a discrete reconstruction of the manipulator's configuration space, is built randomly from the root vertex corresponding to a given initial state.

Each synthesized branch of the tree defines a possible transition to one of the new states, whose generation is performed in the configuration space taking into account

(a) (b) (c)

Fig. 1. Autonomous robotic manipulators for special (a), (b), and industrial (c) purposes with on-board manipulator: (a) autonomous robotic manipulator for special purposes (N.E. Bauman Moscow State Technical University, Russia); (b) Curiosity Mars rover (NASA, USA); (c) KMRiiwa (KUKA Roboter GmbH, Germany)



(a) (b) (c)

Fig. 2. Automatic transformation of the SMORES-EP mechatronic-modular robotic manipulator (University of Pennsylvania, USA) from a mobile platform configuration to a mobile manipulator configuration

the check for its admissibility and continues until the target position is reached. In generalized form, the corresponding algorithm is described by a sequence of key steps.

1. Point c_{init} corresponding to the initial state of the manipulator in its configuration space C is set as the root vertex of the tree T being formed.
2. During a priori given number of iterations N or until the target state c_{goal} is reached, the following sequence of actions is performed (cyclically):

- generation of a random point $c_{rand} \in$ C;
- finding the vertex of the tree $c_{near} \in$ T, which is the closest to the selected point c_{rand} (as shown in Fig. 3);
- finding the point c' lying on the ray $p(c_{near}, c_{rand})$ and remote from the vertex c_{near} at the distance Δc (given by the tree growth parameter) (Fig. 3):

$$c':[c_{near}, c'] \in p, \left\| c_{near}, c' \right\| = \Delta c;$$

- checking the conflict of the transition between the states c_{near} and c' for getting into the region of the configuration space $C_{obs} \in C$, which corresponds to the intersections with obstacles with the accuracy up to the a priori established value ε, characterizing the error of conflict detection (Fig. 4);
- finding the point c_{stop} nearest to c_{near} on the boundary of the admissible states area $C_{free} = C \backslash C_{obs}$ along the ray $p(c_{near}, c_{rand})$ (Fig. 4):

$$c_{stop}:[c_{near}, c_{stop}] \in p \cap C_{free}; \left\| c_{stop}, C_{obs} \cap p \right\| \le \varepsilon;$$

- finding the point c_{new} as a new configuration state:

$$c_{new} = \begin{cases} c', [c_{near}, c'] \in C_{free}, \\ c_{stop}, [c_{near}, c'] \notin C_{free}; \end{cases}$$

- updating the tree by adding new elements c_{near}, c_{new} and $[c_{near}, c_{new}]$ to the description lists of its vertices and branches, respectively, provided that $c_{new} \in c_{near}$;
- check the found point c_{new} for remoteness with respect to the target point; if the condition $\left\| c_{new}, c_{goal} \right\| \le \delta$ is met (δ is a priori accuracy), the path search problem is considered to be solved.

During the tree building process, periodic attempts are made to include the target configuration into the composition of its vertices by repeating all the actions of step 2 once, provided that $c_{rand} = c_{goal}$.

3. If no solution is found, then return to step 2 is to be performed.

Figure 5 shows an example of route planning in a two-dimensional configuration space $C(x, y)$ using the RRT method.

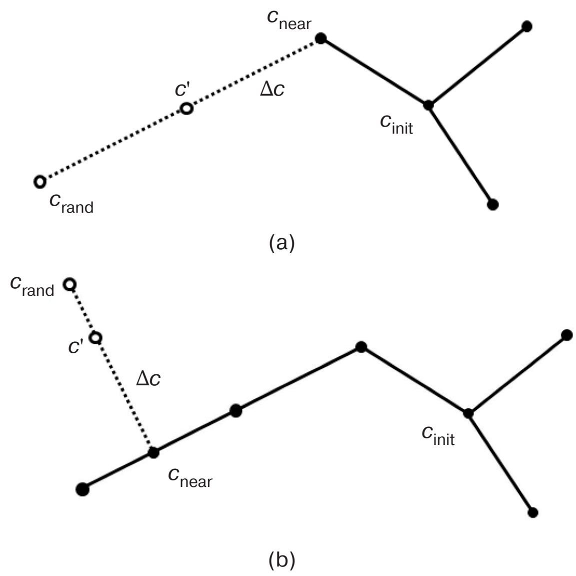


Fig. 3. Options for finding the vertex of the tree nearest to a randomly chosen point

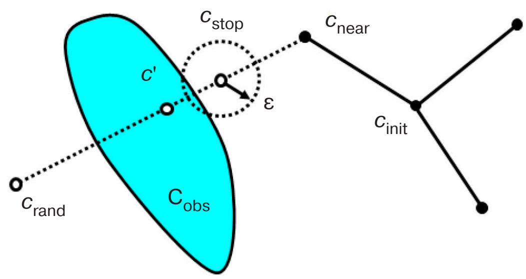


Fig. 4. Checking for transition conflicts between adjacent configuration states

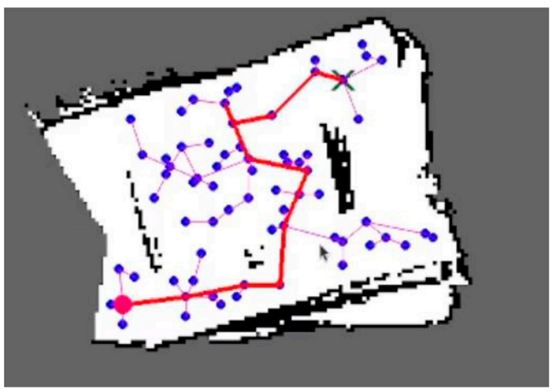


Fig. 5. Using the RRT method to plan a route for purposeful motion of an autonomous mobile manipulator on an automatically synthesized map

In general, the practical application of the RRT method involves additional procedures for smoothing the found tracks.

It should be noted that the ideological basis and features of the method make it possible to use it in solving the motion planning problems, not only for mobile, but also for robotic manipulators, including those with redundant kinematic structure [5, 6].

Obviously, the final dimensionality of the exploring tree, and, consequently, the time of its construction, will largely depend on the given growth factor, which characterizes the values of increments of coordinates of child points relative to parent points in the configuration space of the manipulator. Thus, at small increments, randomly generated points will be located quite close to each other, determining the corresponding dimensionality of the exploring tree. With successive increases in increments, the remoteness between the synthesized points will also increase, resulting in a higher propagation speed of the tree branches and a steady decrease in the total number of its vertices, whose density ensures achievement of the target position. However, a further increase in increments leads to a gradual change in the very nature of the algorithm, when the generation of a new point, which is carried out in reference to the parameters of the parent point, becomes essentially equivalent to the selection of random coordinates having a significant dispersion. The corresponding increase in the length of tree branches is accompanied by a significant acceleration of its growth with a proportional decrease in the density of the exploring space coverage. In this connection, the parameters of the search process duration as well as the finite dimensionality of the tree, both of which are determined by the level of coverage density at which the desired target state will be achievable, will steadily increase. The objectivity of such dependence of the finite dimensionality of the exploring tree on the choice of the value of random increments of the coordinates of the parent points to obtain the children points is convincingly confirmed by the experimental data shown in Fig. 6.

However, the specificity of application of the RRT method in application to robotic manipulators is connected with the necessity to organize indirect checking of selected points of the configuration space for belonging to free, forbidden or target areas. The unavoidability of such an approach is due to the complexity of mapping the peculiarities of the real working environment in the configuration space of a robotic manipulators. Therefore, in the general case, the evaluation of a particular point of the configuration space implies the need to solve the direct kinematics problem $X_M = F(c)$ to calculate the current state of the manipulator X_M using the known values of the generalized coordinates $c \in (q_1, \ldots, q_n)$.

Obtained data allow providing control of the parameters of the manipulator remoteness in relation to the objects of the external environment and the given target position. In the formal form of the record, the conditions of such a check can be represented as follows:

$$c \in C_{obs}, \text{ if } X_{obs} \cap X_M \neq \varnothing,$$

$$c \in C_{free}, \text{ if } X_{obs} \cap X_M = \varnothing,$$

$$c \in C_{goal}, \text{ if } |X_M - X_{goal}| < r,$$

where X_M and X_{obs} are geometric locations of the points occupied by the manipulator and the objects of the external environment acting as obstacles; X_{goal} is the goal position of the manipulator; r is the a priori established accuracy of the goal position.

Figure 7 shows fragments of model experiments on planning of purposeful movements of the manipulator based on the RRT method. The use of heuristics to determine a reasonable choice of parent nodes (such as

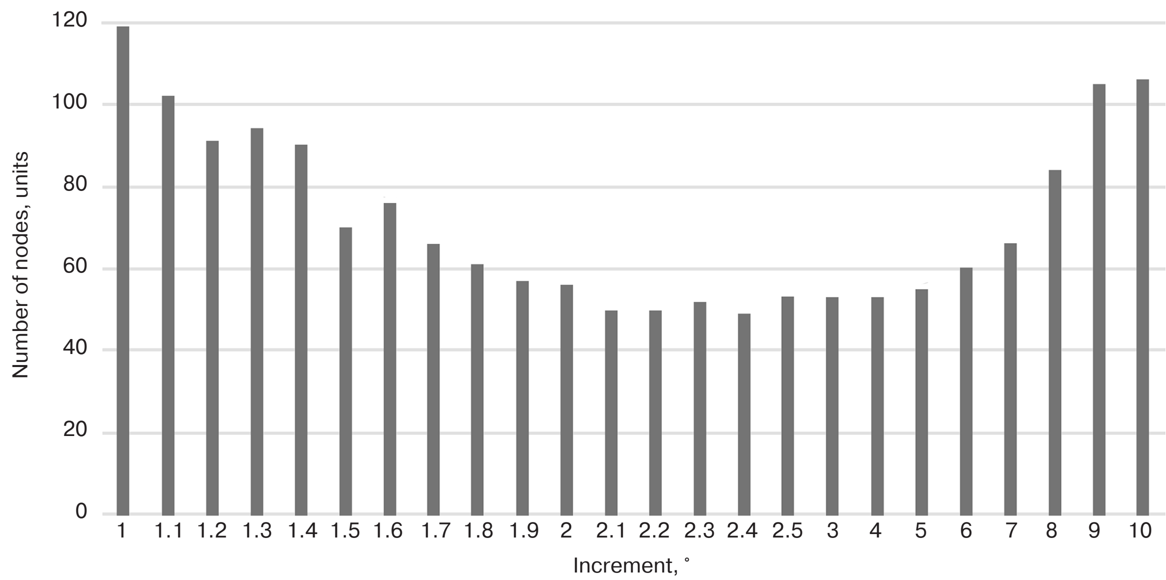


Fig. 6. Changing the dimensionality of the exploring tree depending on the value of the range of the random coordinate increments of the parent points for obtaining the children points in the manipulator configuration space

Fig. 7. Fragments of model experiments on planning of purposeful movements of the manipulator based on the RRT method: in the original version (a); with the involvement of heuristics determining a reasonable choice of the parent configuration (b)

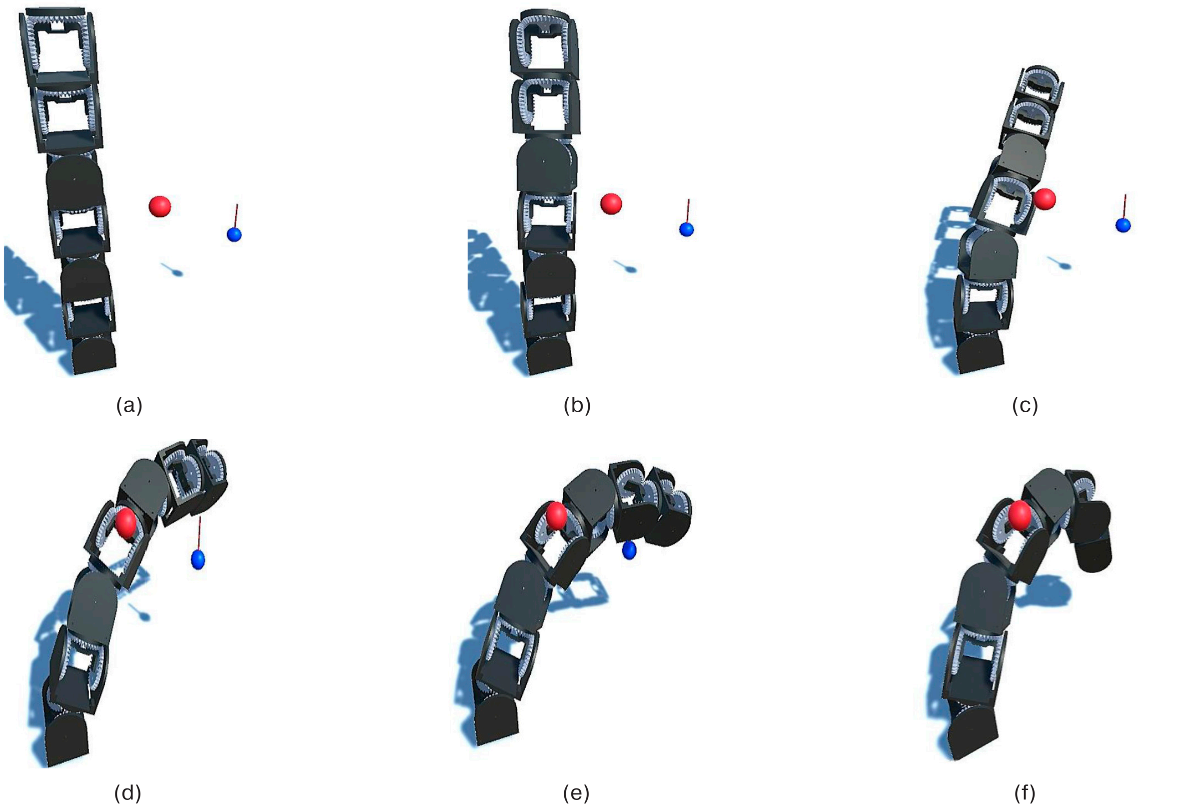


Fig. 8. Fragments of modeling of the purposeful motion formed on the basis of the RRT method for a seven-link manipulator in the environment with a point obstacle: evasion from the obstacle while moving to a given target state (a–d); processing of the required positioning point with a given approach vector (e–f)

those closest to the target state) permits a significantly reduction in the dimensionality of the generated tree (Fig. 7b) with simultaneous reduction of the problem solution time.

Invariance to the dimensionality of the configuration space in which the necessary solutions are searched is one of the most important advantages of the RRT method, which opens up possibilities and prospects of its application for manipulators, not only those having redundant, but also with variable kinematic structures.

Thus, in particular, the modeling results presented in Fig. 8 clearly confirm the effectiveness of the RRT method for the example of planning the purposeful movement of a seven-link mechatronic-modular robotic manipulator in an environment with a point obstacle.

In turn, Fig. 9 shows fragments of field experiments on the use of the RRT method for motion planning of a reconfigurable robotic manipulator, when modification of its kinematic structure is carried out through automatic docking with an additional mechatronic module.

The data of the conducted research represent a practical confirmation of the reality of the development of unified means for motion planning and motion control of robotic manipulators taking into account the requirements for invariance to the composition and operational changes of the existing kinematic structure.

In application to special robotics, many samples of which are built according to the "manipulator on a mobile base" scheme, the application of the RRT method is of special interest. For example, in automatic search, capture and evacuation of objects of target interest, the tasks of planning the movements of the mobile platform and the manipulator are closely interrelated. It is obvious that a successful choice of platform location will not only determine the nature of the manipulator movement, but also the principal achievability of the required point of the working scene with the given parameters of the approach and orientation vectors. In particular, as shown in Fig. 10, the use of the RRT method in its original version provides the possibility of motion planning, not only for the mobile platform and the manipulator considered in a certain order, but also in the case of their representation in a common configuration space as a single system.

The high computational efficiency of the algorithms implementing the RRT method makes it possible to solve the problems of route formation without, however, guaranteeing its optimality with respect to any quality criterion. Attempts to eliminate this disadvantage led to the emergence of the RRT* method focused on finding asymptotically optimal solutions [7–9]. The key features that distinguish the RRT* method from its prototype are related to the introduction of a number of additions and modifications to the basic principles of search tree generation. Thus, in particular, the main innovation consists in establishing the notion of the cost of a path to a particular vertex of the tree.

Finding a new vertex c_{new} in the course of tree construction by the RRT* method is done by analogy with the RRT method. Integration of the found node c_{new} into the synthesized structure implies the choice of such a variant at which the cost of the path $cost(c_{init}, c_{new})$ leading to it in the direction from the root node c_{init} would have a minimum value. In this regard, in the neighborhood centered at the point c_{new} and with a given radius r the search is carried out for such a vertex c_{min} which meets the following condition:

$$c_{min} = \text{argmin}_{c \in C^*}(cost(c_{init}, c) + cost(c, c_{new})),$$

where C* is the subset of tree vertices lying inside the neighborhood of radius r centered at the point c_{new}.

The vertex c_{new} is included in the tree element lists as a child of the vertex c_{min}.

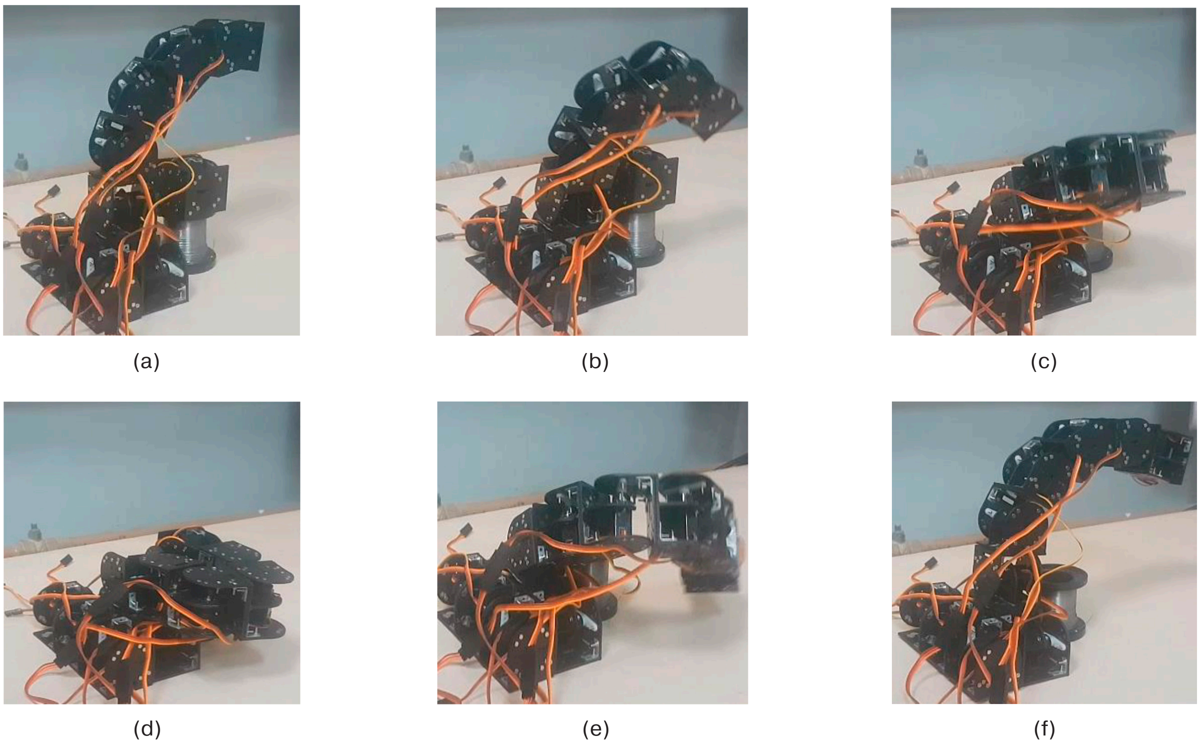


Fig. 9. Fragments of the full-scale experiment on using the RRT method for motion planning of the ARAKS reconfigurable mechatronic-modular robotic manipulator (RTU MIREA, Russia): motion of the manipulator to the place of docking with an additional mechatronic module (a–c); automatic docking with an additional mechatronic module (d); return movement of the manipulator with a modified kinematic structure (e–f)

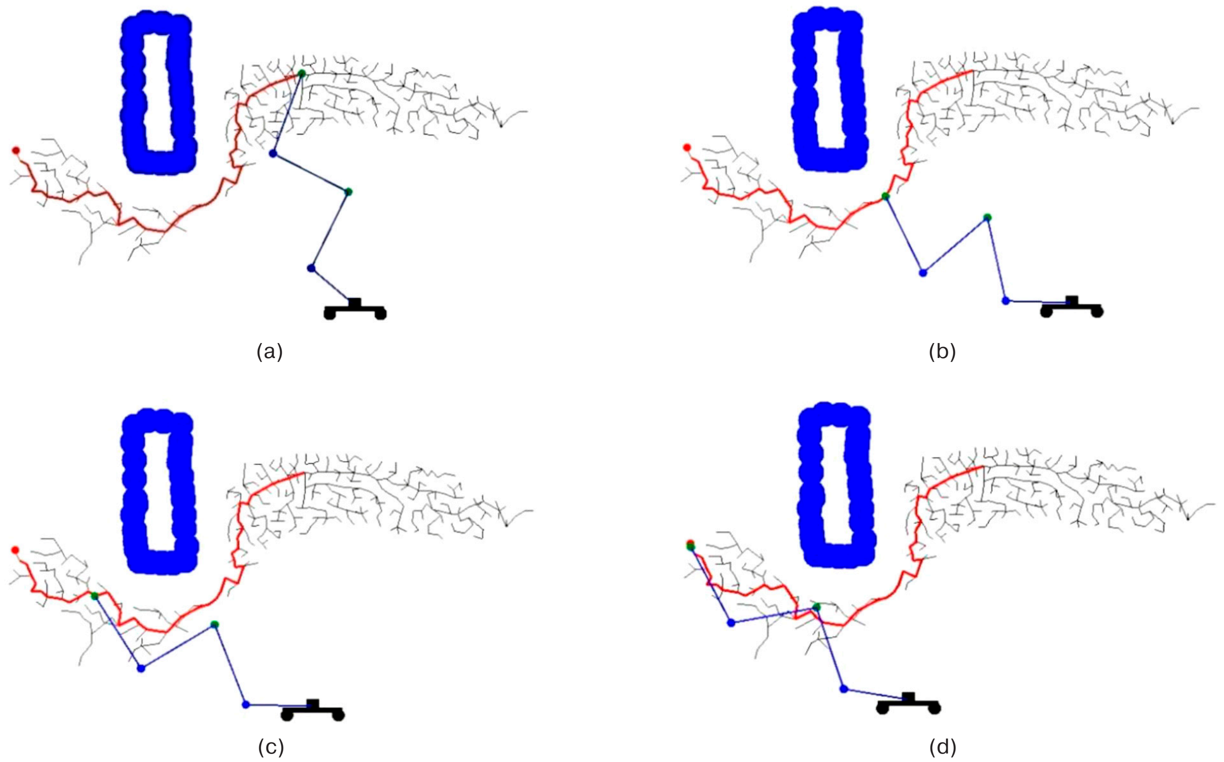


Fig. 10. Application of the RRT method for the purposeful motion planning for a manipulator on a mobile base

It is important to note that the size of the neighborhood in which the search is performed, which is determined according to the current number of tree nodes, decreases as the tree grows [8]:

$$r = \gamma(\log(n)/n)^{1/d+1},$$

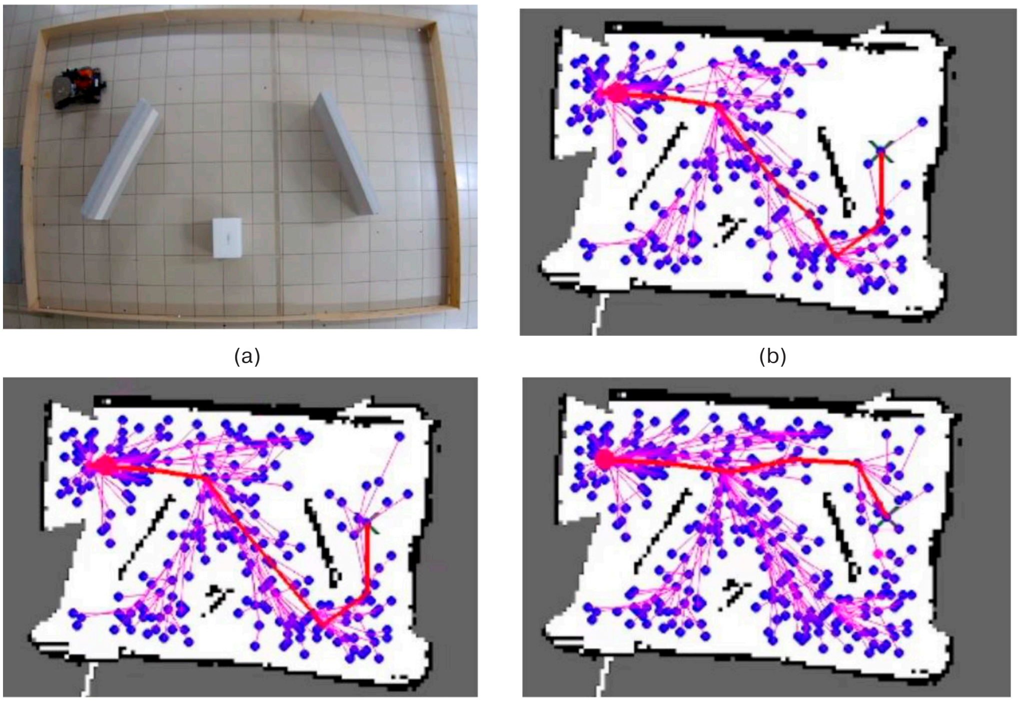
where d is the dimensionality of the configuration space; n is the current number of the tree vertices; γ is a constant coefficient determined by the volume of the allowed configuration space [7].

The following steps are aimed at local optimization of the tree structure in the neighborhood selected earlier around the c_{new} vertex. As part of their execution, for each vertex $c \in C^*$ the possibility of re-forming the path leading to it through vertex c_{new} is analyzed, taking into account the actual change in the cost of the corresponding route. If the value of $cost(c_{init}, c)$ index decreases, a local restructuring of the tree is performed, where the considered vertex $c \in C^*$ becomes a child of c_{new}. As shown in Fig. 11, the application of the RRT* method to robotic manipulator motion planning problems provides the construction of much smoother trajectories compared to those formed on the basis of the original version of the RRT method.

Minor changes in the algorithmic implementation of the method ensure its applicability for solving robotic manipulator motion planning problems in the conditions of a priori unknown and dynamic scenes due to additional mechanisms of operative rearrangement of the synthesized tree [10–12]. Thus, Fig. 12 shows fragments of model experiments on mobile robotic manipulator motion planning in an a priori unknown scene, when the search tree is rebuilt as obstacles are detected directly in the process of movement.

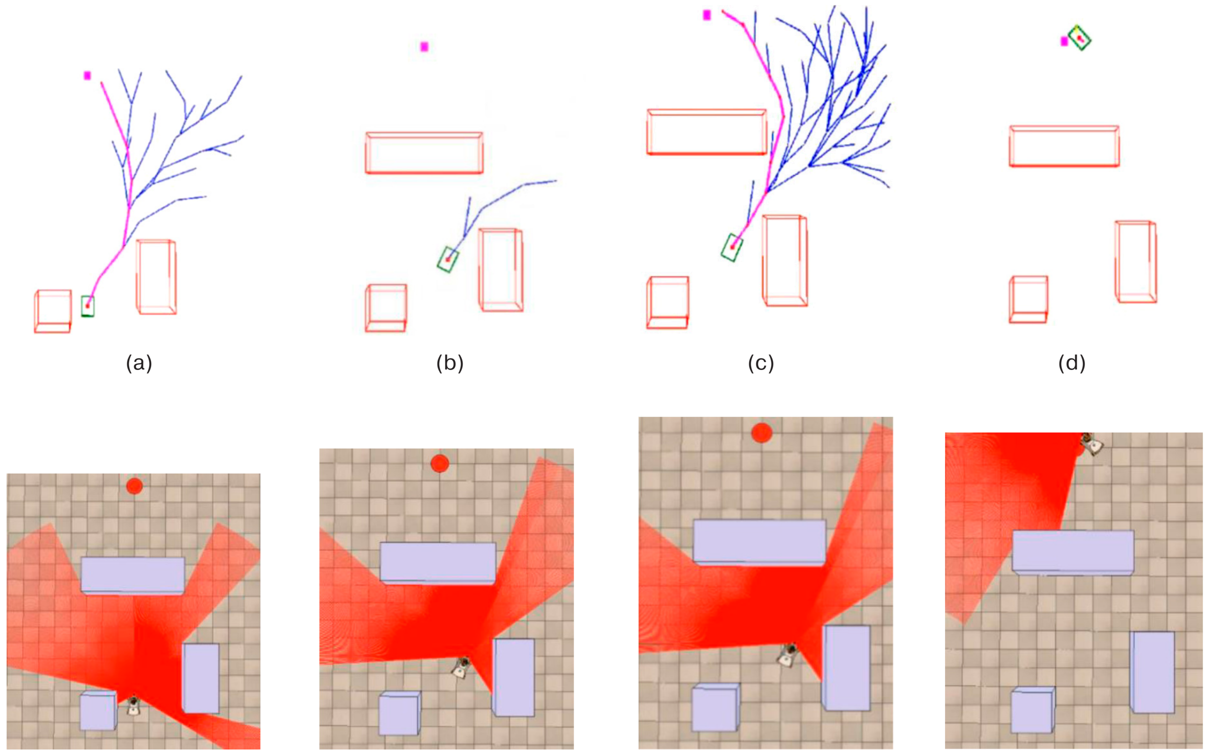
Along with the classical version of the RRT method, its modification RRT-Connect, which is associated with a radical transformation of the order of route network formation to find the trajectory of purposeful manipulator motion in the space of possible configurations, has become widespread. According to the new scheme of its step-by-step reconstruction, the model of the discrete search space is represented by a set of two trees, the alternate growth towards each other of which reflects the allowable changes in the robotic manipulator's states, starting from both the initial c_{init} and the goal c_{goal}, respectively (Fig. 13).

Mutual integration of the synthesized structures is ensured by periodic attempts to include each emerging vertex of one tree into the composition of the other. As is commonly believed, the RRT method with a counter-growth and its modifications [13] have increased efficiency compared to the original prototype, which is fully confirmed by the data of experimental studies shown in Figs. 14 and 15. The capabilities, advantages, and distinctive features of the RRT-Connect method make it promising for use not only in tasks of planning purposeful motions by moving objects of various types in complex environments, but also for group control of autonomous robotic manipulators when performing mutual convergence and automatic jointing operations.



(a) (b) (c) (d)

Fig. 11. Fragments of a complex experiment on motion planning of an autonomous mobile robotic manipulator using the RRT* method: configuration of a real scene (a); construction and adjustment of the desired route during the algorithm operation (b, c, d)



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 12. Fragments of model experiments on using the RRT method for planning mobile robotic manipulator motions in the conditions of a priori unknown scene: rebuilding the search tree (a, c, e, g) as obstacles are detected in the process of manipulator motion (b, d, f, h)

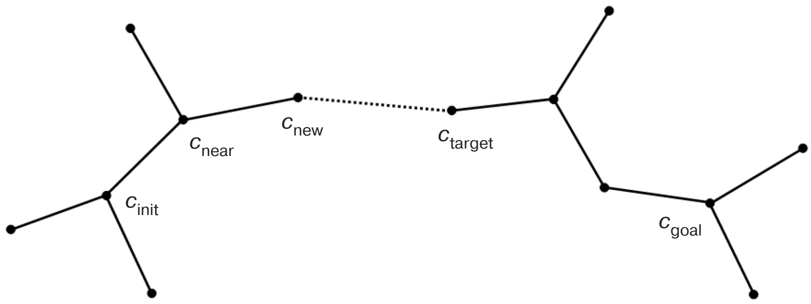


Fig. 13. Bidirectional exploration of configuration space according to the RRT method with counter-growth (RRT-Connect). c_{target} is the nearest vertex for c_{new}, for which the check on the possibility of combining two trees is performed

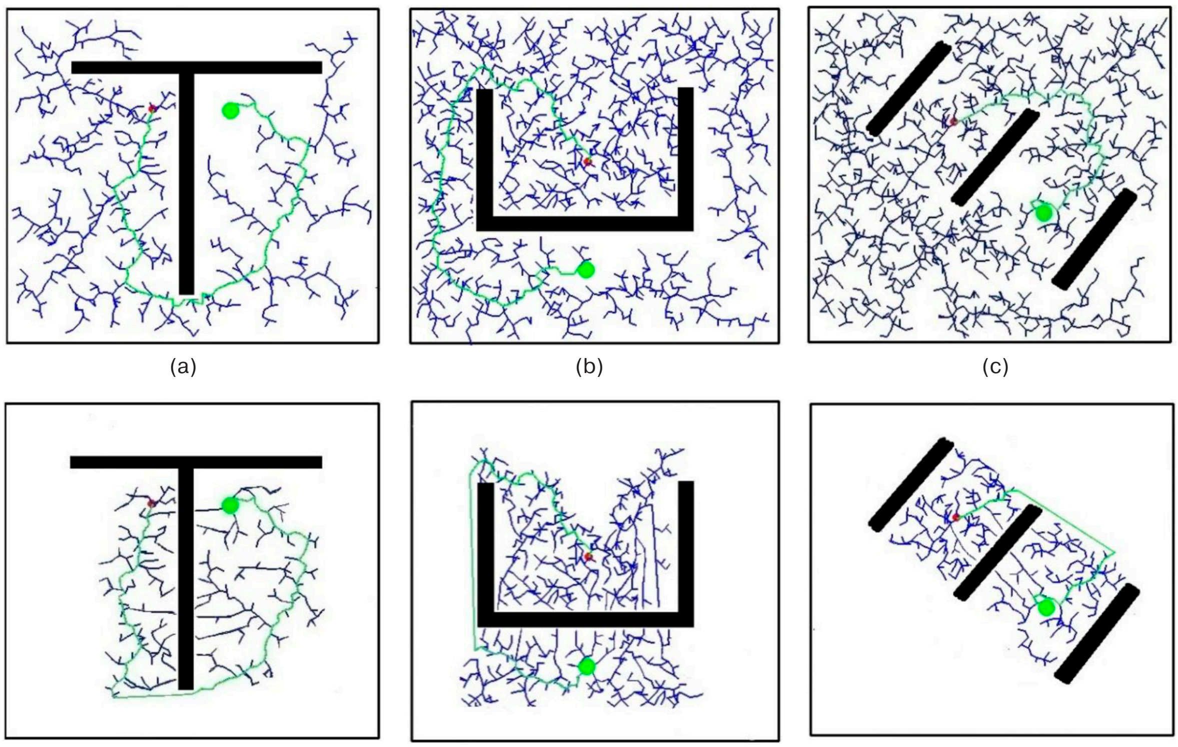


Fig. 14. Experimental results on motion planning of an autonomous mobile robotic manipulator in an obstacle-ridden environment based on RRT (a–c) and RRT-Connect (d–e) methods

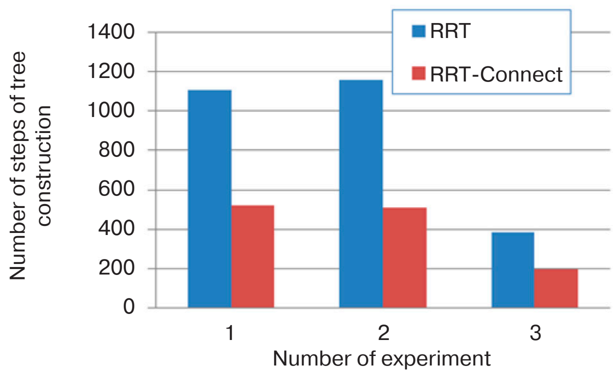


Fig. 15. Experimental results on evaluating the effectiveness of RRT and RRT-Connect methods for motion planning of an autonomous mobile robotic manipulator in an obstacle-ridden environment

CONCLUSIONS

Review of specialized literature and experimental studies have convincingly demonstrated the broad capabilities of the RRT method for providing solutions to motion planning problems for mobile and robotic manipulators of various types and layouts, including manipulators with redundant or reconfigurable structure, placed on a stationary or mobile base. Generalization of the obtained results opens up real prospects for using the RRT method as a constructive basis not only for creating universal means of motion planning for mobile robotic systems with on-board manipulator, but also for solving problems of automating the docking of autonomous mobile platforms.

Authors' contribution. All authors equally contributed to the research work.

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Translated from Russian into English by Lyudmila O. Bychkova
Edited for English language and spelling by Thomas A. Beavitt