Multiple robots (robotic centers) and systems. Remote sensing and non-destructive testing

Роботизированные комплексы и системы. Технологии дистанционного зондирования неразрушающего контроля

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RESEARCH ARTICLE

Automation of autonomous mobile robot docking based on the counter growth rapidly exploring random tree method

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Abstract
Objectives. The article substantiates the relevance of automatic docking of autonomous mobile robots. Specific examples show that the implementation of the automatic docking functions of autonomous robots reveals the potential for creating multi-agent systems with a transformable structure. The aim of the work is to develop means for automatic docking of autonomous mobile robots in complex scenarios and an uncertain environment.
Methods. The proposed approach to automating autonomous mobile robot docking is reduced to a modification of the counter-growth rapidly-exploring random tree (RRT) method. It is based on the parallel execution of a decentralized route planning algorithm with mutual coordination of distributed computing processes. The effectiveness of the complex of algorithmic and software tools developed was evaluated using computer and natural simulation methods. The final series of full-scale experiments was carried out on the example of JetBot AI kit Nvidia platforms for automatic docking of autonomous robots. This was performed using the means and methods of intelligent control, visual navigation, technical vision and wireless network communication.
Results. The study analyzed the features of automatic docking as one of the tasks of group control of autonomous robots. This is part of multi-agent systems, capable of reconfiguring structures for purposeful changes to the existing set of functional properties and application possibilities. The study also proposes a decentralized modification of the counter-growth RRT method. This allows the movements of autonomous mobile robots in the course of their mutual approach and subsequent docking to be planned. A set of software-algorithmic tools was developed to automate the docking of autonomous robots. A series of model and full-scale experiments were carried out to confirm the effectiveness of the approach developed herein.
Conclusions. The modification presented herein of the counter-growth RRT method, traditionally used for planning the movements of manipulators and mobile platforms, is complementary to the tasks it resolves. This enables the docking of autonomous robots to be automated. The results obtained open up the potential for universal schedulers with extended functionality for autonomous robot control systems to be designed.

Keywords: autonomous robot, intelligent control, group control, multi-agent robotic system, automatic docking, counter-growth RRT method

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НАУЧНАЯ СТАТЬЯ

Автоматизация стыковки автономных мобильных роботов на основе развития метода поисковых случайных деревьев со встречным ростом

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Резюме
Цели. В статье обоснована актуальность задачи автоматической стыковки автономных мобильных роботов. На конкретных примерах показано, что реализация функций автоматической стыковки автономных роботов открывает перспективы создания многоагентных систем с трансформируемой структурой. Целью работы является разработка средств автоматической стыковки автономных мобильных роботов, функционирующих в условиях сложных сцен и неопределенности окружающей обстановки.
Методы. Предлагаемый подход к автоматизации стыковки автономных мобильных роботов сводится к модификации метода поисковых случайных деревьев со встречным ростом на основе параллельного выполнения децентрализованного алгоритма планирования маршрутов с взаимной координацией процессов распределенных вычислений. Оценка эффективности разработанного комплекса алгоритмических и программных средств осуществлялась с помощью методов компьютерного и натурного моделирования. Заключительная серия натурных экспериментов проводилась на примере автоматической стыковки автономных робототехнических платформ «JetBot AI kit Nvidia», выполняемой с привлечением средств и методов интеллектуального управления, визуальной навигации, технического зрения и беспроводной сетевой связи.
Результаты. Проведен анализ особенностей автоматической стыковки, как одной из задач группового управления автономными роботами в составе многоагентных систем, способных реконфигурировать свою структуру для целенаправленного изменения имеющегося набора функциональных свойств и возможностей прикладного применения. Предложена децентрализованная модификация метода поисковых случайных деревьев со встречным ростом, позволяющая обеспечить планирование перемещений автономных мобильных роботов по ходу их взаимного сближения и последующей стыковки. Разработан комплекс программно-алгоритмических средств автоматизации стыковки автономных роботов. Проведены серии модельных и натурных экспериментов, подтвердивших эффективность развиваемого подхода.
Выводы. Представленная модификация метода поисковых случайных деревьев со встречным ростом, традиционно применяемого для планирования перемещений манипуляторов и подвижных платформ, дополняет состав решаемых им задач, позволяя обеспечить автоматизацию стыковки автономных роботов. Полученные результаты открывают перспективы создания универсальных планировщиков с расширенным функционалом для систем управления автономными роботами.

Ключевые слова: автономный робот, интеллектуальное управление, групповое управление, многоагентная робототехническая система, автоматическая стыковка, метод поисковых случайных деревьев со встречным ростом

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INTRODUCTION

Modern examples of semi-automatic and autonomous robots must have a set of capabilities consisting of: analyzing received information; evaluating the situation at the current moment of time; and planning actions with subsequent implementation in accordance with specified quality criteria.

The specific character of group control of robots within a joint grouping requires mutual coordination. This includes motion planning and routing. The analysis of the specific features of these tasks, taking into account admissible formulations, is an extremely important issue. It is this issue which largely predetermines the choice of suitable algorithmic solutions.

FEATURES OF AUTOMATIC DOCKING AS A TASK OF GROUP CONTROL OF AUTONOMOUS ROBOTS

In a wide range of tasks for group control of robots, automatic docking can also be considered typical for certain application domains [1]. An illustrative example of this can be seen in the high-precision movement of elements of large-sized structures using KUKAomniMove (KUKAAG, Germany) robotic transportation platforms (Fig. 1). Such platforms are used in the aviation and machine-building industries in the assembly of airplane bodies, high-speed trains, and other large-sized products. KUKAomniMove is a multi-wheeled robotic platform capable of operating in remote or semi-automatic control. When required, robotic transportation platforms of this type, equipped with special interface devices, can dock with each other under operator control to transport objects of the appropriate weight and size.

In the case of robots with a transformable structure, the automatic docking of mechatronic-modular elements with autonomous mobility is a composite step, resulting in the synthesis of a new configuration, as shown in Fig. 2 [2–6].

Automatic docking operations can in general be characterized in terms of the complexity of an a priori unknown environment. This environment is determined by the following factors: significant initial distance of robots from each other; lack of mutual visibility

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

Fig. 1. KUKAomniMove (KUKAAG, Germany) robotic transportation platform: general view of the platform and the manual remote control (a); docking facilities (b); robotic transportation platforms in the docked state (c); transportation of large-sized products (d)

(a) (b) (c)

Fig. 2. Reconfigurable mechatronic-modular robot SMORES (UPenn, USA): autonomous mechatronic module (a); automatic docking of modules (b); synthesized structure (c)

conditions; and the possible presence of obstacles. The detection range of obstacles is limited by the parameters of information-measuring devices. In cases when both robots play an active role in automatic docking, the formulation of the problem is also of special interest and complexity. One promising approach to the creation of special tools, designed to manage automatic docking functions of autonomous robots as part of the software and algorithmic support of their control systems, is the development and decentralization of the counter growth rapidly exploring random trees method: RRT-Connect.

DEVELOPMENT OF THE COUNTER GROWTH RAPIDLY EXPLORING RANDOM TREES (RRT) METHOD FOR THE AUTOMATION OF AUTONOMOUS MOBILE ROBOT DOCKING

The main feature of the RRT family methods is an original approach to the robot motion planning based on the construction of the tree-like models of changes in its admissible states [7, 8].

If in the classical version of the RRT method, the tree synthesis is performed from the point of the robot's initial state until reaching a given target state, then the RRT-Connect version assumes that both the initial and target points of the route are the root nodes of tree structures. The process of tree formation is thus completed at the moment of the first mutual interlocking of the generated branches [9]. The RRT-Connect counter growth (rapidly exploring random trees) method [10], focuses on resolving route construction between two points. It can thus serve as an effective tool for planning the movements of autonomous mobile robots of different structures [11] in the course of their mutual convergence and automatic docking [12–14].

The application of the RRT-Connect method in resolving the automation of docking of autonomous mobile robots requires its modification in accordance with requirements regulating the introduction of necessary changes and additions, as follows:

- decentralization of the computational procedure with division into parallel processes of tree generation with counter-growth according to a single algorithm for both participants of the docking operation;
- coordination of processes performed at the level of mutual exchange of data on the current configuration of formed trees and observed constraints;
- initialization of root nodes of synthesized trees at the points of initial location of the robots before the start of their docking operation with reference to a common coordinate system;
- simultaneous completion of tree generation processes at the first mutual interlocking of branches.

Figure 3 shows a generalized block diagram of the algorithm which implements a decentralized modification of the counter growth RRT-Connect method for robot motion planning during automatic docking. The software implementation of the algorithm must enable the constructed tree and the entire route network to be reinitialized for transformation when detecting obstacles as the robot moves along the previously laid path.

The basic ability of automatic docking of autonomous robots in an obstacle-laden environment based on the decentralized modification of the RRT-Connect method is confirmed by the results of complex computer simulation. Fragments are shown in Fig. 4.

EXPERIMENTAL TESTING OF SOFTWARE-ALGORITHMIC RESOURCES FOR AUTOMATION OF THE AUTONOMOUS MOBILE ROBOTS DOCKING BASED ON THE DECENTRALIZED MODIFICATION OF THE RRT-CONNECT METHOD

A series of *in situ* experiments at a specialized laboratory test site was carried out, in order to assess the practical feasibility of an approach based on the application of a decentralized modification of the counter growth RRT-Connect to automate the docking of the autonomous mobile robots. A general view of the research site is shown in Fig. 5a. It was designed to debug and verify the means and methods of intelligent and group control of autonomous mobile objects. It uses a large fleet of mobile robotic platforms such as Jetson

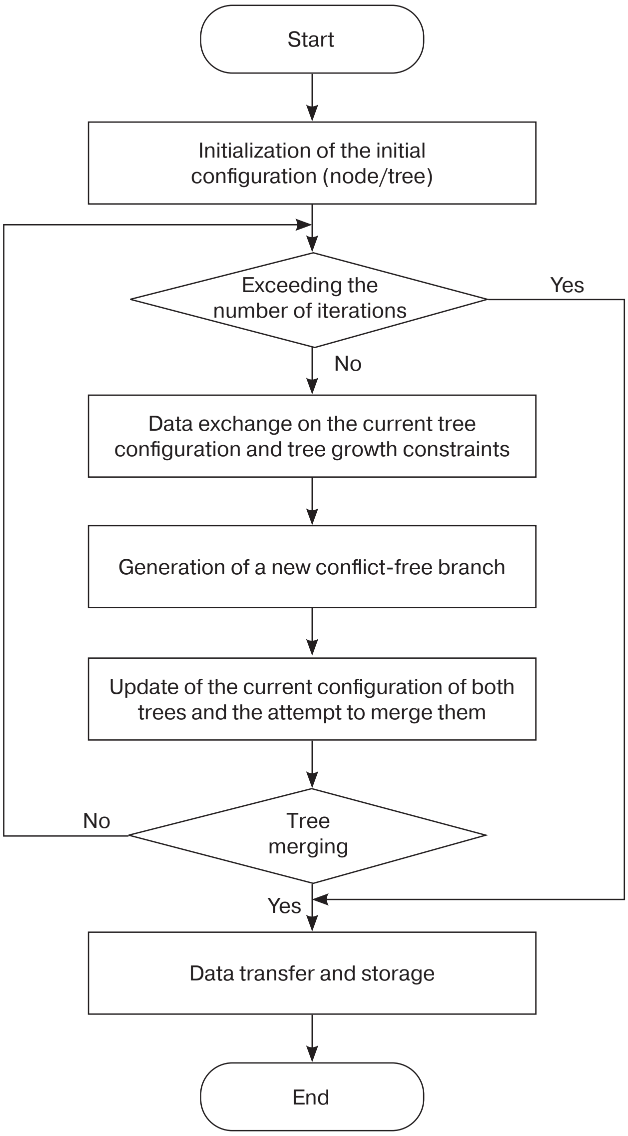

Fig. 3. Generalized block diagram of an algorithm implementing a decentralized modification of the RRT-Connect method for robot motion planning during automatic docking

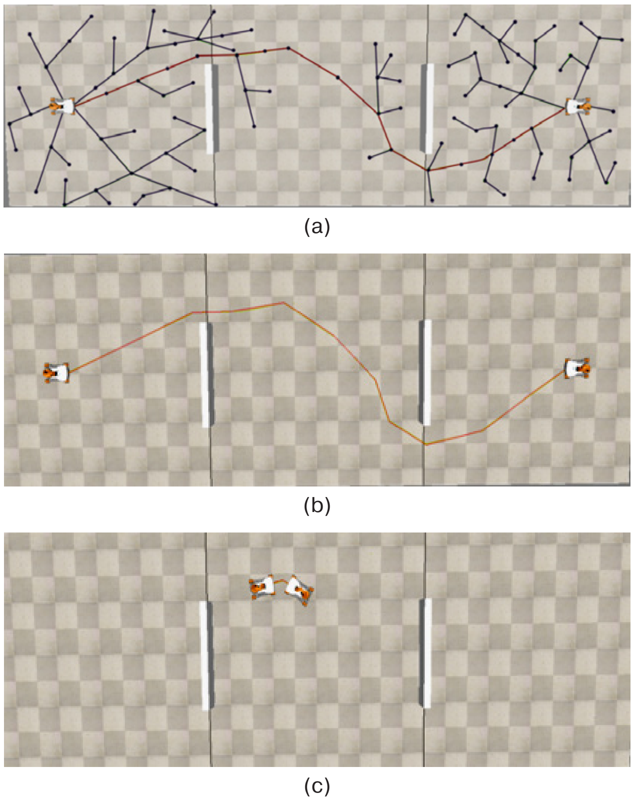

Fig. 4. Computer simulation of automatic docking of autonomous robots in an obstacle-ridden environment based on decentralized modification of the counter growth rapidly exploring random trees method RRT-Connect

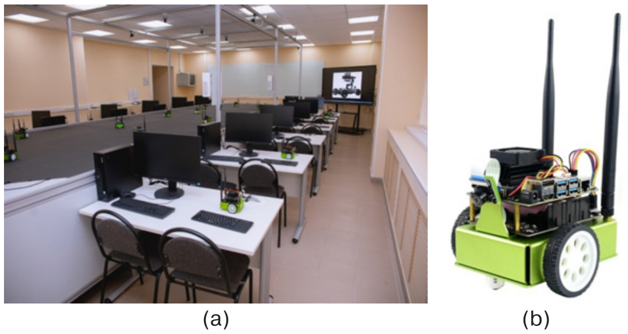

Fig. 5. Specialized laboratory testing site for debugging and verification of tools and methods of intellectual and group control of mobile objects (a) based on Jetson Nano JetBot AI kit Nvidia autonomous mobile robotics platforms (b)

Nano JetBot AI kit Nvidia (NVIDIA and Waveshare, USA)[1], network equipment for maintaining wireless communication channels and external surveillance cameras for monitoring the working environment and resolving visual navigation tasks.

The JetBot AI kit Nvidia Mobile robotics platform is shown in Fig. 5b). It has a wide range of potential capabilities and is equipped with a Jetson Nano (NVIDIA, Waveshare, USA) high-performance microcomputer, a small video camera (and, if necessary, other information-measuring means), a wireless network communication device, and an autonomous power supply based on rechargeable batteries.

The generalized structure of the set of software-algorithmic tools for automatic docking of the autonomous robots is shown in Fig. 6 and includes:

- motion planning subsystem based on a decentralized version of the RRT-Connect method;
- navigation subsystem to determine the current coordinates and orientation of the robot;
- sub-system for obstacle detection and mapping subsystem based on on-board camera image processing;

[1] https://www.waveshare.com/jetbot-ai-kit.htm. Accessed January 15, 2022.

- wireless network communication subsystem for mutual data exchange with the second docking participant;
- motion control subsystem, which ensures movement of the robot along the formed route.

The principles of the navigation subsystem construction are based on the image processing from external surveillance cameras with recognition and localization of ArUco-labels [15] used for robot marking, as shown in Fig. 7.

The requisite information interaction of autonomous robots at all stages of planning and implementation of their automatic docking is achieved in accordance with the standards of Wi-Fi-technology of wireless network communication using the user datagram protocol.

The motion planning subsystem is based on the decentralized version of the counter growth rapidly exploring random trees method RRT-Connect. It forms a route network for building the trajectory of the robot's convergence with the second docking participant. Mutually directed tree growth, simultaneously generated by the planners of both robots, is coordinated through wireless network communication channels with the exchange of necessary data sets.

The composition of the information transmitted reflects the current configuration of trees, as well as the location of obstacles observed by the subsystem for their detection and mapping. At the same time, the areas outside the coverage area of the external situation sensory control means are considered free of obstacles.

The end of the planning stage at the moment of the first interlocking of the branches of the synthesized trees determines the transition to the next stage of the automatic docking of the autonomous robots. This is associated with the control of their movement along the routes formed towards the proposed meeting point.

When previously unobserved obstacles are detected, the robot movement is suspended. The resumption of schedulers and restart of route construction procedures are based on a decentralized modification of the counter growth RRT-Connect method.

Secondary initialization of the scheduler requires the iterative implementation of the following actions:

- re-initialization of the route tree, checking the conditions of compliance with new constraints for

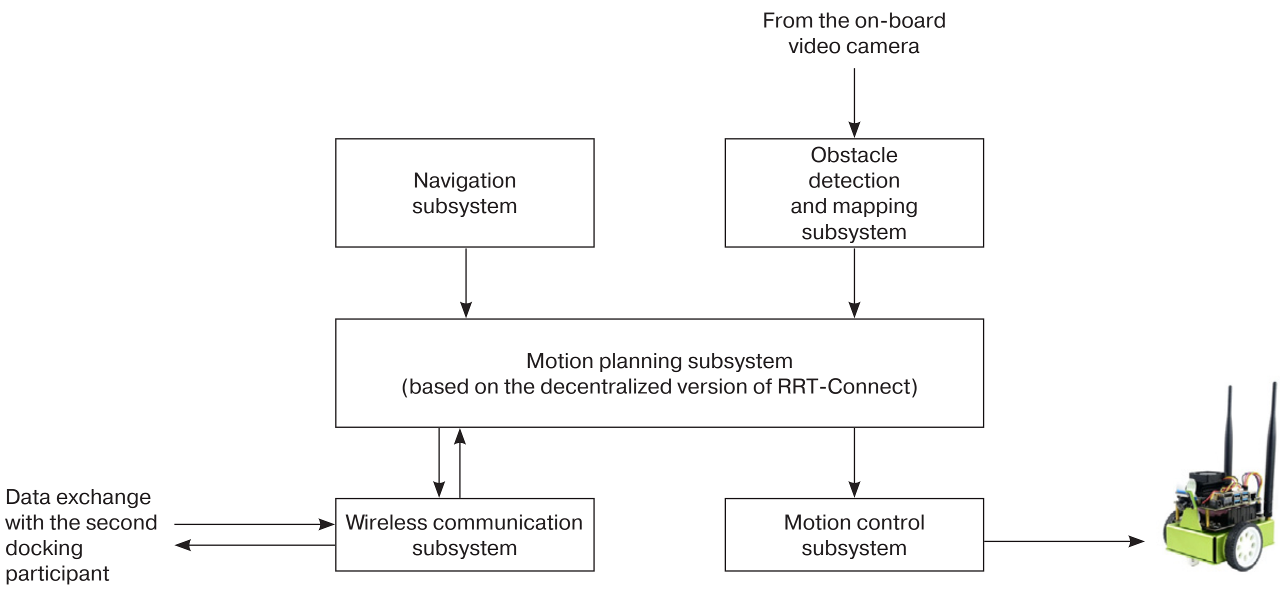

Fig. 6. Generalized structure of the on-board set of software-algorithmic means for the automatic docking of autonomous mobile robots

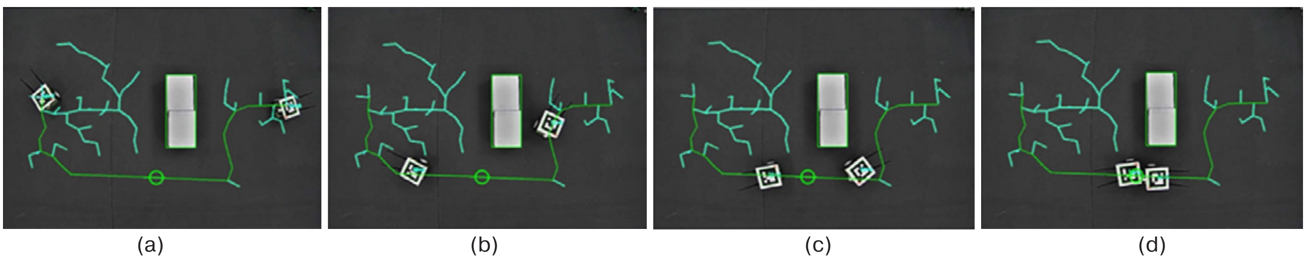

Fig. 7. Fragments of a full-scale experiment on emulation of automatic docking of the autonomous mobile robots

intersection of its branches with the boundaries of detected obstacles;

- removing all branches of the tree which do not satisfy the check conditions;
- removing branches that have lost connection with the root vertex as a result of the previous step;
- if the integrity of the path to the rendezvous point with the second robot is broken, the process of generating the reconstructed tree is resumed before the route to the new meeting point is established;
- transition to the motion continuation phase.

The workability and efficiency of autonomous robots automatic docking based on the decentralized modification of the counter growth RRT-Connect method are confirmed by the results of full-scale experiments, fragments of which are presented in Fig. 7.

CONCLUSIONS

An analysis of Russian and foreign literature shows that the emphasis placed on the development of the rapidly exploring random trees method is due to the wide possibilities of its application in resolving motion planning problems of both mobile and manipulation robots. These include robotic systems with an onboard manipulator (including those with a redundant or reconfigurable structure) on a transport platform. The modification presented herein of the method complements the composition of problems resolved by it. It also allows us to enable the automation of docking of autonomous robots. The results obtained open potential for the creation of universal schedulers with extended functionality for control systems of autonomous robots.

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

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