Trajectory Planning for Manipulators on Mobile Bases and in Dynamic Environments, Using Adaptive Models

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Abstract: This study addresses the challenges of trajectory planning for mobile manipulators whose base moves continuously during capture tasks. The main difficulty lies in adapting planning algorithms to dynamic scenarios, where base displacement compromises motion accuracy and efficiency. Traditional algorithms, developed for static or predictable environments, are unsuitable for unpredictable base movements. Key challenges include recalculating trajectories in real time to maintain safety and efficiency, while considering embedded systems' computational constraints and the need for rapid responses to avoid collisions and optimize manipulation. To overcome these issues, approaches must integrate dynamic data and generate feasible trajectories regardless of base position. This work proposes adapting and evaluating two widely used motion planning algorithms: Rapidly-exploring Random Tree (RTT) and Real-Time Adaptive Motion Planning (RAMP). Both will be modified to account for base displacement, ensuring safe and efficient trajectories. Adjustment strategies will be embedded into the planning process, enabling algorithms to react dynamically to environmental and base position changes. Implementation will occur in a simulated environment, with a manipulator on a mobile base interacting with dynamically modeled objects. Experiments will assess accuracy, response time, and robustness. Expected outcomes include improved adaptation to base variations, reduced execution times, and enhanced object capture performance. These optimizations aim to advance real-world applications of mobile manipulators in industrial and assistive robotics.
Keywords: Mobile manipulator, Dynamic path planning, Manipulator, ROS.

1. Introduction

Mobile manipulators represent an emerging and crucial research area in robotics, combining the mobility of mobile robots with the manipulation capabilities of robotic arms. This integration enables these systems to perform a wide range of complex tasks in diverse environments, ranging from industrial applications to domestic services. These robots have been widely adopted in various sectors, such as manufacturing, smart food services, daily assistance, and healthcare. Their broad applicability stems from their versatility and ability to manipulate objects, characteristics that make them suitable for different tasks such as pushing, pulling, and transporting.

The growing popularity of these robots can be attributed to their ability to meet specific demands, providing adaptable and effective solutions for a wide range of tasks and applications [1]. The capability to avoid obstacles in real time is of vital importance for the efficient completion of tasks in challenging environments, where complex and constantly changing obstacles are present [2]. This is achieved through the use of advanced environmental perception sensors, which enable rapid detection, and effective algorithms, which ensure agile responses to objects and adverse conditions. In this way, this set of technologies guarantees not only safety but also operational success in challenging environments.

Collaborative robots that are or have arms enable interaction between humans and robots in shared workspaces. To date, their applications have been limited to structured and static environments, usually for specific tasks. In industrial contexts, robot trajectory planning is still generally performed offline. To ensure autonomous and safe operations, it is imperative to use online motion planners capable of readjusting the robot's trajectory in the face of unexpected obstacles or variable goals [3]. Therefore, the implementation of real-time motion planners is essential to expand the application of collaborative robots in dynamic industrial scenarios, enabling more adaptive and safer operations in interaction with humans.

Another significant application of mobile manipulators lies in their integration with underwater vehicles, representing one of the primary research areas for scientists. This field requires investigation due to the complexity of the underwater vehicle–manipulator interaction, which involves coupled motion and parameter uncertainties [4]. According to the authors, these vehicles have begun to play an important role in underwater activities, including, but not limited to, seabed exploration, oil-related operations, and military and scientific investigations.

Mobile manipulators have been employed in various applications that would traditionally require multiple fixed-base robots or large-scale robotic systems. This capability is enabled by the mobility of the mobile base. However, the mobile base also introduces redundancy to the system, making the motion planning of the mobile manipulator more challenging [5].

As previously mentioned, mobile manipulators represent a highly versatile and promising technology, with applications spanning various sectors, from manufacturing to underwater operations. Their success is driven by the ability to deliver adaptable and effective solutions for a wide range of tasks and environments. However, persistent challenges, such as dynamic trajectory planning and real-time interaction with obstacles and variable goals, continue to demand ongoing innovation and research.

The need for online motion planners capable of adjusting manipulator trajectories in response to environmental changes and base displacements is essential to ensure autonomous and safe operations, particularly in industrial and collaborative contexts. Furthermore, the integration of manipulators with underwater vehicles opens new frontiers for exploration and discovery in marine environments, enhancing the precision of object retrieval and valve manipulation under maritime disturbance conditions.

This research examines existing models in the literature, focusing on promising approaches and techniques aimed at improving the efficiency of dynamic trajectory computation for manipulators, with the goal of increasing autonomy and safety in mobile manipulator operations. By addressing these challenges in a collaborative manner, it becomes possible to assess and compare the different models proposed, identifying those that yield the best results in object retrieval and transportation tasks within dynamic environments and with constant base displacement, while seeking algorithmic improvements and optimization in dynamic tasks. This comparative evaluation is crucial to highlight the most effective approaches, presenting both strengths and weaknesses to guide future research and developments in the field of continuously moving mobile manipulators. In this way, the sharing of knowledge and experience can foster innovation and drive advances toward more sophisticated and efficient solutions to the challenges faced by these robotic systems.

2. Objective

This research aims to employ dynamic trajectory planning models for mobile manipulators, with an emphasis on performing object pick-and-place tasks between two points while the robot's base is in continuous motion during operation. Based on the results obtained, a comparative analysis of the techniques will be conducted. The study seeks to identify the most effective methods and propose advancements in the development of strategies that enhance the adaptability and efficiency of these systems in industrial and collaborative environments.

In this research, several stages will be carried out to complete the study:

1. Analyze existing trajectory planning techniques in the literature for mobile manipulators, with emphasis on online approaches and their applicability in dynamic environments;
2. Compare the effectiveness of dynamic trajectory planning models in terms of performance in object retrieval and transportation tasks within dynamic environments and with constant manipulator base displacement;
3. Develop an evaluation methodology to test the robustness of mobile manipulators in dynamic and collaborative environments, considering displacement variables and external interferences;
4. Implement and test real-time trajectory planning techniques adapted for mobile manipulators, focusing on improving operational accuracy and safety;
5. Conduct simulated experiments using robotic manipulators on mobile bases to assess the feasibility of the models in real-world scenarios;
6. Analyze experimental results and qualitative observations, identifying strengths and limitations of each trajectory planning model.

The research is motivated by the complexity of operating robotic manipulators in dynamic environments, in which their mobile base is subject to displacements during the execution of specific tasks. This situation is frequently observed in various practical applications, such as object manipulation in spaces shared with humans, operations on the seafloor, where the base is in constant motion, or in industrial environments where autonomous load transportation is required.

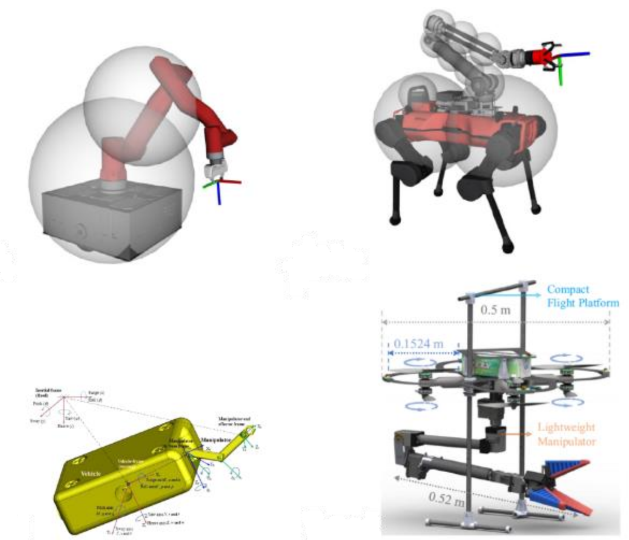
In this context, it is essential to investigate and compare different trajectory planner models, considering not only the dynamics of the mobile base but also the presence of dynamic obstacles. The inclusion of such obstacles, simulating the presence of people or moving objects within the manipulator's operating area, introduces a realistic challenge to the analysis, enabling an accurate assessment of conditions encountered in practical environments.

Through a comparative analysis of trajectory planner models found in the literature, the aim is not only to identify their advantages and limitations but also to gain insights into their ability to estimate dynamic trajectories efficiently and accurately, ensuring acceptable execution times and effective adaptation to dynamic scenarios.

3. Mobile Manipulators

The structure of mobile manipulators consists of multifunctional mechanical arms equipped with grippers or claws, enabling them to handle objects with precision and flexibility, along with integrated sensor subsystems [6]. These devices are complemented by locomotion systems, which may include wheels, thrusters, tracks, or even legs, as shown in Figure 1, providing the capability to move across uneven terrain and operate in challenging environments.

Figure 1. Structural Models of Bases for Mobile Manipulators [9-10].



Mobile manipulators use their bases as approach vehicles to perform tasks. For the trajectory computation to be successfully executed, these bases must remain stable, that is, free from disturbances or displacements during operation. This requirement arises from the fact that manipulator trajectory planning algorithms consider the base as a fixed reference. Consequently, any displacement in the base's position may introduce errors into the trajectory calculation or require recalculating it, which can increase operation time and reduce energy efficiency.

3.1. Trajectory Planning Algorithms for Mobile Manipulators

Trajectory planning algorithms for robotic manipulators are computational methods used to determine the path or sequence of movements that a manipulator must follow to reach its final target. The primary goal of these algorithms is to ensure that the manipulator moves accurately and optimally, while adhering to the constraints of the operating environment, considering factors such as obstacles, the robot's physical limitations, and dynamic environmental conditions. This study addresses two trajectory planning algorithm methods: RRT and RAMP.

3.1.1. RRT

The RRT method is a sampling-based trajectory planning approach widely employed in dynamic trajectories for robotic manipulators with multiple degrees of freedom operating in complex environments [7]. This algorithm is grounded in principles of optimal control theory, nonholonomic planning, and random path strategies, with its core concept consisting of the progressive expansion of a search tree from an initial state [8]. This expansion occurs through the application of control inputs over small time intervals, enabling transitions to new states. Each node in the tree corresponds to a state, while the directed edges represent the inputs applied to connect consecutive states. Upon reaching the target region, the tree structure defines an open-loop trajectory that connects the initial point to the goal. Figure 2 shows the path generated by the RRT algorithm.

Figure 2. Structural Models of Bases for Mobile Manipulators [7].

3.1.2. RAMP

RAMP is an adaptive real-time motion planner developed for robotic manipulators [11]. According to the authors, the RAMP methodology is based on concepts of randomized and optimized planning, operating in a parallel and continuous manner, thereby eliminating several disadvantages of traditional approaches.

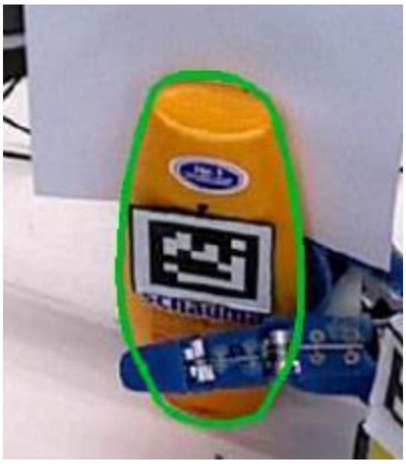
The RAMP method represents complete trajectories in the configuration-time (CT) space and continuously refines them during simultaneous planning and execution. Unlike sequential or incremental approaches, which only provide the final trajectory upon completion of the process, RAMP can quickly generate a valid trajectory and improve it as needed to meet global real-time planning requirements. It allows for the flexible integration of multiple optimization criteria, such as minimizing energy and time or maximizing manipulability, directly in the continuous CT space, avoiding the constraints imposed by graph-based representations. Furthermore, its parallel architecture maintains multiple trajectories active simultaneously, enabling instant adjustments and, when necessary, drastic changes to respond to environmental variations.

The approach is also highly adaptable, continuously adjusting trajectory search and optimization in response to new conditions. Since planning and execution occur in parallel, the robot can follow viable portions of a trajectory while new alternatives are generated to bypass infeasible regions. The method supports partially specified goals, allowing different trajectories to terminate at distinct locations within the same target region. In redundant robots, such as mobile manipulators, RAMP leverages redundancy by representing trajectories as loosely coupled redundant variable paths, thereby maximizing collision avoidance and meeting multiple optimization objectives simultaneously.

3.2. Perception

A simple yet robust alternative for object detection is the use of fiducial markers. The literature presents various types and formats of these markers [12]. In this work, the AprilTag was chosen due to its greater robustness to occlusions and distortions, as well as its lower incidence of false detections [12]. However, the main source of error in AprilTag pose estimation is related to the camera's angular rotation [13], which will not pose a challenge in this study, as the camera will not undergo any rotation. The structure of the AprilTag, for example, consists of black outer borders and internal patterns composed of white squares, which facilitates differentiation through various topologies, as illustrated in Figure 3, which shows an example application.

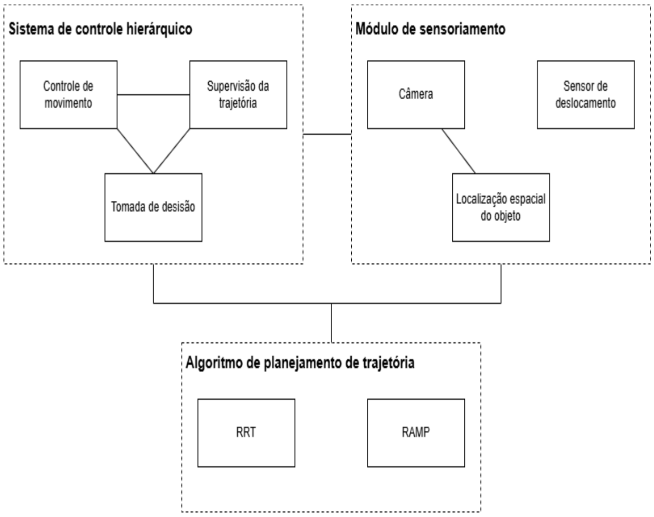
Figure 3. Illustrative Example of an AprilTag [14].



4. Proposed Model for Mobile Manipulator Trajectory Planning

The proposed model consists of three main components: (1) a hierarchical control system, responsible for managing the manipulator's movements, ensuring path supervision to prevent collisions, and guaranteeing that the final objective is achieved safely; (2) a dynamic trajectory planning algorithm, designed to enable the manipulator to capture the object even during continuous base movement, adapting trajectories in real time as needed; and (3) a sensing module, tasked with identifying the object's relative position with respect to the base and providing essential information for system operation, as illustrated in Figure 4.

Figure 4. Diagram of the Proposed Model for Real-Time Object Manipulation.



5. Conclusion

This study presented two path planning methods, RRT and RAMP, for mobile manipulators performing pick-and-place tasks while operating on continuously moving bases. The proposed model, integrating a hierarchical control system, a non-adaptive and adaptive real-time planning algorithm, and a sensing module using AprilTags, demonstrated the feasibility of accurate and efficient manipulation in dynamic environments.

The RRT is widely recognized for its efficiency in exploring high-dimensional state spaces, a feature that makes it suitable for trajectory planning in robotic manipulators. As previously noted, this algorithm can rapidly identify feasible paths in complex environments, which is particularly relevant in scenarios that demand immediate responses. However, its original formulation does not account for variations in the environment, requiring the tree to be reconstructed whenever changes occur. To address this limitation, the algorithm will be modified to allow new replanning whenever alterations to the final goal arise.

The RAMP, in turn, was designed for dynamic scenarios, enabling simultaneous planning and execution. This method generates partially feasible trajectories almost immediately, refining them continuously based on real-time sensory data. Furthermore, it supports the integration of multiple optimization criteria, such as reducing execution time, improving energy efficiency, and enhancing manipulability, thereby ensuring robust performance even under adverse conditions. Thus, while RRT and its variants provide speed in exploring the search space, RAMP distinguishes itself by its continuous adaptability, making it particularly suitable for tasks performed in collaborative environments or under constant perturbations.

Future research will focus on implementing the model, optimizing processing time, expanding sensor integration, and conducting real-world experiments to further validate and refine the proposed approach.

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