DOI: https://doi.org/10.15276/ict.02.2025.28
UDC 004.94

Improving the RRIS method using a collision-depth-based heuristic

Andrii Ya. Medvid[1)]
Postgraduate Student of the Department of Artificial Intelligence Systems
ORCID: : https://orcid.org/0009-0001-4128-4973; andrii.y.medvid@lpnu.ua
Vitaliy S. Yakovyna[1)]
Doctor of Engineering Sciences, Professor of the Department of Artificial Intelligence Systems
ORCID: : https://orcid.org/0000-0003-0133-8591; vitaliy.s.yakovyna@lpnu.ua
[1)] Lviv Polytechnic National University, Lviv, Ukraine

ABSTRACT

Collision-free path planning for redundant robotic manipulators is a significant challenge in robotics, primarily due to the high-dimensional joint spaces and the complexity of real-world environments. While foundational sampling-based planners have proven effective, they often struggle in scenarios with narrow passages or complex constraints. The Recursive Random Intermediate State (RRIS) method was recently introduced as a promising alternative that employs a "divide and conquer" strategy, recursively inserting intermediate states to simplify a complex planning problem into a series of more simple subproblems.

However, the original RRIS implementation relies on a simplistic heuristic for evaluating intermediate states: it counts the number of discrete configurations in a state of collision. This binary metric lacks nuance, treating a path with a minor, grazing contact identically to one with severe interpenetration.

In this paper, we propose an enhancement to the RRIS method by replacing this binary count with a more physically intuitive, continuous metric. Instead of merely counting collisions, we accumulate the penetration depth returned by the collision checker for each state along a path segment. This approach allows the planner to differentiate between the severity of different collisions and prioritize paths that are closer to being collision-free.

Furthermore, we refine the method's early-exit condition to make the recursive search more efficient. The new condition not only requires the cumulative collision depth of a path through an intermediate state to be lower than the direct path but also introduces an adaptive thresholding mechanism: if a new intermediate state reduces the number of unique pairs of objects that are in collision, then a more lenient depth-reduction threshold is applied for early termination. Conversely, if the set of colliding pairs remains unchanged, a much stricter improvement is required.

The experimental validation was conducted on a test suite of 105 start–goal pairs with three distinct tool configurations. The results confirm the efficacy of the proposed enhancements. Switching from the original count-based heuristic to the depth-based comparison reduced the total planning time from 38.3 s to 29.6 s. The introduction of the adaptive distinct-pair check further decreased the total time to 22.9 s, achieving a total speedup of approximately 1.67x over the baseline while preserving a 100% success rate on this test suite. While these results are promising, we position them as preliminary and suggest that future work should involve validation across a broader and more diverse range of complex scenarios.

***Keywords**:* redundant manipulators, motion planning, sampling-based planning, collision detection, collision depth, obstacle avoidance, heuristic search.

1. INTRODUCTION

Path planning for redundant manipulators remains a difficult problem due to the high dimensionality of their configuration spaces. The high dimensionality of the configuration space makes exhaustive searches computationally intractable, which created a need of more efficient heuristic and sampling-based methods like Probabilistic Roadmaps (PRM) [1] and Rapidly-exploring Random Trees (RRT) [2].

The Recursive Random Intermediate State (RRIS) method [3] was recently introduced as an effective approach to solve such problems by recursively simplifying the path planning task. The original RRIS method evaluates the quality of a potential intermediate state by counting the number of discrete configurations that result in a collision along the path segments. This binary (collision vs. no collision) approach does not, however, account for the severity of collisions; a path with minor, grazing collisions is treated the same as a path with significant interpenetration.

This work proposes a significant improvement to the intermediate state selection heuristic within the RRIS method. We replace the discrete collision count with a continuous metric based on the sum of collision penetration depths, provided by the physics engine. This new heuristic allows for a more nuanced comparison of potential paths, prioritizing those that are “closer” to being collision-free. Furthermore, we introduce an adaptive early exit condition that considers both the reduction in total collision depth and the qualitative simplification of the collision landscape, which leads to a notable improvement in planning time.

2. RELATED WORK

The problem of motion planning has been extensively studied for several decades. Early methods often relied on exact geometric representations of the configuration space, but their computational complexity grew exponentially with the degrees of freedom of the manipulator, making them impractical for redundant systems.

A significant breakthrough came with the development of sampling-based approaches, which avoid explicit representation of the obstacle space. Among the most influential is the Probabilistic Roadmap (PRM), which constructs a graph of collision-free configurations that can later be reused to answer multiple planning queries efficiently [1]. For single-query problems, the Rapidly-exploring Random Tree (RRT) became a standard. The RRT algorithm incrementally grows a tree of reachable states from a starting configuration, effectively covering large, high-dimensional spaces [2]. Its widely used extension, RRT-Connect, accelerates the search by simultaneously growing two trees from the start and goal configurations and attempting to connect them [4]. Despite their popularity, these foundational methods may still perform poorly in environments with narrow passages or in scenarios requiring consideration of complex kinematic constraints.

Later work sought to improve convergence and optimality guarantees. Karaman and Frazzoli introduced the RRT* algorithm, which incrementally refines trajectories to achieve asymptotic optimality [7]. Further improvements have included variants such as Bidirectional RRT*, where two trees are grown in parallel, and modified versions that exploit geometric heuristics such as the triangular inequality to accelerate convergence in cluttered environments [8]. These advancements reduce search time and improve solution quality, but at the cost of higher computational overhead.

Another direction formulates motion planning as an optimization problem. For instance, CHOMP (Covariant Hamiltonian Optimization for Motion Planning) refines an initial, possibly colliding, and trajectory by minimizing a cost function that accounts for both smoothness and obstacle avoidance [5]. Such optimization-based methods are effective for local refinement but can become trapped in local minima without a good initial guess. As a result, they are often combined with sampling-based approaches that generate initial feasible trajectories.

More recently, the RRIS method has been proposed as a sampling-based approach tailored for redundant manipulators [3]. RRIS integrates recursive decomposition with intermediate state selection, thereby splitting a complex path planning problem into smaller, more manageable subproblems. Its effectiveness is determined largely by the heuristic used for evaluating intermediate states. The original version of RRIS relied on counting the number of colliding states along discretized trajectories [3]. This work extends RRIS by introducing a more informative evaluation criterion based on the sum of collision depths, which provides a richer physical interpretation of contact severity and offers a more effective heuristic for intermediate-state selection.

Finally, practical implementations of motion planners depend heavily on efficient collision detection. Libraries such as Bullet Physics [6] provide the necessary tools for fast collision checking, including not only binary collision detection but also penetration depth estimation. Such capabilities make it possible to develop methods, like the one proposed in this paper, that leverage detailed collision information to improve the decision-making process within sampling-based planning.

In summary, the trajectory of research has evolved from early geometric approaches to sampling-based methods such as PRM [1] and RRT [2,4], through optimization-based refinements such as CHOMP [5], and toward modern optimal and hybrid planners [7,8]. The RRIS method [3] continues this trend by introducing recursive intermediate state selection. Our contribution builds directly upon it, proposing a depth-based extension that addresses the primary limitation of the original heuristic and improves its applicability to redundant robotic manipulators.

3. PROPOSED METHOD

The core of the RRIS method is to find an intermediate configuration that simplifies the original problem of connecting a start state (q_{start}) to a goal state (q_{goal}). The quality of an intermediate state (q_{inter}) is determined by assessing the two resulting path segments: $q_{start} \rightarrow q_{inter}$ and $q_{inter} \rightarrow q_{goal}$.

Collision-Depth Heuristic. Instead of counting the number of colliding states along a path segment, calculating the sum of penetration depths for all collisions detected along that segment was proposed. The cost of a segment is defined as:

$$C_{pepth} = \sum_{i=1}^{n} d_i \quad (1)$$

where n is the number of checked states along the path segment and d_i is the penetration depth of a collision at state i ($d_i > 0$ if in collision, otherwise $d_i = 0$).

Penetration depth of a collision at state i defined as a maximum penetration depth between all objects pairs that collides at this state:

$$d_i = max(d_i^j) \quad (2)$$

where d_i^j is a penetration depth between j-th objects pair.

When comparing two potential intermediate states, the one that minimizes the cost of the worse of its two segments is chosen.

Using the total penetration depth creates a smoother "cost landscape" for the planning problem. Unlike binary metrics, which create sharp "walls" around obstacles, the depth metric allows the planner to distinguish "almost successful" paths from "absolutely hopeless" ones, which directs the search in a more productive direction.

Adaptive Early Exit Condition. The original RRIS method utilized a simple early exit condition: "*if both parts of the path through the intermediate state have fewer than half collisions of the direct path*" [3]. A new proposal to modify early exit conditions to a more intelligent, adaptive strategy. First, a baseline early exit is considered: the recursion for a given path segment stops if the total collision depth of the path via an intermediate state is less than 50% of the direct path's collision depth.

An additional improvement is introduced by analyzing the set of unique pairs of objects that are in collision along the entire path.

Case 1: Collision Simplification. If the number of unique colliding pairs for the path through □□□□□□ is less than for the direct path, it implies a qualitative simplification of the problem. In this case, a more tolerant early exit condition is applied: the total collision depth must be reduced by at least 20%.

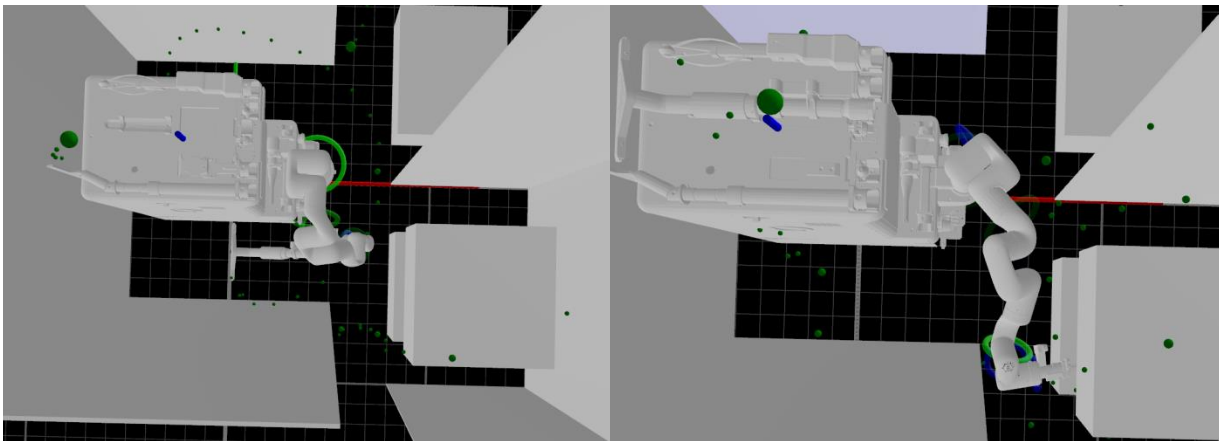
Case 2: No Collision Simplification. If the number of unique colliding pairs does not decrease, a more significant improvement is required to justify the early exit. The total collision depth must be reduced by at least 65%.

These threshold values were determined experimentally to balance solution quality and computation time.

A reduction in the number of unique pairs in collision means that the intermediate state has successfully solved one of the planning sub-problems (e.g., bypassed a specific obstacle). This allows the recursive algorithm to focus on fewer remaining conflicts and justifies the use of a less stringent threshold for early exit.

4. EXPERIMENTAL RESULTS

To validate the proposed enhancements, we conducted experiments using the same test environment and dataset of 105 path planning queries as in the original RRIS study [3]. The environment consists of a 7-DOF redundant manipulator in a cluttered space. The robot with a robotic arm and instruments installed on the arm wrist, together with the test environment can be seen in Fig. a, b.



a *b*

Fig. **The experimental environment with the redundant manipulator and obstacles**

We compared the time required to solve all 105 queries for three different configurations of the RRIS method:

1. **RRIS-Count (Baseline):** The original method using a collision count as an heuristic to compare intermediate states.
2. **RRIS-Depth**: The method using the collision depth heuristic with the simple 50% early exit rule.
3. **RRIS-AdaptiveDepth:** The full proposed method with the collision depth heuristic and the adaptive early exit condition.

All three methods successfully found a valid path for every query in the test set. The computation times are summarized in Table 1.

Table 1. **Total planning time for 105 paths**

Method	Total Time (s)	Speedup vs. Baseline
RRIS-Count (Baseline)	38.3	1.00x
RRIS-Depth	29.6	1.29x
RRIS-AdaptiveDepth	22.9	1.67x

The results clearly indicate that using collision depth as a heuristic (RRIS-Depth) provides a notable performance improvement of nearly 30%. The introduction of the adaptive early exit condition (RRIS-AdaptiveDepth) yields a further significant reduction in planning time, resulting in an overall speedup of approximately 1.67x compared to the original method.

The average planning time per path decreased from 0.36 seconds with the original intermediate state comparison to 0.28 seconds using the collision-depth-based comparison, and dropped further to 0.22 seconds after introducing the adaptive-depth early-exit strategy.

CONCLUSION

This paper addressed a key limitation in the Recursive Random Intermediate State (RRIS) path planning method: its reliance on a binary collision-counting heuristic. We introduced an enhanced heuristic based on collision penetration depth, a continuous metric that provides a more physically intuitive measure of a path's quality. By considering the severity of collisions rather than just their occurrence, the planner can make more informed decisions, distinguishing between paths with minor, easily resolvable contacts and those with severe interpenetrations. This creates a smoother and more realistic cost landscape, guiding the search toward more promising regions of the configuration space.

Building upon this new metric, we proposed an adaptive early exit strategy that further accelerates the search. This strategy dynamically adjusts its termination criteria based on the qualitative complexity of the encountered collisions—specifically, whether the set of unique colliding object pairs has been reduced. This synergy between a more descriptive heuristic and a smarter termination logic allows the planner to prune unpromising search branches more effectively.

The experimental results are promising, demonstrating a significant performance gain on the tested dataset without sacrificing the success rate. However, we acknowledge that the scope of this validation is preliminary. To fully establish the robustness of the proposed method, further testing is required across a broader range of challenges. This includes scenarios with highly constrained narrow passages, different manipulator configurations with higher degrees of freedom, and potentially dynamic environments with moving obstacles.

Future work will focus on several promising directions. The primary goal is to explore the application of this depth-based heuristic to other classes of motion planners. For sampling-based algorithms, it could serve as a cost function in asymptotically optimal planners like RRT* to find paths that are not only short but also safer by maximizing clearance from obstacles. Finally, the experimentally-determined thresholds for the adaptive exit strategy could be a subject for further research, perhaps using machine learning techniques to tune them automatically based on environmental complexity.

USE OF ARTIFICIAL INTELLIGENCE

Generative AI tools (Gemini 2.5 Pro, ChatGPT 5) have been used for grammar checks and text polishing. The authors reviewed and edited all AI-generated content and took the responsibility for the final content of this publication.

ACKNOWLEDGMENTS

The authors would like to express their deep gratitude to Somatic Holdings LTD, whose codebase greatly facilitated the development of the algorithm presented in this paper.

REFERENCES

1. Kavraki L. E., Svestka P., Latombe J.-C., Overmars M. H. “Probabilistic Roadmaps for Path Planning in High-Dimensional Configuration Spaces”. *IEEE Transactions on Robotics and Automation.* 1996; 12 (4): 566–580. DOI: https://doi.org/10.1109/70.508439.

2. LaValle S. M. “Rapidly-Exploring Random Trees: A New Tool for Path Planning, The Annual Research Report”. 1998.

3. Medvid A., Yakovyna V. “Redundant Robotic Arm Path Planning Using Recursive Random Intermediate State Algorithm”. *Radio Electronics, Computer Science, Control*. 2025; 3: 173–181. DOI: https://doi.org/10.15588/1607-3274-2025-3-16.

4. Kuffner J. J., LaValle S. M. “RRT-Connect: An Efficient Approach to Single-Query Path Planning, Proceedings 2000 ICRA”. *Millennium Conference. IEEE International Confer-ence on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065).* San Francisco, CA, USA 2000; 2: 995–1001, DOI: https://doi.org/10.1109/ROBOT.2000.844730.

5. Zucker M., Ratliff N., Dragan A., Pivtoraiko M., Klingensmith M., Dellin C., Bagnell J. A., Srinivasa, S. S. “CHOMP: Covariant Hamiltonian Optimization for Motion Planning”. *The International Journal of Robotics Research.* 2013; 32 (9–10): 1164–1193. DOI: https://doi.org/10.1177/0278364913488805.

6. “Bullet Collision Detection & Physics Library” – URL: https://pybullet.org/Bullet/BulletFull/index.html (date of access: September 27, 2025).

7. Karaman S., Frazzoli E. “Sampling-Based Algorithms for Optimal Motion Planning, International Symposium on Robotics Research”. 2011; 71: 65–70. DOI: https://doi.org/10.1177/0278364911406761

8. Xin P., Wang X., Liu X., Wang Y., Zhai Z., Ma X. “Improved Bidirectional RRT* Algorithm for Robot Path Plan-ning”. *Sensors*. 2023; 23 (2): 1041. DOI: https://doi.org/10.3390/s23021041.

DOI: https://doi.org/10.15276/ict.02.2025.28
УДК 004.94

Удосконалення методу RRIS за допомогою евристики на основі глибини колізій

Медвідь Андрій Ярославович[1)]
Аспірант каф. Систем штучного Інтелекту
ORCID: https://orcid.org/0009-0001-4128-4973; andrii.y.medvid@lpnu.ua
Яковина Віталій Степанович[1)]
Д-р техніч. наук, професор каф. Систем штучного Інтелекту
ORCID: https://orcid.org/0000-0003-0133-8591; vitaliy.s.yakovyna@lpnu.ua
[1)] Національний університет “Львівська політехніка”, Львів, Україна

АНОТАЦІЇ

Планування безколізійного шляху для роботів-маніпуляторів з надлишковими ступенями свободи є значним викликом у робототехніці, переважно через високу розмірність простору станів та складність реальних середовищ. Хоча базові планувальники, що ґрунтуються на семплюванні, довели свою ефективність, вони часто мають труднощі у сценаріях з вузькими проходами або складними обмеженнями. Метод рекурсивного випадкового проміжного стану (RRIS) був нещодавно представлений як перспективна альтернатива, що використовує стратегію "розділяй і володарюй", рекурсивно вставляючи проміжні стани для спрощення складної задачі планування до серії простіших підзадач.

Однак оригінальна реалізація RRIS покладається на просту евристику для оцінки проміжних станів: вона підраховує кількість дискретних конфігурацій, що перебувають у стані колізії. Цій бінарній метриці бракує нюансів, оскільки вона розглядає шлях з незначним, дотичним контактом ідентично до шляху із серйозним взаємопроникненням.

У цій роботі ми пропонуємо вдосконалення методу RRIS, замінюючи цей бінарний підрахунок на більш фізично інтуїтивну, неперервну метрику. Замість простого підрахунку колізій, ми накопичуємо глибину проникнення, яку повертає система перевірки колізій для кожного стану вздовж сегмента шляху. Цей підхід дозволяє планувальнику розрізняти серйозність різних колізій та надавати пріоритет шляхам, які є ближчими до безколізійних.

Крім того, ми вдосконалюємо умову раннього виходу методу, щоб зробити рекурсивний пошук ефективнішим. Нова умова не тільки вимагає, щоб сукупна глибина колізій шляху через проміжний стан була меншою, ніж у прямого шляху, але й впроваджує адаптивний механізм визначення порогів: якщо новий проміжний стан зменшує кількість унікальних пар об'єктів, що перебувають у колізії, для раннього виходу застосовується менш суворий поріг зменшення глибини. І навпаки, якщо набір пар, що стикаються, залишається незмінним, вимагається значно суворіше покращення.

Експериментальна перевірка проводилася на тестовому наборі зі 105 пар "старт-ціль" з трьома різними конфігураціями інструмента. Результати підтверджують ефективність запропонованих удосконалень. Перехід від оригінальної евристики, заснованої на підрахунку, до порівняння на основі глибини зменшив загальний час планування з 38.3 с до 29.6 с. Впровадження адаптивної перевірки унікальних пар колізій додатково зменшило зашальний час до 22.9 с, досягнувши загального прискорення приблизно в 1.67x порівняно з базовим методом, зберігаючи при цьому 100% успішність на цьому тестовому наборі. Хоча ці результати є багатообіцяючими, ми розглядаємо їх як попередні та вважаємо, що майбутня робота повинна включати перевірку на ширшому та різноманітнішому спектрі складних сценаріїв.

Ключові слова: маніпулятори з надлишковими ступенями свободи; планування руху; планування на основі семплювання; виявлення колізій; глибина колізій; уникнення перешкод; евристичний пошук