Safe Route Planning For Manipulator Robot Using Seam Carving Technique

Anderson Lima de Oliveira[1*], Geraldo Luis Bezerra Ramalho[1]
[1]Federal Institute of Education, Science and Technology of Ceará, IFCE; Fortaleza, Ceará, Brazil

Route planning is a critical challenge in ensuring the safe operation of collaborative robotics. Seam Carving, a digital image processing (DIP) technique initially developed for content-aware image resizing, identifies paths of lowest energy within an image. In the context of collaborative robotics, regions with fewer obstacles correspond to lower-energy areas, making this technique a promising tool for determining safe routes. This work explores the application of Seam Carving to generate safe trajectories for robotic manipulators, enabling their operation in diverse environments. Both quantitative and qualitative results demonstrate the effectiveness of this approach, establishing it as an innovative method in the field of collaborative robotics.
Keywords: Seam Carving, Safe Routes, Robotic Manipulator, Collaborative Robotics.

Collaborative robots [1] share workspaces with both machines and humans, performing complex, precise, and dynamic tasks [2]. One of the primary challenges in this context is designing collision-free routes for these robots [3]. Optimizing such routes is crucial, enhancing workplace safety while improving production efficiency. This work presents an alternative approach to addressing this challenge.

Several global methods have been employed for route planning, including tree-based algorithms such as Rapidly-exploring Random Trees (RRT) [4,5], Probabilistic Roadmaps (PRM) [6], Topological Path Planning (TPP) [7], and Generalized Voronoi Diagrams (GVD) [8], a particular case of TPP. However, these approaches often present limitations related to computational efficiency, unnecessary detours, or non-optimal, randomly generated paths.

Generating, evaluating, and validating routes requires real-time image acquisition in dynamic environments. Consequently, leveraging Digital Image Processing (DIP) techniques is viable. This work proposes applying Seam Carving, a technique originally designed for image resizing, to route planning for robotic manipulators.

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Address for correspondence: Eugênio Rocha da Silva Júnior. Av. Treze de Maio, 2081 - Benfica. Zipcode: 60040-531. Fortaleza - Ceará, Brazil. E-mail: anderson.lima.oliveira05@aluno.ifce.edu.br.

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Theoretical Foundation

Methods for Route Planning

Various methods have been developed to address the path-finding problem in robotics. One such method is Probabilistic Roadmaps (PRM), proposed by Kavraki and colleagues [9]. PRM generates random samples (or nodes) within the environment and then connects them to form a graph, representing the relationships between the nodes. Search algorithms like A* or Dijkstra are typically applied to find the shortest path. Due to its probabilistic nature, PRM can generate multiple potential routes for a given environment, offering flexibility in route planning.

Another widely used approach is the Generalized Voronoi Diagram (GVD), introduced by Takahashi and Schilling [8]. This technique processes an environment's free space by creating a simplified representation emphasizing its key structural features. By doing so, it becomes possible to generate collision-free trajectories for the robot. However, the skeletonization process involved in GVD can be computationally expensive, particularly in large-scale or complex environments.

The method proposed by Lavalle [10], called Rapidly-exploring Random Trees (RRT), is based on creating an exploration tree that rapidly and randomly expands from the initial point. However, the solution generated by RRT can be influenced by the distribution of random nodes and the strategy used to grow the tree. As a random approach, RRT often produces different routes for the same scenario, which can hinder its application in tasks that require repeatability and consistency, especially when ensuring safety is a priority.

A more recent and efficient approach for route planning is the Topological Path Planning (TPP) method, proposed by Batista and colleagues [7]. TPP identifies topologically constrained connected points within the environment's free space, enabling homotopic and non-homotopic topological paths [11]. To determine the best possible route, a shortest path algorithm is applied to find the optimal connected points, which results in smoother trajectories and minimizes unnecessary detours.

Seam Carving

The Seam Carving method presented by Avidan and Shamir [12] is a technique that brought a significant change in image processing, providing an innovative approach to image resizing that goes beyond conventional techniques. Its primary objective is to adjust image dimensions, preserving visually important areas of interest while reducing or expanding the image size. The energy map represents the importance of each pixel in the image. Techniques such as gradients are used to create this map, which calculates changes in intensity between nearby pixels. Areas with high pixel intensity variations or containing multiple objects have higher energy values, indicating that they are visually important and, therefore, unsuitable for removal.

Equation (1) shows the concept of the energy function described by e, where I is the image:

$$e(I) = \left|\frac{\partial I}{\partial x}\right| + \left|\frac{\partial I}{\partial y}\right| \quad (1)$$

The image I present in Equation (1) is a matrix n x m, where n represents the number of rows and m is the number of columns.

The ideal seam can be obtained using dynamic programming. Calculating the minimum energy M for all the seams connected to each input (i,j), as demonstrated in Equation (2), returns the chosen ideal seam.

$$M(i,j) = e(i,j) + \min(M(i-1,j-1), M(i-1,j), M(i-1,j+1)) \quad (2)$$

Materials and Methods

Scenarios

Table 1 presents the parameters used in creating the scenarios used for testing. For comparison and conclusion, all methods use the exact specifications of the scenarios.

Metrics

Quantitative evaluation is an essential step in comparing and validating these approaches. The

Table 1. Scenario parameters.

Parameter	Definition
Scenario	100 random scenarios with the presence of obstacles in varying shapes, positions and quantities.
q_{start}	Defined in x = 15 cm, y = 15 cm.
q_{goal}	andom position, defined within the manipulator's working space and away from obstacles.
RGrid	The workspace and obstacles are presented in a grid of 60cm x 60 cm, divided into 1cm x 1cm for the methods.
Safety Margin	A safety margin of 4cm is used for the diameter of the manipulator in relation to the proximity of obstacles.

proposed metrics play a key role in the outcome, providing objective measurements to compare different methods and techniques. They are derived from the joints' manipulator angular displacement (θ). The following metrics were used in this work: path distance (in centimeters), number of points, standard deviation of joint acceleration (θ), maximum jerk (θ), and processing time (in seconds).

Proposed Method

The approach used in this research acts on the lowest energy present, whether horizontal or vertical. Some mathematical transformations are used to align the points. First, the distance between the points must be verified to define the direction of the rotation performed, as seen in Equation 3.

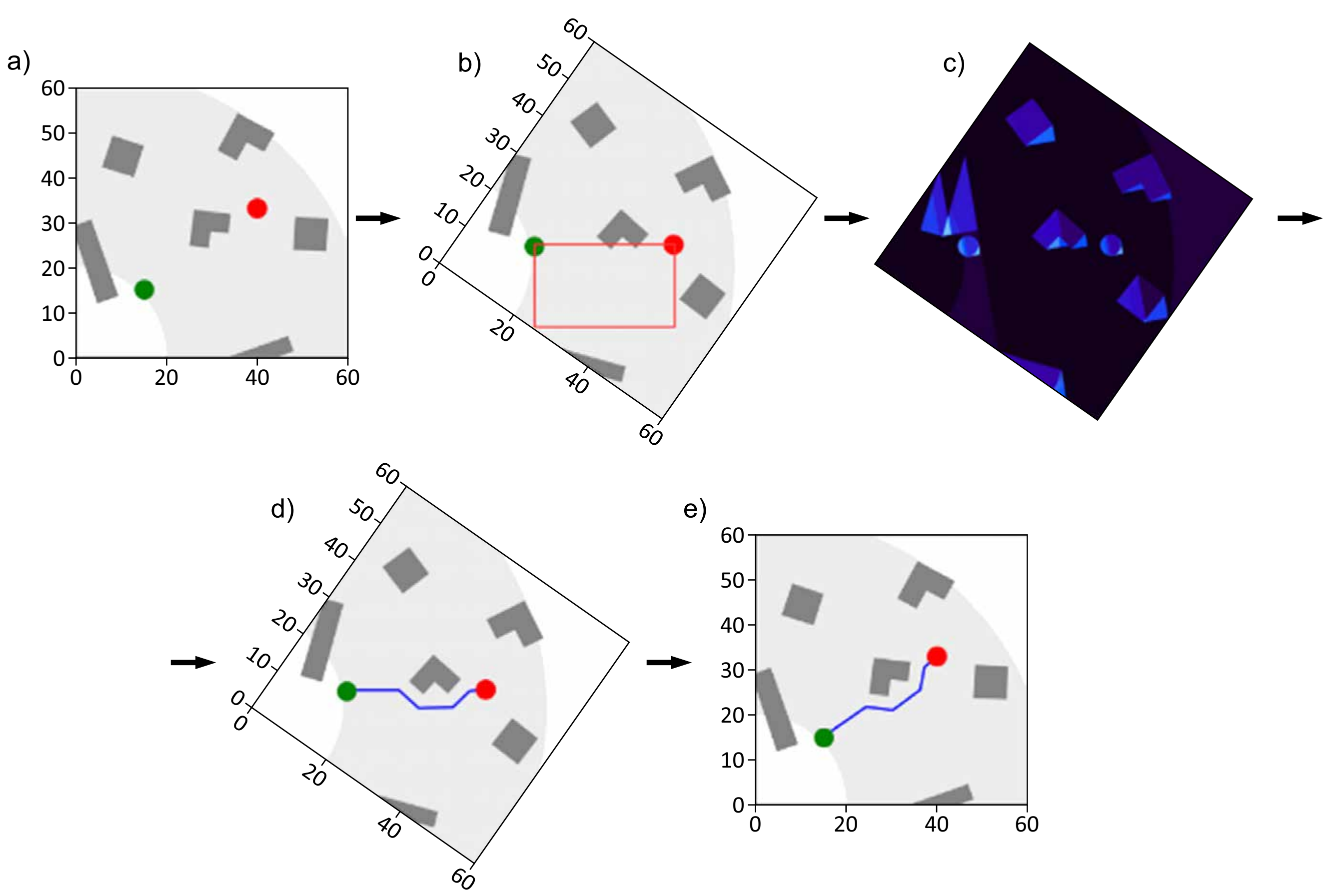
$$D_{AB} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (3)$$

After this step, the direction of the rotation performed can be determined. The next step is to calculate the necessary rotation angle to align the points. Equation 4 shows the calculation used to define the rotation angle.

$$a^2 = b^2 + c^2 - 2.x.y.\cos\alpha \quad (4)$$

With the points aligned, the use of the technique becomes simpler. A region of interest is used to apply Seam Carving, as seen in Figure 1b. By calculating the energy map shown in Figure 1c, it is possible to identify the areas with lower energy in the image.

Figure 1. Proposed method. a. Input image with the starting point (green), end point (red), and obstacles (dark gray). b. Space transformation and selecting the region of interest for use with Seam Carving. c. Energy map of the scenario. d. Route drawn on the rotated image. e. Image in the original space with the path drawn.



Using Equation 2, we return to the positions used to trace the route (seam), as shown in Figure 1d. Finally, Figure 1e uses an inverse mathematical transformation to return the workspace and the traced route to the original position.

Results and Discussion

This section presents the results of the proposed method and compares them with those of other methods in the literature. In Table 2, we compare the classical methods in the literature, such as PRM, TPP*, TPP, and RRT, using quantitative metrics to evaluate and compare them to the proposed method (PM) in this work.

Table 2 shows that based on the Seam Carving technique, the proposed method stood out in reducing the distance traveled compared to the classical methods mentioned. This result suggests that the route returned by the proposed method, on average, provides shorter trajectories, minimizing the robot's travel time. Another important analysis is the number of points needed to trace the path. It is worth noting that a more significant number of points allows for smoothing out the movements, influencing the acceleration and jerk values, as the movements made are more precise. When analyzing metrics related to movement dynamics, such as acceleration and jerk, the values demonstrated by the proposed method were low compared to classic methods, such as PRM and RRT.

With values in this range, the traced path presents smooth movements with slight variations in acceleration and jerk.

Furthermore, when considering the execution time to create the best route, it was observed that the proposed method presented values comparable to classical methods, such as PRM and TPP*, while outperforming techniques such as TPP. This implies that the proposed method approach offers a balanced solution between fast route feedback and computational accuracy, making it a viable option for practical applications in collaborative robotics.Figure 2a presents a case where there are no obstacles between the starting and ending points of the route. In this scenario, the proposed method traces a more direct route without unnecessary detours, indicating that the proposed method minimizes the distance traveled. Compared to other methods, these tend to trace longer paths and unnecessary detours. A more in-depth analysis of these results reveals the effectiveness of the proposed method in simple scenarios where there is no need to bypass obstacles.

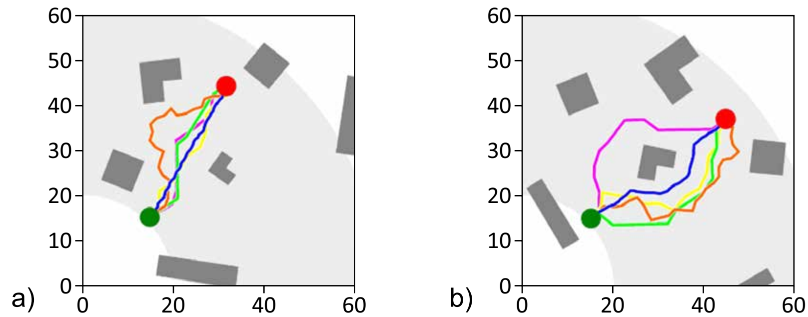
In Figure 2b), the proposed method demonstrates its effectiveness in tracing a route close to the obstacle, generating a minimum deviation and consistent results in the search for efficient trajectories. On the other hand, the RRT method presents trajectories with unnecessary deviations, consequently generating longer paths.

When observing PRM and TPP's behavior, we see trajectories with some deviations, such as the one presented by RRT. Finally, the TPP* method presents an alternative behavior by returning a longer and less smooth path. This behavior results in less optimized trajectories in terms of distance and smoothness.

Table 2. Comparative metrics between methods.

Method	Distance (cm)	Points	Std_Acc	Max Jerk	Time (s)
PRM	42.83 ± 6.71	13.71 ± 2.12	3.28 ± 0.61	10.94 ± 2.84	2.31 ± 0.75
TPP*	45.42 ± 6.83	14.45 ± 1.88	2.91 ± 0.57	9.01 ± 4.06	2.68 ± 0.50
TPP	43.02 ± 6.07	13.47 ± 1.79	2.62 ± 0.56	7.97 ± 3.21	5.28 ± 1.87
RRT	48.78 ± 6.42	25.30 ± 3.28	2.35 ± 0.31	10.04 ± 1.98	0.81 ± 0.48
PM	35.83 ± 2.80	39.8 ± 4.06	0.62 ± 0.11	3.09 ± 0.41	2.03 ± 1.01

Figure 2. The PRM method is in yellow, TPP* in magenta, TPP in green, RRT in orange, and the proposed method in Blue.



Conclusion

The proposed method, with a resolution of 1cm x 1cm, presents an alternative approach to safe route planning in collaborative robotics. Observing the data from the different methods presented in Table 2 and qualitatively analyzing the routes traced by all methods, we can conclude that the proposed method based on the Seam Carving technique proved to be an alternative approach for tracing routes for collaborative robotics, returning smoother paths with more minor deviations towards the goal. Finally, the approach proposed in this work does not require parameter adjustments for different scenarios, does not require the use of shortest-path search algorithms, and guarantees path repeatability for the same scenario. Since it acts on the lowest energy, it will always return the same path, demonstrating an advantage in guaranteeing the path's reliability, which random approach methods cannot guarantee. This method shows great promise for modifying a technique created for image processing and applying it to collaborative robotics.

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