Safe Route Planning For Manipulator Robot Using Seam Carving Technique

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Abstract. *Route planning is a frequently addressed problem that aims to ensure safe operation in collaborative robotics. Seam Carving is a digital image processing (DIP) technique used in content-aware image resizing tasks, based on the identification of the lowest energy present. In the context of collaborative robotics, areas that present a lower incidence of obstacles indicate areas of lower energy. This work presents the use of this technique to obtain safe routes for the robotic manipulator, allowing its operation in different scenarios. The quantitative and qualitative results demonstrate that this approach presents itself as a new approach in the area of collaborative robotics.*

1. Introduction

Collaborative robots [Li Liu and Duffy 2024] share the workspace with other machines and humans, performing complex, precise and dynamic tasks [Weiss et al. 2021]. In this context, one of the main challenges is to design collision-free routes for collaborative robots [Gasparetto et al. 2012]. Ensuring the optimization of these routes is of utmost importance, as it promotes safety in the work environment and increases production efficiency. The following work aims to present an alternative approach to this issue.

Several global methods are used for route planning, such as in the works proposed by [Wu et al. 2022, Long et al. 2023], using tree-based route planning algorithms (RRT), probabilistic paths proposed by [Liu et al. 2009] (PRM), based on topological paths by [Batista et al. 2023] (TPP) and the one proposed by [Takahashi and Schilling 1989] (GVD), a particular case of TPP. These different approaches still have limitations, such as computational efficiency, routes traced with the presence of unnecessary detours or random routes.

Due to the fact that, in dynamic environments, it will be necessary to acquire images to create routes, evaluate them and validate them, the use of Digital Image Processing (DIP) techniques becomes a convenient approach. Therefore, this work proposes the use of the properties of Seam Carving, a technique originally created for image resizing, in the task of route planning for manipulator robots.

2. Theoretical Foundation

2.1. Methods for Route Planning

Several methods have been developed to solve the path-finding problem. Proposed by [Kavraki et al. 1996], probabilistic routing (PRM) generates random samples (nodes) and then connects them. After that, a graph is created representing these relationships between nodes. To determine the shortest route for the robot, search algorithms such as A* or Dijkstra are used. Furthermore, due to its probabilistic nature, different routes can be generated for a given environment. The GVD method, presented by [Takahashi and Schilling 1989], is a widely used technique in the area of route planning. This technique processes the free space of the environment using a simplified representation that highlights its fundamental structural features. Thus, it is possible to create collision-free trajectories for the robot. However, the skeletonization procedure can be computationally expensive, especially in large-scale environments.

The method proposed by [Lavalle 1998], called RRT, has as its fundamental concept behind this approach the creation of an exploration tree that grows rapidly and randomly from the initial point. However, the solution found may depend on the distribution of random nodes generated and the strategy used to expand the tree. Furthermore, RRT is a random approach, so the routes generated are often different for the same scenario, thus making it difficult to apply in tasks that require repeatability to ensure greater security.

A more recent approach that has proven to be quite efficient for the problem is the so called TPP, a method proposed by [Batista et al. 2023]. This method determines topologically constrained connected points in the free space of the workspace, providing both homotopic and non-homotopic topological paths [S. Bhattacharya and Kumar 2012]. Finally, a shortest path algorithm is used to find the connected points that represent the best possible topological path within all possible routes. The chosen path presents smoother routes and minimizes unnecessary detours.

2.2. Seam Carving

The Seam Carving method presented by [Avidan and Shamir 2007] 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 make adjustments to image dimensions, preserving visually important areas of interest while reducing or expanding the image size. The energy map is a representation of the importance of each pixel in the image. To create this map, techniques such as the use of gradients are used, which calculate 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 not suitable for removal.

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

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

The image I present in Equation 1 can be described as a matrix $n \times m$, where n represents the number of rows and m the number of columns.

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

$$M(i,j) = e(i,j) + min(M(i-1, j-1), \\ M(i-1, j), M(i-1, j+1)) \tag{2}$$

3. Methodology

3.1. Scenarios

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

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}	Random position, defined within the manipulator's working space and away from obstacles.
Grid	The workspace and obstacles are presented in a grid of $60\,cm \times 60\,cm$, divided into $1\,cm \times 1\,cm$ for the methods.
Safety Margin	A safety margin of $4\,cm$ is used for the diameter of the manipulator in relation to the proximity of obstacles.

3.2. Metrics

Quantitative evaluation is an essential step to compare and validate these approaches. The proposed metrics play a key role in the outcome, providing objective measurements to compare different methods and techniques. They are derived from the manipulator angular displacement (θ) of the joints. The following metrics were used in this work: path distance (in centimeters), number of points, standard deviation of joint acceleration ($\ddot{\theta}$), maximum jerk (θ), and processing time (in seconds).

3.3. Proposed Method

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

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

After this step, it is possible to know the direction of the rotation performed, the next step is to calculate the necessary angle of rotation so that the points are aligned. The equation 4 shows the calculation used to define the rotation angle.

$$a^2 = b^2 + c^2 - 2.x.y. \cos\alpha \tag{4}$$

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

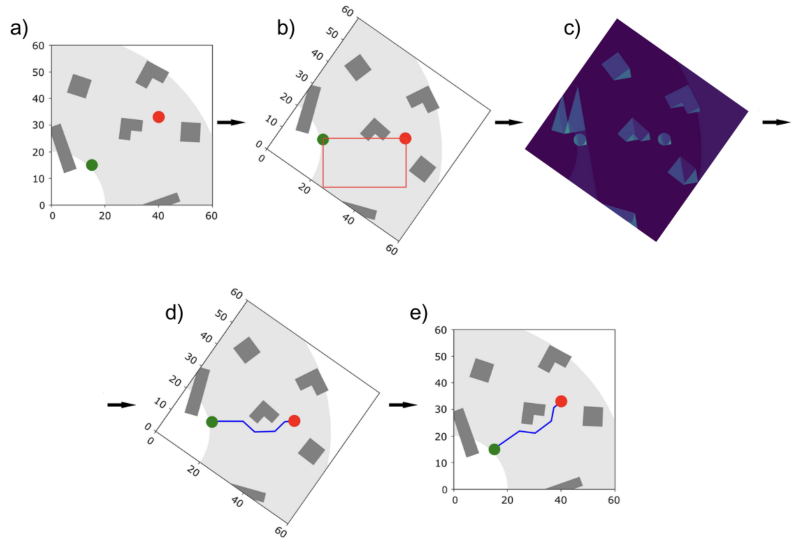

Figure 1. The proposed method. a) Input image with the starting point (green), end point (red) and obstacles (dark gray). b) Space transformation and selection of the region of interest for use with Seam Carving. c) Energy map of the scenario. d) Route drawn on the rotated image. e)Image in the original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

map shown in Figure 1c), it is possible to identify the areas with lower energy in the image. 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.

4. Results and Discussion

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

Table 2. Comparative metrics between methods for plotting routes.

Method	Distance	Points	Std Acc ($\ddot{\theta}$)	Max. Jerk (θ)	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

As seen in Table 2, it is worth mentioning that the proposed method, based on the Seam Carving technique, 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 greater number of points allows for smoothing out the movements made, 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 when compared to classic methods such as PRM and RRT. With values in this range, the traced path presents smooth movements with little variation 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. When 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.

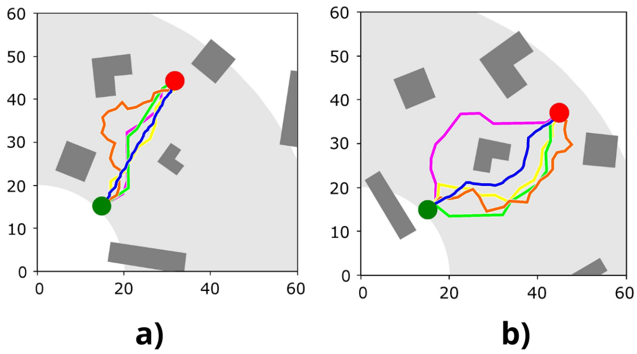

Figure 2. The PRM method is in yellow, TPP* in magenta, TPP in green, RRT in orange and the proposed method in Blue.

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 and, consequently, generating longer paths. When observing the behavior of PRM and TPP, they present 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.

5. Conclusion

The use of the proposed method with a resolution of 1×1 cm presents an alternative approach for the area of 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 smaller deviations towards the goal.

Finally, the approach proposed in this work does not require parameter adjustments for different scenarios and does not require the use of shortest path search algorithms and guarantees path repeatability for the same scenario, since by acting on the lowest energy, it will always return the same path, demonstrating an advantage in guaranteeing the reliability of the path, which cannot be guaranteed by random approach methods. The use of this method shows great promise for modifying the use of a technique originally created for image processing and using it for the area of collaborative robotics.

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