Optimal Trajectory Planning Based On Bidirectional Spline-RRT* For Wheeled Mobile Robot

Priyanka Sudhakara, Velappa Ganapathy and Karthika Sundaran
School of Computing, SRM University,
Kancheepuram-603203, Tamil Nadu, India
{priyanka.k@ktr.srmuniv.ac.in, ganapathy.v@ktr.srmuniv.ac.in, karthika.su@ktr.srmuniv.ac.in}

***Abstract*— This paper proposes a trajectory planning of a mobile robot using bidirectional-Rapidly-exploring Random Tree star [RRT star] algorithm with spline technique. In the proposed method, the basic bidirectional-RRT star algorithm is combined with the spline technique to generate smooth trajectories, which are important for curved path navigation of a wheeled mobile robot. The bidirectional-RRT star tree structure is extended by using a spline method based on a cubic Ferguson's curve. Trajectories that are been generated using the proposed bidirectional spline-RRT star algorithm satisfies direction constraints approach on both source and target positions. This makes the proposed algorithm remarkably unlike from other trajectory planning algorithms. As a result, the paths produced by the mobile robots are sub-optimal, dynamically and geometrically feasible, and satisfy direction constraints approaches. Simulation results that are performed affirm these bidirectional spline-RRT star algorithm properties and show the validity of the proposed algorithm, implying that it can be efficiently applied to trajectory planning of wheeled mobile robot operating in real-time environments.**

Keywords*— *Bidirectional-RRT*; Spline Curve; Trajectory Planning; Mobile Robots; Obstacle Avoidance

I. Introduction

Trajectory planning of a mobile robot is a vital issue in robotics to attain autonomy. Presently, in the area of robotics, significant amount of works has been spent on trajectory planning algorithms and have been proposed [1]. Diverse varieties of algorithms have been proposed for producing a feasible trajectory. Especially, sampling based trajectory planning algorithms like Rapidly Exploring Random Trees (RRT) and Probabilistic Roadmaps (PRM) [2] attain considerable demand in motion planning communities. They deal and overcome the computational problems of deterministic motion planning approaches by circumventing the representation of obstacles that are explicit in the scenario. Numerous variants of RRTs have been generated for utilization of these techniques to various conditions. For example, a randomized planner that can handle kino-dynamic constraints was proposed in [3]. Though RRT approaches are successfully applied in diverse fields [4], [5], [6], unfortunately the solutions are essentially distinct from optimal solutions and can occasionally produce an unusual path. To avoid this situation, spline-based smoothening methods have been applied to RRT-based trajectory planning algorithms [7], for generating substantially better trajectories. The utilization of smoothening techniques to RRT-based trajectory planning algorithms has given global utilities with mobile robotics, fixed-wing UAVs, robotics arm, etc. For example, the experimental results produced in an RRT-based trajectory planning algorithm, proposed in [8], are dynamically and geometrically feasible for a fixed-wing aircrafts.

In this paper, a bi-directional spline-based-RRT* algorithm which utilizes cubic ferguson's spline technique is proposed. Unlike other trajectory planning techniques, the proposed algorithm can produce an optimal and smoothened trajectory that could be utilized in mobile robotics and it is asymptotically optimal. Section 2 describes the optimal bidirectional spline-based RRT* trajectory planning followed by Section 3 describing simulation results and conclusions are thereafter.

II. Optimal Bidirectional Spline-RRT* for Trajectory Planning

A. Bi-directional spline-RRT:*

The Spline-based RRT which adopts cubic Bezier splines technique as trajectory planning is suggested in [9]. Though the time interval and accurate actions made by traditional RRT algorithms are needed to construct the path, the problems related with discretization of these two can be circumvent through Spline-based RRT method. This can be attained by utilizing the cubic splines as a local trajectory planner which resolves the two-end boundary value problem. This assures the flow of the trajectory arc by permitting only links between end-points that satisfy upper-bounded curvature constraints.

We propose a bidirectional spline-RRT* algorithm which utilizes cubic Ferguson's spline method for mobile robot trajectory planning. The proposed algorithm is based on the classic RRT* algorithm and can efficiently solve complicated trajectory planning issues in greatly constrained scenarios. The classic RRT* algorithm cannot generate smoothened trajectories. Hence, to generate such trajectories, combination of the cubic spline technique based on cubic Ferguson's curve with the bi-directional RRT* algorithm, which eases the production of smoothened curved trajectories for wheeled mobile robots. In this combinational algorithm, the boundaries

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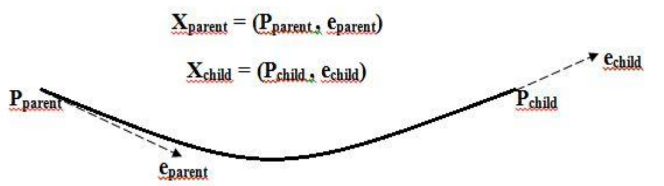

Fig. 1. Edge and node illustration in bidirectional spline-RRT star

of the tree structure that are created by bi-directional RRT* can be linked to make a smoothened ultimate trajectories that have direction flow. The direction, position and the robots' path angle of the goal signifies the nodes of the tree structure.

In Fig. 1, parent node x_{parent} has vector position p_{parent} and unit vector direction e_{parent}, as does child node x_{child}. Two tree structures are extended in the proposed algorithm, one from the starting point and another one from the target point. This approach functions much faster than single tree-based algorithms, was first introduced as RRT-connect by Kuffner, and trajectories produced utilizing this method can satisfy source and target configurations as the two tree structures extends from both source and target positions[10]. The bidirectional spline RRT* methods simulations are work done by [11]. The bidirectional method that extends two tree structures in the proposed method, uses the spline technique, so that the linking processes is quite different from the classic RRT-connect algorithm between the two tree structures.

B. Cubic Ferguson's Spline Technique:

Splines are a good choice for robot's trajectory movements for its ease of implementation and high degree of smoothness. Considering the start position P0 and the target position P1 of the spline and their corresponding tangent vector P`0 and P`1, we can seek Ferguson spline using the following equation in [27]:

$$X(a) = P_0 f_1(a) + P_1 f_2(a) + P_0' f_3(a) + P_1' f_4(a) \quad (7)$$

Where corresponding f1, f2, f3, f4 are Ferguson-multinomials and a ε [0, 1] is parameter which are described by

$$f_1(a) = 2a^3 - 3a + 1 \quad (8)$$
$$f_2(a) = 2a^3 - 3a^2 \quad (9)$$
$$f_3(a) = a(a-1)^2 \quad (10)$$
$$f_4(a) = a^2(a-1) \quad (11)$$

Equations (7) through (11) simply the source position P0 and target position P1 can be acquired by X(0) and X(l). Values of the positions P`0 and P`1 are acquired by derivative substitution.

$$f_1'(a) = 6a^2 - 6a \quad (12)$$
$$f_2'(a) = -6a^2 + 6a \quad (13)$$
$$f_3'(a) = 3a^2 - 4a + 1 \quad (14)$$
$$f_4'(a) = 3a^2 - 2a \quad (15)$$

By using the equations (1) and (12 - 15), we can deduce $P_0' = X'(0)$ and $P_1' = X'(1)$.

3.3.1 Fitness Function and Food Coding: To clarify the issues of trajectory planning, mathematical notations of Ferguson spline are showed in 2d space as follows:

$$r(a) = \big(x(a), y(a)\big) = b_0 + b_1 a + b_2 a^2 + b_3 a^3 \quad (16)$$

Where

$$\begin{cases} b_0 = 2P_0 - 2P_1 + P_0' + P_1' \\ b_1 = -3P_0 + 3P_1 - P_0' + P_1' \\ b_2 = P_0' \\ b_3 = P_0 \end{cases} \quad (17)$$

Each spline is defined only by points P0 and P1 and vectors P_0' and P_1'. In equation (16), the string that contain two neighboring splines share the corresponding vector and one of the terminal points. The whole trajectory that is defined by total number of variables in 2D space is 4(n+ 1), where *n* is the number of splines in the string.

A prime part of a bio-inspired computing technique is to find a better fitness function for evaluation. The functions global minimum could be compatible to smooth paths that are short and safe. Long distance tracing of the path and the paths that causes obstacle collisions are penalized using two function parts in [27]. The fitness function is followed as:

$$f = f_1 + \alpha f_2 \quad (18)$$

Where α is a weight factor that adjusts the proportion of the length. f_1 is defined by following equation:

$$f_1 = \frac{L}{L_{min}} \quad (19)$$

Where

L is the path length and

L_{min} is Euclidian distance between source and target point. f_2 is defined by following equation:

$$f_2 = \begin{cases} L, & d_{min} > d_{safe} \\ e^{(D\_(safe+1)/d\_(min+1))+1} & d_{min} \le d_{safe} \end{cases} \quad (20)$$

Where d_{safe} is a constant that determine the influence of the obstacles.

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III. Simulation Results

To validate the performance of our proposed bidirectional spline-RRT* algorithm, we carried out several simulations in five different varied environments. The trajectory planning scenario utilized in this paper comprised of resolution of original map: 500×500, fixed source point and target points for all four varied scenarios at [10, 10] and [490, 490] respectively. Fig. 2 to 6 illustrates the simulation results for five different environments. Simulation results (a) and (b) shows the trajectory traced by the robot using bidirectional -

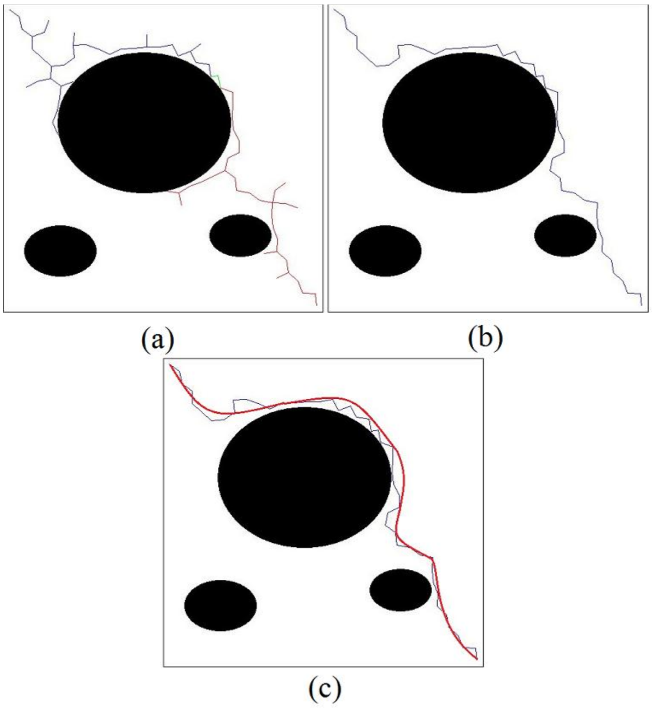

Fig. 2. Simulation Results 1: Trajectory Planning (a) to (b) using bidirectional RRT star, (c) after applying ferguson's spline

RRT star and (c) shows the trajectory traced using Ferguson's spline technique and the results are been tabulated in table 1. Table 1 shows the time of travel taken by the robot to reach the goal and the path length traversed by the robot from starting point

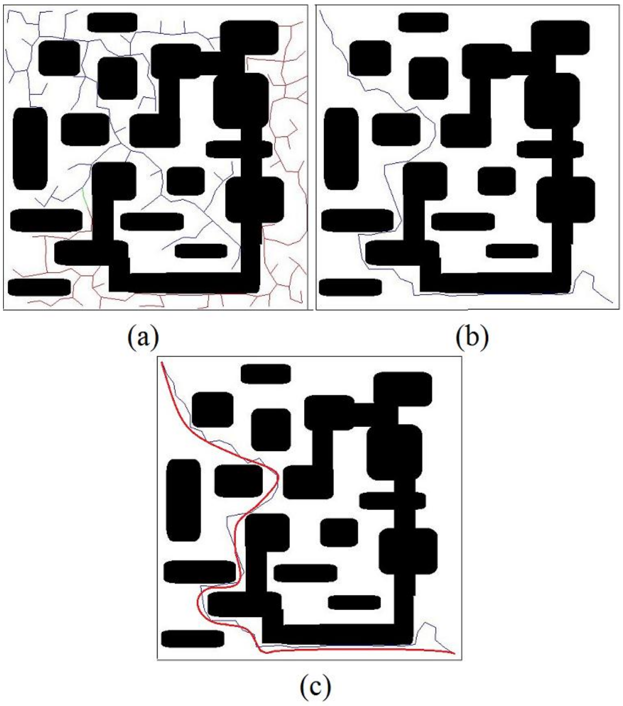

Fig. 3. Simulation Results 2: Trajectory Planning (a) to (b) using bidirectional RRT star, (c) after applying ferguson's spline

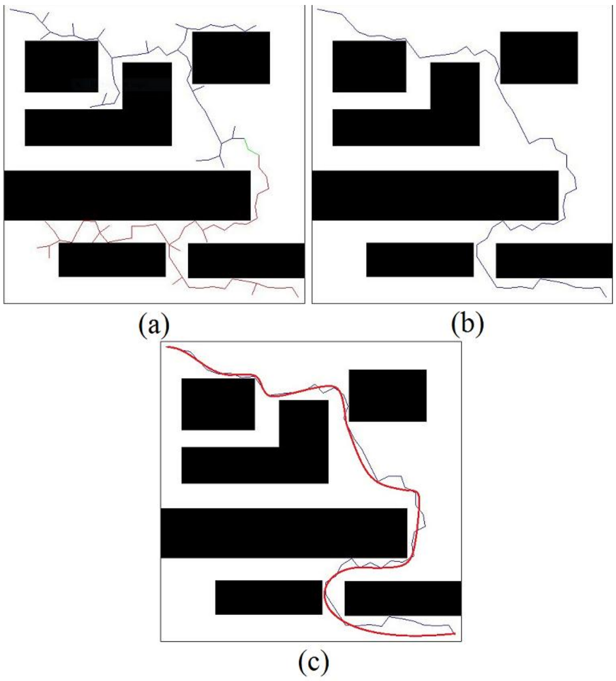

Fig. 4. Simulation Results 3: Trajectory Planning (a) to (b) using bidirectional RRT star, (c) after applying ferguson's spline

to the target in the Simulation Results-1 to 5 using bidirectional-RRT, bidirectional-RRT* algorithm and after applying Ferguson's spline on it. From the simulation results 1 to 5, we have found that the time of travel by the robot to reach the goal after

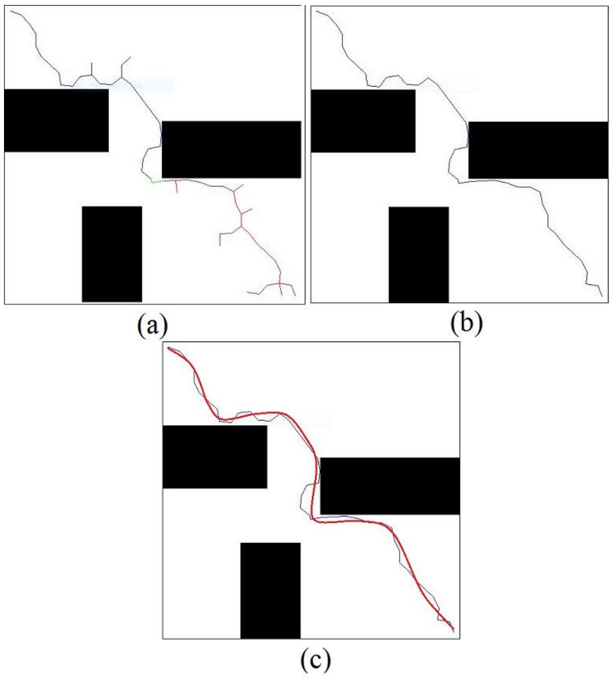

Fig. 5. Simulation Results 4: Trajectory Planning (a) to (b) using bidirectional RRT star, (c) after applying ferguson's spline

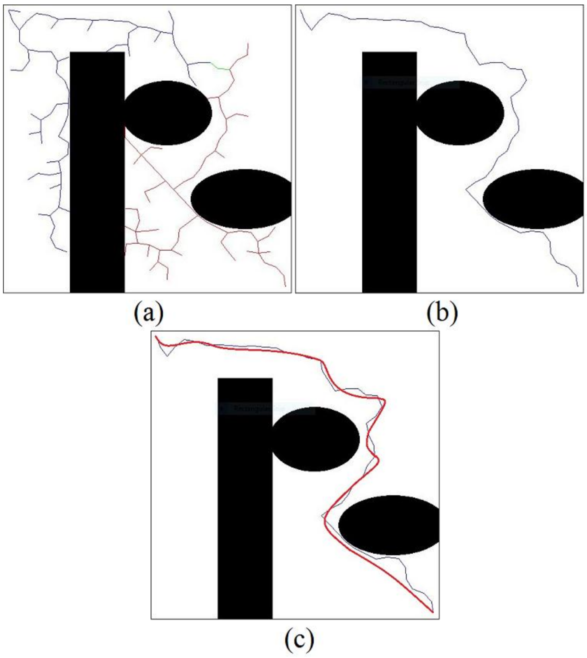

Fig. 6. Simulation Results 5: Trajectory Planning (a) to (b) using bidirectional RRT star, (c) after applying ferguson's spline

applying ferguson spline is drastically reduced as compared to that of the bidirectional-RRT*. As the rough turning points of the path are smoothed to curves, it will be easy for the robots to turn and move forward. This will reduce the time traversed by the robots to reach the goal as the robot doesn't want to stop while turning directions.

TABLE I. TIME TAKEN AND PATH LENGTH TRAVERSED BY THE ROBOT USING THE BIDIRECTIONAL-RRT, BIDIRECTIONAL-RRT STAR AND AFTER APPLYING CUBIC FERGUSON'S SPLINE TO REACH THE TARGET (SIMULATION RESULTS 1 TO 5)

	Bidirectional-RRT		**Bidirectional-RRT***		**With Cubic Ferguson's Spline**	
	Time Taken for the robot to reach the Target (in sec)	***Path Length***	***Time Taken for the robot to reach the Target (in sec)***	***Path Length***	***Time Taken for the robot to reach the Target (in sec)***	***Path Length***
Simulation Results 1	13.754	1024	10.780	953	6.003	881
Simulation Results 2	25.025	1307	20.831	1225	14.907	1106
Simulation Results 3	38.991	1389	35.139	1269	25.799	1005
Simulation Results 4	14.768	999	12.814	898	8.044	805
Simulation Results 5	26.349	1103	22.978	1028	15.996	981

IV. Conclusion

In this paper, a trajectory planning approach for wheeled mobile robot is proposed. The proposed method combines the classic bidirectional RRT algorithm with the cubic Ferguson's spline technique to generate trajectories that directs smoothness and continuation without any computation. To validate the capability of the proposed algorithm, simulations were processed and showed that the proposed algorithm is feasible in both geometrical and dynamical environment. Like the classic bidirectional RRT algorithm, our proposed method is also optimally asymptotic and can satisfy direction limitations approach on both source and target locations. The applications of this proposed algorithm relies on the cost function and can be utilized in various numbers of other fields.

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