Title:

A Spline-based Flexible Method of Virtual Force Design for Dynamic Motion Planning of Robots

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Introduction:

Motion planning for mobile robots is a problem on how a team of robots can achieve collective motion objectives in a shared working place while avoiding interference with one another [12]. Its applications include logistics, military operations, and disaster rescue [5, 7]. As most applications take place in dynamic environments with frequently changing conditions, updating and maintaining route validity and optimality becomes a daunting task.

There are some popular techniques for multi-robot motion planning, such as protocol-based methods [11], sampling-based techniques [8], genetic algorithms [15], spatiotemporal planning [2], potential field methods [9], virtual force approaches [4], graph-based techniques [10], etc. Each of these techniques has its own pros and cons. The virtual force approach is generally preferable for robots to perform team work in dynamic environments. This approach composes virtual attractive forces that drive the robots towards their targets and, at the same time, exert repulsion to steer the robots away from the obstructing robots [6, 13]. The design of virtual forces plays a pivotal role in improving robot motions to avoid robot collisions and enhance overall team performance.

However, most traditional methods lack design flexibility to locally adjust the virtual forces according to the changing situations, hampering responsiveness of robot motions in dynamic environments and leading to possible robot collisions.

Main Idea:

This paper presents a flexible method of enhancing the design freedom of virtual forces, while maintaining computational efficiency of the force functions. The proposed method adopts interpolating cubic splines for force design to generate desirable force magnitudes at specified locations of each robot. The shape of a spline can be locally adjusted to modify the virtual force without jeopardizing the interpolation properties of other control points. As such, the robots can manoeuvre in great agility to react responsively in dynamic situations. Motion safety and operational time serve as two criteria to validate the proposed method. This paper is aimed at enhancing motion safety and shortening operational time.

The proposed spline-based virtual force design method consists of four main steps: (1) Assignment of control points; (2) Establishment of spline coefficient equations; (3) Derivation of spline coefficients; (4) Virtual force calculation. The first three steps are carried out offline, while the last step is realised online for real-time planning and control motion mobile robots in dynamic environments.

Results:

A simulator based on the Player/Stage open-source platform, which is widely used for multi-robot control and simulation [14], has been developed to incorporate the proposed spline-based virtual force design method for operation planning and control of mobile robots for various applications. To demonstrate this simulator and to validate the proposed method, we present a case study of military robots, which have been receiving increasing popularity in modern battle fields, such as unmanned aerial vehicles for reconnaissance, ground robots for combats, and underwater robots for scouting [3].

Figure 1 shows a simulated battle field, which involves sixteen military robots fighting together in a mission to destroy five types of enemies. The battle field covers an area of 3800m × 2500m. Each robot, modelled as a small black triangle, measures 10m×4m and weighs 30 tonnes. The maximum speed is $35\mathrm{m\cdot s^{-1}}$. The maximum acceleration and deceleration are $3\mathrm{m\cdot s^{-2}}$ and $-3\mathrm{m\cdot s^{-2}}$, respectively. The sensing range of a sonar is 400m. It is assumed that a military satellite spies above the battle field and commands the robots to destroy the enemies detected. The stealth robots prowl to the enemies and destroy them, without being discovered and fought back. This assumption is seen in a number of realistic military operations, such as unmanned aerial vehicles (UAVs) in stealth attack missions and submarines to secretly assault the adversarial warships [1]. The five types of enemies appear stochastically and continuously at different locations. It is also assumed that enemy targets are stationary, such as radar stations, missile bases, and forts.

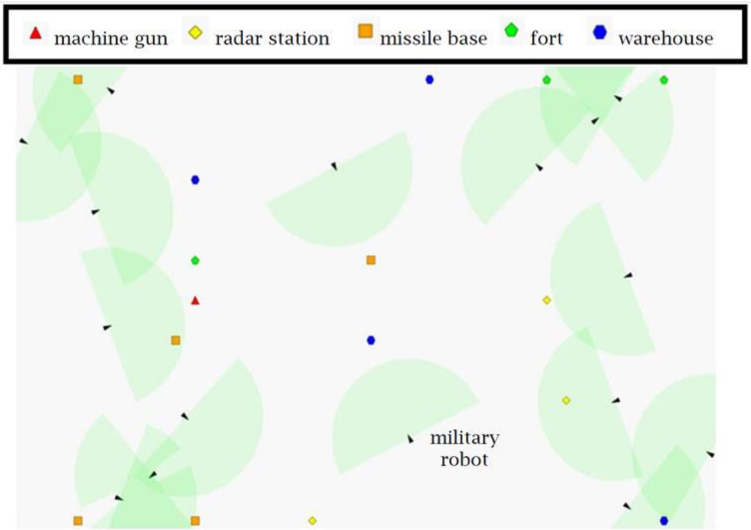

Fig. 1: A simulated battle field with sixteen robots to destroy five types of enemies.

A mission for the sixteen stealth robots to destroy five types of enemies is described in Table 1. The robots are assumed to be capable of destroying all the five types of enemies. There are two major operational uncertainties, namely unpredictable appearance of enemies and dynamic interferences between the comrade robots.

In the simulations, the proposed spline-based virtual force design method is compared with the traditional method with proportional attractive force and inversely proportional repulsive force. Both methods accomplished the same mission as described in Table 1.

To validate the proposed approach in terms of motion safety, Fig. 2(a) and Fig. 2(b) show the snapshots of the simulations with two different methods. For the traditional method in Fig. 2(a), two robots collided near the left bottom corner, as highlighted in the dashed circle. The weak repulsive forces to the two robots by only a single inversely proportional function led to this collision. In Fig. 2(b), the spline-based method streamlined the motions of the two robots, allowing them to operate safely with a comfortable distance between each other. This validated that the spline-based method could responsively tune the force magnitudes, according to the real-time dynamic situations. As such, the motions of robots are streamlined and the likelihood of robot collisions reduced.

Types of Enemies	Time to Destroy (minute)	Amount	Characteristics
Machine gun	0.25	100	• appear stochastically and continuously • stationary • attacking targets rather than the stealth robots
Radar station	1	10	
Missile base	1	10	
Fort	0.5	50	
Warehouse	1	20	

Tab. 1: Mission description of sixteen robots to destroy five types of enemies.

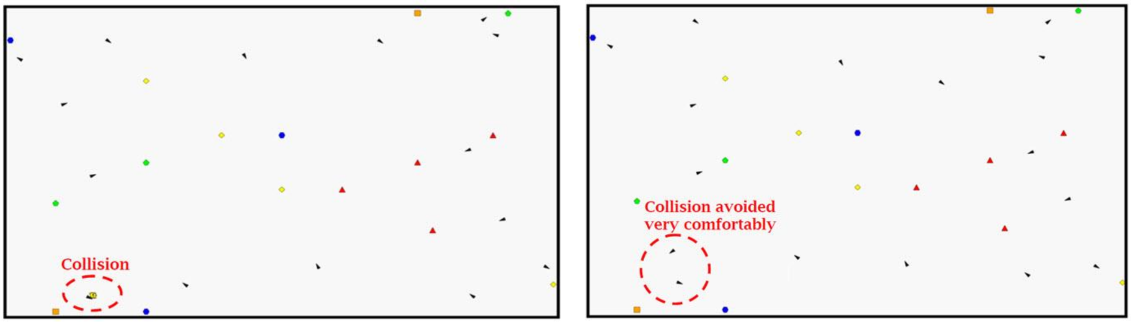

Fig. 2: (a) Snapshot with proportional attractive force and inversely proportional repulsive force, (b) Snapshot with spline-based attractive force and repulsive force.

Fig. 3 evaluates the operational time. The proposed spline-based method could shorten the mission time by 27.8%, in comparison with the traditional method. This confirmed that the flexibly designed splines could formulate responsive virtual forces for the robots in a dynamic battle field. The operation efficiency of the military mission was secured accordingly.

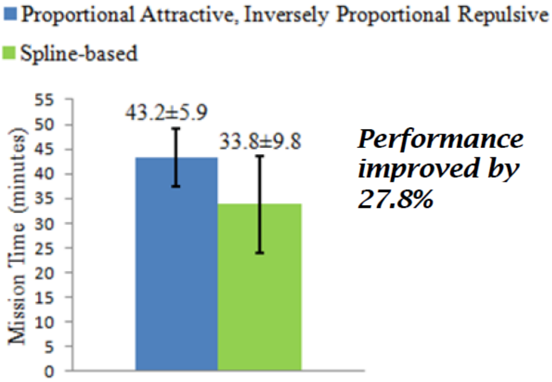

Fig. 3: Mission times by two virtual force designs.

Conclusion and future work:

This paper proposes a spline-based method to improve the design flexibility of virtual forces for dynamic motion planning of mobile robots. Interpolating user-assigned control points facilitates flexible force design that generates more desirable force magnitudes for each robot at specified locations. The shape of a spline can be flexibly designed and locally tuned to modify the force values, without jeopardizing the interpolation properties of other control points. The resulting smooth virtual forces provide good agility needed for the robots to response to real-time and dynamic situations during operations. A military case study shows that the likelihood of robot collisions can be reduced and the operations become safer. Moreover, the overall operational time of the robot team is shortened substantially.

Since the Player/Stage robotic simulation system has been widely used in multi-robot control and simulation and it provides a network interface to a variety of physical robots and sensors, the proposed spline-based virtual force design method and the motion planning module can be readily adopted for operations of physical robot teams to benefit various real-world applications, such as logistics, military, and disaster rescue.

Nevertheless, it should be noted that, similar to most traditional force design methods, the virtual force design by our method is in accordance with the specific applications and on a trial-and-error basis. As future work, it would indeed be more fruitful if a preliminary effective analytic guideline could be derived to assist the design of force splines. It is expected that, with such a guideline, the design process would be more effective and automatic.

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