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A Short Survey on Recent State-of-the-Art Methods for Optimal Path Planning for Small On-Orbit Space Robots*

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***Abstract*— Optimal path planning in the presence of multiple kinodynamic constraints and limited onboard computation power is a key challenge for small on-orbit space robots. This work surveys parameterized function and machine-learning based path planning approaches based on number of constraints solved and computation complexity. Limitations of the existing approaches and potential directions are discussed.**

Keywords—space robot, on-orbit operations, path planning, parametrized curves, machine learning, survey

I. Introduction

Robots are gaining popularity in on-orbit operations such as assembly, de-orbit, service and manufacturing due to their capability to perform repetitive tasks in time and cost-effective manner in extreme environments without risking human life. Typically, an on-orbit space robotic operation considers a space robot with an attached manipulator touching/capturing a target object. Four main phases can be distinguished in the capturing stage: (1) observing and planning, (2) final approaching, (3) impact and capture, and (4) post capture stabilization [1]. Focusing on small space robots with limited computation resources, this work surveys recent works on the planning phase.

High number of kino-dynamic constraints, and limited computation resources pose challenges for small space robot optimal path planning problems which require computationally simple solutions. As the main contribution of this work, existing parameterized function and machine-learning based state-of-the-art path planning works are surveyed based on the number of constraints solved and computation complexity. The advantages and disadvantages of the existing approaches are discussed.

II. Considered Path planning Problem

Given an initial and final positions, x_i and x_f, respectively of the manipulator, and a set of desired constraints, find a continuous path such that the path starts from xi at initial time t_0 and reaches x_f at a given time t_f while satisfying all constrains at all time during the operation. The considered constrains are: (1) obstacle avoidance (static or dynamic relative to the service robot), (2) collision avoidance, (3) singularity avoidance (kinematic and dynamic), and (4) dynamic coupling effect minimization or (5) attitude control [3,5,7]. Fast and on-line solution of this problem is also a vital feature for the space robots, and for this analysis.

In addition, different spacecraft configurations are considered: (1) Free-floating, (2) free-flying, or (3) controlled-flying. The number of arms in the service robot is relevant to the methods presented as well: (1) single or (2) double manipulator configuration. Similarly, the number of Degrees of Freedom (DoF) varies in each study case, and it is also a significant point in the path planning problem solutions presented.

III. Survey and Discussion

A. Classification Criteria

The considered methods were selected according to the following criteria:

1) *Number of constraints solved:* Achivement of several conditions expands the aplicability of the method for different scenarios.

2) *Computational Expense:* The limitation of the computational resources in spacecraft makes the computation complexity a paramount aspect.

a) *Resources:* The amount of computation power and storage required to achieve the calculations in the method.

b) *Computation time:* required for the method to converge to a feasible solution.

3) *Type of method used to solve the problem:* As it has a relevant relationship with the number of constrains able to solve and the computation expense required for it.

B. Observations

The details of the selected methods based on the classification criteria are provided in Table 1. It shows that polynomial function based approaches can provide near-optimal solutions with fast speed however their performance decreases with number of constraints. On the other hand, machine learning based approaches can provide optimal solutions with fast speed however require computation power during training.

Additionally, relevant features stand out, for example: collaborative use of the base and manipulator for planning [3,5], effective handling of multiple constraints via dynamic adjusting of optimization penalty factors [5], as well as by constraint prioritization depending on the task [6]. On-line path planning was allowed by reducing the number of constraints and thus computation power [7], and by training machine learning models (ML) to derive optimal path planning policies off-line [8]. ML was also used to provide an initial guess for the optimization procedure [9], contrasting to the methods which do not require a priori knowledge [3]. For detailed discussion, readers are referred to papers [3-9].

C. Limitations

Given the nature of the methods used relevant disadvantages from the solutions are: High computational cost [3,4,5], limitation on the number of constraints handled to gain computation speed, and thus lacking an overall path optimal solution [6]. Performance bound to information feed in the ML training scenarios (although it can be expanded) and a high computation power required for off-line path planning [8,9].

D. Potential Directions

There is room for novel solutions methods able to handle multiple constraints in a computationally efficient manner.

Possible future work, based on the advantages and limitations of the work surveyed, can be based on dynamic constraint priority handling which provides computation allocation only on the required constraints. It can be leveraged by

1) *Fast constraint optimizers:* which would only handle a reduced number of constraints at a specific time improving the overall computation time.

2) *Pre-trained policies:* which would provide a behavioral guideline for the system.

3) *Offline optimal motion primitive library:* which would provide ready to use optimal paths to the optimizer.

TABLE I. COMPARISON OF PATH PLANNING METHODS

Path Planning methods comparison		***Work reviewed***						
Method characteristics		***[3]***	***[4]***	***[5]***	***[6]***	***[7]***	***[8]***	***[9]***
Robot type [a]	Operation mode – No. of arms – DoF	*CFlo-1-12*	*FFlo-1-4*	*FFlo-2-8*	*FFlo-2-n*	*FFly-1-6*	*FFlo-2-7*	*FFly-1-3*
Constraints solved	path planning (optimal)	o	o	o			o	o
	path planning (on-line)					o	o	
	trajectory planning	o	o	o	o			
	obstacle avoidance (static)	o	o				o	
	obstacle avoidance (dynamic)			o				
	collision avoidance	o	o	o	o	o		o
	kinematic singularity avoidance	o		o				
	dynamic singularity avoidance	o						
	dynamic coupling effect minimization	o	o	o	o		o	o
	attitude control		o	o				
	Others		o	o			o	o
Computation [b]	resources required in spacecraft	H	H	H	H	L	H	H
	time required in spacecraft	H	H	H	L	L	L	L
Path Planning Method	parametrized function based	o	o	o	o	o		
	machine learning						o	o

a. Space robot operation mode: Free-Flying (FFly), Free-Floating (FFlo), Controlled-Flying (CFlo), DoF: total Degrees of Freedom in the entire spacecraft (including the base if it operates in CFlo).

b. Not all papers included computation cost evaluations. The H (high) and L(low) grades were assigned based on the optimization techniques usual high cost and the comments of the authors.

IV. CONCLUSSIONS

Parameterized function and machine learning based optimal path planning approaches are surveyed which shows that both approaches can generate optimal/near-optimal solutions on small on-orbit robots. It shows that polynomial function based approaches can provide near-optimal solutions with fast speed. However, their performance decreases with number of constraints. On the other hand, machine learning based approaches can provide optimal solutions with fast speed but require high computation power during training. Fast constraint optimizers, pre-trained machine learning policies and motion primitive-based path libraries are some of the potential approaches to reduce the computational complexity of the optimal path planning for small space robots.

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