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A distributed variable density path search and simplification method for industrial manipulators with end-effector's attitude constraints

Key words: Path planning; Industrial robots; Distributed signed-distance-field; Attitude constraints; Path simplification

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Motivation

The collision-free path planning of industrial robots is a complex problem, and it is difficult to find the feasible path efficiently. The main factors affecting efficiency include:

(1) The search method (2) Inverse kinematics (3) Collision detection

1. End-effector's attitude control: Most of the current mainstream motion planning algorithms, such as covariant Hamiltonian optimization for motion planning (CHOMP), rapidly-exploring random tree (RRT) connect, and stochastic trajectory optimization for motion planning (STOMP), are solved in the configuration space, which makes it difficult to directly control the attitude of the end-effector. To cope with end-effector's attitude constraints in the Cartesian space, the conventional inverse kinematic analytical method is generally complicated and will generate multiple solutions, and the selection of solutions is time-consuming.
2. Excessive collision detection: Collision detection of industrial robots has high time complexity. Besides, to ensure that the trajectory is reachable, it will be repeated in the planning process, resulting in a large computational load.
3. Unnecessary twists: The grid-based path search will generate unnecessary twists in the path, and a significant number of inverse kinematic solutions and collision detections are needed to perform path simplification to remove redundant path points, which has a great impact on efficiency.

Main idea

DVDP-AC		
Number	**Main factors affecting efficiency**	**Improvement measures**
1	Inverse kinematics	Position–attitude constraints reconstruction (**PACR**)
2	Collision detection	Distributed signed-distance-field (**DSDF**) Single-step safety sphere (**SSS**)
3	The search method	Variable density path search & Forward sequential path simplification (**FSPS**)

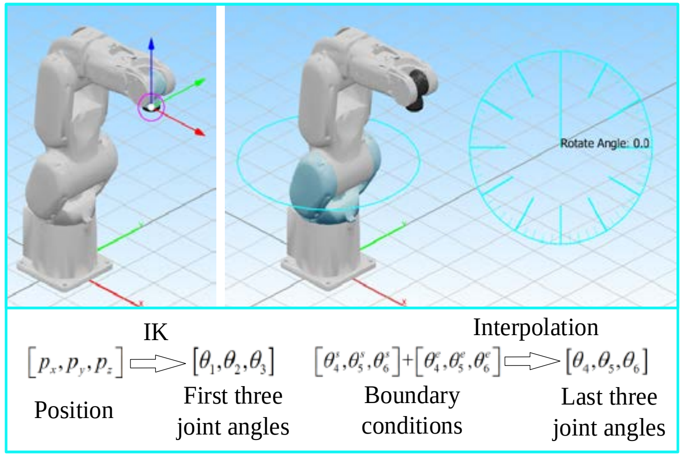


Fig. S1 PACR

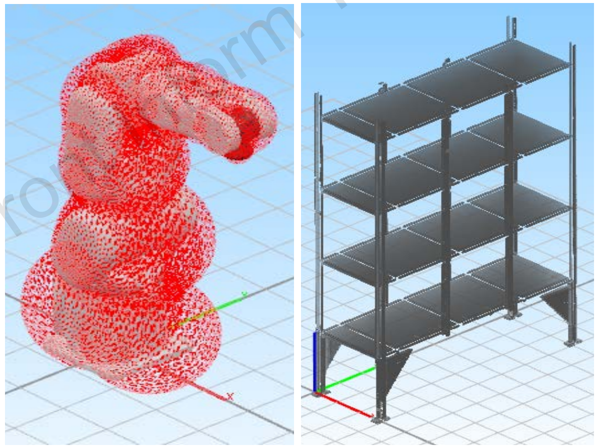


Fig. S2 DSDF & SSS

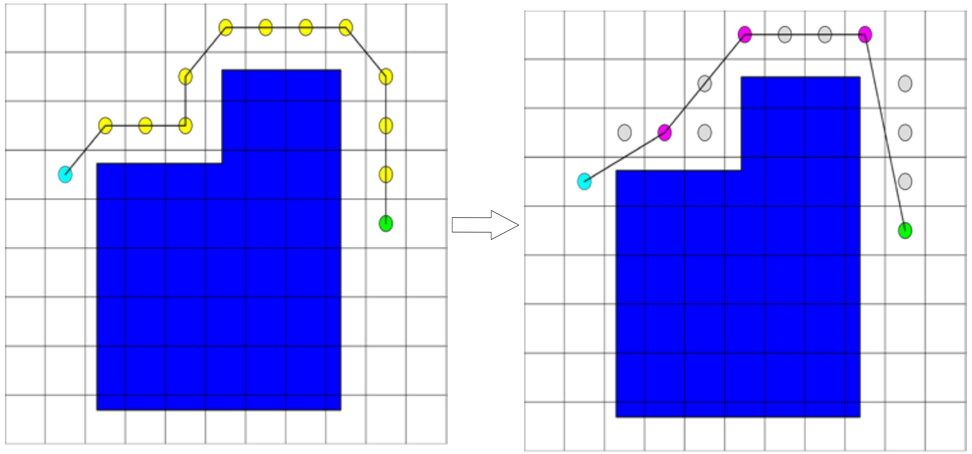


Fig. S3 Forward sequential path past-processing

Method

DVDP-AC		
Number	**Main factors affecting efficiency**	**Improvement measures**
1	Inverse kinematics	Position–attitude constraints reconstruction (**PACR**)
2	Collision detection	Distributed signed-distance-field (**DSDF**) Single-step safety sphere (**SSS**)
3	The search method	Variable density path search & Forward sequential path simplification (**FSPS**)

1. Inverse kinematics: In tasks that require attitude constraints, accurate positioning is needed only at the starting and ending points, but not in the process of motion. Therefore, a position–attitude constraints reconstruction (PACR) inverse kinematics solution approach is proposed, which can satisfy the attitude constraints in the intermediate process and improve the efficiency of solving inverse kinematics.
2. Collision detection: For efficient collision detection, the models of distributed signed-distance-field (DSDF) and single-step safety sphere (SSS) are proposed. DSDF solves the problem of low reconstruction efficiency of the original SDF, and SSS can help reduce the number of collision detections during the single-step search and path simplification.
3. Path simplification: Aiming at the inherent defect of a grid-based search, a novel forward sequential path simplification approach (FSPS) is proposed to eliminate the redundant path points and speed up the process of path simplification.

Experiment results

Brief introduction of each group in simulation cases and experiment 1

Groups	Inverse kinematics	Collision detection	Search space	Post-processing
OBUO	O	B	U	O
OSUO	O	S	U	O
OSVO	O	S	V	O
MSVO	M	S	V	O
MSVM	M	S	V	M
MSVN	M	S	V	N

Brief introduction of each group in experiment 2

Groups	Inverse kinematics	Collision detection	Search space	Post-processing
OBUO	O	B	U	O
OSUO	O	S	U	O
OSVO	O	S	V	O
OSVM	O	S	V	M
OSVN	O	S	V	N

O: original; M: modified; B: bounding volume hierarchy (BVH) based; S: signed-distance-field (SDF) based; U: uniform; V: variable; N: none. MSVM and MSVN use the algorithm proposed in this paper and OBUO uses original D* lite algorithm

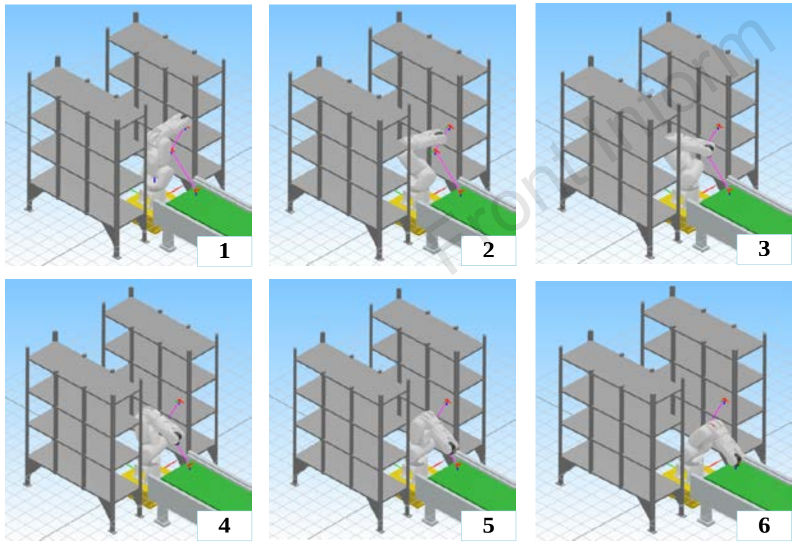


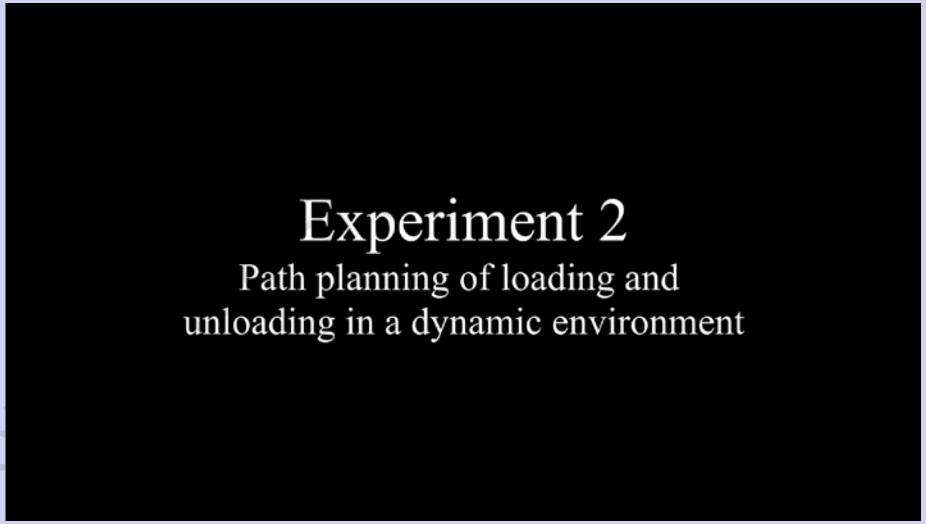
Fig. 15 Motion process of simulation case

Table 4 Performance comparison in the simulation cases

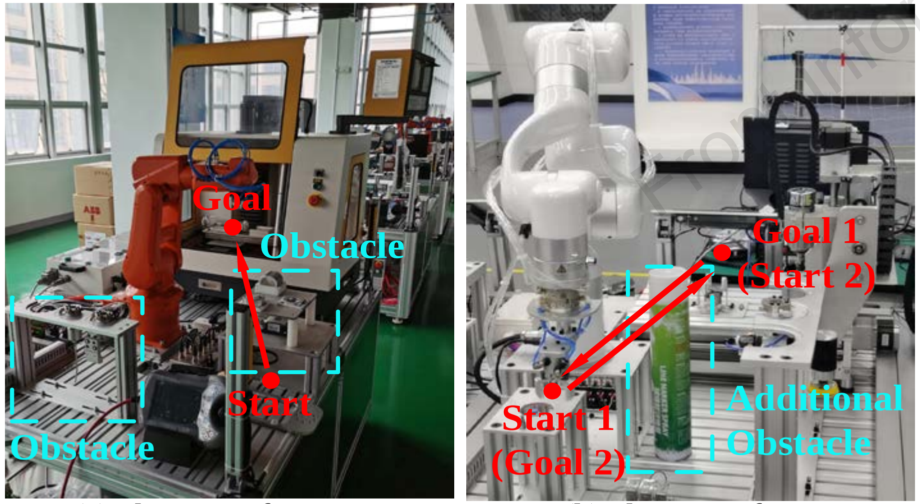
	Average time (ms)	Maximum time (ms)	Minimum time (ms)	Average length (mm)
OBUO	38.24	65.65	28.74	751.31
OSUO	32.65	53.92	26.13	756.17
OSVO	30.69	50.43	24.94	756.17
MSVO	26.18	45.57	19.67	761.43
MSVM	19.99	31.04	14.74	737.11
MSVN	17.79	28.24	14.27	917.17

Experiment results

Video. Experiment I.



Video. Experiment II.



(a) The setup of case 1 **(b) The setup of case 2**

Fig. 16 The setup of the experiments

Table 6 Performance comparison of case 1

	Average time (ms)	Maximum time (ms)	Minimum time (ms)	Length (mm)
OBUO	196.37	206.83	180.54	1006.08
OSUO	111.10	115.33	108.91	1006.08
OSVO	100.57	104.39	98.62	1006.08
MSVO	92.74	97.06	89.54	1172.55
MSVM	78.37	82.04	75.67	1049.53
MSVN	55.57	58.18	53.95	1295.52

Table 7 Performance comparison of case 2

	Average time (ms)	Maximum time (ms)	Minimum time (ms)	Length (mm)
OBUO	2748.51	2764.42	2719.25	2233.58
OSUO	2001.04	2009.75	1994.36	2219.94
OSVO	1990.14	1998.12	1975.50	2219.94
OSVM	1739.87	1754.54	1722.70	2221.03
OSVN	1356.66	1367.09	1337.79	3174.12

Experiment results

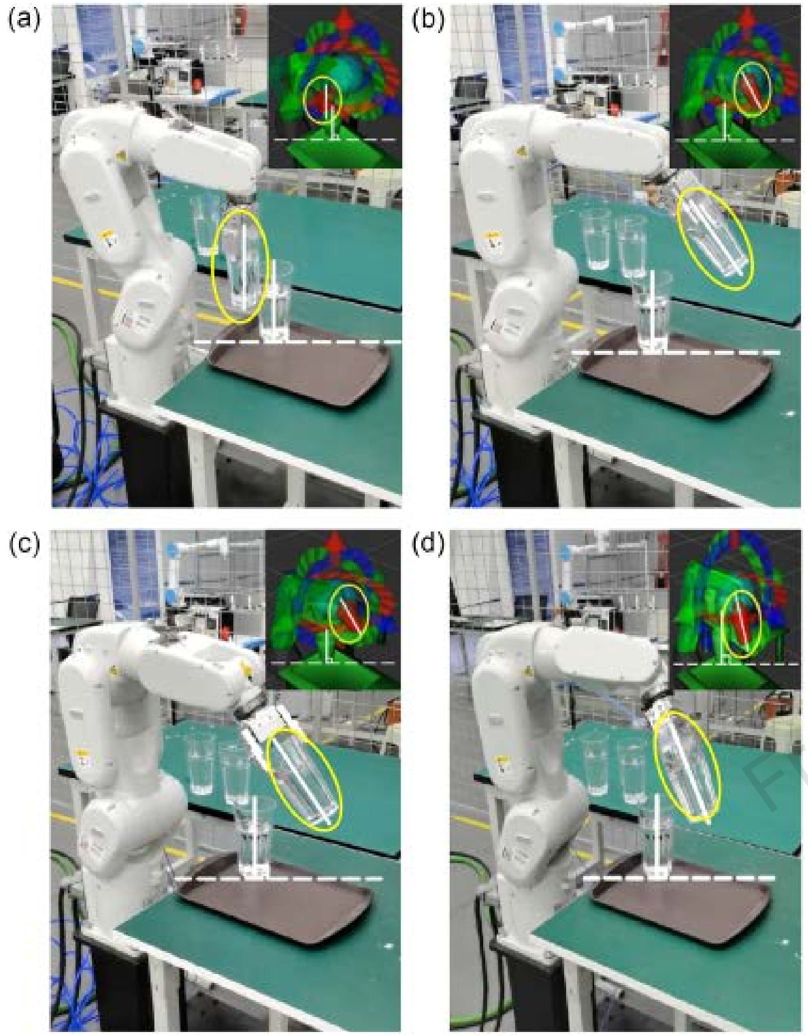
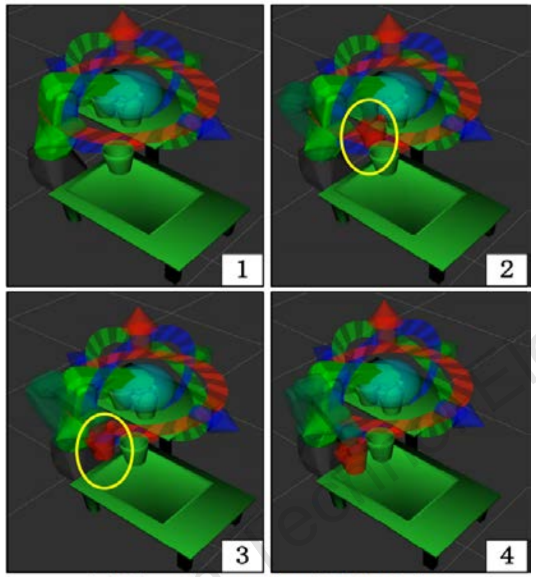


Fig. 18 Effect comparison among four methods of the attitude constraint: (a) DVDP-AC; (b) CHOMP; (c) RRT-connect; (d) BFMT*



(a) Planning result of DVDP-AC

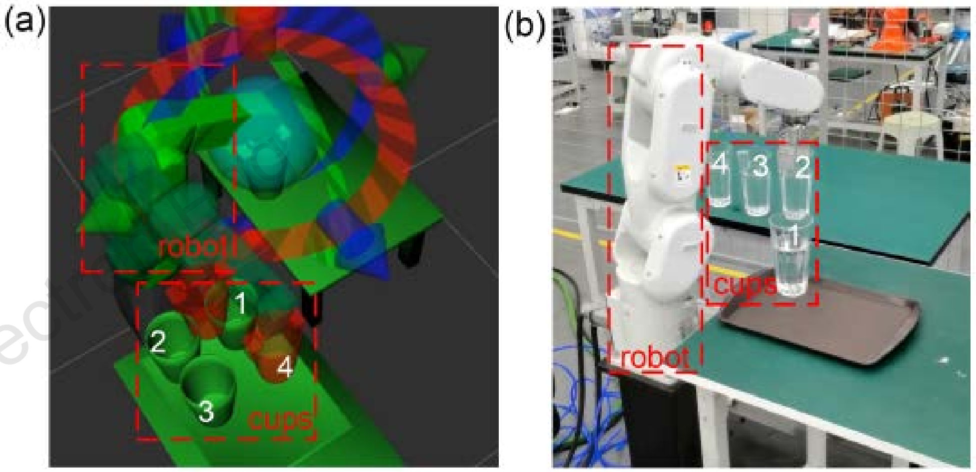


Fig. 17 The setup of case 3: (a) simulation environment; (b) experimental environment

Table 12 Comparison of planning time

Path	Time (ms)	DVDP-AC	CHOMP	Decrease rate 1	RRT-connect	Decrease rate 2	BFMT*	Decrease rate 3
1	Average	34.9	109.0	67.98%	49.3	29.21%	48.8	28.48%
	Maximum	40.0	111.0	63.96%	55.0	27.27%	52.0	23.08%
	Minimum	34.0	108.0	68.52%	45.0	24.44%	45.0	24.44%
2	Average	63.7	123.6	48.46%	103.0	38.16%	88.9	28.35%
	Maximum	77.0	128.0	39.84%	117.0	34.19%	96.0	19.79%
	Minimum	59.0	119.0	50.42%	92.0	35.87%	82.0	28.05%
3	Average	69.5	118.3	41.25%	95.8	27.45%	76.3	8.91%
	Maximum	72.0	121.0	40.50%	103.0	30.10%	82.0	12.20%
	Minimum	69.0	116.0	40.52%	84.0	17.86%	70.0	1.43%
4	Average	65.1	126.4	48.50%	101.1	35.61%	71.2	8.57%
	Maximum	69.0	132.0	47.73%	122.0	43.44%	78.0	11.54%
	Minimum	63.0	122.0	48.36%	86.0	26.74%	67.0	5.97%

Conclusions

In this paper, a distributed variable density path planning method named DVDP-AC is proposed. In our proposed method, the inverse kinematic solution, collision detection, and post-processing are modified.

First, collision detection based on DSDF and SSS generally improves efficiency, especially in the scenarios where obstacles are densely distributed. In the ablation study cases, the computation time is reduced by 14.63% to 27.20% due to DSDF-based collision detection.

Second, PACR inverse kinematics can further improve efficiency while meeting the requirements of the handling task. In the ablation study cases, the computation time is reduced by 7.79% to 14.68% due to PACR.

Third, the adoption of FSPS further improves the quality and efficiency of path simplification. In ablation study cases, FSPS reduced the computational time by 12.58% to 23.64%.

Moreover, in baseline comparison, DVDP-AC shows advantages in efficiency and attitude constraints compared with existing mainstream algorithms.

Authors

Jin WANG is an associate professor at the School of Mechanical Engineering of Zhejiang University, Hangzhou, China. He received his BS degree in Mechatronic Engineering in 2003 and PhD degree in Mechanical Engineering in 2008, both from Zhejiang University. His research interests include computer vision, computer graphics, and industrial robot, especially in modelling and simulation, control and planning for robotics.

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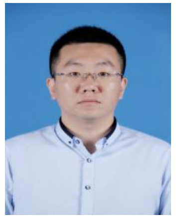

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