Investigation on the Influence of Obstacle Size in Path Planning by a Hybrid Model Combining an Improved A-star Algorithm and Digital Twin

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Abstract The development of simulation technology has made it possible to create digital copies that are identical to a real system from geometry to dynamics. With reference to this, digital twin technology can help us determine the minimum collision-free distance between a robot and an obstacle on the virtual system, thereby planning the corresponding better path for the real system. In addition, the A-star algorithm was invented and many improvements were made to boost the efficiency of the original A* path planning algorithm. The advanced method shows the first breakthrough about the local path planning between a goal node and a current node, which has been already planned for the following search in the region of a current node. The local path will be adopted directly if it is safe and collisionless. This method also shows the second breakthrough about the application of the post-processing stage for path planning optimization by aligning the local path to lower a number of local paths along with path length. In this study, a combination of digital twin and an improved A-star algorithm was used for planning the robotic path in a light bulb assembly production line. The influence of obstacle size was also evaluated in terms of the efficiency of either method (i.e. A-star algorithm and digital twin) to further enhance robotic path planning when applied in practice to a system with obstacles of different sizes.

Keywords Industrial robotics · A-star algorithm · Digital twin · Path planning · Hybrid model

1 Introduction

The aim of emerging the concept of Digital Twins (DT) is to help software users and developers be accessible on digital platforms to physical things and related data sources [1]. For comparable or partly coinciding concepts, the readers can refer to

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a series of terms such as digital counterpart, virtual twin, virtual object, product agent, and avatar [2]. A digital replica is a virtual representation that serves as a real-time digital replica of a process or a physical object. Although the concept had been proposed before (by Michael Grieves at first and in 2002 by the University of Michigan), the term "a digital twin" was officially defined by NASA in 2010 for the enhancement of physical model simulation of a spacecraft [3]. Digital twin consists of three components: (i) an object or a physical system, which can be a device, a production line; (ii) a virtual model built from CAD files (computer aided design), an identical simulation of a physical device or system; (iii) a real-time communication connection between the physical system and the virtual system [4]. A* (as "A-star") is a graph traversal and path search algorithm, which is frequently employed in many fields of computer science owing to its absoluteness, optimality, and ideal efficiency [5].

2 Improved A* Algorithm

In literature, the query phase of the probabilistic roadmap planner consists of the path planning relied on the improved A* algorithm [6, 7]. There are two phases in the probabilistic roadmap planner i.e. a pre-processing one and a query one. In the former phase, a random generation of collisionless sampling points occurs in robotic configuration space. The local path planner then builds a collisionless path and a local safety between these points. To check possible collision and path validity, the plans are mapped to robotic joint space by the local path planner and this execution is done by joint space constraints (e.g. velocity, acceleration, and energy optimization). Local safety paths and collisionless sampling points are thus constituents of the probabilistic roadmap. In the latter phase, with the adoption of the improved A* algorithm the constituted probabilistic roadmap planner searches and acquires a safe path for robotic movement connecting the initial node s (starting point) and the goal node g (ending point). There are two stages in the proposed improved A* algorithm: the pre-processing one and the post-processing one [8].

3 Experiments

3.1 The Physical Space

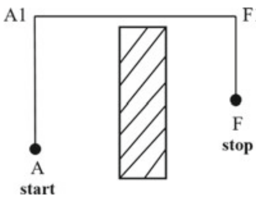
Testing the proposed method was done for a high-skill preparation of a lamp assembly production line. We set up a station by mounting a Universal Robots' UR3 on a stand placed on a table. This station works by receiving a sub-assembly from the preceding station, mounting additional parts on it and transfering it to the succeeding station. The UR3 robot lifts alternately a socket and a bulb to put in the punch hole. It is followed by bringing light bulbs from the conveyor belt and placing sockets in the pallet. After lowering the stamping cylinder to create a force for sticking the socket to the bulb, the UR3 robot lifts and puts the finished product on the conveyor belt to transfer it to the warehouse.

3.2 The Digital Space

A simulation model (digital space in digital twin) is a dynamic environment built by incorporating 3D computer-aided design (CAD) objects into Tecnomatix Process Simulate software. Tao and Zhang [9] suggested that the virtual model consists of four layers, i.e. geometry (generating 3D CAD objects), physical location (position of CAD objects in the scene), behavior (robotic kinetics) and rules (sequence of an assembly process). Tecnomatix can import CAD data in JT (Jupiter Tessellation) format. TCP/IP protocol is used to connect real-time communication connection between a real robot and a virtual robot via Ethernet port. The “Live Mode” in Tecnomatix Process Simulate software is used to connect real and virtual robot. The digital twin of the UR3 robot was conceived, where every action in the real robot is instantly reflected in real time on the virtual robot.

4 Results

Consider the moving distance of the UR3 robot when it transports (i.e., picks up and places on) an assembled product (i.e., a bulb) from the punching hole to the conveyor belt for warehouse. The obstacle herein is the stamping cylinder. More obstacles are added when measuring the robotic moving time with the digital twin, A* algorithm and improved A* algorithm applied. Using digital twins for robotic path planning. Use the collision detection feature in Technomatix software to find a suitable path for robotic movement. According to [10], the robotic path planning was found by the digital twin method as shown in Fig. 1. Durations for robotic movement corresponding to the acceleration speed 500–800–1200 mm/s^2 and the velocity speed 250–500 mm/s at 50-mm/s steps are displayed in the following Table 1.



	x	y	z
A	98	-353	-3
A1	98	-353	230
F1	308	38	230
F	308	38	58

Fig. 1 Robotic path found by the digital twin method

Table 1 Durations for robotic movement according to AA1F1F

A = 500 mm/s²		A = 800 mm/s²		A = 1200 mm/s²	
V (mm/s)	AA1F1F duration (s)	V (mm/s)	AA1F1F duration (s)	V (mm/s)	AA1F1F duration (s)
250	4.896	250	4.336	250	4.024
300	4.632	300	3.952	300	3.584
350	4.504	350	3.736	350	3.304
400	4.448	400	3.624	400	3.128
450	4.424	450	3.552	450	3.016
500	4.424	500	3.52	500	2.944

Case 1

Case 1A: Using the original A* algorithm, the robotic path planning was shown in Fig. 2 (in the left side) as ABCDEF; according to [10], we have the following data (Table 2).

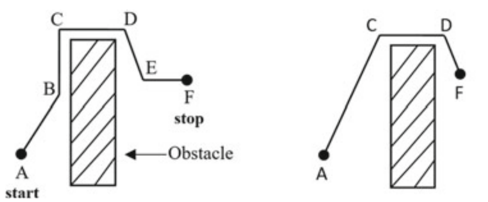
Case 1B: Using the A* improved algorithm for robotic path planning, we have the robotic path as ACDF (Fig. 2 in the middle position). This path is 6-points shorter than that obtained by the original A* algorithm. We have the durations for robotic movement obtained by the improved A* algorithm in Table 2.

Case 2: The improved A* algorithm with the addition of obstacles of the same height.

Case 2A: adding a 30-mm width obstacle with the same height (Fig. 3 in the left side). Case 2B: adding a 50-mm width obstacle with the same height (Fig. 3 in the middle position), we have the results in Table 2.

Case 3: The improved A* algorithm with placing consecutively pairs of obstacles 1–2 (case 3A), 3–4 (case 3B), 5–6 (case 3C) in a 50-mm decreasing order of height as shown in Fig. 4, we have the results in Table 3.

Measuring the duration for robotic movement with an increasing number of passing points from D3 to D8, we have the results in Table 3.

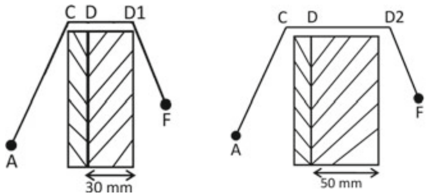


	x	y	z
A	98	-353	-3
B	150	-257	106
C	150	-257	230
D	159	-240	230
E	241	-87	58
F	308	38	58

Fig. 2 Robotic path found by the c A* algorithm (the left side) and by the improved A* algorithm (the middle position), coordinate parameters (the right side)

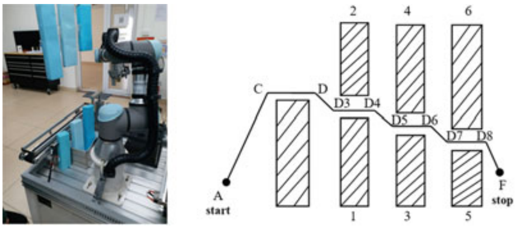
Table 2 Coordinate parameters and durations for robotic movement according to ABCDEF (case 1A), ACDF (case 1B), ACD1F (case 2A) and ACD2F (case 2B)

A (mm/s^2)	V (mm/s)	ABCDEF-duration (s)	ABCDEF-%	ACDF-duration (s)	ACDF-%	ACD1F-duration (s)	ACD1F-%	ACD2F-duration (s)	ACD2F-%
500	250	4.808	− 1.80	3.856	− 21.24	3.992	− 18.46	4.056	− 17.16
	300	4.664	0.69	3.64	− 21.42	3.8	− 17.96	3.88	− 16.23
	350	4.648	3.20	3.56	− 20.96	3.72	− 17.41	3.816	− 15.28
	400	4.648	4.50	3.52	− 20.86	3.696	− 16.91	3.8	− 14.57
	450	4.656	5.24	3.52	− 20.43	3.696	− 16.46	3.8	− 14.10
	500	4.648	5.06	3.52	− 20.43	3.704	− 16.27	3.808	− 13.92
800	250	4.024	− 7.20	3.4	− 21.59	3.488	− 19.56	3.52	− 18.82
	300	3.824	− 3.24	3.112	− 21.26	3.216	− 18.62	3.264	− 17.41
	350	3.704	− 0.86	2.952	− 20.99	3.064	− 17.99	3.12	− 16.49
	400	3.68	1.55	2.856	− 21.19	2.976	− 17.88	3.048	− 15.89
	450	3.68	3.60	2.8	− 21.17	2.936	− 17.34	3.008	− 15.32
	500	3.688	4.77	2.792	− 20.68	2.928	− 16.82	3.008	− 14.55
1200	250	3.544	− 11.93	3.136	− 22.07	3.184	− 20.87	3.208	− 20.28
	300	3.304	− 7.81	2.808	− 21.65	2.88	− 19.64	2.904	− 18.97
	350	3.144	− 4.84	2.6	− 21.31	2.68	− 18.89	2.712	− 17.92
	400	3.048	− 2.56	2.456	− 21.48	2.552	− 18.41	2.6	− 16.88
	450	3.024	0.27	2.368	− 21.49	2.472	− 18.04	2.52	− 16.45
	500	3.008	2.17	2.32	− 21.20	2.424	− 17.66	2.48	− 15.76
Mean							− 18.07		− 16.44



	x	y	z
A	98	-353	-3
C	150	-257	230
D1	173	-213	230
D2	187	-186	230
F	308	38	58

Fig. 3 Robotic path found by the improved A* algorithm when a 30-mm obstacle added (in the left side); Robotic path found by the improved A* algorithm when a 50-mm obstacle added (in the middle position); coordinate parameters (in the right side)



	x	y	z
A	98	-353	-3
C	150	-257	230
D	159	-240	230
D3	173	-213	180
D4	197	-169	180
D5	169	-124	130
D6	244	-80	130
D7	267	-36	80
D8	290	8	80
F	308	38	58

Fig. 4 Real image of the pairs of obstacles (in the left side); Representation of the pairs of obstacles (in the middle position); coordinate parameters (in the right side)

5 Discussion

Consider Case 1 when the A* algorithm (1A) and improved A* algorithm (1B) were used. In case 1A, it is shown that the robotic moving time could be shorter or longer when A* algorithm used in place of digital twin (Table 2). It obviously means that the A* algorithm is not always better than the digital twin method. We see that in the case of a few obstacles, the duration for robotic movement obtained by the improved A* algorithm is smaller than that obtained by digital twin method. In contrast, in case 1B the improved A* algorithm is always better than digital twin method. Consider Case 2 when obstacles with constant height (case 2A: an obstacle with 30-mm larger in width and case 2B: an obstacle with 50-mm larger in width) were added. The improved A* algorithm reduced the average robotic moving time by − 18.07% and − 16.44%, respectively (Table 2). Consider Case 3 when obstacles with varying dimensions were added in pair. It is shown that for obstacles with < 50 mm in height. The improved A* algorithm using increased the robotic moving time in most cases. In case 3, when the number of obstacles increases with varying heights, leading to an increase in the number of passing points. In Table 3, for case 3A the duration for robotic movement obtained by digital twin method is getting shorter with speeds of 350 mm/s and acceleration of 800 mm/s^2 (− 0.43%). When the obstacles 3–4 with < 50 mm in height were added (case 3B), the A* algorithm using increased the robotic moving time over the range of velocity and acceleration under study (the average robotic moving time is 23.9%). When the obstacles 5–6 with < 50 mm in height were

Table 3 Durations for robotic movement when more pairs of obstacles added in a 50-mm decreasing order of height

A (mm/ s^2)	V (mm/ s)	ACDD3D4F-duration (s)	ACDD3D4F-%	ACDD3D4D5D6F-duration (s)	ACDD3D4D5D6F-%	ACDD3D4D5D6D7D8F-duration (s)	ACDD3D4D5D6D7D8F-%
500	250	4.792	− 2.12	5.944	21.41	6.792	38.73
	300	4.648	0.35	5.872	26.77	6.720	45.08
	350	4.6	2.13	5.848	29.84	6.696	48.67
	400	4.6	3.42	5.84	31.29	6.696	50.54
	450	4.6	3.98	5.84	32.01	6.696	51.36
	500	4.6	3.98	5.848	32.19	6.704	51.54
800	250	4.064	− 6.27	4.88	12.55	5.504	26.94
	300	3.84	− 2.83	4.728	19.64	5.392	36.44
	350	3.72	− 0.43	4.664	24.84	5.336	42.83
	400	3.656	0.88	4.632	27.81	5.304	46.36
	450	3.632	2.25	4.616	29.95	5.288	48.87
	500	3.64	3.41	4.624	31.36	5.296	50.45
1200	250	3.608	− 10.34	4.216	4.77	4.664	15.90
	300	3.344	− 6.70	4.008	11.83	4.512	25.89
	350	3.176	− 3.87	3.888	17.68	4.424	33.90
	400	3.08	− 1.53	3.824	22.25	4.376	39.90
	450	3.016	0.00	3.792	25.73	4.344	44.03
	500	2.984	1.36	3.776	28.26	4.328	47.01
Mean					23.90		41.36

also added (case 3C), the improved A* algorithm using further increased the average robotic moving time by (the average robotic moving time is 41.36%). It implies that the digital twin method is better than the improved A* algorithm when obstacles with varying heights used; whereas the reverse is true when obstacles with constant height used.

6 Conclusion

In this study, the experiments have been performed to find robotic path with a difference in size and number of obstacles. Our results show that the applicability of improved A* algorithm and digital twin method is dependent upon the robotic speed, acceleration, and number of passing points. Although the improved A* algorithm is always better than the digital twin method in terms of shortening robotic moving distance, the influence of robotic velocity and acceleration on its inertia when changing direction of movement must be taken into account. It results in the fact that the robotic moving time could get shorter by the improved A* algorithm in the case of adding obstacles with constant height or by the digital twin method in the case of adding obstacles with varying heights. Thus, the application of a robotic path planning method needs to adapt to the characteristics and a number of obstacles in reality.

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