Gait-Planning-Based Path Planning for Crocodile-Inspired Pneumatic Soft Robots

Yize Ma[1,2], Qingxiang Wu[1,2](✉), Zehao Qiu[1,2], and Ning Sun[1,2]

[1] Institute of Robotics and Automatic Information Systems (IRAIS), College of Artificial Intelligence, Nankai University, Tianjin 300350, China

[2] Institute of Intelligence Technology and Robotic Systems, Shenzhen Research Institute of Nankai University, Shenzhen 518083, China

wuqx@nankai.edu.cn

Abstract. In many cases, soft robots with their inherent flexibility, ease of interaction, and high adaptability in complex environments, receive widespread attention. Among them, gait planning is a key technology to ensure the performance of soft robots. This paper proposes a gait-planning-based path planning method for crocodile-inspired pneumatic soft robots. Based on the crocodile-inspired pneumatic soft robots, the motion characteristics of the robot with different gaits are analyzed. Then, a path planning method using A* algorithm is proposed according to the environmental characteristics of road width, obstacles, and other road information. The experimental environment is built independently to complete robot path planning and gait selection and verify the effectiveness of the proposed gait-planning-based path planning method.

Keywords: Gait planning · Path planning · Soft robots · A* algorithm · Pneumatic robots

1 Introduction

In recent years, many different types of soft robots have entered people's vision, and they are widely used in various fields, including production, life, scientific research, and exploration [1,2]. What's more, soft robots perform excellently in human-computer interaction [3]. Additionally, due to their simple structure, pneumatic soft robots have become increasingly popular [4]. Compared with rigid robots, pneumatic soft robots can avoid irreversible damage when subjected to external impacts. Because soft robots generally have the characteristics of lightweight and softness, they are more suitable for movement in complex environments. In theory, pneumatic soft robots have infinite degrees of freedom [5], making their applications flexible [6]. Flexibility makes it possible for pneumatic soft robots to achieve complex nonlinear movements relying solely on simple inputs.

X. Jing et al. (Eds.): ICANDVC 2023, LNEE 1152, pp. 677–688, 2024.
https://doi.org/10.1007/978-981-97-0554-2_51

Conventional quadruped robot research has been fully developed [7], while the quadruped soft robots are still worth exploring. Mosadegh *et al.* have designed pneumatic networks actuating rapidly [8]. Wu *et al.* designs a quadruped robot inspired by tortoises using pneumatic networks as actuators [9]. The tortoise-inspired robot performs amphibious movements on land and water and is considered capable of many tasks, such as disaster rescue and field exploration, due to its excellent adaptability to the environment. Inspired by these works, this paper proposes a path planning method based on gait analysis for crocodile-inspired pneumatic soft robots, and independently builds a set of experimental platform for verification.

2 Design of Robots and Gaits

2.1 Robots Introduction

A pneumatic soft robot inspired by crocodiles with 8 actuators is established in Fig. 1, which includes four leg actuators, one trunk actuator, and one tail actuator. Due to the interlinked and orthogonal structure, the crocodile's legs will bend down and back simultaneously if inflated. Alternating inflation and deflation can make the crocodile-inspired pneumatic soft robot move forward. Two traditional bellows pneumatic actuators are placed parallel on both sides of the spine for turning. The tail actuator can swing left and right through the grid chambers arranged on both sides. In addition, tail swinging will affect the center of gravity and stability of crocodiles, which serves as the main organ for swimming in the water.

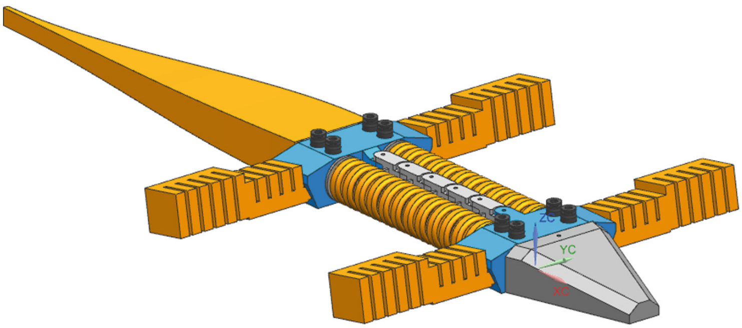

Fig. 1. Three-dimensional model of the crocodile-inspired pneumatic soft robot.

2.2 Gaits Analysis of Crocodile-Inspired Pneumatic Soft Robots

According to the motion mode of crocodiles, three typical gaits of crocodile-inspired pneumatic soft robots are analyzed. (see Fig. 2). In detail, a **tort** gait is designed for a pneumatic soft crocodile. Due to the low center of gravity of the

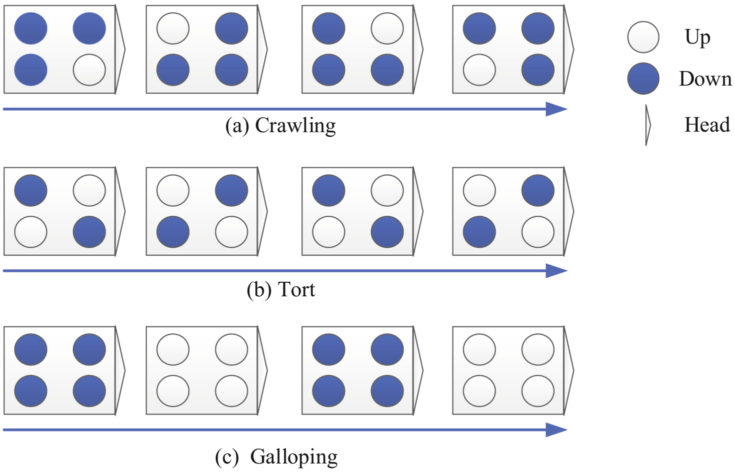

Fig. 2. Three typical gaits of the crocodile-inspired pneumatic soft robot.

crocodile-inspired pneumatic soft robot, it is usually not necessary to consider its stability. Based on the movement of crocodiles in nature state, a **crawling** gait is designed. When crocodiles leisurely walk, they only move one leg at a time, which consumes less energy for their actions. A **galloping** gait is usually not considered by rigid robots because it may impact on the driver, while the resilience of soft robots allows them to use this easily controlled gait. Additionally, the crocodile-inspired pneumatic soft robots use ubiquitous air to transmit energy without the need to carry additional actuated and control module, making the robot lighter. Specifically, lightweight will help reduce the impact of actuators interacting with the environment during movement. When input different air pressures into the bellows on both sides of the spine, the crocodile-inspired pneumatic soft robot can achieve steering.

Several experiments are conducted to measure the characteristics of the crawling gait, the tort gait, and the galloping gait. Table 1 shows that the tort gait runs fastest, galloping gait slower than the tort but rectilinearity is high, and the crawling gait is the slowest. Furthermore, the tort gait with the fastest linear velocity is beneficial for turning. Based on these data, different gaits will be integrated into path planning.

2.3 Gait-Planning-Based Path Planning

A* Algorithm with Orientation Constraint. A* algorithm is mature and widely used [10,11]. In this paper, a constrained A* algorithm is adopted, which considers that crocodile-inspired pneumatic soft robots can only move forward and turn, and introduces a turning radius to determine whether the robot can reach the next point. In other words, the orientation of robots is taken into account. Although the robot position is considered discrete, its orientation is

Table 1. Characteristics of gaits for the crocodile-inspired pneumatic soft robots

Experiment	v_{Crawling}(mm/s)	v_{Tort}(mm/s)	$v_{\text{Galloping}}$(mm/s)	Turning radius (mm/s)
1	1.09	4.01	2.15	28.57
2	1.15	4.18	2.29	33.02
3	1.04	4.29	2.01	29.75
4	1.19	4.22	2.39	29.41
5	1.20	4.25	2.33	30.09
Average	1.13	4.19	2.23	30.16
Rectilinearity	High	Low	High	-

continuously changing and constrains the direction of motion. The A * algorithm always chooses the position where the sum of past costs and future costs is the lowest, and this minimum value is usually represented by $f(i)$. In this paper, the direction should be restricted, then $f(i)$ is modified as follows:

$$f(i) = g(i) + h(i) + m \cdot t(i), \tag{1}$$

where $h(i)$ is the Euclidean distance meaning the cost estimation between the current cell and the target cell, $g(i)$ is the length of the path from the initial cell to the current cell through the selected path, $t(i)$ is the value brought by turning, and m is the weight. Especially, $t(i)$ is a nonlinear function that depends on the turning radius of the crocodile-inspired pneumatic soft robot. To make $t(i)$ meaningful, cells are given a direction d as the robot passes through it. The turning radius of the crocodile-inspired pneumatic soft robots is 0.3 m (see Table 1), and the side of the cell is determined as 0.1 m. In this paper, $t(i)$ can be expressed as follows:

$$t(i+1) = \begin{cases} e^{k|d_{i+1}-d_n|} - 1, & 0 < |d_{i+1} - d_n| < d_{\text{Max}}, \\ \infty, & \text{other}. \end{cases} \tag{2}$$

where d_{i+1} is the angle between this cell to the next cell, which is usually $\pi/4$, 0, and $-\pi/4$, d_n is the direction of the robot when it is passing through the cell (see Fig. 3), $|d_{i+1} - d_n|$ represents the angle between the upcoming cell and the current direction and k is the weight of $|d_{i+1} - d_n|$, k and m can determine range of $t(i)$, d_{Max} is the maximum turning angle. By increasing $f(i)$ to ∞, the algorithm is restricted from reaching cells the crocodile-inspired pneumatic soft robots cannot reach, thereby making the A* algorithm more in line with the actual situation of crocodile-inspired pneumatic soft robots. In a word, by introducing $t(i)$, constraints on the direction of robot motion can be achieved.

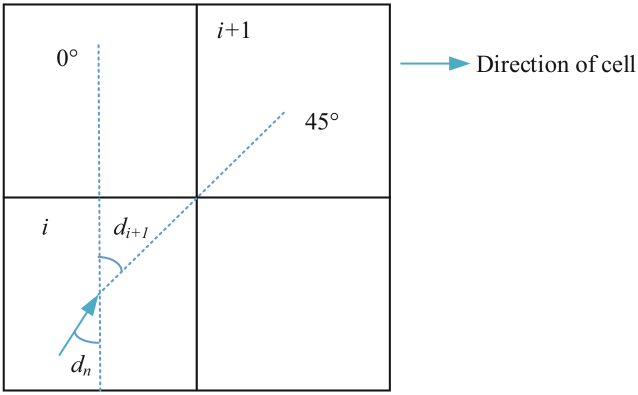

Fig. 3. Diagrammatic sketch of d_{i+1} and d_n.

At the same time as each iteration, the cell's directional information of d_n is updated. If the cell diagonally ahead is the next to arrive, the crocodile-inspired pneumatic soft robots will make a turn, which action makes the direction change when the crocodile-inspired pneumatic soft robots reach the next cell. The angle increment (Δd) is the distance between two cells divided by the turning radius, which is rewritten as follows:

$$\Delta d = \begin{cases} l_{(i,i+1)}/r, & \text{turning right,} \\ -l_{(i,i+1)}/r, & \text{turning left,} \end{cases} \tag{3}$$

where $l_{(i,i+1)}$ is the distance between this cell and the next cell, and r is the turning radius of the crocodile-inspired pneumatic soft robots. Defining clockwise as the positive direction, then Δd is positive when turning right but is negative when turning left. In addition, expanding obstacles is a common method to avoid the tedious calculations caused by the collision volume of robots. In this paper, two experimental scenes are built:

Scene 1: A passage surrounded by four obstacles, with a narrowest point of 0.43 m can be passed through.

Scene 2: A passage surrounded by four obstacles, with a narrowest point of 0.30 m can be passed through.

Based on the these two scenes, Fig. 4 and Fig. 5 are obtained. Through introducing direction into the A * algorithm and considering the changing angle, when and where the crocodile-inspired pneumatic soft robots should turn can be obtained, which is helpful for gait switching and control.

Gaits-Planning-Based Path Planning. In terms of gaits, crocodile-inspired pneumatic soft robots can be considered with a crawling gait for normal cruising

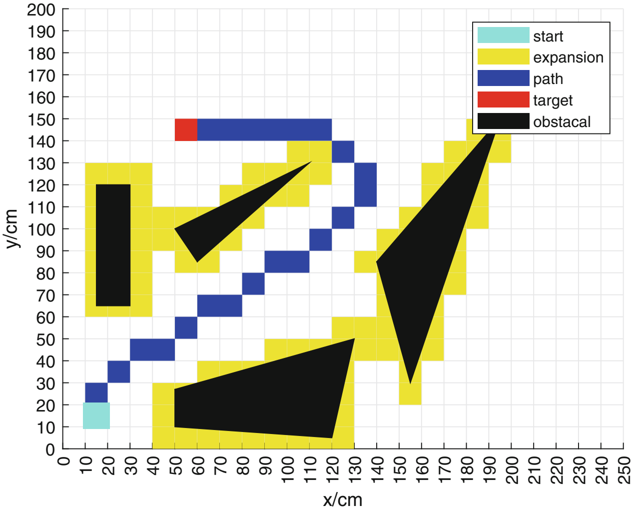

Fig. 4. Path in scene 1 (wide road).

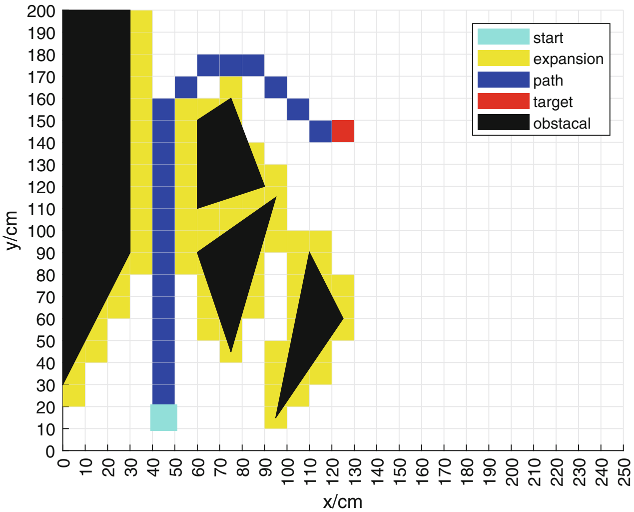

Fig. 5. Path in scene 2 (narrow road).

before receiving a task. After receiving tasks or signals, the tort gait with fast speed is considered. If the path requires the rectilinearity, a galloping gait with better rectilinearity will be adopted. The limbs and tail of the crocodile-inspired pneumatic soft robots are all soft material, so in case the robot collides with an obstacle, as long as the approximate direction is correct, it can return to the predetermined track on its own. Although the crocodile-inspired pneumatic soft robots can pass through a restricted narrow passage, when the two sides of the passage are not rigid obstacles but traps, the situation will be different. At this point, it is necessary to consider the rectilinearity of the robot's actions, such as when crossing a single wooden bridge without guardrails on both sides. In scene 2 (see Fig. 5), the channel through which robots can pass is narrow, and a more linear gait must be adopted not only to ensure that the robot can enter the predetermined channel but also to avoid collision with obstacles.

2.4 Experimental Results

In the experiments, the crocodile-inspired pneumatic soft robots achieve different gait movements by setting with a series of input signals that conform to the predetermined path. The motion capture platform (SLIK PRO 700DX) is applied to obtain the trajectories of the crocodile-inspired pneumatic soft robots. The marked points are located on both sides of the connector which connects the crocodile's tail and truck (see Fig. 6). In the experiments, an air pump is used to drive the crocodile-inspired pneumatic soft, which is the only energy source of the crocodile-inspired pneumatic soft robots. A computer is used to connect to the MicroLabBox (dSPACE R2021a) for valves control and is also used to operate the motion capture platform. The valves are the components that adjust the air pressure proportionally based on voltage. The MicroLabBox provides a platform for combining software and hardware. The entire system cannot only input sequence signals in advance to operate the crocodile-inspired pneumatic

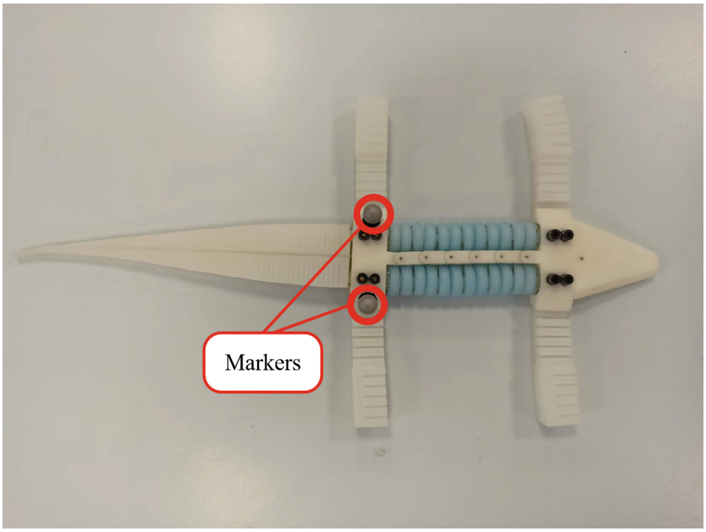

Fig. 6. The self-fabricated crocodile-inspired pneumatic soft robot.

soft robots offline, but also operate the crocodile-inspired pneumatic soft robots in real-time through the computer and the MicroLabBox. The experimental environment for crocodile-inspired pneumatic soft robots is shown in Fig. 7.

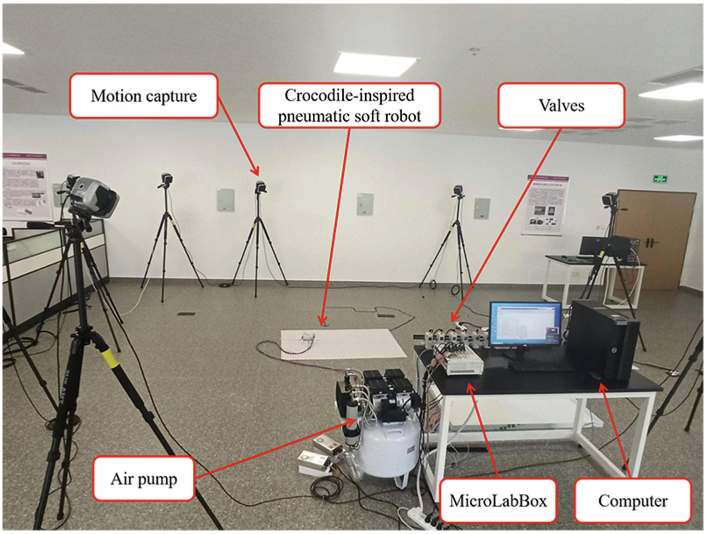

Fig. 7. Experimental environment for crocodile-inspired pneumatic soft robots.

In scene 1 (Fig. 8, Fig. 9, and Fig. 10), where the road is wide, crawling is chosen to reach the target quickly. According to the path obtained by the A* algorithm, the crocodile-inspired pneumatic soft robot needs to first move forward, turn right, and then go straight. In the long straight motion, the obstacles on both sides are far from the head, tail, and limbs of the crocodile-inspired pneumatic soft robot, so it is possible to directly choose a faster gait. Then the crocodile-inspired pneumatic soft robot needs to turn right to reach the target. Figure 10 shows the trajectory of the crocodile-inspired pneumatic soft robot in a wide channel environment. Based on Fig. 10, it can be acquired that the crocodile-inspired pneumatic soft robot with proposed method can reach the target without collision.

In scene 2 (Fig. 11, Fig. 12, and Fig. 13), the road is just enough to accommodate the crocodile-inspired pneumatic soft robots, so we ensure that its route is straight to avoid colliding with obstacles. Galloping gait is the best one for this situation. Then the crocodile robot needs to turn right at an obtuse angle to reach target. Figure 13 shows that the crocodile-inspired pneumatic soft robot with proposed method can maintain straightness in a narrow and long straight channel, enter a predetermined orbit, and reach the target.

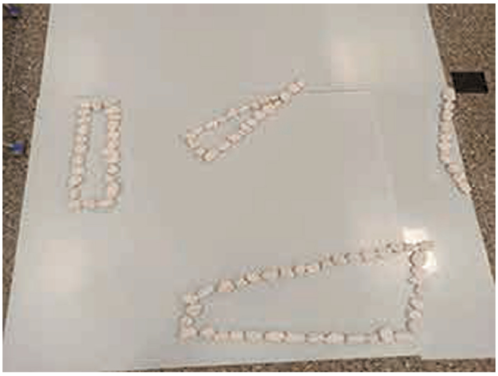

Fig. 8. Scene 1: wide road experimental environments.

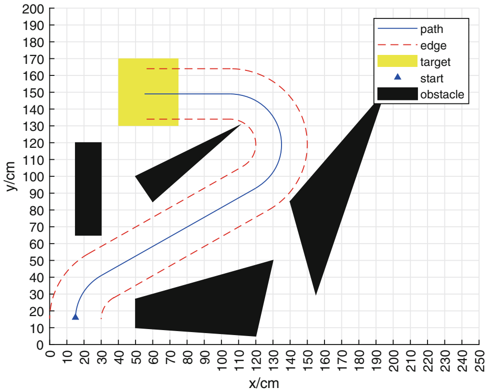

Fig. 9. Trajectories acquired A* algorithm in scene 1.

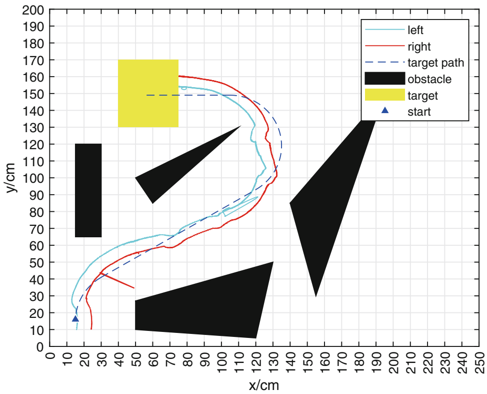

Fig. 10. Actual trajectories of crocodile-inspired pneumatic soft robot in scene 1.

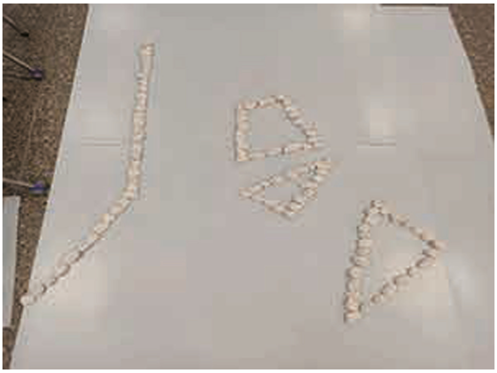

Fig. 11. Scene 2: narrow road experimental environments.

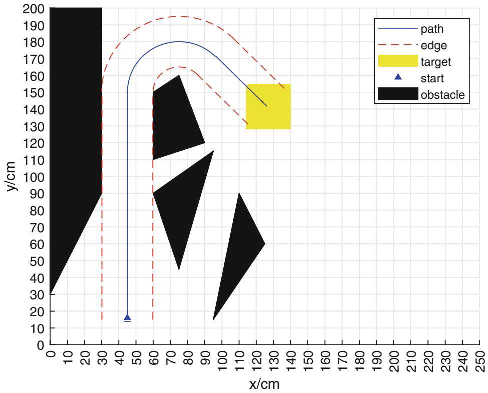

Fig. 12. Trajectories acquired A* algorithm in scene 2.

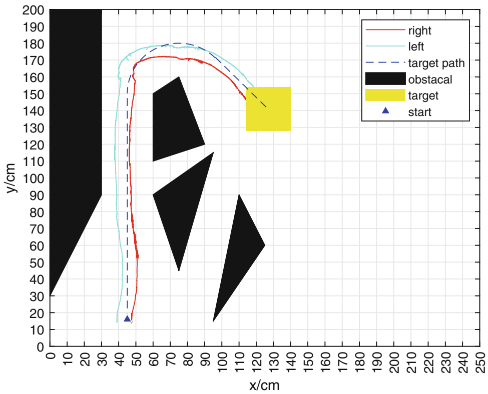

Fig. 13. Actual trajectories of crocodile-inspired pneumatic soft robot in scene 2.

3 Conclusion

This paper proposes a gait-plan-based path planning method for a pneumatic crocodile-inspired soft robot. By analyzing three gaits (crawling, tort, and galloping), the characteristics of three gaits are obtained. In detail, the crawling gait consumes less energy, with high rectilinearity, but slow speed, making it suitable for autonomous cruising without tasks. The tort gait is fast and suitable for targeted tasks, but it is limited in narrow environments because of poor rectilinearity. The galloping gait has moderate speed, with high rectilinearity, which can compensate for shortcomings of the tort gait, and also has obstacle-crossing ability. To this end, a path planning algorithm based on A* algorithm is proposed, taking path width and robot mobility into account. Finally, the effectiveness of the proposed method is verified through two scenes of different environmental experiments (the narrow scene and the wide scene). At the same time, the experimental results demonstrate that the proposed method can ensure the pass ability of the crocodile-inspired pneumatic soft robots.

Acknowledge. This work was supported in part by the National Natural Science Foundation of China under Grant 52205019 and Grant 62373198, in part by the Guangdong Basic and Applied Basic Research Foundation under Grant 2023A1515012669, in part by the China Postdoctoral Science Foundation under Grant 2021M701779, in part by the Fundamental Research Funds for the Central Universities under Grant 078-63233098, and in part by the State Key Laboratory of Robotics and Systems (HIT) under Grant SKLRS-2023-KF-13.

References

1. Armanini, C., Boyer, F., Mathew, A.T., Duriez, C., Renda, F.: Soft robots modeling: a structured overview. IEEE Trans. Rob. **39**(3), 1728–1748 (2023)
2. Rus, D., Tolley, M.: Design, fabrication and control of soft robots. Nature **521**, 467–475 (2015)
3. Whitesides, G.: Soft robotics. Angew. Chem. **57**(16), 4258–4273 (2018)
4. Polygerinos, P., Correll, N., Morin, S., Mosadegh, B., Onal, C., Petersen, K., Cianchetti, M., Tolley, M., Shepherd, R.: Soft robotics: review of fluid-driven intrinsically soft devices; manufacturing, sensing, control, and applications in human-robot interaction. Adv. Eng. Mater. **19**(12), 1700016 (2017)
5. Trivedi, D., Rahn, C., Kier, W., Walker, I.: Soft robotics: biological inspiration, state of the art, and future research. Bionics Biomech. **5**(3), 99–117 (2008)
6. James, W., et al.: Soft robotics: a review of recent developments of pneumatic soft actuators. Actuators **9**(1), 3 (2020)
7. Li, J., Wang, J., Yang, S.X., Zhou, K., Tang, H.: Gait planning and stability control of a quadruped robot. Comput. Intell. Neurosci. **2016**, 9853070 (2016)
8. Mosadegh, B., Polygerinos, P., Keplinger, C., Wennstedt, S., et al.: Pneumatic networks for soft robotics that actuate rapidly. Adv. Func. Mater. **5**, 2163–2170 (2014)
9. Wu, M., et al.: A fully 3D-printed tortoise-inspired soft robot with terrains-adaptive and amphibious landing capabilities. Advanced Materials Technologies **7**(12), 2200536 (2022)

10. DuchoE, F., Babinec, A., Kajan, M., BeEo, P., Florek, M., Fico, T., Jurišica, L.: Path planning with modified A star algorithm for a mobile robot. Procedia Engineering **96**(2014), 59–69 (2014)
11. Abed, M., Lutfy, O., Al-Doori, Q.: A review on path planning algorithms for mobile robots. Eng. Technol. J. **39**(5), 804–820 (2021)