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COMFORT NAVIGATION IMPROVEMENT OF PATH PLANNING TASK IN HUMAN–ROBOT INTERACTION

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Abstract. Navigation is the core of mobile robot applications, but traditional configurations have great difficulties in dealing with dynamic human factors. This means that new service robots must not only undertake the task of autonomous navigation, but also be good at social interaction and consider harmonious coexistence with others. This paper designs a social navigation based on improving the comfort of human–robot interaction. The social space costs and constraints are modeled using asymmetric Cauchy functions, and predictions are made using human–human or human–robot interaction, and pedestrian encounters are considered. The difference in the degree of attention paid to oneself, front, rear, left, and right when encountering obstacles or pedestrians establishes the benchmark for the corresponding model. On this basis, a map cost function is constructed, which can use different constraints on the path and specify that the robot does not enter certain spaces, or enter specific spaces under certain circumstances. The A* and jump algorithms were modified based on the map cost function, and experiments were conducted in MATLAB. The experimental results show that the designed social comfort navigation can effectively realize the function, pedestrians' personal space is guaranteed, and goal-oriented intentionality is understood by the robot. Understanding, coexistence and adaptability of mobile service robots are significantly improved.

Keywords: *mobile robot control, A* algorithm, comfort navigation, obstacle avoidance, path planning*

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ПОВЫШЕНИЕ КОМФОРТА НАВИГАЦИИ ПРИ ВЗАИМОДЕЙСТВИИ ЧЕЛОВЕКА И РОБОТА В ЗАДАЧЕ ПЛАНИРОВАНИЯ ПУТИ

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Аннотация. Автономное движение мобильных роботов в динамически меняющейся внешней среде сопряжено с существенными трудностями. Это означает, что мобильные роботы должны не только выполнять задачу автономной навигации, но и хорошо взаимодействовать не только с неподвижными препятствиями, но и с людьми, движущимися в рабочем пространстве робота. Разработан алгоритм планирования и управления траекторным движением с учетом социальной навигации, обеспечивающей комфортное взаимодействие человека и робота. Затраты и ограничения социального пространства моделируются с использованием асимметричных функций Коши, составляются прогнозы взаимодействия „человек–человек“ или „человек–робот“. На этой основе строится функция стоимости карты, которая может использовать различные ограничения. Алгоритмы A* и jump были модифицированы на основе функции стоимости карты. Результаты экспериментов, выполненных в среде MATLAB, показывают, что предложенные алгоритмы могут эффективно реализовать решать задачу планирования пути с учетом социальной навигации. Благодаря разработанным алгоритмам выстраивается оптимальный маршрут робота, и личное пространство пешеходов гарантировано. Комфорт с учетом социальной навигации при взаимодействии человека и робота значительно улучшился.

Ключевые слова: *управление мобильным роботом, A* алгоритм, комфортная навигация, объезд препятствия, планирование пути*

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Introduction. Since mobile robots can be widely used in industrial manufacturing, agricultural production, medical services, daily life and other fields, research interest in the field of robotics has become increasingly intense in the past few decades. From industrial robotic arms and drones to today's Autonomous Ground Vehicles (AGVs) and various home robots, the types and functions of robots are becoming more and more diverse. People are paying more and more attention to the use of robots, and have put forward higher requirements for robots to be autonomous, intelligent, and "humane". From the initial problem of autonomous navigation of mobile robots to the large-scale emergence of mobile service robots, people are more inclined to study the interaction between humans and robots, so that the comfort between humans and robots can be greatly improved.

Based on the current development trend of robot technology, two predictions can be made: first, the focus of robot application will shift from the industrial structured environment to the unstructured environment where humans live; second, the emerging industry of robots will become, like computers, a must-have for every home. For example, researchers across Europe are innovating mobile robot designs and solving fundamental indoor problems, efforts that could eventually lead to home robots becoming a world standard. Some countries, such as South Korea and the United States, have formulated strategic plans involving companies, universities, and research institutions with the aim of occupying the indoor service robot market.

The International Federation of Robotics (IFR) defines a service robot as a semi-autonomous or fully autonomous robot that can complete service tasks that are beneficial to human health [1]. In the past ten years, the market demand for service robots has been growing day by day, showing huge development space [2].

In the battle against the COVID-19 epidemic that broke out in early 2020, mobile service robots also played an important role, helping medical staff reduce their work, reduce contact frequency, and achieve contactless distribution and delivery. In addition, smart spaces such as smart homes and unmanned offices have also expanded the application scope of service robots and enriched the ways they serve and help humans [3].

The entry of service robots into our homes and workplaces provides broader opportunities for engineering research into mobile robots. However, in order to naturally integrate into the environment where humans live, mobile robots must not only be technologically advanced, but also have good interaction design and consider human preferences, needs or other influences.

Therefore, in order to work in a more social way, the robot must understand the corresponding spatial conventions and behave accordingly. In short, when service robots share activity spaces with people, they need to maintain a social space related to social conventions to take into account human comfort.

Social space refers to the spatial distance maintained by individuals in various social and interpersonal relationships. It is a direct reflection of social accessibility and will directly affect the human-robot interaction experience, that is, comfort. Different environments or cultures will lead to differences in spatial language. The term was originally proposed by Hall to describe human management of space [4]. People's spatial interaction relationships include intimate, personal, social and public, and different spaces are reserved for specific relationships [5]. When humans are too close, they often cannot remain comfortable and they feel personal space has been violated. Therefore, intrusion into the personal space of others must be avoided as much as possible. For example, when a robot crosses a crowd, it is likely to affect the people around it, especially when the robot's behavior is considered extremely unsociable [5].

Now, the problem of human–robot interaction can be seen as finding an optimal or suboptimal trajectory without collision based on some pedestrians and obstacles between the starting position and the destination in a working environment with obstacles. Robot path planning methods can be divided into two categories [6–12], namely classic algorithms and heuristic methods. The main classic algorithms include cell decomposition, visibility map, artificial potential field and sampling-based methods [13]. The robot's free workspace can be divided into cells and an adjacency graph planner is used to find collision-free paths. Between the starting point and the target point on the plane, if their connecting line segments can directly reach each other, a feasible path is drawn to find the optimal shortest path of the robot in the graph.

In order to better integrate robots into human life and improve comfort, this paper has done the following research: on the problem of path planning, a comfort level based on the improved A* algorithm [2] and the jump point algorithm is proposed navigation.

The core application context for this algorithm lies within the realm of service robots operating in public spaces. These environments are inherently dynamic and populated with individuals who may have varying degrees of comfort with robots. Our algorithm specifically addresses the challenge of maintaining comfortable social distances while ensuring efficient navigation and task execution by robots.

First discusses the interaction between pedestrians and robots, combines the comfort issue of human–robot interaction, uses the asymmetric Cauchy function to establish a model, and then implements robots, pedestrians and obstacles on the A* algorithm and jump point algorithm obstacle avoidance to improve user comfort during human–robot interaction.

Social space costs and constraints. In this section, we start from the comfortable distance between people and between people and obstacles, supplemented by Hall's concentric circle theory to define the basic criteria of social constraints, and then design a method to enable people to interact with robots with comfortable distance. Finally, the cost modeling and simulation of the social space is performed, in which the non-standard Cauchy function surface value is used to define the passing cost size. And in practical applications, pedestrian comfort can be fully guaranteed.

People's spatial interaction relationships can be divided into intimate, personal, social and public, and different spaces are reserved for specific relationships [8]. When the robot crosses the crowd, it may affect the people around it, especially when the robot's behavior is considered extremely unsociable.

Personal space [14] refers to the surrounding area actively maintained by an individual, which usually includes the scope of his or her physical activities and a certain social distance. This concept is also known as spatial comfort because it is closely related to the level of comfort an individual feels. Others should not intrude into a personal space without the individual's permission, as doing so may cause discomfort or uneasiness.

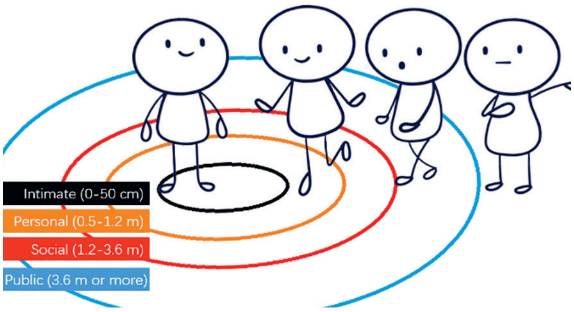
According to the concentric circle theory proposed by Hall [4], the space around an individual can be divided into four specific areas based on social interaction distance. The first level is intimate distance. This is the minimum or no gap in interpersonal communication, which is what we call "intimacy". Its range is between 6 to 18 inches (~15–44 cm).

The second level is personal distance. This is a slightly measured distance between people, with less direct physical contact. The short range of personal distance is between 1.5–2.5 feet (46–76 cm), which is just right for shaking hands and friendly conversation, and is suitable for socializing with acquaintances.

The third level is social distancing. This has gone beyond an intimate or acquaintance relationship, but reflects a more formal relationship of social or etiquette. Its close range is 4 to 7 feet (1.2 to 2.1 meters), suitable for work environments and social gatherings.

The fourth level is the public distance, which is the distance maintained between the speaker and the audience during public speaking. Its close range is 12 to 25 feet (about 3.6 to 7.6 meters). The definitions of these areas and distances in this article are shown in Fig. 1. Pedestrian comfort guarantee based on social space.

Our selection of distance parameters was meticulously guided by Edward T. Hall's theory of proxemics and relevant psychological research findings. The purpose behind these chosen distances is to simulate an ideal range for robot–human interactions, thereby fostering natural and comfortable communication between both parties. By maintaining suitable social distances, we aim to minimize



Schematic diagram of concentric circles

Space	Distance
Public space	>3.6 m
Social space	1.2 m
Personal space	0.45 m
Intimate space	≤0.45 m

Fig. 1

Fig. 2

human discomfort or perceived threats from robots, enhancing the comfort and naturalness of human–robot interactions.

According to daily life experience, space comfort is affected by both subjective and objective factors. Subjective factors refer to individual feelings, which often play a decisive role in interactions; objective factors are more complex, such as gender differences, length of sight distance, walking speed, and density of pedestrians and obstacles in the environment. A lot of related research work has emerged to study changes in personal space. Some studies have shown that when bypassing obstacles, personal space will be adjusted according to the speed of movement, or that the spatio-temporal model of individual comfort can be determined based on changes in speed parameters. In addition, there are also theories related to dynamic scenarios [15].

It is generally accepted that personal space is asymmetric, and this article focuses specifically on asymmetries resulting from direction sensitivity. Pedestrians generally have different sensitivity to interactions from different directions, or the sensitivity is related to the orientation of the posture. For example, when pedestrians move, they mainly pay attention to the dynamics of pedestrians and obstacles in front, and are less sensitive to the movements behind them and to the left and right sides; for example, during peak hours, people walk on the right, so they pay attention to the right side, as shown in Fig. 2.

Based on the above understanding, this article proposes the following social space establishment rules, which serve as the benchmark for the following establishment costs [16]:

1) generally, when stationary pedestrians or obstacles are detected, the personal space distance proposed by Hall is used as the reference distance for social interaction;

2) at the same time, using distance to represent the directional sensitivity of pedestrians determines that the distance to the front of the personal space is slightly larger than the rear, and the distance to the right is slightly larger than the left;

3) the private space closest to the human body should be strictly off-limits;

4) when there are crowds of people, you should try to avoid them.

Cost modeling and simulation based on social space. In social interactions, pedestrian status information and underlying social conventions are very important. Therefore, in order to better reflect the information status, living habits and potential social customs of pedestrians in the social interaction space, in this subsection we establish a social interaction space model that uses the two-dimensional asymmetric Cauchy formula to calculate the space the value of each point within is used as the passing cost of the mobile robot. When the value of a certain point is larger, it means that the point is closer to the human body, and the robot should not pass here; and when the value of a certain point is smaller, it means that the point is further away from the human body, and the robot can consider passing it. These values are added to the A-star algorithm cost function to reflect the cost of passing a certain point. In this way, when planning the robot's path, we can prioritize lower-cost paths and avoid areas that are too costly.

In general, the mathematical form of the two-dimensional Cauchy function is as follows:

$$f_c^i(x, y) = A\frac{1}{(1 + f_{cx}^i + f_{cy}^i)}. \tag{1}$$

Formula (1) represents the personal space cost function based on the Cauchy function, where each variable and symbol is defined as follows: f_{cx}^i — the cost value at position (x, y) for the i-th pedestrian; A — amplitude, representing the magnitude of the Cauchy function (this parameter determines the projection range of personal comfort space, which can be adjusted through social attributes to change the personal comfort space); $1 + f_{cx}^i + f_{cy}^i$ — the denominator of the Cauchy function, incorporating the cost components in both the and x directions.

Components in the x and y Directions described with the help of formulas:

$$f_{cx}^i = \frac{(d\cos(\theta_p + \theta_i))^2}{\sigma_x}, \tag{2}$$

$$f_{cy}^i = \frac{(d\sin(\theta_p + \theta_i))^2}{\sigma_y}. \tag{3}$$

These formulas represent the components in the x and y directions, respectively: $d\cos(\theta_p - \theta_i))$ — the distance component in the x direction; σ_x — the variance in the x direction, used to adjust the range of personal comfort space; $d\sin(\theta_p - \theta_i))$ — the distance component in the y direction; σ_y — the variance in the y direction, used to adjust the range of personal comfort space.

We also need to consider calculation of distance and angle:

$$d = \sqrt{(x_i - x_p)^2 + (y_i - y_p)^2}, \tag{4}$$

$$\theta_i = \text{atan2}(y_i - y_p, x_i - x_p). \tag{5}$$

Formulas (4) and (5) are used to calculate the distance and angle between the pedestrian and the reference point: d — the Euclidean distance between pedestrian i and reference point p; $(x_i - x_p)^2 +$ $+ (y_i - y_p)^2$ — the formula for calculating the distance between two points; θ_i — the azimuth angle between pedestrian i and reference point p; $\text{atan2}(y_i - y_p, x_i - x_p)$ — the function for calculating the angle from the reference point to the pedestrian, correctly handling angles in all four quadrants.

The asymmetric two-dimensional Cauchy surface simulated with MATLAB is shown in Fig. 3.

In order to establish a social interaction space model, the corresponding parameter values need to be determined:

1) when pedestrians are in a stationary state, referring to Hall's theory, the maximum distance H_q of the social space in the front direction can reach 1.2 m, while the maximum distance H_h of the invisible area directly behind is selected to be 1.0 m;

2) in general intersection situations, pedestrians will pass on the right side of the road according to social custom. Therefore, the farthest distance H_y of the social space on the pedestrian's right side should be larger than the left side H_z. Value: H_y = 1.2 m, H_l = 1 m.

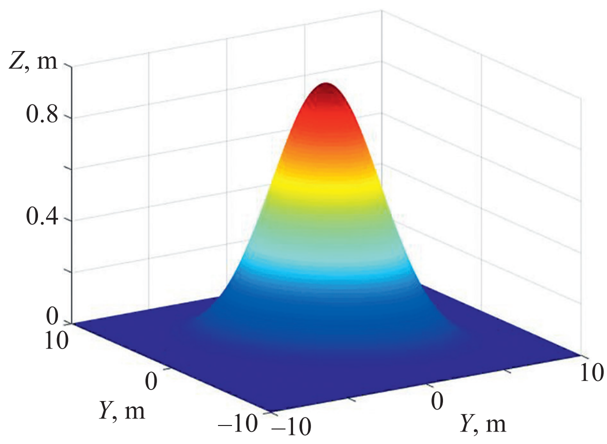


Fig. 3

Hierarchical social dynamic cost map construction. Layered Costmaps technology based on occupancy grids was first proposed by

David V. Lu. These layers include static layers, barrier layers, expansion layers, etc. [3], with the purpose of providing richer semantic information for planning, thereby achieving more ideal results. This section builds a hierarchical social dynamic map based on the established social cost model, aiming to improve people's comfort during human–robot interaction.

Traditional cost maps only deal with costmap as hard constraints. If hard constraints are used to increase social space, many valid paths (non-collision paths) will be excluded. However, in a dynamic cost map, the space points around obstacles are assigned a value 0 ~ Inf calculated by the two-dimensional Cauchy function, with free space marked as the lowest cost 0 and obstacles as the highest cost Inf. Because of some special behaviors of humans, this method can be used to account for the areas affected by human factors and reduce the space occupied, thereby affecting costs.

Map cost function is written:

Algorithm: Compilation of Map Cost Function

```
Input:s,g,n,obs
Output:field,startposind,goalposind, costchart, fieldpointers
function[field….]=initializeField(….)
field = zeros(n,n);
q=sub2ind( [nn],obs(:,1),obs(:,2));
k=length(q);
for i=1:k
field(q(i))=inf;
end
h=1.2;
segema=power(1/2*sqrt(power(h,2)/log(10)),2);
for t=1:
field(obs(t,1)+0,obs(t,2)+1)=field(obs(t,1)+0,
obs(t,2)+1)+ceil(100*exp((power(0,2)+power(1,2))/(2*segema1)));
end
startposind=sub2ind([n,n],s(1),s(2));
goalposind=sub2ind([n,n],g(1),g(2));
field(startposind)=0;
field(goalposind) = 0;
costchart = NaN*ones(n,n);
costchart(startposind) = 0;
fieldpointers = cell(n,n);
fieldpointers{startposind}='S';
fieldpointers{goalposind}='G';
fieldpointers(field==inf)={0};
```

Fig. 4 takes the A-star algorithm as an example. In this algorithm, the cost of pedestrians and obstacles in the map is set to infinite, and their surroundings are assigned values based on the cost calculated by the asymmetric Cauchy function above.

costchart | costs | field | field2

10x10 double

	1	2	3	4	5	6	7	8	9	10	11
1	0	0	0	0	0	0	0	0	0	0	
2	0	0	0	1	1	0	0	0	0	0	
3	0	0	5	Inf	Inf	5	0	1	0	0	
4	0	0	0	10	Inf	6	5	Inf	5	0	
5	0	0	1	5	Inf	Inf	0	Inf	5	0	
6	0	5	Inf	5	5	5	0	5	0	0	
7	0	0	5	0	0	0	0	0	0	0	
8	0	0	0	1	0	0	1	0	0	0	
9	0	0	5	Inf	5	5	Inf	5	0	0	
10	0	0	0	5	0	0	5	0	0	0	
11											

Fig. 4

It can be seen from Fig. 4 that obstacles and pedestrians will be given Inf, which becomes the highest cost and is not allowed to pass. However, a calculated cost will be given near obstacles and pedestrians, so that if the robot passes, it will avoid obstacles and pedestrians, ensuring robot and pedestrian comfort. This can be optimized through the map cost function [17], and using softer constraints on the path, you can specify that the robot does not enter certain spaces, but can enter a certain space under certain circumstances, or enter certain distances.

This section establishes a cost map based on the Cauchy function mentioned above and applies it to the algorithm to improve people's comfort during human–robot interaction.

Algorithm improvement based on social cost. The A* algorithm (A-Star) is an efficient direct search method for solving the shortest path in a static road network. It is also an effective algorithm for solving many search problems [18]. In this algorithm, the closer the distance estimate is to the actual value, the faster the final search speed is. The A* algorithm is the most commonly used heuristic algorithm, and its core formula is:

$$F(n) = G(n) + H(n).$$

This article adds the map cost function $I(n)$, and its core formula becomes:

$$F(n) = G(n) + H(n) + I(n).$$

Among them, $G(n)$ represents the accumulation of costs from the starting node to the current node; $H(n)$ represents the heuristic function, used to estimate the movement cost from the current node to the end node, usually calculated using Euclidean distance or Manhattan distance; $I(n)$ represents the map cost [19]; $F(n)$ is the sum of the three costs. According to this formula, when searching for a path with the A* algorithm, the node with a smaller $F(n)$ value is always selected.

To implement path search based on the A* algorithm and Cauchy, two sets are needed: open list and close list. In the open list, the grids that the path may or may not pass are stored; while the closed list contains grids that no longer need to be paid attention to. The block diagram of the algorithm is shown below in Fig. 5.

Experiment and comparison. This experiment runs on a Windows 10 64-bit system and uses the MATLAB platform for simulation experiments. The CPU uses Intel i5-4200U, 4 cores and 4GB. The environment model of the simulation experiment uses a grid map. The map consists of $n \times n$ grids, where black grids represent obstacles and white grids represent free movement areas. In the experiment, the red one is the starting point and the blue one is the end point.

Aiming at the path planning problem of mobile robots, this experiment designed three sets of comparative experiments to verify the performance of the algorithm. The first experiment compared the effects of the traditional A* algorithm and the improved A* algorithm after adding the Cauchy function; the second experiment compared the effects of the jump point algorithm and

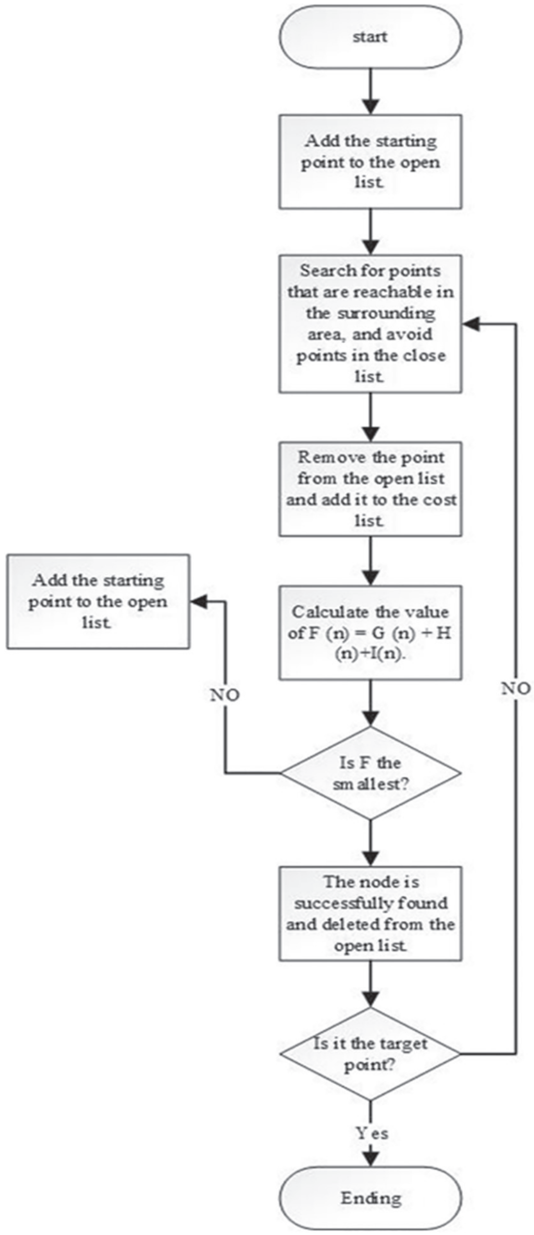


Fig. 5

the improved A* algorithm; the third experiment compared The effect of the improved jump point algorithm and improved A* algorithm is improved.

Experiment 1 uses a 10 × 10 map, using the A* algorithm and the A* algorithm that adds map cost. The map in this experiment is relatively simple and easy to visually demonstrate the difference between the traditional A* algorithm and the improved A* algorithm.

From Fig. 6, it can be clearly seen that compared with the traditional A* algorithm when encountering pedestrians or obstacles, the improved A* algorithm can effectively avoid pedestrians or obstacles.

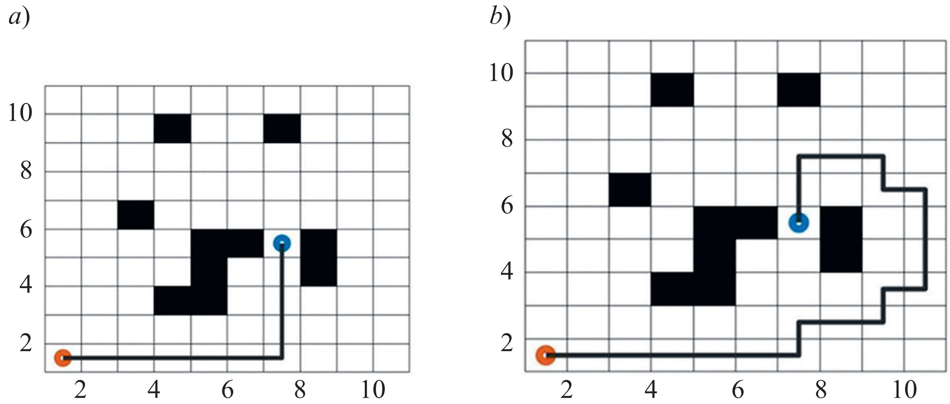


Fig. 6

Experiment 2 uses a 20 × 20 map, and conducts two comparative experiments using the traditional jump point algorithm and the improved A*. The black movement trajectory in the picture is the jump point algorithm, and the red movement trajectory is the improved A* algorithm.

Jump point algorithm and improved A* algorithm experimental diagram is shown in Fig. 7. It can be seen that the improved A* algorithm is much better than the jump algorithm in avoiding pedestrians and obstacles.

Experiment 3 uses a 10 × 10 map to test the improved jump point algorithm and improved A* algorithms for comparison.

Jump point algorithm and improved A* algorithm experimental diagram is shown in Fig. 7, *f*. It can be clearly found that the improved jump point algorithm still avoids obstacles as much as possible while ensuring the optimal solution.

Experiment 4 uses a 10 × 10 map to test the improved jump point algorithm and improved A* algorithms for comparison.

Experimental diagram of improved jump point algorithm and improved A* algorithm is shown in Fig. 8. It can be clearly found that the improved jump point algorithm and the traditional A* can still avoid obstacles as much as possible while ensuring the optimal solution.

Many obstacles can be overcome when using the asymmetric Cauchy function algorithm. This algorithm is very useful in public environments. It can help robots avoid most people. It can also help when searching for missing people or items. For example, in natural disasters such as fires and earthquakes, it can avoid some obstacles to ensure safety. To ensure the safety of rescuers and prevent them from being put into dangerous situations again while rescuing people.

Conclusion. This article is based on the hot topic of promoting human–robot interaction, starting from the design of the navigation system that takes human factors into consideration, and takes into account the comfort of pedestrians walking on the road when planning pedestrians' paths. It has broad prospects in promoting the application of robot technology in medical and service industries. The theoretical content will provide certain reference for meeting the comfort navigation needs of mobile robots and improving the level of human–robot interaction. The conclusions drawn are as follows:

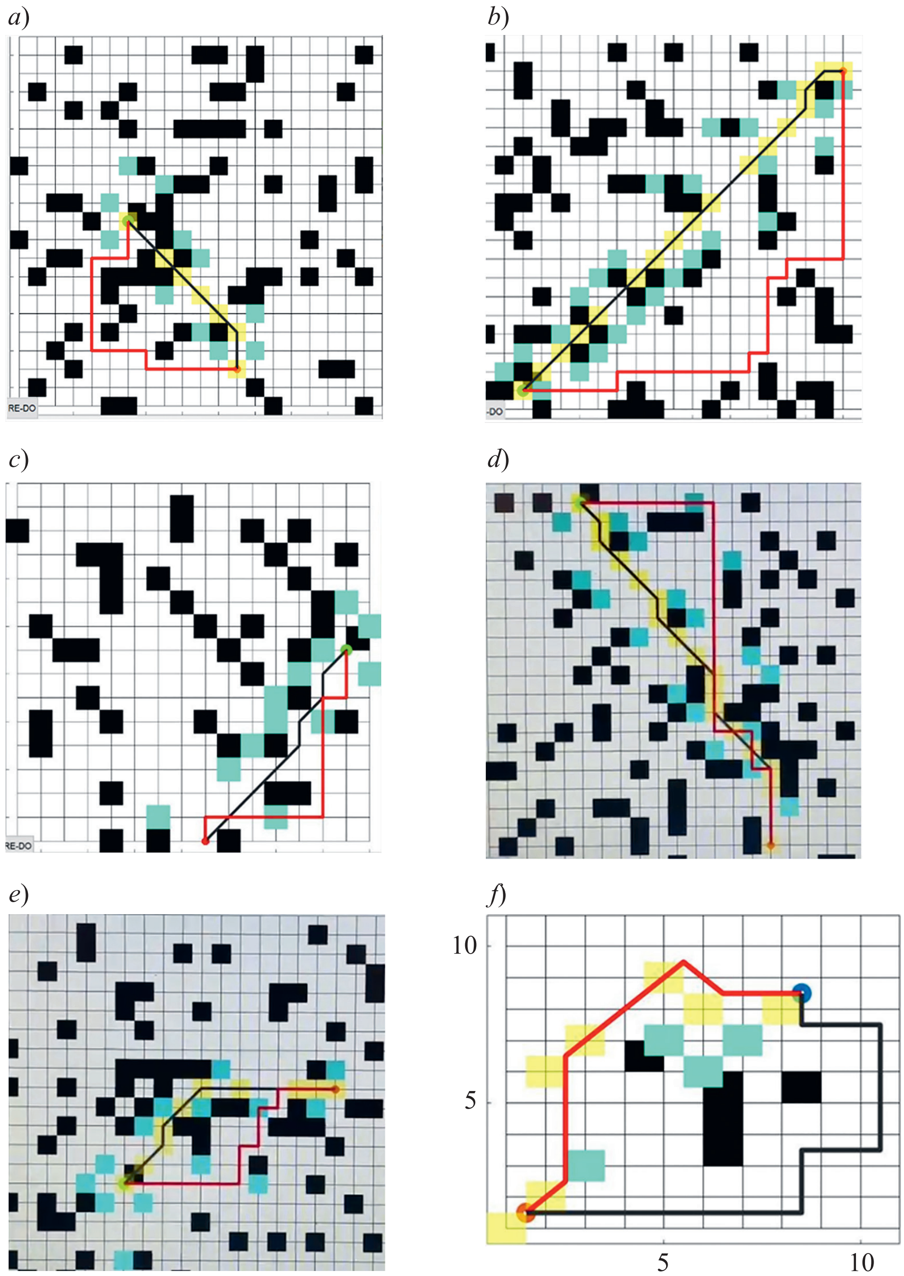


Fig. 7

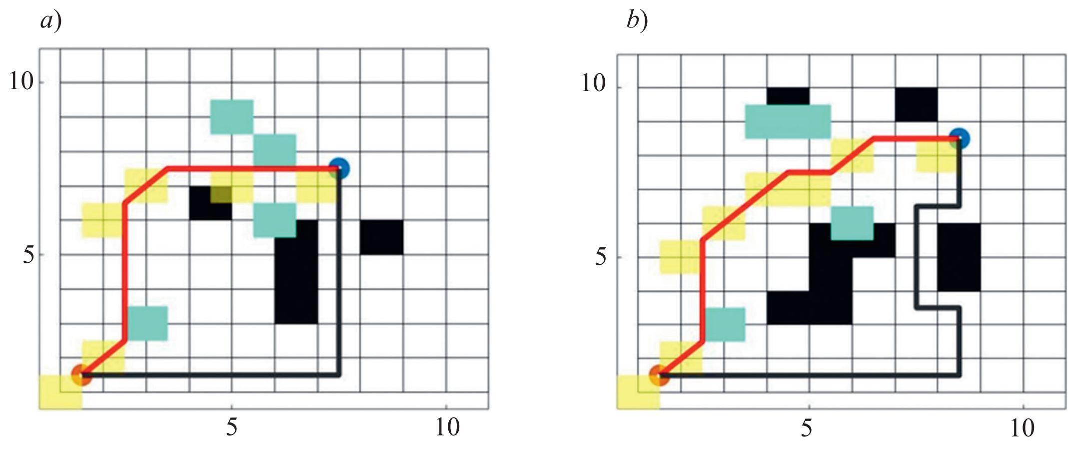


Fig. 8

1) a model based on human walking comfort is proposed, taking into account pedestrians' perception of pedestrians and obstacles around them. In addition, pedestrian-to-pedestrian interaction and attention mechanisms are also considered;

2) an asymmetric Cauchy function model based on social space cost was established, taking into account the impact of pedestrians (pedestrians, vehicles) and traffic facilities (crosswalk boundaries);

3) based on the established social space cost model, a hierarchical social dynamic map is constructed, aiming to improve people's comfort during human–robot interaction. You can specify that the robot will not enter certain spaces, but it can enter a specific space under specific circumstances;

4) based on the A* and jump algorithms, the proposed model is verified. The results show that the performance of the model can help pedestrians improve their comfort and happiness when walking.

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