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Visual Tracking Control of Humanoid Robot

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ABSTRACT This paper realizes the independent complex route tracking based on the NAO robot hardware platform and an image processing technology. The camera captures an image and extracts a path through a series of image processes, such as threshold, filtering, and edge detection. The path recognition algorithms and its edge array were used to calculate these relative parameters that drive the anthropomorphic robot for complex route walking for autonomous tracking. These paths include the straight-route curves and the cross routes, which were identified by the different features accurately. Particularly, the slope-matching method is proposed to enable it to track in accordance with the established rules when meeting the cross routes. These methods separately calculate the slope from the intersection to paths in all directions, and then, the matching rate can be obtained by a predefined matching formula in terms of choosing the best path forward. All complex route tracking experiments were conducted by an anthropomorphic robot. The experimental results show that the robot imposed a strong anti-interference ability to filter out the noise and have accurate complex route tracking, which is significant for the anthropomorphic robot visual guide.

INDEX TERMS Complex route tracking, anthropomorphic robot, image processing, path recognition, autonomous tracking, visual guide.

I. INTRODUCTION

Visual guide of the mobile robot is now in an important research direction for the anthropomorphic robot. Indoor guide based on vision can be divided into three categories: map-based guide, guide based on the map building, and without map guide [1]. With the development of service robots and gradual promotion into the family, it is essential for robots to complete service-relevant tasks independently in the indoor environment, which is closely related to guide technology. Gartshore *et al.* [2] proposed a guide algorithm occupying a grid-based map building frames and feature location detection, which processes RGB color images through a single camera online. The algorithm first detects the edge of objects by Harris edge and corner detection in the current image frame and then determines a peak from the edge-scanned features. Then, it considers all locations under arbitrary depth. The detected features are projected into a 2D image plane, and the system module can calculate the location according to the odometer data and extraction features of an image.

A method based on map building needs to rely on the global map as a basis of guide decisions [3]–[6]. This method of guide will produce problems when the environment changes. Saitoh *et al.* [7] proposed a method for the wheeled mobile robot tracking in the middle of the corridor with a single USB camera and laptop. The method uses the Hough transform to detect corridor boundaries and walls, then the robot goes along the center of corridors. These methods cannot meet the robots in complex environments for complement-related tasks. One of the methods on the automatic guided vehicle guide system uses a guide technology based on the guideroute [8]–[9]. In one practical application, the mobile robot moves along a predesigned geometry of completed search-and-rescue missions [10]–[12]. Many researchers have proposed applying the visual system to autonomous mobile vehicles [13]–[16] to capture and analyze the visual images of guideroutes laid in the ground to overcome the limitations of other sensors. So this research applies this guide technology to the anthropomorphic robot by laying an indoor guide route, which can effectively address the complex issues of the

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indoor environment, and it will have significance on service robots in the family in the future.

In recent days, the visual guide is mainly on the wheeled robot with a camera in the exact position. At the same time, the anthropomorphic robot moves like people, causing more difficult motion control and control accuracy compared to the wheeled mobile robot. Because people's pursuit of anthropomorphic robots impels the study of the biped robot and the visual guide, that is the purpose of this research. The anthropomorphic robot is a anthropomorphic robot not exceeding a meter in height [17] with visual, auditory, tactile, walking, greeting, dancing, and other human-like actions. Owing to its body and movements, the anthropomorphic robot attracts the attention of more and more people. Combined with its lovely appearance, it can be a companion robot accompanying a child in the family. The NAO robot indoor guide can be utilized to grasp a tiny toy, drop litter, and even walk into the room to wake up the baby. At the same time, the rich indoor information greatly reduces the speed of image processing, and puts higher requirements on the self-location algorithm [18]–[26].

In order to simplify the guide and enable better adaptability to the environment, so this paper applies the route technology to anthropomorphic robot by laying indoor guide routes. The anthropomorphic robot with visual-route guide system can help complete some relatively fixed-position tasks, in a certain sense, liberate the labor force. The main difficulty of this research is how to generate real-time appropriate output according to the obtained image to control the anthropomorphic robot walking and minimizing the deviation between the robot and the center of the route.

In order to achieve the expected testing target, we need to solve the following problem: to propose a high-speed route extraction method which not only can quickly find the path of interest from the image, but also can accurately find the forward path when encountering the intersection.

Futhermore the proposed curvature and slope estimation parameters were used as the input to the PID controller can reduce tracking error. The PID controller with angle compensation to adapt to different curves. When applied collectively, the anthropomorphic robot's navigation performance was comparatively robust and accurate compared with other control methods with complicated algorithm designs. Therefore our control advancement is low time consumption. In this paper, we develop the visual system of the anthropomorphic robot and show how it follows the guideroutes. We use the image mean filter and the edge extraction of a Canny operator to obtain the trajectory information and wield the interval scan method to improve the accuracy of information. In path recognition, the slope-matching methods were used to choose the best path forward when meeting a cross.

This paper is organized as follows: For the first section it gives the visual guide principle of robot tracking, the image recognition method, and its theoretical basis for a variety of paths. For the second section, it introduces the software and hardware platforms and gives some pseudo code. Finally, we present experimental data and analyze the results of the anthropomorphic robot visual tracking.

II. METHODS

A. BASIC THEORY

The basic autonomous tracking theory of an anthropomorphic robot based on visual is: assume that the anthropomorphic robot can walk on a flat surface and depend on the difference of the grey value between the black routes and background to identify the guide paths by the image processing. And we can find the path's center route by extracting the edge point of a path. On the basis of the center's location, it determines the robot's attitude and the relative position of the path to control robot autonomous walking forward in the right direction. The anthropomorphic robot visual guide principle is shown in Fig. 1. The guide parameters as the primary inputs of the controller comprise the angle deviation and position deviation [25]. The controller outputs the control directives based on the algorithm of the controller to make the robot change its attitude; angle deviation and position deviation changes accordingly. The updated value obtained by the vision sensor and the image processing transfers into the controller again. In the course of autonomous tracking, the robot will meet routes, curves, cross, and each path model, which will be presented in this paper.

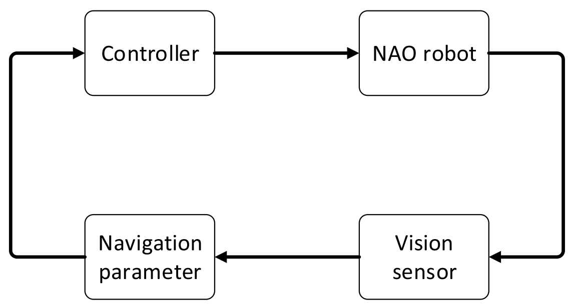

FIGURE 1. The robot guide schematics.

The simple straight-route path-tracing model is shown in Fig. 2. The anthropomorphic robot camera acquires the guide path of the model as a straight route, through the edges of image identification algorithms for the path and the path's center route. The distance between the center route and the center of the image bottom is the position deviation, d. The angle deviation between the center route and the Y-axis is the angle α.

When walking on the curve path, the best tracking state is to keep the robot's forward direction always tangent to the curve path, so unlike the routine path tracking model. Following a curved path model of the angular deviation, α cannot be obtained directly through the edge. The follow curved path model is shown in Fig. 3. In the model, the midpoint of the connection at both ends of the curve direction of V1 and V0 are in the front-end of the curve tangent direction.

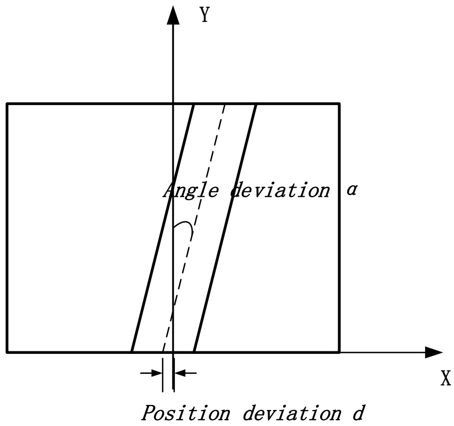

FIGURE 2. **The route model of robot guide.**

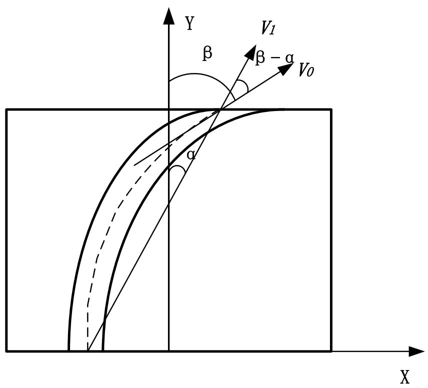

FIGURE 3. **The curve model of robot guide.**

The route model methods will make the β-α bias in the viewpoint of guide parameters. In order to compensate for the angle deviation β-α, this definition of the curvature of the path is as follows: the path center route of the arc length and chord length ratio is the curvature of the path, and the ratio is close to 1, closer to a straight route. Introducing the curvature, while it does not exactly make the robot forward direction tangent, it can remain on the path. It can be used to track the path and has good robustness.

The PID controller specially represents a common feedback loop component in industrial control applications and includes a proportional element P (which provides proportional control), an integral element I (which can eliminate steady-state errors), and a derivative element D (which can speed up the response of large inertial systems and weaken the overshoot trend). To be more refined, in this research, there two PID controllers are used: one to control the lateral speed and another to control the angular velocity of the anthropomorphic robot.

Fig. 4 is a block diagram for a path tracking control system for a anthropomorphic robot. Input signals to the control system are predicted values of positions and predicted angles. Position and angle errors are used as inputs to the PID controller, while the outputs are Vy and w parameters for driving the robot.

The discretized PID controller can be expressed as:

$$\mathrm{c}\,(\mathrm{n}) = K_P * e\,(n) + K_I * \sum_0^n e\,(n) + K_D * (e\,(n) - e\,(n-1)) \tag{1}$$

The first PID controller will control the positional deviation of the robot so that the distance between the center of gravity and the target path is minimized as it advances. The second PID controller will control the rotational angular velocity of the robot's footsteps, so that the robot keeps the forward direction tangent to the path, regardless of whether it is a curve or a straight route. If the angle of deviation between the reference point and the starting point is straightly used as the input parameter of the controller, the robot will have a large direction deviation and position deviation when tracking the curved path. Worse, it may lose the path information in the field of vision, resulting in tracking failure. Furthermore, when calculating the angle error, the angle of the tangent direction of the reference point and the difference of the target angle are estimated using the angle compensation method as follows:

$$e_\theta(n)^* = e_\theta(n) + c \tag{2}$$

where c presents the angle value of the compensation. Take the sin curve as the target path and use traditional PID controllers and PID controllers with angle compensation for comparison.

Autonomous robot track tends to encounter two paths that cross. The robot learns how to judge and choose along the path and is required to solve the problem. Due to time, the slope based on matching the path selection algorithm is proposed in this paper to solve the problem of cross direction in selecting the path. The cross-path tracing model is shown in Fig. 5. The O is for the intersection of the center route of the two cross paths, the center is as a regional center of the square, the four center routes will intersect with the edge of the square, and the O point slopes, respectively, for K1, K2, K3, and K4. Here the formula for matching K is defined:

$$K_{l,m} = 1 - \frac{k_l - k_m}{k_l + k_m} \tag{3}$$

where $l \in [1, 4]$ of the integer, $m \in [1, 4]$ of the integer, and $l \neq m$, when the matching rate K is closer to 1, then the most likely of the two paths is a continuous path. By matching the slope of the path selection algorithm, one can correctly select the forward path without intersections and sometimes may not know what is encountered.

B. PROCESS AND METHOD OF IMAGE RECOGNITION

The visual tracking comes from the main sensor camera. The camera obtains the path information and methods to find the edges of the path information by the image recognition, and the guide is obtained through the algorithm parameter. The preprocessing of the image recognition process is shown in Fig. 6. Therefore, the speed, the noise immunity of the

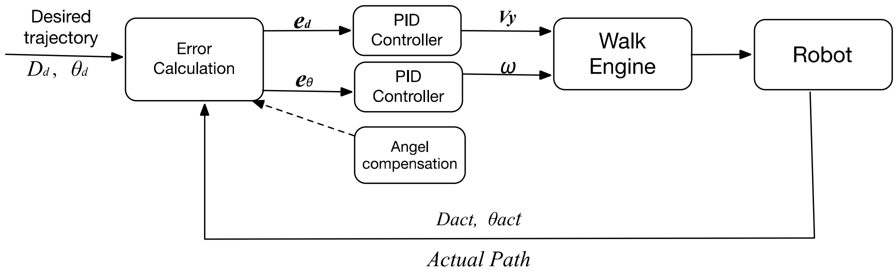

FIGURE 4. Block diagram for anthropomorphic robot trajectory tracking control.

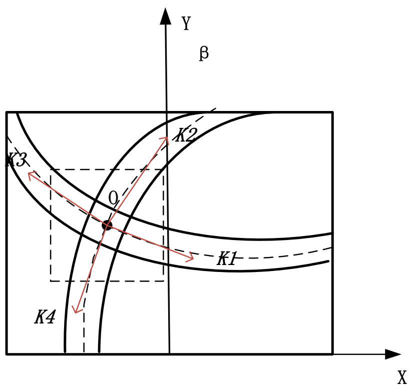

FIGURE 5. The crossed route models of robot guide.

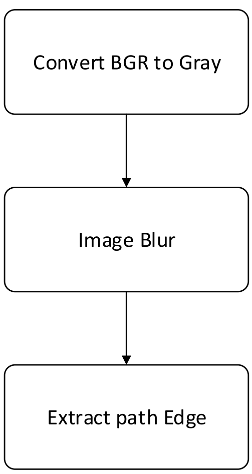

FIGURE 6. The image processing flow.

image processing capability, and the accuracy of edge detection are the prerequisites to get the guide parameters.

In the image processing, most of the treatment is required prior to color being converted into gray-scale calculations and identification. The conversion formula is as follows:

$$\text{Gray} = \frac{\text{R} * 30 + \text{G} * 59 + \text{B} * 11 + 50}{100} \tag{4}$$

Path recognition's main purpose is to detect the edges of the guide path. Commonly used algorithms for edge detection are the Sobel operator, Canny operator, and Laplacian operator. Due to the strength of the edge detection algorithm based on the image first derivative, second derivative, and derivation of noise sensitivity, it must use some filters to improve the performance of noise-related edge detection. An image under the condition of keeping the detail of image noise suppression on the target image is indispensable to the image preprocessing operations, whose effect will directly affect the subsequent image processing and the analyses of the effectiveness and reliability. The image filters commonly used are the Gaussian filter, mean filter, and median filter.

Mean filter approach is about tackling the current pixel, choose a template, which is composed of several pixels in the vicinity, the mean value for the original pixel values of the template method is as follows.

$$g(x, y) = \frac{1}{\text{M}} \sum_{f \in s} f(x, y) \tag{5}$$

Because the extraction path requires very high detail in the image, the filter can effectively remove noises.

The Canny edge detection algorithm for the general process is as follows:

1. The image convolution with the Gaussian smoothing filters:

$$S[i, j] = G[i, j; \sigma] * I[i, j] \tag{6}$$

2. Using the first-order finite difference calculate the partial derivatives of two arrays P and Q:

$$\begin{aligned} P[i,j] &\approx (S[i,j+1]-S[i,j]+S[i+1,j+1]-S[i+1,j])/2 \\ Q[i,j] &\approx (S[i,j]-S[i+1,j]+S[i,j+1]-S[i+1,j+1])/2 \end{aligned} \tag{7}$$

3. Calculate the magnitude and position angle:

$$M[i, j] = \sqrt{P[i, j]^2 + Q[i, j]^2} \tag{8}$$

$$\theta[i, j] = \arctan(Q[i, j]/P[i, j] \tag{9}$$

4. Non-maxima suppression: refinement in the magnitude image of the roof retains only the points of local maximum amplitude. Reducing the variation range of the gradient angle to one of the four sectors, the direction angle and amplitude are as follows:

$$\xi[i, j] = Sector(\theta[i, j]) \tag{10}$$

$$N[i, j] = M/S(M[i, j], \xi[i, j]) \tag{11}$$

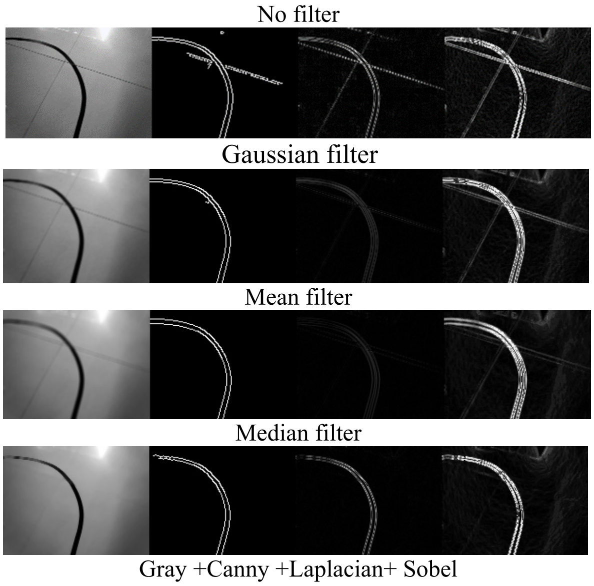

FIGURE 7. The filters combined with edge detection algorithm.

5. The threshold will be below the threshold of all assigned zero in order to get the edges of the image array.

The three types of filters and three edge detection algorithm image processing are shown in Fig. 7. Through three filters and the comparison of three kinds of edge detection effects, we can see the mean filter is the best and the effect can be obtained by a combination of a Canny operator, which can effectively filter out tile cracks and edges caused by light interference. The best path edges laid the groundwork for the accurate guide of the robot.

After the image preprocessing to a binary image that contains the path edges, the two-dimensional image is actually a grey value of two-dimensional array. The size of a two-dimensional array is the resolution of the image size. If the array $f(x, y)$ represents as shown in Fig. 8, then the coordinates (x, y) are the grey value of $f(x, y)$. The function $f(x, y)$ is a mathematical model of digital image, sometimes referred as the image function. The progressive scanning method obtains the path of the edge coordinates and are taken

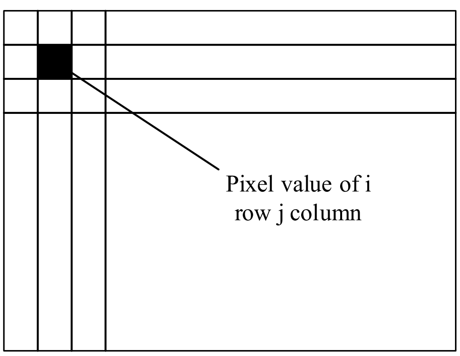

FIGURE 8. The digital image array.

into the center route of the column matrix by Formula (12). The matrix will serve as the guide parameters for the primarily calculated basis.

$$F(x, y) = \begin{pmatrix} f(1,1)\, f(1,2)\, \ldots\, f(1,j) \\ f(2,1)\, f(2,2)\, \ldots\, f(1,j) \\ \\ f(i,1)\;\; f(i,2)\;\; \ldots\;\; f(i,j) \end{pmatrix}$$
$$index = \left(I_1\ I_2\ \ldots\ I_i\right)^T$$
$$I_i = \frac{\sum y|F(x, y) = 255}{2} \qquad (12)$$

C. REAL-TIME PROCESSING METHOD

When a robot walks in the real time, it must make sure the image sampling periods are completed before the arrival of a next sampled image processing, that is, a real-time image processing. Identifying guide paths at the same time must also ensure the path velocity of image recognition. In identifying a frame path image, all the completed steps are shown in Fig. 6. To a certain extent, there will be assurance that it is robust, but it also brings a large amount of data processing, resulting in a decline in real time. Taking into account the guide path makes up the rows of pixels of the image, the continuous path between two adjacent routes is similar to the corresponding left and right edge points. For this purpose, in addition to dividing the upper and lower processed region, furthermore, in order to reduce the amount of image data processing, the same frame and upper row of the path image edge points are used to qualify the next route of the adjacent range. Thereby reducing the required number of pixels processed in the route and achieving the aim of enhancing the real time. The steps are as follows:

In the image processing area, the first row of all pixels shown in Fig. 6 get the path around the edge. If it is not detected (corresponding to the row area without the path), then it continues on the next route until the left and right edges have detected points L1 and R1 as shown in Fig. 8.

After testing points to the first route, in the second row no longer handles the entire route, like step 1, but establishes a width, f, which is in pixels. The row [L1 − f, R1 + f] location within the process gets the edge points L2 and R2, then [L2 − f, R2 + f] between the left and right edges of the third row. Each row repeats until it has the guide paths in the region around the edge. As long as the f value selection in the interval [L1 − f, R1 + f] is found on the left and right edge of the route. When the f value is small, it may find an error or could not be found; if the f value is too large, it may be guaranteed to find them, but it increases the amount of computation and is not conducive to improve real-time performance.

Advantages: It significantly reduces the required number of pixel filters and edge detection, and the data throughput is reduced greatly and enhances the real-time effect. When the points on the test route, the edge points, are qualified as the candidate in a smaller range of candidates, to some extent, it improves the anti-jamming ability.

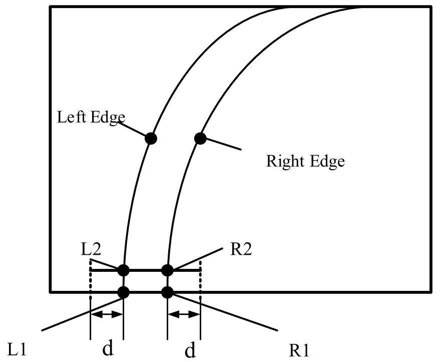

FIGURE 9. The path identification for the real-time processing diagram.

The problem: The method can be performed under no crossing paths by significantly reducing the image-processing time, but for the intersection, it will cause the robot to lose the path information and not be able to walk in the correct direction. Therefore, it must be introduced in the path mechanism of image processing. When it comes to intersections without using the real-time method, instead of the three-stage image processes, split the images into the top, middle, and bottom three parts as shown in Fig. 10. The processing time can be greatly reduced with the loss of most path information. In order to accelerate the image-processing speed and access more accurate path information, it uses the middle value method as shown in Fig. 10. The midpoints of the top and middle route with the actual paths are different, so it takes a middle route between their central at the top and make them move on the center point of the path and wire them; this method can reduce the processing time and make the path much closer to the true path.

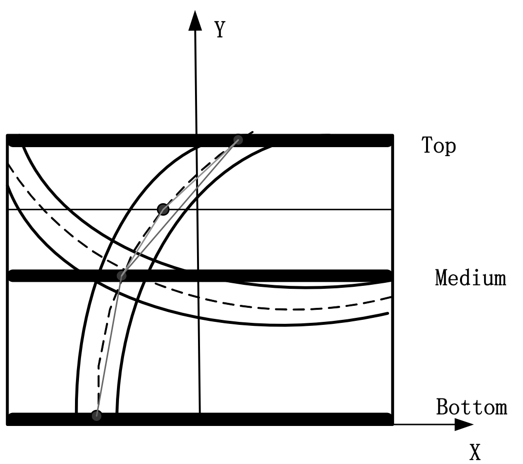

FIGURE 10. The crossed routes of the real-time processing method.

III. EXPERIMENTS

This vision-based complex route tracking robot research uses the French company Aldebaran's NAO anthropomorphic robot developed for the hardware platform. Its hardware uses the latest design and manufacturing, ensures the fluency of it, and is equipped with a variety of sensors. In addition, the NAO is available in Linux, Windows, or Mac OS operating systems using a variety of languages such as C++, Python, and Java. The programming software also provides graphical Choregraphe. Users are free to use their imaginations for its program; it can do many actions.

This research focuses on the anthropomorphic robot vision for development. Its head is up to 30 frames per second of a total of two 1280∗960-resolution cameras, whose locations and views are shown in Fig. 11. The path information is the anthropomorphic robot on the ground along the main source of information. So far, the image does not have much value, so choose the bottom camera and its head angle of rotation fixed down, enable it to get the foot path information, and do not obstruct the views by its feet. Their initial standing position and their views are shown in Fig. 12.

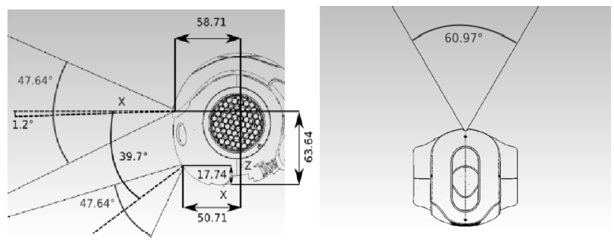

FIGURE 11. The anthropomorphic robot head camera field of view.

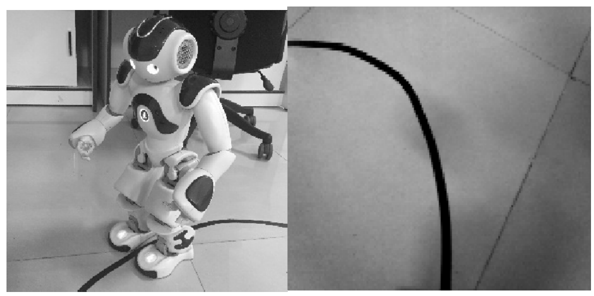

FIGURE 12. The anthropomorphic robot stands initial attitude and its vision.

This robot is designed using a graphical programming software, which is applicable for no-software-programming enthusiasts. Meanwhile, it also provides a development environment for many multiple languages, such as C++, Python, and Java. This research uses the Python2.7+OpenCV2.4 for the visual tracking software development. The Python is currently a very popular programming language. It is rich and powerful environment and can be convenient to write programs with application software. OpenCV is a BSD license (open source) release cross-platform computer vision library, which can be run on Linux, Windows, Mac OS, and Android operating systems. It is lightweight and efficient—a list of C functions and a small amount of C++ classes that are formed, as well as Python, Ruby, and MATLAB language interface, implements many common image processing and the computer vision algorithms.

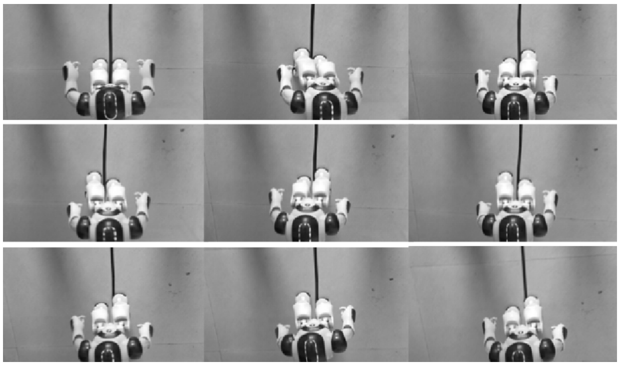

FIGURE 13. The anthropomorphic robot walks in straight.

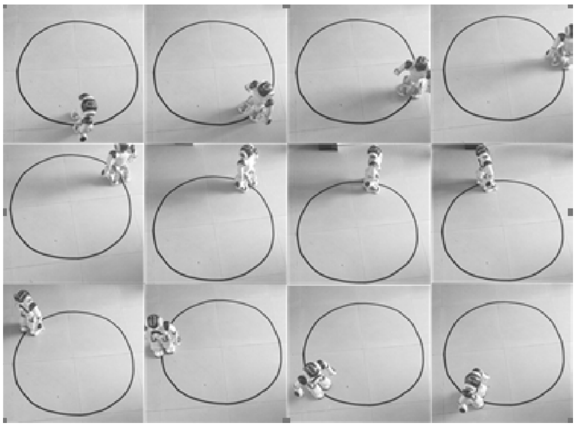

FIGURE 14. The anthropomorphic robot walks along a circular.

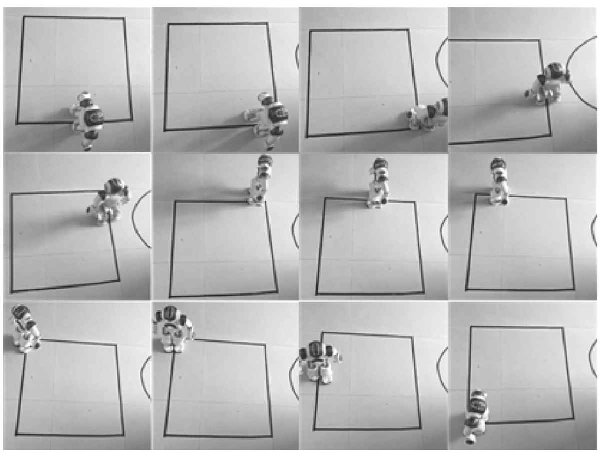

FIGURE 15. The anthropomorphic robot walks along a square.

This section will give some code and pseudo-code for using the Python programming language development.

A. PARAMETERS AND CODES

Keep the anthropomorphic robot initialization process in a fixed posture, select the bottom camera, enable it to capture the foot path from its beginning, and set its color space to RGB and the resolution to 160×120.

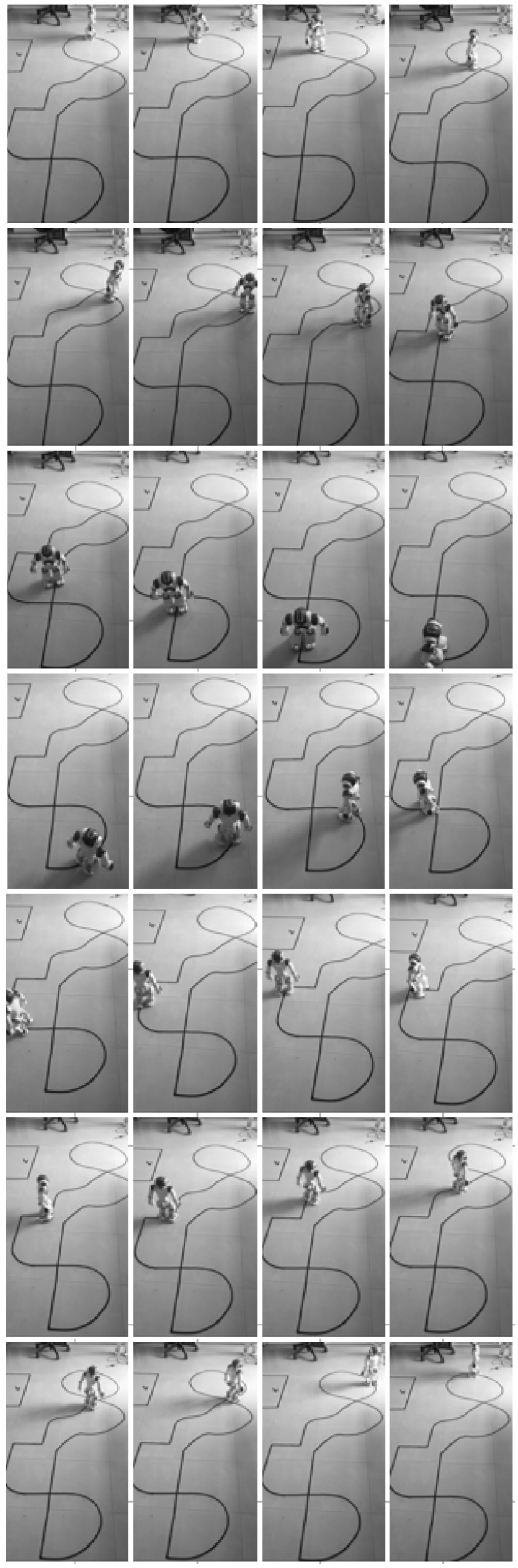

FIGURE 16. The anthropomorphic robot walks along a complex mixing route.

The GetImageRemote gets the ALVideoDeviceProxy agent of images. The image filtering and edge detection use OpenCV functions in the library as follows:

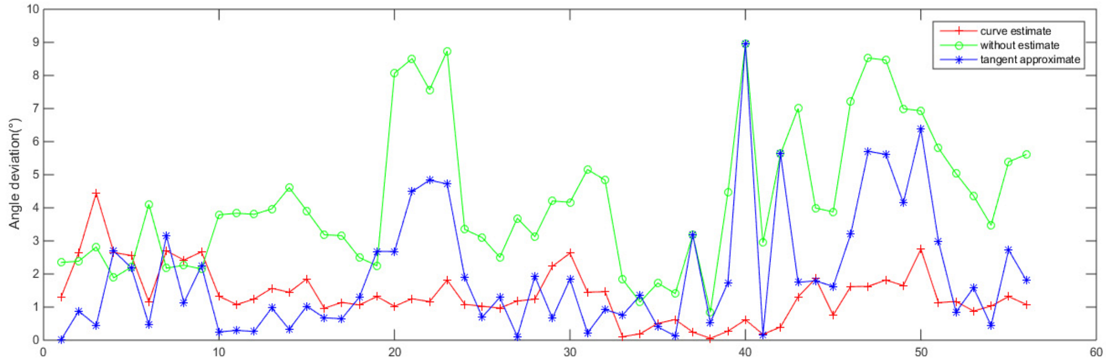

FIGURE 17. The comparisions of angle deviation for the three different methods.

The pseudo-code for the image processes

```
Input Image;
Image Blur
Convert RGB to Gray
Edge detector
```

The pseudo-code for path detection algorithm

```
If Route Cross: Kmatch();
Find Path Edge()
Else:
Bottom left index, Bottom right index = Find Path
Edge()
For i in range(1, Process Width)
Left index, right index = Find Path Edge()
Calculate Theta and Offset
Walk
```

This method will greatly reduce the amount of data for image processing. The extraction of the path can achieve different effects (at the sixth statement to the ninth statement in the pseudocode) by setting the length and width of the rectangle (at the first statement to the fifth statement in the pseudocode) at the same time. Properly reducing the long side of the rectangle provides good noise immunity from the noise outside the target path (at the tenth statement to the eleventh statement in the pseudocode). The path restored by connecting the center point is closer to the original path by decreasing the short side of the rectangle, but it will increase the processing time loss in response.

B. EXPERIMENTAL TESTS

This complex rout tracking experiment is set on the ground laying routes, curves, and crossed routes to verify the accuracy and stability theory. A 15mm-wide black-tape stick was used in experiments on the light-colored marble floor. The anthropomorphic robot-tracking experiments are shown in Fig. 13–16. Fig. 13 is the anthropomorphic robot walking in a straight route. Fig. 14 is the anthropomorphic robot circle route tracking. Fig. 15 is the anthropomorphic robot along the path of the quadrangle tracking. Fig. 16 is the anthropomorphic robot along a complex mixed-route tracking. Table 1 shows its accuracy for a variety of complex route tracking.

TABLE 1. The accuracy for a variety of complex route tracking.

Path	Test (number)	Success (number)	Percent %
Straight	20	20	100%
Circle	20	20	100%
Squar	20	20	100%
Complex	20	18	90%

C. RESULTS AND DISCUSSION

For tracking the comparatively simple route, it performs robustly and accurately. As for these complex routes, it may lose views when the anthropomorphic robot walks along a high curvature of the curve. The error comes mainly from the anthropomorphic robot in walking forward in the process due to the foot-striding swaying the view of lead. Furthermore, The proposed method can quickly determine the angle of rotation of the robot during walking. It does not need to obtain the curve equation by the binomial fitting of the sampling point to calculate the tangent slope of the point. The proposed method is acquired by fitting with the binomial formula. the method of uncompensated lateral deviation and approximate tangent estimation is compared with the steering angle error. The results are shown in Fig. 17.

It can be seen from Fig. 18 that the deviation of the steering angle value obtained by this method from the angle obtained by binomial fitting is basically around 1 degree, enabling the robot to move forward during the course of walking along the arc. Better to stay tangential to the route, and at the same time

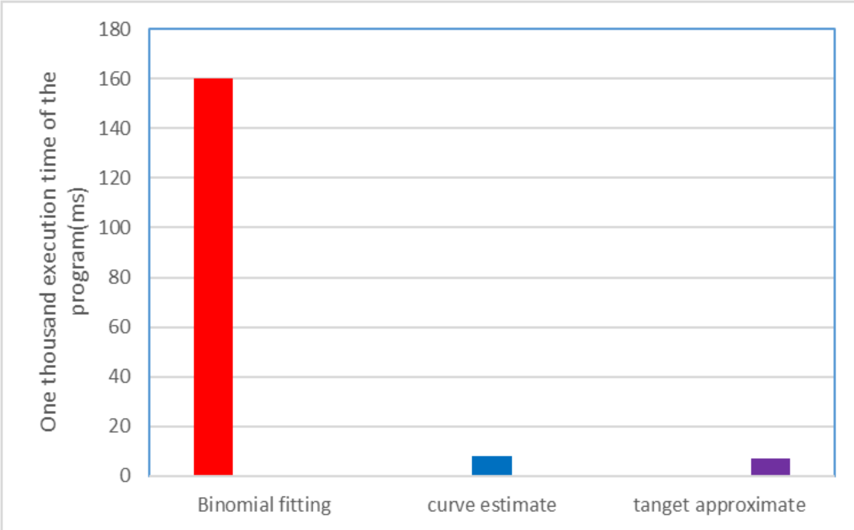

FIGURE 18. The comparisions of program execution time for various methods.

nearly 25 times faster than the binomial fit in the running time of the program.

IV. CONCLUSIONS

The aim of this paper is to study a visual route guide system for a anthropomorphic robot. In this proposed system, the anthropomorphic robot was used and its own vision sensor to realize the guide. The proposed method for rectangular search in this paper can quickly and accurately extract the path in the image, which not only improves the real-time performance of the robot visual guide, but also lays a foundation for the robot to accurately follow the route.

These experimental tests show that using image processing can effectively extract edge information of the path recognition algorithm, distinguish the various paths, and accurately calculate the control parameters, so that the robot can follow the path of stable walking. But the camera jitter has certain interference on the track, which needs to be improved in later studies.

AUTHORS' CONTRIBUTIONS

A method uses the mean filter and Canny operator to extract edge information and improve the processing speed by using interval threshold and segmented scanning. We proposed a slope-matching method to find the exact direction to walk forward. All these methods applied on the anthropomorphic robot perform comparatively robustly and accurately in the experimental tests.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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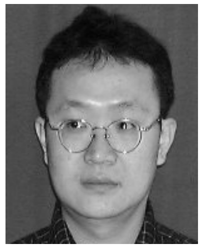

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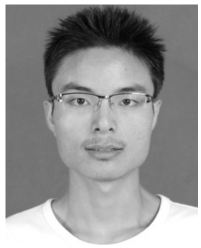

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