Structural parameter optimization of bionic eye based on improved adaptive genetic algorithm

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Abstract

Aiming to improve the dexterity of the camera device (i.e.,bionic eye) designed to imitate the human eye), a bionic eye was designed based on an improved genetic algorithm to optimize the structural parameters. According to the motion characteristics of human eye and spherical analytic theory, the structural parameters of the bionic eye equipped with spherical parallel mechanism are optimized by using improved adaptive genetic algorithm. This improved algorithm takes the dexterity maximization of the bionic eye mechanism as the objective, and enables a more flexible and stable design of the bionic eye. Compared with the traditional algorithm, the improved adaptive genetic algorithm can change the crossover and mutation probability with individual adaptation, which reduces the possibility of falling into the local optimal solution and gives better results. By comparing with the classical genetic algorithm and other improved genetic algorithms, the superiority of the improved adaptive genetic algorithm in enhancing the performance of genetic algorithms is verified. On the basis of the optimized structural parameters, the bionic eye mechanism is designed for conducting concrete experiments, and the experimental results show that the bionic eye with op-timized structural parameters by the improved adaptive genetic algorithm exhibits higher flexibility and stability, and better meets the requirements.

Keywords

Improved genetic algorithm, Spherical parallel mechanism, Bionic eye, Parameter optimization.

1. Introduction

With the rapid technological developments in robotics field, robots can be relied on for doing certain high-risk jobs (such as earthquake relief, deep sea exploration, coal mining, etc.) that need to be performed in harsh environments and cannot be directly dealt with by human beings[1]. To improve the performance of robots, we can install a camera on the mobile robot to obtain stable and clear images in real time, and transmit the image to the display terminal through the network, thereby realizing the remote control of the robot. At present, most of the camera devices have only two degrees of freedom and lack the spin around the visual axis, which often leads to the blurring or even distortion of the acquired images in complex environments, thus affecting the operation of the robot. By comparison with traditional devices, the three-degree-of-freedom bionic eye has greater potentials in dealing with complex and harsh environments.

Unlike the tandem mechanism, the parallel mechanism has a larger load and a more compact structure[2], and the spherical parallel mechanism is more similar to the human eye in terms of structure and movement characteristics, making it more suitable as the robot's "eye" than the tandem mechanism.

Although the parallel mechanism is superior to the tandem mechanism, the three sets of connecting rods of the spherical parallel mechanism receives tangential forces, so the rods are prone to deformation, and the three sets of components constrain each other. Therefore, the movement space and flexibility of the spherical parallel mecha-nism will be limited.

In order to overcome the problems of spherical parallel mechanism. Li[3] com-bining tandem and parallel mechanisms, proposed a tandem-parallel redundant mechanism, performed kinematic and mechanical analysis of the mechanism, and op-timized the energy consumption. However, the overall structure of the mechanism has not been optimized, which makes it impossible to carry out miniaturization and light-weight experiments. Liu[4] added a set of connecting rods and spherical vices in the center of the classical spherical parallel mechanism, which effectively dispersed the force on the fixed table. Then the effect of singular bit shape on the performance of the mechanism was analyzed, and the condition number of Jacobi matrix was determined as the evaluation index of the mechanism. It should be noted that this research is a theoretical investigation, and did not use the evaluation index to optimize the struc-ture of the mechanism. To maximize the working space and motion dexterity of the mechanism, Yang[5] proposed a genetic algorithm with the condition number of the Jacobi matrix of the mechanism as the optimization objective, and optimized the angle of each motion vice and the motor input, and other structural parameters of the mechanism. However, it could not guarantee that any attitude has good dexterity. Li[6] found the worst case of the mechanism by analyzing multiple paradigms of the com-parison matrix in the workspace, defined the worst dexterity of the mechanism, and optimized the mechanism by taking it as the optimization objective, and verified the dexterity of the improved mechanism through experiments. Chen[7] studied the asymmetric spherical parallel mechanism, and with the kinematic positive and nega-tive solutions being established, the mechanism was optimized in terms of workspace, dexterity, and output axis torque. In addition, the weight of the three evaluation in-dexes was reasonably assigned through fuzzy hierarchical analysis to determine the optimal parameters that can meet the requirements. The aforementioned methods have improved the performance of the spherical parallel mechanism and provided an effective solution to specific problems.

However, it is worth noting that most researchers still tend to use classical genetic algorithms for structural parameter optimization [5, 8]. Moreover, classical genetic algorithms are prone to premature convergence. When dealing with nonlinear large-scale, highly complex problems, at the early stage of algorithmic iteration, the random generation of the individual genes and inappropriate selection of hyperpa-rameters such as the number of individuals, the number of iterations, usually lead to the premature emergence of highly adapted individuals in the population. In such cases, "super individuals" will seriously squeeze the survival space of other less adapted individuals, enormously reducing the diversity of the entire species in the early stage and resulting in premature convergence to the local optimal solution, which hinders the further improvement of the optimization performance. Therefore, the algorithm should be improved. Guo[9] used dynamically changing crossover and mutation operators to improve the crossover and mutation process of the genetic algo-rithm, which effectively solved the problem of precocity of the genetic algorithm, but it was not used in the field of bionic eye. Yan[10] used the idea of preserving the optimal individual to improve the genetic algorithm and improve the stability of the algorithm. Therefore, the improved adaptive genetic algorithm is used to optimise the structural parameters of the bionic eye and its performance is verified.

2. Characteristics of human eye movement and spherical parallel mechanism

2.1. Characteristics of human eye movement and establishment of coordinate system

The human eye accomplishes complex movements through the contraction of six muscles around the eyeball[11], which are shown in Fig 1: (1) superior rectus, (2) inferior rectus, (3) medial rectus, (4) lateral rectus, (5) superior oblique and (6) inferior oblique.

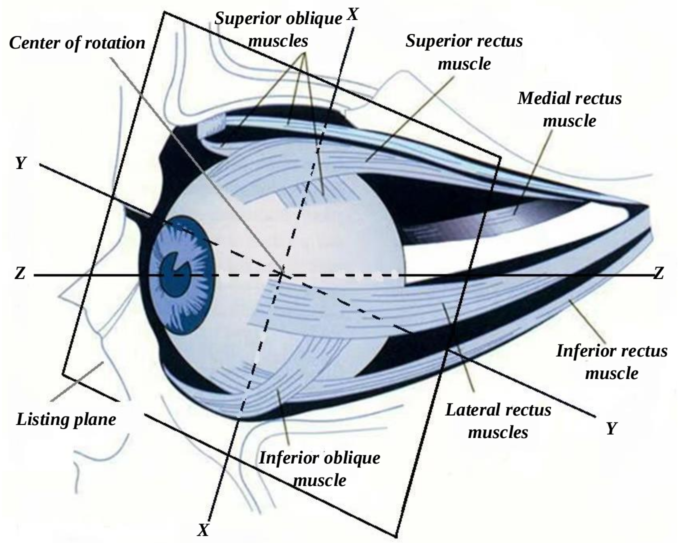


Fig 1. Tectonic diagram of the human eyeball.

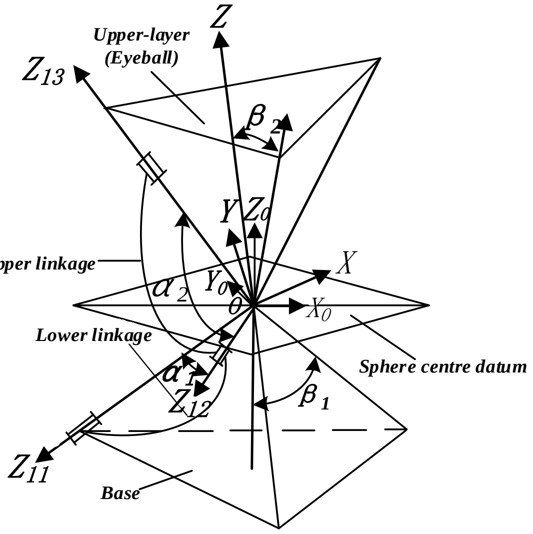


Fig 2. Spherical parallel mechanism sketch

Eye movement is a mechanical movement, which can be approximated as a three-degree-of-freedom spherical movement of the eye around its geometric center[12], and each rotation requires the coordination of multiple muscles. The spherical parallel mechanism is similar to the human eye in that it has three degrees of freedom rotating around the origin of the mechanism, and also needs three sets of branched chains to coordinate the movement. Considering the many strengthens of the spherical parallel mechanism, this paper decides to use it for the bionic eye de-signing. The sketch of the spherical parallel mechanism is shown in Fig 2. The mechanism is mainly composed of power source and actuator, and the servo provides power for the active axis of the spherical parallel mechanism to realize the attitude changes of the mechanism. In addition, the spherical parallel mechanism consists of a rotating platform, a fixed platform and three sets of branch chains with the same structural parameters. Each set of branched chains contains two curved rods and three rotating axes. The mechanism is characterized by the intersecting of all the rotating axes at the center of the sphere. The rotating platform and the two curved rods move on the surface of the sphere with the same center but different radii, and the rotating platform has three rotational degrees of freedom relative to the fixed platform, thus realizing the attitude change of the mechanism.

2.2. Description of the system.

According to the D-H parameter method, the linkage coordinate system from the fixed platform to the rotating platform is established: with the center of the sphere O as the origin, the fixed coordinate system $O-X_0Y_0Z_0$, the dynamic coordinate system $O-XYZ$, and the linkage coordinate system $O-X_{ij}Y_{ij}Z_{ij}$ are established respectively. i , j=1,2, 3 denotes the j-th rotating vice of the i-th group of branch chains. The line between the center of the fixed platform H and the origin O is taken as the Z_O-axis, and the line between the center of the rotating platform and the origin O is regarded as the Z -axis, and the positive direction points to the rotating platform; the Z_{ij}-axis is the axis of the j-th rotating vice of the i-th group of branch chains, and the direction points to the outside of the ball; the axis is the normal to the plane constituted by the axes; the X_O-axis is the normal to the plane constituted by the Z_O-axis and the Z_{11}-axis; the X_{ij}-axis is the normal to the planes constituted by the Z_{13}-axis and the Z_{ij+1}-axis; the X-axis is normal to the planes constituted by the Z-axis and the Z_{13}-axis; the right-hand rule determines the direction of the Y-axis for each coordinate system.

For i branched chains, first determine that the unit vector u_i denotes the rotation axis connecting the fixed platform and the master rod, and the direction overlaps the axis of Z_{i1}; the unit vector v_i denotes the rotation axis between the master rod and the follower rod, and the direction coincides with Z_{i2}; and the unit vector w_i denotes the rotation axis between the follower rod and the rotating platform, and the direction coincides with Z_{i3}. The structural parameters to be determined by the mechanism are $\alpha_1, \alpha_2, \beta_1, \beta_2, \eta$ (the same structure of the three sets of branched chains). The structural angle α_1 of the active rod denotes the angle between the unit vectors u_i and v_i, the structural angle α_2 of the follower rod denotes the angle between v_i and w_i, β_1, β_2 are the half-cone angles of the fixed platform and the rotating platform, respectively; and η denotes the initial torsion angle of the rotating platform and the fixed platform in the initial state.

2.3. Velocity Jacobi Matrix and Dexterity Metrics

Using the direct derivation method, the equation between the input and output angles is derived with respect to time to obtain the velocity Jacobi matrix.

$$\dot{\theta} = J\omega \tag{1}$$

The vectors ω: output angular velocity, $\dot{\theta}$: input angular velocity, J:Jacobi matrices, which are determined by the intermediate parameters $\alpha_1, \alpha_2, \beta_1, \beta_2, \eta_{1i}, \eta_{2i}$ (i = 1,2,3) and the eye postures Φ_x, Φ_y, Φ_z.

To measure the dexterity and control accuracy of the machine, we use the inverse of the Jacobi matrix condition number ζ as the dexterity evaluation index.

$$\zeta = \frac{1}{K} = \frac{1}{\|J\|\|J^{-1}\|} \tag{2}$$

K is the condition number of the Jacobi matrix, and the dexterity ranges from 0 to 1. The larger the value of ζ, the higher the dexterity of the designed bionic eye, and the easier it can be accurately controlled.

3. Structural optimization based on improved adaptive genetic algorithm

3.1. Optimization goals

3.1.1. Targeted workspace

Physiologically, it can be concluded that the up-down, left-right rotation of the human eye is roughly in the range of [-38°, 38°], and the rotation around the optic axis falls in the range of [-15°, 15°][13]. This was used as the basis for designing the working space of the bionic eye. It was experimentally proved that the motion space of the bionic eye matches with that of the human eye very well.[6]

3.1.2. Structural parameters

According to the structural requirements of the bionic eye, preliminary optimization of the relevant parameters was carried out before the optimization of structural parameters. As for the position angles η_{1i} and η_{2i} of the static angle table and the dynamic angle table, the design adopted a spherical three-degree-of-freedom parallel mechanism with three branches uniformly distributed.

$$\eta_{1i} = \eta_{2i} = \frac{(i-1)2\pi}{3}, (i = 1,2,3) \tag{3}$$

As for the structural angles α_1 and α_2 of the connecting frame rod and the connecting rod, theoretically the values of α_1 and α_2 should be in the range of [0°, 180°]. However, previous experiments have proved that if these two parameters take a too large value, it would cause interference among the branches, thus affecting the normal movement of the mechanism and reducing the movement space of the whole mechanism. Additionally, a too big rod easily causes obstruction to the camera mounted at the end, limiting the selection of camera. In contrast, if a too small value is taken, it will also constrain the movement space of the bionic eye. Therefore, a value falling into a suitable range is very vital to the bionic eye. In this study, the range of these two parameters was set between 50° and 80°, as shown in Fig 3.

Based on the structural parameters of the bionic eye selected in this paper and considering the space required for installing the motor in the fixed part, the radius of the fixed part was set to be the largest, the radius of the intermediate rods the second largest, and the radius of the end moving part the smallest. Each part is moving on a sphere with the same center and with no interferences. The size of moving part at the end was determined by the size of the camera, and the radius of the fixed part which varies with the angle of β_1 was considered affecting the size of the whole bionic eye the most. While a too small radius of the fixed part will make it inconvenient to install the motor, the value of β_1 was decided to fall into the range of [25°, 35°]. As shown in Fig 4, on the basis of Li's research[6] on the bionic eye, the value of β_2 was set in the range of [45°, 55°].

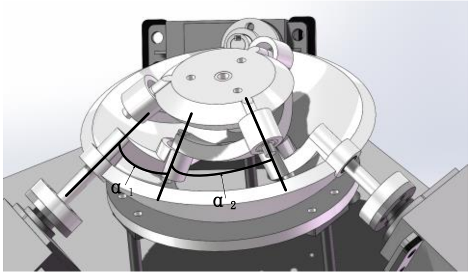


Fig 3. Bionic eye model diagram

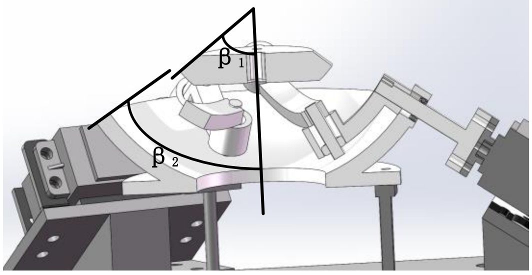


Fig 4. Side sectional view

In this article the minimum performance index ζ_{min} was used to optimize the structural parameters.

$$\zeta_{min} = min\left[\frac{1}{\|J\|\|J^{-1}\|}\right] = \frac{1}{\|J\|_{\infty}\|J^{-1}\|_{\infty}} \bigcup \frac{1}{\|J\|_{1}\|J^{-1}\|_{1}} \tag{4}$$

The dexterity index is guaranteed to be minimized under the combined consideration of 1-parameter and infinite-parameter.

After determining the target motion space and combining the actual structure of the bionic eye, it was necessary to find appropriate design parameters $\alpha_1, \alpha_2, \beta_1, \beta_2$ to maximize the worst value ζ_{min}.

3.2. Fundamentals of Genetic Algorithm

The idea of genetic algorithm[14] is to transform the parameters to be optimized into the genes of the population, utilizing the property of global traversal of the random function in the programming language, and then after a specified number of generations of selection, crossover, and mutation to make the genes of the population evolve towards optimizing the objective, and finally obtain the optimal solution.

3.3. Flow of genetic algorithm

Encoding Classical genetic algorithms need to first transform the parameters in the decimal solution space into binary to complete the mapping from expression to genotype.

Initialization of population Firstly, N individuals are randomly generated to form a population, with each individual composed of genes of the parameter to be optimized, and the genetic composition of the individual is determined by the number of parameters.

Calculate the fitness According to the mathematical model established in the previous stage, the individual genes are mapped into the fitness function to obtain the fitness value of each individual.

Evolution Evolution consists of three parts: selection, crossover, and mutation.

Selection: depending on the differences in fitness of individuals in the population, keep most of the good individuals and some of the poorly adapted individuals as well.

Crossover: simulates the reproduction process of a species by randomly selecting fathers and mothers in a population and swapping their gene segments to produce new individuals (offspring).

Mutation: the genes of the pseudo-offspring from the crossover are randomly inverted to find better individuals in a localized search and also to maintain the diversity of the population.

The crossover probability and mutation probability need to be adjusted appropriately according to the specific situation; the crossover probability is adjusted between 0.1-0.9, while the mutation probability is between 0.0001-0.1.

Iteration Repeat the evolutionary steps until the stopping condition is satisfied (e.g., the maximum number of iterations is reached).

Output result When the optimization algorithm stops iterating, the design parameters corresponding to the individual with the highest fitness value are output, i.e., the optimal parameter combination sought.

3.4. Improved adaptive genetic algorithm

Improvements to various aspects of the classical genetic algorithm, the existing Adaptive Genetic Algorithm (Adaptive Genetic Algorithm-AGA) which improves on crossover and mutation operations [15, 16]; the features of the Adaptive Genetic Algorithm (AGA) include:

1. Dynamic Parameter Adjustment:

AGAs possess the ability to dynamically adjust their parameters during the optimization process. This adaptability ensures fine-tuning in response to the changing landscape of the search space, enhancing the algorithm's ability to converge towards optimal solutions.

2. Population Diversity Preservation:

Unlike traditional genetic algorithms, AGAs emphasize the preservation of population diversity. Mechanisms such as dynamic variation of mutation rates or crossover probabilities con-tribute to maintaining a diverse gene pool, preventing premature convergence and promoting exploration of the solution space.

3. Self-Adaptive Mechanisms:

AGAs integrate self-adaptive mechanisms, allowing the algorithm to autonomously modify its strategies based on the historical performance of individuals within the population. This intrinsic learning capability contributes to improved convergence rates and solution quality.

4. Incorporation of Learning Strategies:

AGAs often incorporate learning strategies inspired by natural systems. This may involve mimicking the principles of natural selection, environmental adaptation, or other biologically in-spired mechanisms. These strategies enhance the algorithm's robustness and applicability to various problem domains.

5. Robustness in Noisy Environments:

AGAs demonstrate robustness in noisy or uncertain environments by dynamically ad-justing their exploration and exploitation strategies. This adaptability enables effective optimization even when the fitness landscape contains inherent uncertainties or fluctuations.

6. Efficient Handling of Constraints:

AGAs excel in handling optimization problems with constraints. Through adaptive mechanisms, the algorithm can effectively navigate constraint boundaries, optimizing solutions while adhering to specified limitations.

7. Hybridization and Integration:

AGAs are amenable to hybridization with other optimization techniques. Integration with local search heuristics, machine learning algorithms, or problem-specific heuristics enhances the algorithm's versatility and performance across diverse problem domains.

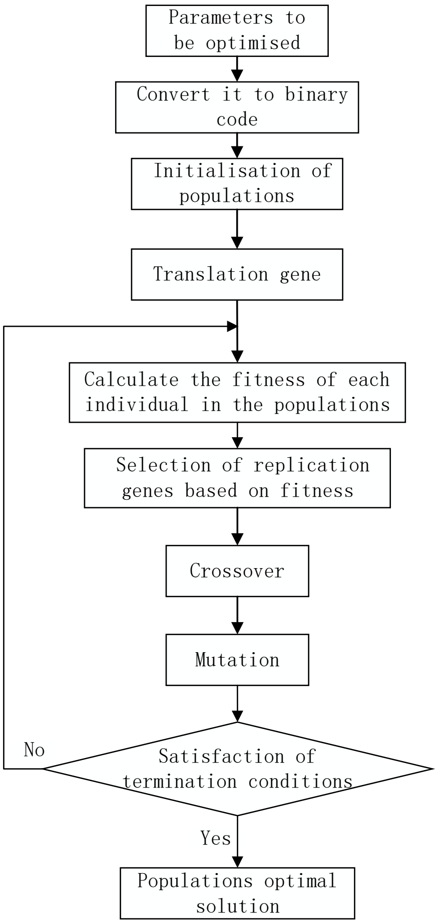


Fig 5. Flowchart of Improved Adaptive Genetic Algorithm

4. Control design

4.1. Simulation experiments

In this study, the number of iterative convergence and the value of fitness function will be used as two indicators for the performance evaluation of genetic algorithms in order to compare the performance of classical genetic algorithm, adaptive genetic algorithm (AGA), and Improved Adaptive Genetic Algorithm (IAGA) in the optimization of mechanism parameters.

In order to implement the classical genetic algorithm, adaptive genetic algorithm, and improved adaptive genetic algorithm mentioned in the paper, the corresponding codes are written using PyCharm tool. The iteration process is recorded in each algorithm and imported into "Original".

As shown in Fig 6, the number of iterations is the x-axis and the fitness function value is the y-axis. After 500 iterations, the optimization results of different algorithms are sorted: classical genetic algorithm has large uncertainty, so the fitness value is the worst; adaptive genetic algorithm in the iteration process, the crossover and mutation probability will change according to the change of individual fitness value, which reduces the risk of falling into the local optimal solution, so the fitness value is larger than that of the traditional genetic algorithm; the improvement of adaptive genetic algorithm is due to the optimal preservation strategy is relatively large; the adaptive genetic algorithm has a higher fitness value than the traditional genetic algorithm. The improved adaptive genetic algorithm saves the optimal individuals obtained in each iteration to prevent them from being erased by randomness, thus increasing the probability of obtaining the optimal individuals in the final iteration, and the fitness becomes larger compared to the classical genetic algorithm. Therefore the results are the best. It is also worth noting that changing the hyperparameters did not significantly affect the results.

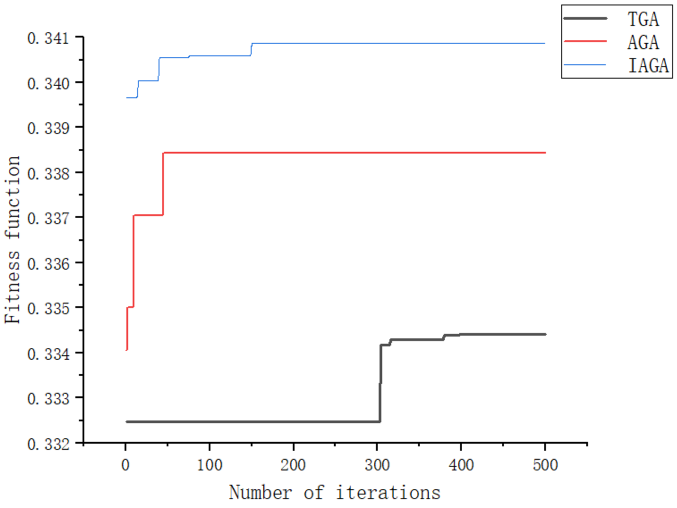
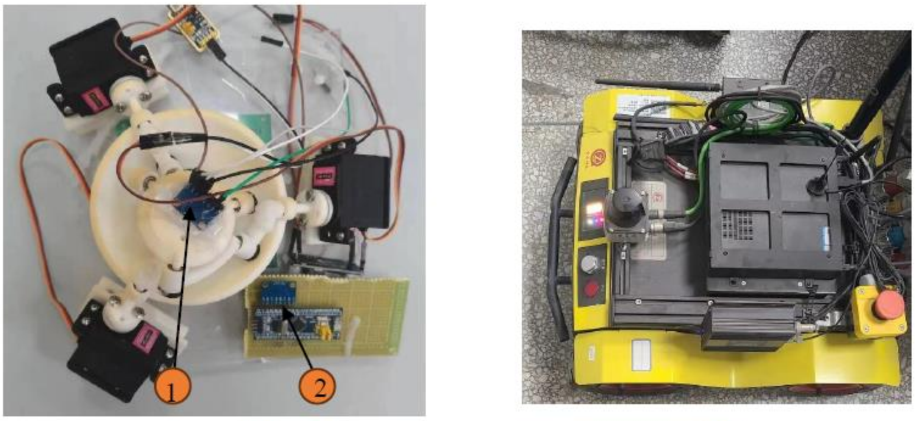


Fig 6. Performance comparison of multiple algorithms

4.2. Simulation experiment on corrective attitude performance of spherical parallel mechanism

The structure of the physical platform consists of two parts: the structurally optimized bionic eye mechanism and the Robuster MR500 car (in Fig 7). The bionic eye mechanism is powered by three servos mounted on a fixed platform, and the bionic eye sphere and the platform fixed to the vehicle body are each equipped with a gyroscope (Gyro ①, Gyro ②). The gyroscope is used to identify and record the attitude changes of the vehicle body and the bionic eye in bumpy envi-ronments, and stabilize the sphere-parallel mechanism's attitude in real time through the PID control system. The three-axis angles of the gyroscope (shown in Fig 8): Roll (roll angle), Pitch (pitch angle), and Yaw (yaw angle) are mapped as the attitude angle changes of the sphere-parallel mechanism and the vehicle in x, y, and z axes, respectively. Fig 10 shows the variation curves of roll angle, Fig 11 shows the variation curves of pitch angle and Fig 12 shows the variation curves of yaw angle.



(a) (b)

Fig 7. Experiment platform.(a) Physical bionic eye; (b) Robuster MR500 car

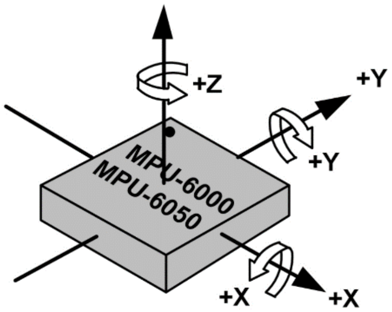


Fig 8. Gyroscope three-axis angle

5. Experimental Results and Analysis

A complex experimental setting was set up indoors, including a bionic vision platform, a simulated bumpy road surface, and cross markers for comparison. A camera on the bionic eye and a camera on the platform recorded the offset of the cross markers on the wall during the movement of the cart. The offset of the markers was the change in attitude of the bionic eye and the platform. This experiment was conducted to verify the bionic vision system's bump resistance in complex environments.

5.1. Simulation experiments

Fig 9 shows a mobile platform equipped with the bionic eye system; Fig 10 shows an indoor simulation of a bumpy environment; and Fig 11 shows a crosshatch pattern used to compare the bionic eye with the body camera image.

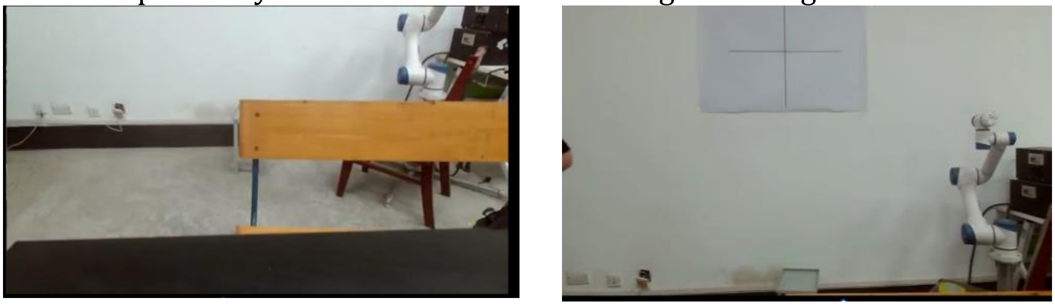
Fig 9. Mobile platform

Fig 10. Indoor bumpy environment

Fig 11. Cross pattern

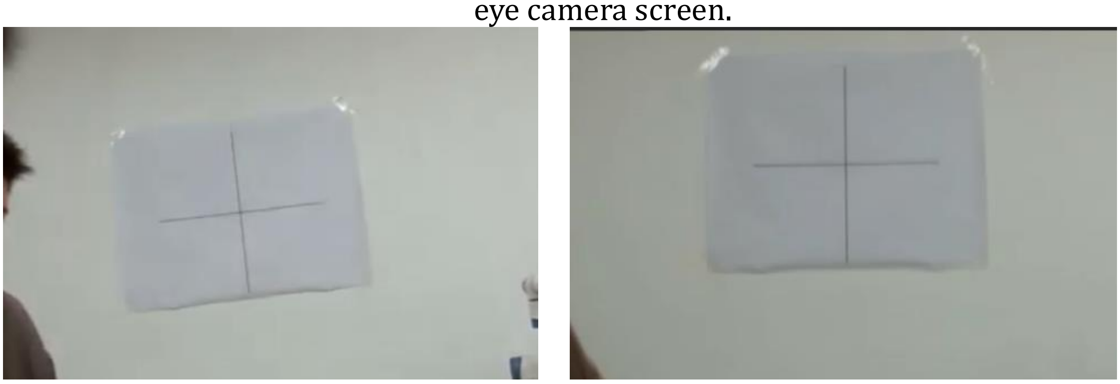
5.2. Comparison of expermental results

Maneuvering the mobile platform to go over the bumpy road causes changes in the pitch and roll angles of the mobile platform. As for pitch angle changes: Fig 12 shows a screenshot of the screen captured by the camera when the pitch angle is changed, and Fig 13 shows a screenshot of the screen captured by the camera when the roll angle is changed.



(a) (b)

Fig 12. Pitch angle change. (a) Screenshot of body camera screen;(b) Screenshot of the bionic eye camera screen.



(a) (b)

Fig 13. Cross-roll angle change. (a) Screenshot of body camera screen;(b) Screenshot of the bionic eye camera screen

The experimental results show that the spherical parallel bionic eye mechanism of bionic eye itself has superior adjustment ability, which can flexibly adjust the attitude according to the changes of the complex environment and obtain a clear and stable picture in real time.

6. Conclusion

In this paper, the spherical parallel mechanism is taken as the ideal mechanism for the bionic eye, and th e maximum value of the worst dexterity of the mechanism is taken as the optimization objective. Applying improved adaptive genetic algorithms to solve the "early convergence problem" of classical genetic algorithms. so as to obtain the suitable structural parameters for the mechanism of the bionic eye, and the results of the simulation experiments show that the adaptive index is better than the other improved algorithms. More than that, it has been shown that its adaptability is better than the other improved algorithms as well. Compared with the less-degree-of-freedom camera in the physical experiment, the bionic eye mechanism compensates for the attitude change of the platform, reduces the jitter of the camera, and makes the output image smooth and clear, which further verifies that the bionic eye has a good anti-jamming property in complex environments.

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