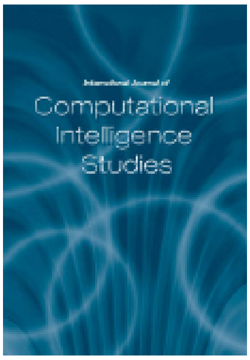

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Nonlinear modelling and analysis of stable behaviour of robot gait control system based on image processing technology

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Abstract: Walking stability is an important index to measure the walking performance of robot, and is the key to realise its wide application. However, the traditional gait control system has low control accuracy and long control time. Therefore, aiming at the above problems, a nonlinear modelling and analysis method of stable behaviour of robot gait control system based on image processing technology is studied and designed. The robot gait control system is composed of main control system hardware, wireless control system, robot debugging software and image pre-processing module. The hardware design of the main control system includes the DSP minimum system and the steering gear control board. The image pre-processing module pre-processes the image collected by the CCD camera to remove the noise in the image. Finally, the speed of the robot is controlled by visual servo control method, and a nonlinear sliding mode control closed-loop system of the robot is constructed. The simulation results show that the designed method has the highest accuracy of 100%, and the longest time is only 27.96 s. It has high control accuracy and control efficiency, which provides a method reference for further realising the optimal control of the robot.

Keywords: image processing techniques; robot; gait control; stable behaviour; nonlinear analysis.

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1 Introduction

Robot, also known as humanoid robot, has similar mechanical structure and degree of freedom distribution to human beings, and imitates the motion state of human beings. More importantly, through the sensors placed in various parts of the body, they sense the state information of themselves and the surrounding environment, form their own sensory system, and have the ability of thinking, so as to achieve the purpose of adaptive behaviour activities in different environmental states. The robot has the following main characteristics:

1. Higher flexibility: In the human activity space, the robot can not only move forward on the flat ground, but also flexibly go up and down steps, cross and avoid obstacles, and walk stably on the rugged road (Zhou et al., 2019).
2. Similar to human limb structure: The limb of the robot has multiple degrees of freedom, which enables it to achieve complex and diverse actions, such as grasping and lifting.
3. Lower power consumption: Compared with wheeled and crawling robots, robots rely on their legs to swing alternately and support them to walk forward, which have lower power consumption and higher walking efficiency. In the research field of robot, the stable walking of robot is the premise of its practical application (Gong et al., 2017).

After 2005, the theory of robot dynamic walking was put forward, which makes the gait control of robot closer to the normal walking state of human beings, which has great research value and practical significance. In complex environment, whether the robot can stably maintain periodic motion is the primary consideration index. The precision and stability requirements of robot system control are becoming higher and higher, and the research in the field of robot control has a more detailed direction. Robot control system is not only a typical nonlinear system control problem, but also a complex multi-input multi output system control problem. These characteristics make the control design of robot system more complex than simple linear control system, and it is difficult to obtain the desired ideal control effect in practice. Therefore, the control theory and method of robot system have attracted extensive attention, and the research on robot control has high research significance and research value (Shang et al., 2018).

Singh et al. (2022) proposed deep learning and probabilistic learning models for predicting the trajectory and gait control of bipedal robots. The results showed that deep learning and probabilistic learning models performed better for both types of mappings, and probabilistic models outperformed models based on deep learning in terms of maximum error. Xu et al. (2022) introduced the fuzzy PID position control algorithm to address the issues of low efficiency and poor control accuracy of traditional palletising robots, and implemented a motion control system based on the FPGA hardware platform of palletising robots. The results showed that this method has fast response time, small actual overshoot, and is more suitable for motion control algorithms of palletising robots. Chen et al. (2018) proposed an optimal gait generation method of walking robot based on double generation function. Taking joint angle and torque as state and input variables and considering energy consumption, a linear quadratic optimal control problem is constructed. The solution of the problem is derived based on a pair of generation functions, which can be parameterised into offline calculation coefficients and boundary conditions. The corresponding solution process is composed of offline numerical integration part and online algebraic operation part. Through setting multi-step simulation examples, the results show that this method can significantly improve the online generation efficiency of robot gait and design proportional differential controller. When the robot walks with reasonable step size and appropriate time period. The modelling error caused by linearisation can be controlled in a small range, and the trajectory of nonlinear model can track the trajectory of linearised model well. However, when this method is used to control the gait of the robot, there is a large deviation between the tracking trajectory and the actual path, and the time required is long. Zhang (2018) proposes a robot robust stabilisation control method based on robust reliability method. Firstly, the influence of uncertain parameter perturbation on the robot is analysed, and the nonlinear uncertain parameters in the robot dynamic model are treated equivalently. Then, the state feedback controller is designed by using the LMIs of robust reliability and its function, finally, the controller is connected to the simulation model for simulation experiments and numerical comparison to verify the control effect and performance changes of the system before and after optimisation. The research results show that this method can improve the control performance of the system with a certain reliability, limit the perturbation range of uncertain parameters within a reasonable range, and ensure the accurate tracking of the known trajectory. However, the accuracy of robot gait control by the above two methods is low, resulting in poor robot gait control effect. However, the feedback function of the state feedback controller of this method is difficult to be fully exerted, the gait control effect is poor, and it is also difficult to achieve accurate trajectory tracking. Ge et al. (2018) proposed a control method of under-actuated biped robot based on gait switching. Firstly, taking the minimum energy consumption as the optimisation objective, several groups of gaits with different steps and speeds are designed in advance through the nonlinear optimisation method as the reference gait to build a gait library. Then, by comprehensively considering the stability and energy efficiency in the process of gait switching, the multi-objective gait switching function is established, Finally, the gait switching function is taken as the optimisation objective, and the minimisation problem is solved to obtain the next reference gait, so as to realise gait switching and achieve the purpose of robust control of under-actuated biped robot. In summary, among existing robot gait control methods, linearisation methods can effectively reduce errors and achieve stable gait switching. However, traditional linear methods require high accuracy of data and can only perform planning constraints on linear problems, with high computational complexity. Although there are follow-up methods to make up for it, such as the nonlinear programming method evolved from linear programming, the calculation amount has increased a lot. The disadvantage of the same nonlinear estimation method is that the estimation of parameters for medium to weak nonlinear models is very complex after considering high-order Taylor expansion terms, making it difficult to maximise its effectiveness in practical applications. At the same time, both of these traditional methods currently have problems such as insufficient stability, poor control accuracy, and large trajectory tracking deviation, which must be further improved. Therefore, it is necessary to optimise the robot gait control system and achieve stable control of the robot gait on the basis of improving control accuracy.

Image processing is a highly targeted technology. Different image processing methods are adopted according to different applications and different requirements. Image filtering, that is to suppress the noise of the target image under the condition of preserving the detailed characteristics of the image as much as possible, is an indispensable operation in image pre-processing. Its processing effect will directly affect the effectiveness and reliability of subsequent image processing and analysis (Raghunathan et al., 2022). Due to the imperfections of imaging system, transmission medium and recording equipment, digital images are often polluted by a variety of noise in the process of their formation, transmission and recording. In addition, in some links of image processing, when the input image object is not as expected, noise will also be introduced into the result image. These noises often appear as isolated pixel points or pixel blocks that cause strong visual effects. Generally, the noise signal is not related to the object to be studied. It appears in the form of useless information and disturbs the observable information of the image. For digital image signals, the noise table is either large or small extreme values. These extreme values act on the real grey value of image pixels through addition and subtraction, resulting in bright and dark point interference in the image, greatly reducing the image quality and affecting the subsequent work such as image restoration, segmentation, feature extraction and image recognition. In recent years, there are many researches on image filtering theory, and the filtering methods are becoming more and more mature (Li et al., 2022). Image filtering includes image smoothing and image sharpening, both of which belong to the category of image enhancement. Image acquisition module is an indispensable part of robot gait control, and image processing technology is one of the core of the module application. By optimising the image processing technology, pre-processing the image and reducing the adverse effect of noise on the image quality, we can better restore the edge contour information of the obstacle and improve the stability of the robot gait control. In view of this, it is necessary to apply image processing technology to robot gait control system, but there are few studies on the specific application and optimisation of image processing technology in control system, and it is difficult to meet the requirements of current practical application. Therefore, unlike current methods, innovative research has been conducted to apply image processing technology to robot gait control systems, with image processing as the core of the software design system. Image filtering is used to pre-process the environmental images obtained by the robot, eliminate noise interference in the process of collecting image information, make the image smoother, enhance the robustness of the image, and facilitate robot identification and recognition. Then, the hardware of the main control system is composed of a DSP minimum system and a steering gear control board. Then, the speed of the robot is controlled through visual servo control method, and a robot gait control system based on image processing technology is established. Through the joint application of image processing and visual servo methods mentioned above, the research aims to improve the stability and accuracy of the robot gait control system, and achieve improvement in control efficiency, ultimately achieving high automation of the robot and improving its application capabilities in various fields such as industry. The main contributions of the study are:

1 The core of the software design system is graphic processing, which utilises image filtering to pre-process the environmental images obtained by the robot, minimising the noise interference of image information during the collection process, and enhancing the robustness of the image.

2 The stability behaviour of the robot gait control system was modelled and analysed. First, visual servo control method is used to control the speed of the robot, and then a nonlinear sliding mode control closed-loop system of the robot is constructed.

3 Under the proposed robot gait steady control system, the stability and accuracy of the robot gait control system are improved, while also improving the control efficiency of the robot.

The organisation of the paper is as follows:

1 The first part of the article first introduces the basic characteristics of robots and introduces the importance of control theory and methods for robot systems. Subsequently, there is a literature review on robot gait control, which includes research results both domestically and internationally. At the same time, the introduction section includes a basic introduction to image processing technology and its application in robot control systems.

2 The second part of the article mainly focuses on the design of the robot gait stability control system, including hardware and software design, as well as the overall design of the image pre-processing module.

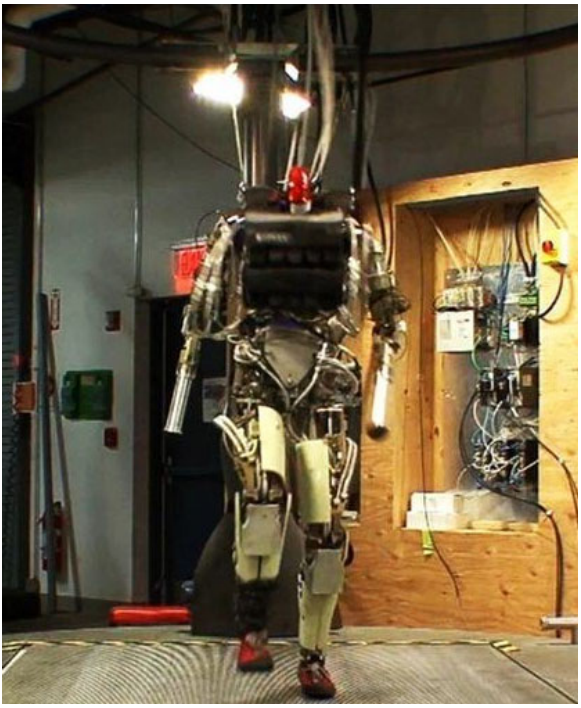
3 The third part of the article is the nonlinear modelling and analysis of the stable behaviour of the robot gait control system. Visual servo control method is used to control the speed of the robot, and then the nonlinear Sliding mode control closed-loop system of the robot is constructed. Finally, the stability of the system is analysed.

4 The final part of the article verifies the gait control accuracy, control time, and response time of the proposed control method, and compares it with other methods in the field to verify its superiority.

2 Design of robot gait stability control system

The robot gait stability control system mainly includes three parts: the first is the main part of the control circuit, including data processing function and steering gear control, which is placed in the middle and rear of the robot (Takei et al., 2020). The second part is the wireless control system, which realises the wireless control of the action state of the robot. The third part is the upper computer debugging program, which can understand the robot state in real-time during the robot debugging process, including angle, centre of gravity height and other information, as shown in Figure 1.

Figure 1 Overall schematic diagram of the system (see online version for colours)



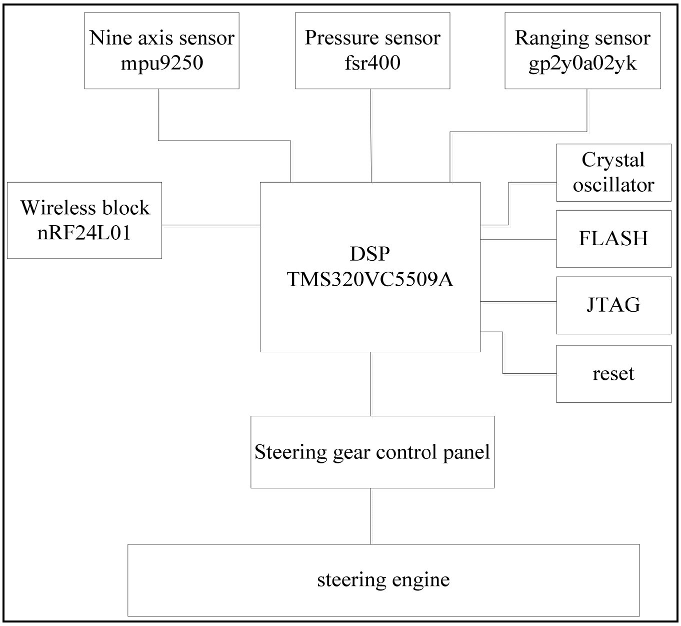
The core of robot data processing is tms320vc5509a; the wireless control part takes stm32f103rct6 as the core, sends control commands and displays the status on the touch screen. The communication between each part uses 2.4 G wireless communication module to realise two-way data transmission. The program of upper computer debugging software is developed in C# language (Yimin et al., 2018).

2.1 Hardware design of main control system

2.1.1 DSP minimum system

The robot main control system is used to realise the functions of sensor data acquisition, robot attitude calculation and steering gear control. The overall structure of the main control circuit is shown in Figure 2.

Figure 2 Overall structure of main control circuit



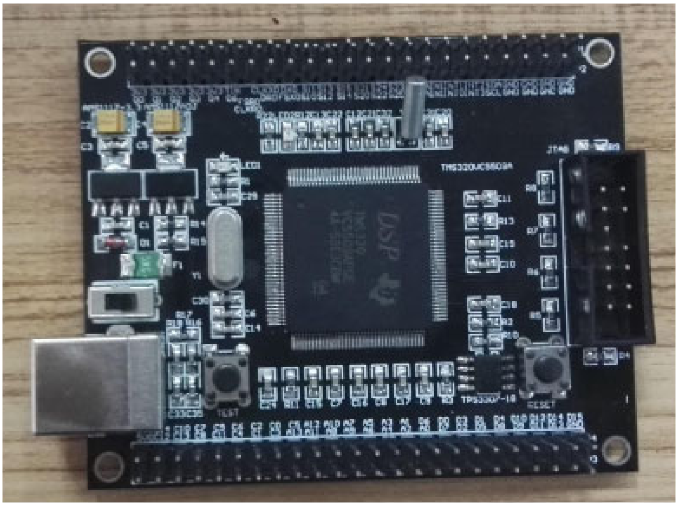
The main control circuit includes DSP minimum system (power supply, crystal oscillator, reset and flash), nine axis sensor, pressure sensor and infrared ranging sensor, steering gear control board, JTAG interface for program debugging, wireless module for data interaction with other parts, and finally includes the power supply part to provide energy for each module, which adopts high-capacity 7.4 V aircraft model battery, Because the voltage required by each part of the circuit is different, it is converted into 5 V, 3.3 V and 1.6 V through multiple linear voltage stabilising circuits to supply power to each module (Yun et al., 2021).

This paper selects 16-bit fixed-point DSP as the core processor. It has a hardware multiplication accumulation unit with fast calculation speed, and many common modules are integrated on-chip, such as SPI, IIC, MC BSP and ADC, which is convenient to connect with peripheral circuits. The off-chip storage space is 16 MB. It has rich peripheral resources and meets the hardware design requirements of robot gait stability control system. The minimum system of DSP is shown in Figure 3.

The minimum system is the smallest unit that DSP can work normally. The 12 MHz crystal oscillator is used as the clock source. Because there is no ROM to store the program in DSP, the EEPROM connected with SPI bus is used to store the program.

When powered on, detect the input level of gpio0~3 port, and use the corresponding boot mode to load the written program onto the DSP through the boot loading program.

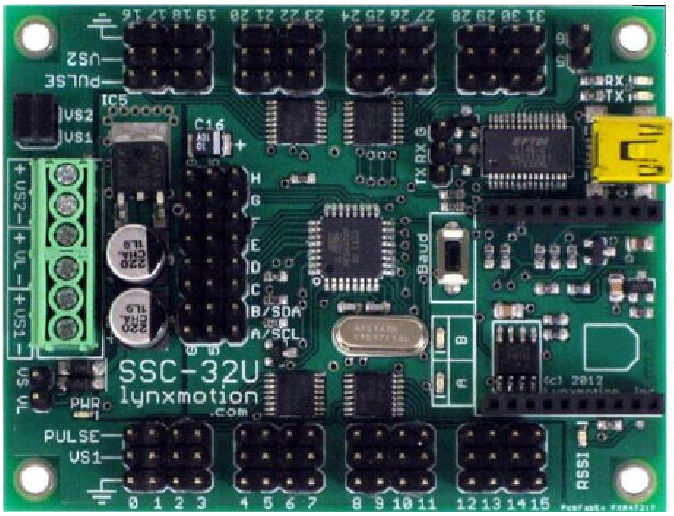
Figure 3 DSP minimum system (see online version for colours)



2.1.2 *Steering gear control panel*

Tms320vc5509a is weak in control ability. If DSP is used to directly control the working state of 19 channel steering gear, it will be very weak. Therefore, this paper assigns the task of steering gear drive to the steering gear control board, and uses DSP to send instructions to control the actual output of the steering gear control board to form a ‘two-stage’ structure, and its appearance is shown in Figure 4 (Chowdhury et al., 2018).

Figure 4 Steering gear control board ssc-32u (see online version for colours)

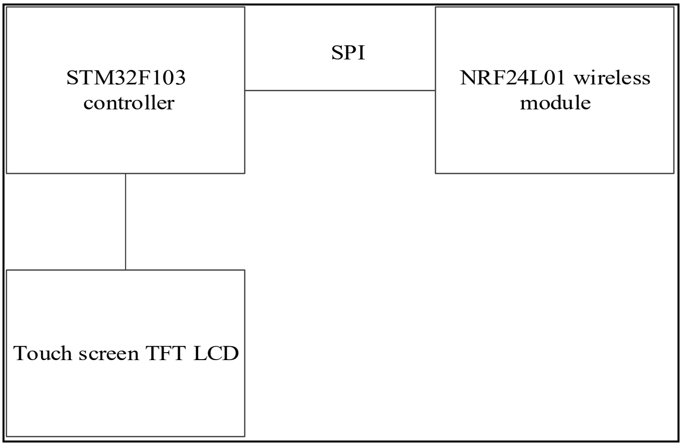


Ssc-32u is a special steering gear control board. Atmega328 is used as the main control chip. It can drive and control up to 32 steering gears at the same time by receiving the instructions of the upper computer and converting the instructions into PWM pulse signals. It can drive both digital and analogue steering gears (Céspedes et al., 2020). DSP needs to send instructions to the control board in the form of asynchronous serial communication (UART). On the control board, the chip supplies power separately from the steering gear power pin. It has the function of converting the aircraft model battery voltage into 5 V voltage to drive Atmega328.

2.2 Design of wireless control system

This paper provides a wireless remote control function for the control of the robot, which avoids the limitation of the mobile range of the robot caused by the use of connecting wires. The wireless remote control function can realise more convenient communication between the robot and the controller, and accurately control the robot joints through the controller (Wu and Li, 2020). The wireless remote control system takes STM32 micro-controller as the core, and selects to send instructions and receive status feedback through TFT LCD with touch screen function. The wireless communication module adopts nRF24L01 and works in the 2.4 GHz frequency band (Figat and Zieliński, 2022). It has the advantages of low power consumption and fast transmission. The overall connection of the robot wireless control system is shown in Figure 5.

Figure 5 Wireless controller structure



NRF24L01 and the master controller transmit the data to be transmitted through SPI protocol. SPI bus consists of four lines: chip selection signal (CS), clock signal (CLK), master input slave output (MISO) and master output slave input (MoSi) (Tomida et al., 2019). The interface circuit is shown in Figure 6.

NRF24L01 has five working modes, as shown in Table 1. During normal operation, the sending mode and receiving mode are mainly used, as shown in Table 1.

Through nRF24L01, the information measured by the sensor placed on the robot can be returned in real-time, and then the returned data information can be used for analysis and remote control the robot to make corresponding actions. The communication process requires two nRF24L01, one is placed on the wireless remote control system, the other is installed on the robot and connected with DSP. There is no special SPI interface in DSP chip. The realisation of SPI slave function is simulated by IO port. UART function can be realised by reasonably configuring MC BSP, and the hardware connection needs to be changed accordingly (Jaeho and Yijung, 2018).

Figure 6 Schematic diagram of interface circuit

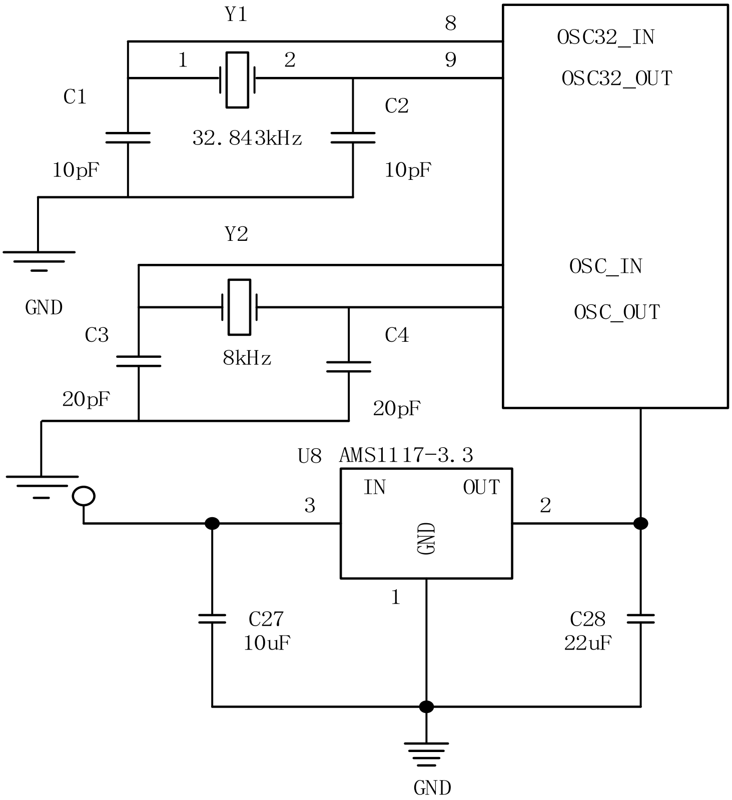


Table 1 Five modes of nRF24L01

Pattern	*PWR UP*	*RRIM RX*	*CE*	*FIFO status*
Receiving mode	1	1	1	-
Launch mode	1	0	1	Data in TX FIFO
Launch mode	1	0	1→0	Keep the transmission mode until the data is sent
Standby mode I	1	0	1	TX FIFO is empty
Standby mode II	1	-	0	No data is being transferred
Power down mode	0	-	-	-

2.3 Robot debugging software design

In the process of robot walking attitude adjustment, we cannot intuitively understand the height of robot centre of gravity, stability margin and other information, which brings difficulties to the design of new robot actions. This paper designs an upper computer software with friendly interface for robot debugging status display, and has the function of storing attitude data (Dong et al., 2019). The upper computer debugging interface can receive and display the original data of the sensor; you can also send the command string to the steering gear control board according to the steering gear control command format to control a group of steering gears. The debugging software is developed in C# language under the integrated development environment of Visual Studio 2013. C# is derived from C and C++. Using C# to develop desktop applications can make use of many existing libraries and tools, with short development cycle and high efficiency (Hui et al., 2020). The robot host computer debugging software shall have the following functions:

1 Serial port function settings, including communication port number, baud rate, data frame format, etc. so that the formats of both sides are the same.

2 The sensor raw data display window displays the sensor data in real-time and has the function of saving.

3 In the attitude analysis interface, the basic parameters, centre of gravity height, lateral tilt angle and other information of the robot can be intuitively understood.

When designing a new action for the robot by using the upper computer debugging software, the reliability of the action can be improved, and the symmetry of the action can be ensured by observing the angle and centre of gravity (Zhang et al., 2020).

2.4 Image pre-processing module

When the system receives the scene picture collected by CCD camera and image acquisition card, it enters the image acquisition and image pre-processing module. In this module, image filtering, adaptive selection of grey threshold, image binarisation and opening and closing operation of image by image mathematical morphology are mainly completed to remove the discontinuity of image edge. At this time, the robot image scene is a black-and-white binary image, and only contains the mark image information pasted on the robot body. However, due to the non-uniformity of CCD sensitivity in the photoelectric signal conversion process, the quantisation noise in the digitisation process and the channel error in the transmission process, the image information is often disturbed by various noise sources in the acquisition process. If this interference is not removed, it will affect the future micro robot mark recognition, positioning and tracking.

The software system designed in this paper takes image processing as the core, pre-processes the environmental image obtained by the robot through image filtering, eliminates the noise interference of image information in the acquisition process, makes the image smoother and enhances its robustness.

The original image collected by the camera is a three-channel image. In order to facilitate image processing, select the interest area containing complete objects and not blocked for subsequent processing, we are adjusting the focal length of the camera for many times (Bai et al., 2019). Because the original image is RGB colour image, only R-B channel and G channel are required. Because the target is green plants, the contrast colour is retained. The advantage of this is that it can filter out the highlighted part in the background. The formula is as follows:

$$W = \frac{R - B}{2} \tag{1}$$

where W represents the pixel value of the new channel.

Image filtering, that is to suppress the noise of the target image under the condition of preserving the detailed characteristics of the image as much as possible, is an indispensable operation in image pre-processing. Its processing effect will directly affect the effectiveness and reliability of subsequent image processing and analysis. In this paper, the bilateral filtering method is used to filter the grey image. Firstly, the pixel value of the image is restored by local weighting method:

$$h(x, y) = \frac{\sum_{(i,j)\in S_{x,y}} w(i, j)g(i, j)}{\sum_{(i,j)\in S_{x,y}} w(i, j)} \tag{2}$$

where $S_{x,y}$ is a square neighbourhood with x, y as the centre and odd width, that is, $(2N + 1)(2N + 1)$ pixels. The right side in equation (3) is the weighted average, and the weighting coefficient $w(x, y)$ consists of two parts:

$$w_s(x, y) = e^{-\frac{(i-x)^2+(j-y)^2}{2}} \tag{3}$$

$$w_r(x, y) = e^{\frac{(i-x)^2+(j-y)^2}{2}} \tag{4}$$

Moreover, $w_s(x, y)$ is the spatial proximity factor and $w_r(x, y)$ is the brightness similarity factor. It can be seen that the weighting coefficient of the bilateral filtering method is a combination of two parts of nonlinearity. The spatial proximity represents the Euclidean distance from the centre point to the pixel point, which decreases with the increase of the distance, and the latter decreases with the increase of the difference between the brightness values of the two pixels (Yuan, 2019).

3 Nonlinear modelling and analysis of stable behaviour of robot gait control system

The stability behaviour of the robot gait control system is modelled and analysed. Firstly, the visual servo control method is used to control the speed of the robot, then the nonlinear sliding mode control closed-loop system of the robot is constructed, and finally the system stability is analysed (Chen et al., 2019).

Set the motion space velocity of the robot as v and the image space matrix as s. the relationship between the two is as follows:

$$s = J(v)\dot{v} \tag{5}$$

where the planned motion speed of the robot is $\dot{v}$ and the time-varying matrix is $J(v)$. when the robot is visually servo controlled, the motion speed can be transformed into the control variable u and $u = \dot{v} = [u_x, u_y, u_z]^T$. In the control process, the estimated value $\hat{J}$ of $J(v)$ can be obtained according to the initial motion speed of the robot. The estimated value $\hat{J}$ obtained is fixed by the expansion state monitor, so as to avoid the influence of calculation error on path selection.

Based on the robot's own visual servo system, the motion speed of the robot needs to be discretised. The process is as follows:

$$s^*(k)-s(k)=\begin{bmatrix} s_x^*(k)-s_x(k) \\ s_y^*(k)-s_y(k) \end{bmatrix}=\begin{bmatrix} J_{11}(k) & J_{12}(k) & J_{13}(k) \\ J_{21}(k) & J_{22}(k) & J_{23}(k) \end{bmatrix}=\begin{bmatrix} u_x(k) \\ u_y(k) \\ u_z(k) \end{bmatrix} \tag{6}$$

where the discretised robot speed vector is $s^*(k)$, the target position vector of the robot's claw in the coordinate at time k is $s(k)$, and the initial position vector in the coordinate is $s^0(k)$. x, y, z is the position variable respectively. Set the current motion vector of the robot as $u(k)$. Based on the above discretisation processing, the influence of unknown disturbance ξ is avoided.

When the target moves in a two-dimensional plane, u_z is 0. Based on the discrete form of motion speed and nonlinear error feedback, the nonlinear sliding mode control closed-loop system of the robot is constructed. The process is as follows:

$$f(e,\alpha,\delta)=\begin{cases} |e|^{\alpha}\operatorname{sgn} e, & |e|>\delta \\ e/\delta^{1-\alpha}, & |e|\le\delta \end{cases} \tag{7}$$

where the constructed nonlinear sliding mode control closed-loop system is $f(e, \alpha, \delta)$, e is the input signal, α is the constant between [0, 1], and the filter factor of a robot.

The stability of the constructed robot nonlinear sliding mode control closed-loop system is analysed. Given the continuous expected trajectory, if the designed control law ensures that the closed-loop system reaches the switching surface in a limited time and the origin of the error system state space is the globally asymptotically stable equilibrium point, the robot system is stable.

The designed control law ensures that the robot nonlinear sliding mode control closed-loop system reaches the switching surface in a limited time, any constant satisfies $F_i > 0$, and represents that the joint related sliding variable s reaches the sliding surface in a limited time. According to the sliding variable, once entering the sliding mode, there are:

$$E=-\beta Lf(e,\alpha,\delta) \tag{8}$$

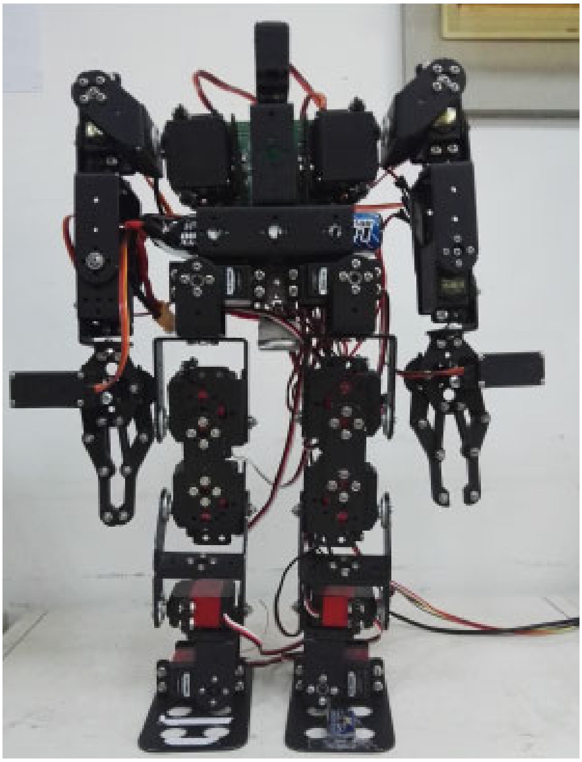
The origin of the error system state space is the globally asymptotically stable equilibrium point. For each joint, the error E is zero, which is independent of the initial configuration of the robot in the operation space. The origin of the error state space is the critical point of the asymptotic stability of the controlled system, and the stability is proved.

4 Simulation experiment analysis

In order to verify the effectiveness of the nonlinear modelling and analysis method of stable behaviour of robot gait control system based on image processing technology in practical application, a simulation experiment is carried out. Set the average speed of the robot: the maximum speed is set to 1 m/s, the maximum acceleration is set to 50 cm/s, the maximum sudden acceleration is set to 20 cm/s, the initial speed is 0, accelerate to 1 m/s within 3 S, maintain the speed for 3 S, then control the robot to stop running and reduce the speed to 0 again.

In this experiment, the biped robot built independently is used, and the appearance of the prototype is shown in Figure 7. It meets the characteristics of small size, low power consumption and high flexibility. The robot has 19 degrees of freedom, including five degrees of freedom for both legs. The degrees of freedom are distributed as follows: two degrees of freedom for hip and ankle and one degree of freedom for knee. The appropriate degree of freedom allocation provides a guarantee for the biped robot to complete complex and flexible actions, so that it can adjust its posture through actions more similar to human beings when it is unstable.

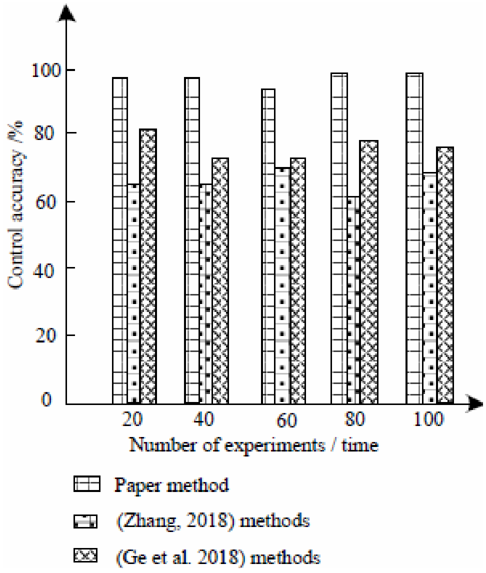
Figure 7 Prototype structure of biped robot (see online version for colours)



The biped robot weighs 2.64 kg, is 42 cm high, has a centre of gravity height of 21.8 cm, and has a two foot support area of 200 cm^2 in an upright state. A large capacity aircraft model battery is placed in the trunk U-slot, and the control board is located in the middle and rear of the robot.

The robot gait control accuracy is compared and analysed by using the nonlinear modelling and analysis method of stable behaviour of robot gait control system based on image processing technology designed in this paper, the robot robust stabilisation control method based on robust reliability method designed in Zhang (2018), and the under-actuated biped robot control method based on gait switching designed in Ge et al. (2018), The comparison results are shown in Figure 8.

Figure 8 Comparison results of robot gait control accuracy of three methods



It can be seen from Figure 8 that the accuracy of robot gait control by the nonlinear modelling and analysis method of stable behaviour of robot gait control system based on image processing technology designed in this paper can reach 100%, while the accuracy of robot gait control by the robot robust stabilisation control method based on robust reliability method designed in Zhang (2018) is only 70%, and that in Ge et al. (2018). The designed control method of under-actuated biped robot based on gait switching has the highest accuracy of only 80%. The robot gait control accuracy of this method is higher than that of Zhang (2018) and Ge et al. (2018). Then the method is compared with the control system based on gait deviation correction method designed in Zhang et al. (2022), the control system based on gait pattern generation algorithm proposed in Hwang et al. (2021), the robot control strategy based on colour and depth images designed in Seppänen et al. (2022), and the modular neural control system based on gait adaptation and obstacle avoidance developed in Srisuchinnawong et al. (2021), the accuracy results under the control of the five methods are shown in Figure 9.

It can be seen from Figure 9 that the highest control accuracy rate obtained in Zhang et al. (2022) is 88%, and the lowest is about 80%. The highest accuracy rates of Hwang et al. (2021) and Seppänen et al. (2022) are 75% and 79% respectively, which are relatively low. The highest control accuracy rate in Srisuchinnawong et al. (2021) is about 84%, but the lowest is about 60%. The method proposed in the study is basically stable at more than 95%, up to 99%, which is superior to the other four methods and has a high accuracy. In order to verify the computational complexity of the proposed method, the five methods are compared, and the computational complexity is reflected by comparing the reaction time of the five methods in control. At the same time, in order to enhance the scientific nature of the results, two experiments were carried out, and the results are shown in Figure 10. It can be seen from Figure 10 that in the first test, the method in Zhang et al. (2022) takes the longest time, 0.410 s, while the proposed method only takes 0.194 s, which is the shortest of the five methods. At the same time, it can be found that in the second test, the proposed method takes 0.202 s, which also takes the shortest time, indicating that its complexity is low and it can react quickly.

Figure 9 Control accuracy results of the five methods

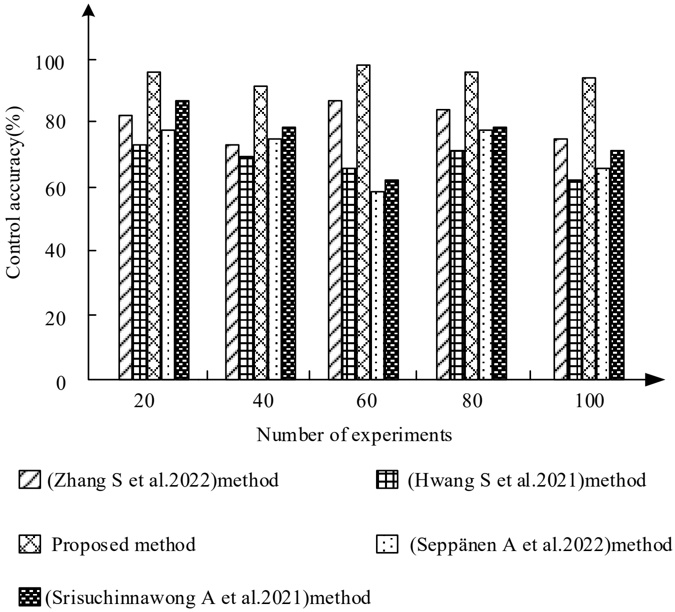
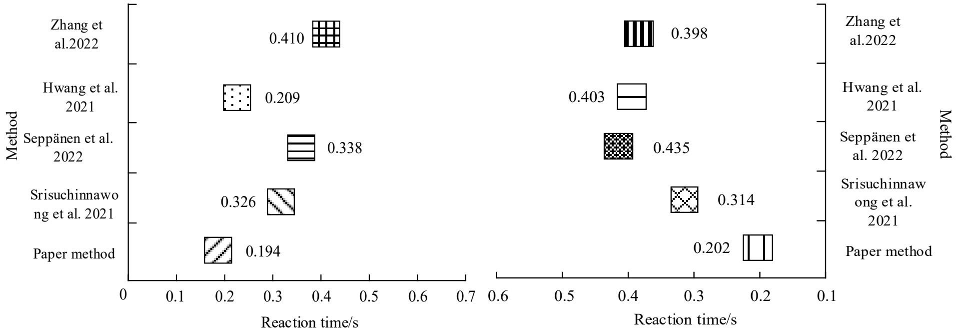


Figure 10 Comparison of control reaction time of five methods, (a) the first test (b) the second text



(a) (b)

In order to further verify the effectiveness of this method, the nonlinear modelling and analysis method for the stable behaviour of robot gait control system based on image processing technology designed in this paper is adopted, and then the gait control time is compared with the methods proposed in the four references. See Table 2 for the comparison results.

Table 2 Comparison table of gait control time results of five methods

Number of experiments/ times	*Control time/s*				
	Paper method	*Zhang et al. (2022) method*	*Hwang et al. (2021) method*	*Seppänen et al. (2022) method*	*Srisuchinnawong et al. (2021) method*
10	20.52	35.10	40.10	41.32	39.58
20	20.41	38.03	37.55	36.04	37.69
30	20.47	32.58	35.78	35.18	38.58
40	20.69	38.63	41.96	37.34	40.73
50	25.74	36.14	38.85	34.85	37.55
60	27.96	35.85	36.47	37.09	39.64
70	25.14	31.74	34.56	41.13	43.17
80	26.36	37.96	30.36	39.52	39.39
90	20.14	36.63	35.74	38.41	37.48
100	22.45	39.52	35.04	38.74	45.25

It can be seen from Table 2 that in terms of comparison of gait control time, the maximum control time of the three methods in Zhang et al. (2022) is 38.63 s. The maximum control time of the three methods in Hwang et al. (2021), Seppänen et al. (2022) and Srisuchinnawong et al. (2021) exceeds 40s and is basically stable at more than 35 s. The control time is long and the control efficiency is low. The minimum time of the proposed method is 20.14 s, and it is stable within 28 s. The control time is lower than that of the other four methods, and the maximum time is 25.11 s, with higher control efficiency.

5 Conclusions

As a product of the development of science and technology, robots have a high anthropomorphic state and can reproduce human gait to a large extent in the process of movement. In this process, because there are many operating parts in the robot, the operation difficulty is greatly improved. At the same time, the robot gait control system will face large gait operation differences in the design process, the machine operation has great limitations, and the control efficiency is low. Therefore, aiming at the above problems, this paper proposes a new nonlinear modelling and analysis method for the stable behaviour of robot gait control system based on image processing technology. The simulation results show that the control accuracy of the proposed method is basically above 95%, the control time is within 28 s, and the lowest is 20.14 s. The control accuracy and efficiency have better performance, which provides the necessary method reference for further realising the stable control of robot gait. Although the research has optimised the hardware and software of the whole robot gait control system, the image processing algorithm has not been further optimised, and has not been involved in the control of complex robots. Therefore, this method needs to be applied to the gait control of complex robots in various situations to verify, and further improve the control performance by improving the trajectory planning method.

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