JOURNAL OF ARTIFICIAL INTELLIGENCE AND ROBOTICS
Jan-Mar 2024, VOL. 1, ISSUE 1, pp. 4-10
https://doi.org/10.61577/jaiar.2024.100002

RESEAPRO JOURNALS

OPEN ACCESS

ORIGINAL ARTICLE

Research on key technology of semiconductor robot controller

Bin Zhao[1,2], Xue Zhao[3], Ruo-huai Sun[1] and Xue-jiao Zhang[2]

[1]College of Information Science and Engineering, Northeastern University, Shenyang, China
[2]Faculty of Robot Science and Engineering, Northeastern University, Shenyang, China
[3]Daniel L. Goodwin College of Business, Benedictine University, Chicago, USA

ABSTRACT

In order to solve the nationalization of Chinese semiconductor robot controllers, this paper studies the critical technology of semiconductor robot controllers. Firstly, the article describes the industry background and primary application of semiconductor robots and analyzes the core components' main problems. Secondly, the paper introduces the semiconductor robot's software architecture and technical index and designs a real-time controller function software based on x86 architecture. Third, the article studies the key software technologies of semiconductor robot controllers, and critical technologies such as high-precision trajectory planning, active wafer center, safety protection, and fast teaching are introduced. Finally, the robot controller software designed in this paper adopts layered architecture to ensure system reliability and meet the needs of the semiconductor manufacturing industry. The robot controller software supports non-standard requirements flexibly through modular design in the advanced technology and platform reliability to reach the domestic leading level.

KEYWORDS

Robot controller; Software architecture; Wafer alignment technology; High precision trajectory planning; Security protection

ARTICLE HISTORY

Received 24 August 2023; Revised 28 September 2023; Accepted 4 October 2023

Introduction

Semiconductor robots are widely used in the whole industry chain of semiconductor manufacturing, such as integrated circuits, advanced packaging, compound semiconductors, and new displays. The reliable and efficient transmission of semiconductor processing materials in various process links is an indispensable part of all process equipment in the semiconductor industry, and its performance directly determines the production efficiency and product yield of semiconductor products [1-3]. Due to the high threshold of semiconductor robot technology, significant investment, and high trial and error costs, many enterprises in the United States and Japan have long monopolized such products [4,5]. Semiconductor robot products are strongly related to the upstream and downstream, involving core and critical components such as materials, transmission, sensing, drive, and controller. Deep research has also been conducted on semiconductor technology both domestically and internationally. Wang Z, et al. proposed a direct vibration reduction method for semiconductor manufacturing robots to meet new silicon wafer production and processing standards [6]. This method can reduce energy by 47% and amplitude by 30%. Aribowo W and Terashima K proposes a free pass point method to achieve cubic spline optimization to reduce motion time, combined with input shaping to suppress vibration [7]. Although China's semiconductor robot has realized the domestic substitution of the whole machine product, the supporting capacity of the domestic industrial chain still needs to improve [8-11]. There are some gaps in domestic robot controllers' performance, function, and reliability.

After more than ten years of continuous research and industrial development, SIASUN has developed a series of semiconductor robot controller products [12]. This paper introduces semiconductor robots' software architecture and technical index and designs a real-time controller function software based on x86 architecture [13]. The semiconductor robot controller software uses a layered architecture to ensure system reliability and meet the needs of the semiconductor manufacturing industry. It has also developed the supporting circumstances for industrialization and has implemented batch product applications. The whole machine products have been successfully applied in domestic semiconductor process equipment such as power semiconductors, LED, and advanced packaging. It also entered the production line of the HUAHONG group, JCET semiconductor integration (SHAOXING), SANAN optoelectronics, TCL cost, and other terminal factories. Break through the constraints of foreign robot controllers, and complete the development and industrial application of semiconductor robot controllers.

Overview of Semiconductor Robots

Semiconductor robot applications and problems

Semiconductor robots are divided into two categories: clean robots and vacuum robots. In semiconductor production, clean robots are mainly used for transporting wafers, wafer boxes, cartridges, mask plates, and glass substrates. Vacuum robots are divided into two major series of products: magnetic fluid and vacuum direct drive, which achieve the transmission of wafers and trays in a vacuum state. Semiconductor robots are widely used in complete equipment such as plasma etching machines, CVD, PVD, and ion implantation machines and have become the most commonly used general equipment in

*Correspondence: Dr. Bin Zhao, College of Information Science and Engineering, Northeastern University, Shenyang, 110819, China, e-mail: zhaobin@stumail.neu.edu.cn

IC manufacturing. Due to the relatively lagging research on semiconductor robots in China and the high threshold for technological development of semiconductor robot products, much research and development investment is required for technical breakthroughs, product development, and application verification. The development and industrialization process of semiconductor robot controllers is slow, and semiconductor robots have become one of the significantly weak links in China's chip industry chain. Due to the characteristics of high efficiency, high performance, and high reliability, semiconductor robot controllers used in IC equipment mainly rely on imports, with long lead times and high prices. In the current global supply chain instability era, there is a significant supply safety risk, which has become a bottleneck problem in the entire IC equipment manufacturing industry. Shenyang SIASUN has designed a domestically produced robot controller software to establish a vacuum (clean) robot function, performance, reliability testing, application verification platform, and a pilot production line.

Core components of semiconductor robots

The critical components of vacuum (clean) industrial robots include arm structural components, guide rail screw bearing transmission components, servo motors and drives, controllers and software, harmonic reducers, cables and connectors, lubricants, etc. The origin is divided into three types: imported from the United States, Japan, and Europe, imported from other countries, and domestically produced. SIASUN has been doing localization replacement work for imported components for many years. Some progress has been made in structural components, transmission components, servo motors and drives, controllers, and software, and partial replacements have been achieved. Figure 1 shows the core components of SIASUN's existing semiconductor robot products.

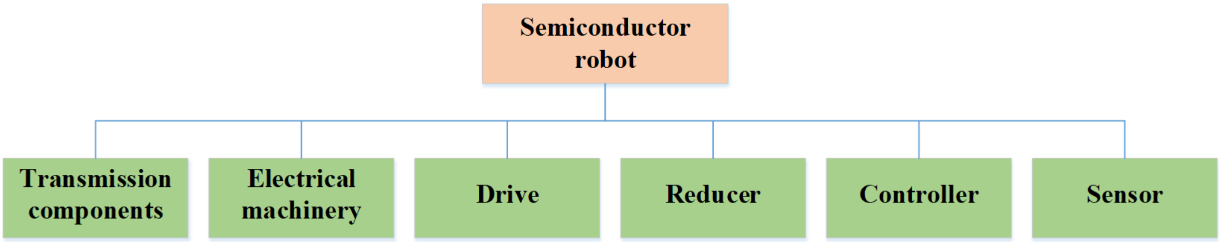

Figure 1. Core and key components of semiconductor robots.

1. Transmission components: bearings, guide rails, and screw;
2. Controller: robot control board (x86, ARM), IO board, and interface board;
3. Sensors: encoder and photoelectric switch;
4. Motor and driver: direct drive motor and driver, servo motor and driver;
5. Reducer: harmonic reducer;
6. Others: cables, connectors, and lubricants.

The central core components of vacuum (clean) semiconductor robots are divided into three parts. Firstly, the mechanical drive part includes structural components, transmission components, direct drive motors, servo motors, vacuum coders, reducers, and guide screws. Direct drive motors and vacuum coders are mainly American and Japanese brands, while structural and transmission components are mainly domestically matched. The second part is the controller and software, mainly focusing on position control and IO control board cards. This part is the core part of controlling the motion unit. Currently, the controller and software are independently designed by SIASUN, and the hardware board cards are outsourced for manufacturing. The third part is the electrical components section, which focuses on the electrical components inside the control cabinet. The main drivers and sensor units are mainly American and Japanese products, while relevant domestic manufacturers produce other cables, connectors, and other parts. This article mainly studies the software-related issues of semiconductor robot controllers.

Controller Software Architecture and Technical Indicators

Technical specifications of the robot controller

The project indicators of the China semiconductor robot controller are as follows:

1. Support at least one domestic chip, support ARM, x86, and other hardware processor platforms with no less than two instruction architectures;
2. Support open Euler Embedded domestic autonomous real-time operating system kernel to achieve an average interrupt delay ≤3us maximum interrupt delay ≤15us;
3. Support Ether CAT communication protocol to achieve data communication cycle ≤500us;
4. Support Linux native ecosystem software migration, support POXIS interface, support package management, support applications to CPU division, binding;
5. Repeated positioning accuracy of vacuum wafer transfer robot ≤0.1mm
6. Vacuum wafer transfer robot controller MTBF is not less than 10,000 hours;
7. Provide a library of standard functional modules related to vacuum wafer transfer robots, covering dynamic planning, robot teaching, motion control, dynamic compensation, and other functions;
8. Support the motion simulation of the vacuum wafer transfer robot and realize the simulation debugging software;
9. With an open secondary development environment, it can realize the customized development of process software packages for different applications, covering configuration, control, process, and other instructions.

The successful application of domestic semiconductor robot controllers can replace imported equipment and improve the domestic manufacturing industry's independent research and development and production capacity.

Real-time operating system for robots

The real-time performance of the robot controller is

https://doi.org/10.61577/jaiar.2024.100002

significant. The real-time performance of the robot controller refers to the rapid response and real-time execution ability of the robot control system to the input signals (sensor data, commands, etc.). In simple terms, it measures the ability of the control system to meet real-time requirements during the control of the robot. Real-time is very important in robot control because robots usually need to make immediate decisions and actions based on real-time environmental information. The low-level software of the robot controller is the real-time operating system, and real-time performance, reliability, and efficiency to ensure the precision and efficiency of wafer fabrication processes.

As shown in Table 1, all real-time operating systems show unique advantages in domestic and foreign markets. First, VxWorks, a real-time operating system developed by Wind River Systems in the United States, shows excellent real-time performance and system compatibility with its time scheduler, modular design kernel, and object-oriented interfaces and components. Second, Ubuntu+Preempt-RT effectively improves the real-time response speed of the system by adding PREEMPT-RT patches to the Linux kernel so that all system calls, interrupt handlers, and kernel threads can be preempted by real-time tasks. Moreover, the domestic real-time operating system SylixOS, based on microkernel architecture and real-time scheduling algorithm, not only supports multi-tasking but integrates rich middleware and protocol stack to cope with various complex environments. In addition, as the root community of the Chinese operating system, open Euler optimizes the open-source Linux kernel and supports various hardware platforms. The open-source feature allows developers to customize freely. As the Embedded version of the openEuler operating system, openEuler Embedded provides excellent real-time performance and stability. Finally, Linux+xenomai and RTAI-Linux have good complex real-time performance in Linux environments by implementing dual kernel architecture and real-time application interface. In general, these real-time operating systems have advantages; developers can choose the most suitable for their real-time operating system development according to the specific needs and application environment.

Table 1. Comparison of real-time operating system products.

Real-time operating system	Opening situation	Characteristic
VxWorks	United States, the core code is not open	Excellent real-time performance in the field of universal controllers
SylixOs	Domestic, charging	Good real-time performance and average ecosystem
OpenEuler Embedded	Mainly open source, free, and domestic maintenance	Open Atom Foundation, open source, hybrid deployment
Linux+xenomai/ RTAI-Linux	Mainly open source, free, and non-domestic maintenance	Good real-time performance in the field of general controllers
Ubuntu+Preempt-RT	Mainly open source, free, and non-domestic maintenance	Rich ecology, non-mainstream real-time performance

In China, SylixOS and open Euler Embedded, as domestic real-time operating systems, are more in line with the needs of the localization background. With its microkernel architecture and real-time scheduling algorithm, SylixOS has advantages in high-concurrency and high-real-time application scenarios. However, its ecology could be sounder, and it needs to strengthen ecological construction further and verify its effect in large-scale applications. Opener Embedded's optimized Linux kernel and support for various hardware platforms make it have a wide range of application prospects in embedded devices, and its open-source attribute provides a strong impetus and possibility for localization.

Robot controller software architecture

As shown in Figure 2, the software architectu re software code of the semiconductor robot controller is divided into application layer, intermediate layer, and platform layer:
(1) Application layer: This layer includes semiconductor applications (apps), communication applications (commu), and teaching box interfaces (teach box).
App: Contains application functions for four types of robots: MAG, MHD, ATM, and FPD, as well as cleaning instructions for corresponding models. Commu: Application layer interfaces for DNet, CANopen, COE, serial port, and TCP.

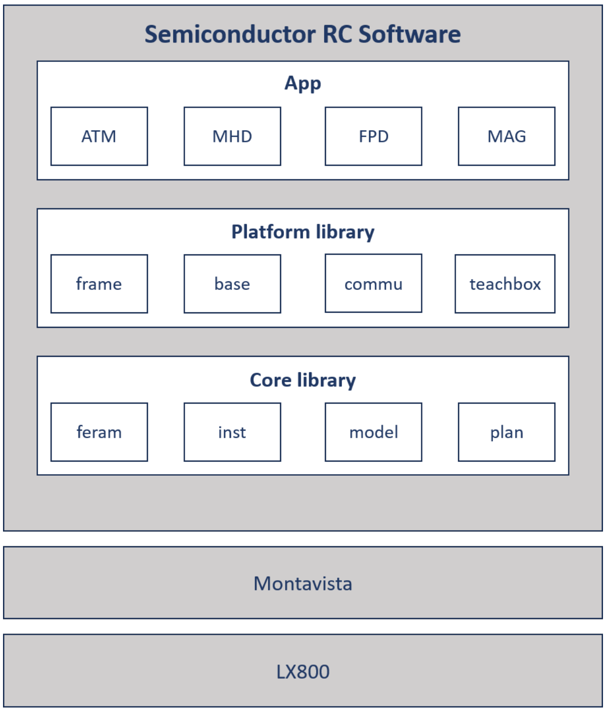

Figure 2. Software architecture of semiconductor robot.

https://doi.org/10.61577/jaiar.2024.100002

(2) Middle layer: This layer contains two libraries: base and frame
Base: This library includes the display, parameter transfer, alarms, system logs, and job-related functions.
Frame: This library includes initialization, buttons, threading, power on, dialog boxes, and software button functions.

(3) Platform layer: This includes the plan, model, inst, feram, mathematics, and algorithm libraries.
Plan: The trajectory interpolation and planning of a robotic arm, involving planning in cylindrical coordinates, upper computer calls planning, continuous trajectory, and dual hand trajectory. Model: cylindrical coordinate model; Joint Space Manipulation Space Model: Models of frog hands, MAG8 double arms, D156 double arms, and SCARA robotic arms. Inst: Inherited from the primary and clear instructions in the industrial robot code. Feram: Ferroelectric management. Mathematics: Basic mathematical functions (numerical analysis, linear algebra, and robot mathematics). Algorithm: Business-related algorithms (collision protection, single sensor AWC, and dual sensor AWC).

Semiconductor Robot Controller Algorithm

Main algorithm of the controller software

Semiconductor robot controllers and functional software play many vital roles in semiconductor manufacturing.

The following will introduce its primary role:

1. Motion control and precision control: The semiconductor robot controller realizes various precision operations in the semiconductor manufacturing process by precisely controlling the robot's motion trajectory, speed, and strength parameters. For example, the inflection points movement of the vacuum direct drive manipulator in the narrow chamber and the prevention of wafer sliding by optimal motion planning.
2. Task scheduling and collaborative work: the controller and functional software can schedule tasks for multiple robots to make them work together. Efficient execution of complex processes in semiconductor manufacturing is achieved through rational task allocation and collaboration between robots. For example, in the chip packaging process, the controller can realize the synchronous work of multiple robots to complete accurate transmission, packaging, and testing steps.
3. Autonomous decision-making and fault handling: The semiconductor robot controller and functional software can make autonomous decision-making and fault handling according to real-time sensor data and preset algorithms. When abnormal conditions or faults occur, the controller can detect and take appropriate measures in time, such as suspending work, alerting the operator, or automatically adjusting process parameters to ensure the continuity and stability of the manufacturing process.
4. Data acquisition and analysis: The semiconductor robot controller and functional software can collect and analyze a large amount of real-time data in the production process. Through processing and analyzing the data, we can obtain the real-time status, process parameters, and performance indicators of the production line and provide the basis for production management and optimization. At the same time, data analysis can be used to predict equipment maintenance requirements and failure risks to achieve preventive maintenance and improve equipment reliability and stability.
5. System monitoring and remote management: semiconductor robot controllers and functional software can perform real-time monitoring and remote management of semiconductor robot systems. The monitoring system lets the operator know the robot's status, operation, and production efficiency at any time and perform remote operations and adjustments. This allows operators to control and manage the semiconductor manufacturing process, even remotely.
6. AWC calibration: Wafer calibration is a process of calibrating and adjusting the wafer's position, orientation, and shape using specific algorithms and equipment. In the semiconductor manufacturing process, wafer calibration is a very critical step because the silicon wafer needs to go through multiple processes in the manufacturing process, such as lithography, etching, deposition, etc., each process has very high requirements for the position, and direction of the silicon wafer. The accurate position or orientation of the silicon wafer will lead to accurate photolithographic pattern correspondence, which will affect the performance and yield of the device. Optical equipment, robots, control algorithms, and other technical means usually achieve silicon wafer calibration.
7. Data backup and recovery: Using XML to back up the database can flexibly transfer the information to other platforms and database systems, and the backup database occupies minimal space. Another feature of XML is that it can be used to exchange data in different databases. A particular type of database file in one system can be exported with XML, and then the data can be imported into other databases in another system. XML makes the data exchange between different databases on different platforms more convenient.
8. Flexibility and scalability: The design and development of the controller and functional software consider the flexibility and scalability of the semiconductor manufacturing process. They have the characteristics of flexible configuration, adjustable parameters, and function expansion and can adapt to different product requirements and process changes. The new process can be introduced and adapted quickly by upgrading and adjusting the software.

In summary, semiconductor robot controllers and functional software are key in semiconductor manufacturing. They enable precise motion control, task scheduling, and collaborative work to improve production efficiency and product quality. At the same time, through autonomous decision-making, fault handling, and data analysis, the stability and reliability of the manufacturing process can be guaranteed. The controller and functional software also enable system monitoring and remote management, providing support for production management. Its flexibility and scalability enable it to adapt to changing process requirements and market demands.

Semiconductor robot controller software

Trajectory planning technology

The joints of the semiconductor robot are transmitted through steel belts, and the flexibility and small reduction ratio of the

https://doi.org/10.61577/jaiar.2024.100002

steel belts give the mechanical body a certain degree of flexibility. During the movement of the robotic arm, there will be residual vibrations of a specific frequency.

1) Trajectory delay filtering

Frequency measurement: Based on the characteristics of reduced amplitude oscillation in robot joint follow-up, the vibration period T of the system can be obtained by dividing the total interval time of multiple consecutive peaks or valleys by the number of intervals n. T = ΔT/n, vibration angle frequency is $\omega_n = 2\pi/T$.

The design of a time delay filter involves introducing a time delay link into the control system, convolving pulses (referred to as input shapers) with any command signal, and driving the system through the tuned instructions. Figure 3 shows a schematic diagram of time-delay filtering. If the residual vibration generated by the instructions after the filter is smaller than the vibration generated by the original command. The system's natural vibration frequency and damping ratio will determine the pulse's amplitude and time. Input signal shaping can be adjusted to have high robustness against system parameter errors. The transfer function of a time delay filter with n pulses can be expressed as:

$$G(s) = A_1 e^{-t_1 s} + A_2 e^{-t_2 s} + \cdots + A_n e^{-t_n s} \quad (1)$$

Among them, A_i represents the amplitude corresponding to the pulse, and t_i represents the duration of each pulse. It can ultimately reduce the response amplitudes of two signals to zero after 0.5 natural cycles, achieving vibration suppression and mutual cancellation of the two pulses.

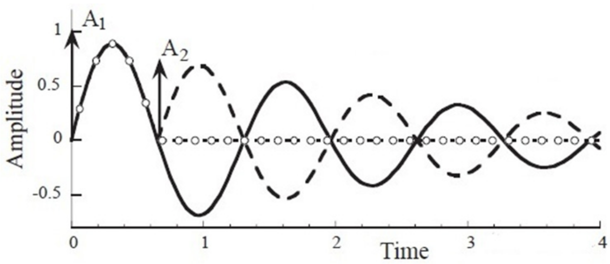

Figure 3. Schematic diagram of time delay filtering.

When a pulse A_1 is applied to a flexible system, the vibration response of an underdamped system is shown in Figure 3. Suppose the action of the second pulse A_2 produces a vibration with an amplitude exactly opposite to that of the first pulse after half a period. In that case, the system's vibration will be wholly suppressed after it is applied to the system.

2) PVT (Position-Velocity-Time) interpolation

The calculation method of PVT interpolation is as follows:

$$P_n(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 \quad (2)$$

Differential the above equation to obtain the velocity formula:

$$P_n'(t) = V_n(t) = b_1 + 2 * b_2 t + 3 * b_3 t^2 \quad (3)$$

According to the above two equations, it can be determined:

$$\begin{cases} P_n(0) = b_0 \\ V_n(0) = b_1 \end{cases} \quad (4)$$

Bring the time period T into equation (2) and rewrite $P_n(T)$ to get b_2:

$$b_2 = (P_n(T) - P_n(0) - V_n(0)T - b_3 T^3)/T^2 \quad (5)$$

Then differential $P_n(T)$ is performed to obtain $V_n(T)$, and finally, b_3 is obtained as follows:

$$b_3 = \frac{V_n(T)+V_n(0)}{T^2} + 2 * (P_n(0) - P_n(T))/T^3 \quad (6)$$

The position and velocity information of the interpolated trajectory are obtained by b_0, b_1, b_2, and b_3 parameters.

Active wafer center technology

The AWC algorithm based on dual-sensor data fusion is shown in Figure 4 below. The AWC process is divided into three stages.

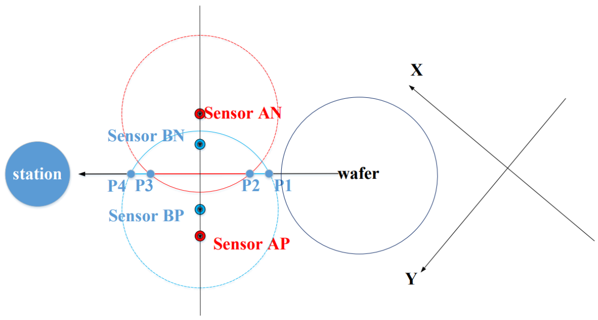

Figure 4. Schematic diagram of AWC operating conditions based on dual-sensor feedback data fusion.

1. Calibration: the paper considers that the finger center of the robot coincides with the wafer center. By controlling the manipulator to perform the high-level expansion operation of the station, the spatial position of the manipulator when the sensor is triggered is collected, and the position of the sensor in the robot's basic coordinate system is calculated accordingly. After the center of the wafer coincides with the center of the finger, the station (R, T) is extended at a high level, and the sensor is triggered twice in sequence. The distance from the sensor to the trigger point (p_1, p_2, p_3, p_4) is equal to the radius of the wafer to construct the equation group. p_1, p_2, p_3, and p_4 are the positions of the manipulator when the sensor is triggered.
2. Deviation and correction calculation: Determine the deviation of the wafer center from the finger center of the manipulator (described in the manipulator coordinate system) according to the following conditions. When the wafer is returned from the station, the deviation value needed to correct the wafer can be calculated by combining the spatial position information of the sensor. Solving the inverse kinematics of the biased kinematics equation constructed in the deviation calculation, the polar diameter r and Angle θ are obtained, which are the compensated robot poses. For the i-th trigger (i=1,2,3,4), the coordinates of M are known to be (x_i,y_i). Then the coordinates corresponding to P_i are:

$$\begin{pmatrix} x_i' \\ y_i' \end{pmatrix} = \begin{pmatrix} x_i \\ y_i \end{pmatrix} - d_x \begin{pmatrix} c\theta_i \\ s\theta_i \end{pmatrix} + dy \begin{pmatrix} s\theta_i \\ -c\theta_i \end{pmatrix} \quad (7)$$

The distance from p_1 to sensor A and from p_2 and p_3 to sensor B is the wafer radius *wr*:

$$\begin{cases} F_1 = (x_1' - x_a)^2 + (y_1' - y_a)^2 - wr^2 = 0 \\ F_2 = (x_2' - x_b)^2 + (y_2' - y_b)^2 - wr^2 = 0 \\ F_3 = (x_3' - x_b)^2 + (y_3' - y_b)^2 - wr^2 = 0 \\ F_4 = (x_4' - x_a)^2 + (y_4' - y_a)^2 - wr^2 = 0 \end{cases} \quad (8)$$

In fact, due to the delay of the sensor, there are errors in the acquisition of the positions of the four trigger points. So, these four equations cannot be satisfied at the same time. This problem should be transformed into a nonlinear optimization problem:

https://doi.org/10.61577/jaiar.2024.100002

$$\begin{cases} \min\left(\sum_{i=1}^{4} F_t^2\right) \\ \text{s.t. } \left(d_x^2 + d_y^2\right) < W_R^2 \end{cases} \quad (9)$$

By solving the above optimization problem, the actual wafer deviation can be obtained.

Active safety protection technology

Collision protection based on torque estimation and trajectory deviation

1. The errors of theoretical displacement, velocity, acceleration, and actual displacement and velocity of the robot are taken as input information;
2. Compare the output information with the preset threshold to determine whether a collision occurs.

Effect: The collision of the robot will react as a block to the movement trajectory, and the detection sensitivity intensity can be set as shown in Figure 5.

As is shown in Figure 6, it is a hierarchical security monitoring policy.

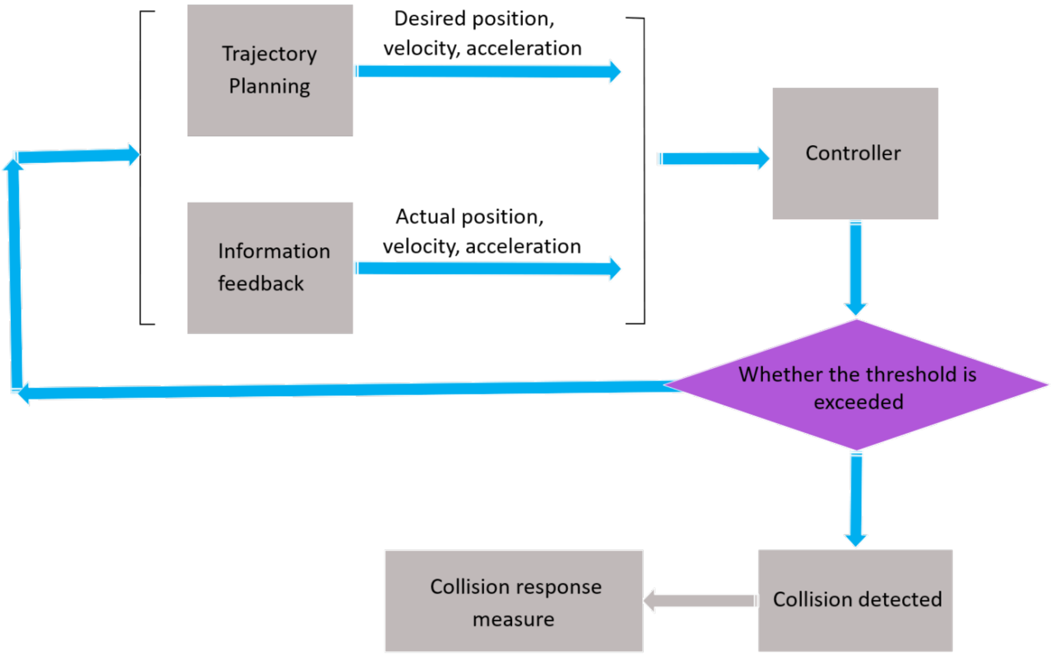

Figure 5. Collision protection strategy.

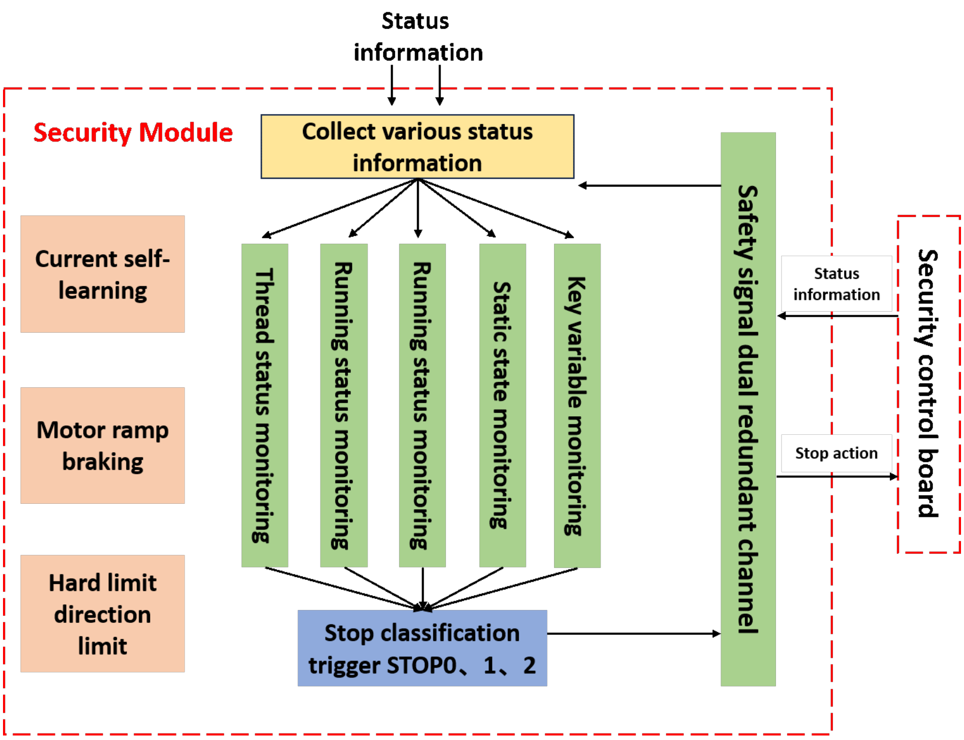

Figure 6. Hierarchical security monitoring strategy.

https://doi.org/10.61577/jaiar.2024.100002

By monitoring various running states of the robot in real-time, and triggering the corresponding safety stop action according to the abnormal state level, the safety of the robot body and the chamber can be guaranteed. Safety control is a top priority in the design of clean (vacuum) robots.

1. Safety stop level: (1) STOP0 - high; (2) STOP1 - medium; (3) STOP2 - low.
2. Support bus, thread, and running status monitoring; Key variables, static state monitoring; Safety torque off;
3. Self-learning of lock current; Hard limit direction limiting function.

Conclusions

There are no relevant application cases of clean semiconductor controllers in China. In order to solve the nationalization of Chinese semiconductor robot controllers, we will develop controller application software based on platformed software. The paper designs a real-time controller function software based on x86 architecture. In controller design, high-performance semiconductor robot AWC stability algorithms are developed to improve the transmission accuracy of different customer sites and silicon wafers of different sizes. Develop collision protection strategies for semiconductor robots, develop self-learning collision protection technologies, and effectively protect robotic arms and customer wafers. The robot controller software supports non-standard requirements flexibly through modular design with advanced technology and platform reliability.

Compared with Brooks in the United States and Rorze in Japan, the software functional level of robot controllers is similar, and some software functions are even slightly better than foreign brands. However, there should be a particular gap in the quality level of real-time system and hardware board technology, mainly reflected in the need for technical breakthroughs in durability, real-time performance, and software stability.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

1. Zhu Q, Wu N, Teng S. Petri net modeling and deadlock analysis of multicluster tools in semiconductor manufacturing. J Southeast Univ (Nat Sci Ed). 2010;40(z2):267-271. https://caod.oriprobe.com/articles/26769189/Petri_net_modeling_and_deadlock_analysis_of_multicluster_tools_in_semi.htm#
2. Wang JS, Liu XF, Duan LC, Cai G. Dynamic modeling and parameter identification of space robot considering joint friction. Chin Q Mech. 2015;36(4):594-601. https://caod.oriprobe.com/articles/48225227/Dynamic_Modeling_and_Parameter_Identification_of_a.htm
3. Yao J, Li H, Cao CC, Wang Q. Robot soccer path planning based on vector potential field. J Sichuan Univ (Eng Sci Ed). 2006;(02):70-73,99. https://caod.oriprobe.com/articles/10349354/Robot_Soccer_Path_Planning_Based_on_Vector_Potential_Field.htm
4. Yang Y, Zhao J, Liu Y, Zhu Y. Solving forward kinematics of 6-PRRS parallel robot. J Jilin Univ (Eng Technol Ed). 2008;38(03):731-734. http://xuebao.jlu.edu.cn/gxb/EN/Y2008/V38/I03/731
5. Ham A. Transfer robot task scheduling in semiconductor manufacturing. In Proceedings of the 2019 Winter Simulation Conference, Mustafee N, Bae K-HG, Lazarova-Molnar S, Rabe M, Szabo C, Haas P, et al. (Eds.), 2019:2248-2256. https://www.informs-sim.org/wsc19papers/216.pdf
6. Wang Z, Wang C, Tomizuka M. Vibration cancellation of semiconductor manufacturing robots. Manuf Lett. 2015;4:6-9. https://doi.org/10.1016/j.mfglet.2015.01.004
7. Aribowo W, Terashima K. Cubic spline trajectory planning and vibration suppression of semiconductor wafer transfer robot arm. Int J Autom Technol. 2014;8(2):265-274. https://doi.org/10.20965/ijat.2014.p0265
8. Cao WM, Wang Y, Feng Y. Study on real-time 3D monitoring of telerobot movement. Chin J Sci Instrum. 2010;31:727-735. https://caod.oriprobe.com/articles/23600052/Study_on_real_time_3D_monitoring_of_telerobot_movement.htm
9. Yang Z, Wang J, Zhang J, Jiang X. Data driven wafer pattern defect pattern recognition method. Chin Mech Eng. 2019;30(02):230-236. http://www.cmemo.org.cn/EN/Y2019/V30/I02/230
10. Tang J, Li L. Semiconductor processing cycle prediction based on multi-layer data analysis framework. Comput Integr Manuf Syst. 2019;25(05):1086-1092. http://www.cims-journal.cn/EN/10.13196/j.cims.2019.05.006
11. Li X, Zhou B, Lu Z. Real-time scheduling algorithm for semiconductor wafer etching system based on residency constraints. J Shanghai Jiaotong Univ. 2009;43(11):1742-1745.
12. Hua N, Li H, Wang Y, Sui M. Quartz glass wafer processing technology. Infrared Laser Eng. 2016;45(S2):96-100.
13. Huang Y, Qu D, Xu F. Frog-a study on the dynamics of a space-free manipulator. J Sichuan Univ (Eng Sci Ed). 2013;45(3):158-163. https://caod.oriprobe.com/articles/37520477/frog_leg_xing_zhen_kong_ji_xie_shou_de_dong_li_xue_kong_zhi_yan_jiu_.htm

https://doi.org/10.61577/jaiar.2024.100002