

Kinematic Analysis, Workspace Optimization, and Structural Validation of the XB4 Robotic Arm for Intelligent Manufacturing

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Abstract: Advancements in automation have led to widespread adoption of robotic arms in industrial, medical, and service sectors, accelerating intelligent transformation. This study investigates the XB4 robotic arm by analyzing its kinematics, workspace reachability, and structural reliability using the modified Denavit-Hartenberg (D-H) parameter method, Monte Carlo simulations, and finite element analysis. A refined link coordinate system is established, and MATLAB simulations are conducted to evaluate workspace distribution. Additionally, structural analysis verifies the strength and rigidity of the robotic arm's base. Results demonstrate that the XB4 robotic arm exhibits high kinematic accuracy, an optimized workspace, and robust structural integrity, making it well-suited for automation in complex industrial environments. The findings provide theoretical guidance for robotic arm design and optimization, facilitating advancements in intelligent manufacturing.

Keywords: Robotic Arm Kinematics, Denavit-Hartenberg Parameter Method, Monte Carlo Workspace Analysis, Finite Element Structural Validation

1. Introduction

Automation technology has advanced rapidly, leading to widespread adoption of robots in manufacturing, healthcare, and aerospace. Among these, robotic arms play a crucial role due to their precision, flexibility, and efficiency. The 2024 Global Robotics Report [1] by the International Federation of Robotics (IFR) states that 4,281,585 robots were operational in factories worldwide by the end of 2023. The annual installation rate has exceeded 500,000 units for three consecutive years, with robotic arms constituting a substantial proportion. These systems enhance productivity, reduce labor costs, and replace human operators in hazardous environments, enabling high-precision, high-stress tasks.

Extensive global research on robotic arms has advanced kinematics, strength calibration, and workspace analysis. Significant research has been conducted on robotic arm kinematics. For instance, Zhang Xuyang et al. [2] developed a kinematic model for a six-degree-of-freedom ball mill relining robotic arm using the Denavit-Hartenberg (D-H) parametric method. MATLAB simulations confirmed the model's validity, demonstrating seamless and stable movement within the prescribed workspace. Furthermore, Kai Wang's PhD thesis [3] explored the technological underpinnings of soft robotic arms for surgical robots, proposing an inverse kinematic solution method based on a neural network. This approach yielded substantial enhancements in terms of solution accuracy and

convergence speed. In terms of trajectory planning, Lou et al. [4] proposed a time-optimal trajectory planning method based on the Improved Sand Cat Swarm Optimisation Algorithm (YSCSO), which successfully reduced the joint movement time of the robotic arm by 42.72% and achieved smooth and continuous trajectories. In the field of workspace analysis, Qin et al. [5] conducted an in-depth analysis of the workspace of dual cable-suspended robots for construction, investigating their wrench-feasible workspace and collision detection methods to determine the collision-free buildable workspace. With regard to the strength calibration of key stress components, Sallam A. Kouritem et al. [6] restructured the robotic arm through ANSYS and finite element method (FEM) simulations and selected materials to withstand different loads. Furthermore, Xiao Jie and Wang Dahong [7] conducted a calibration analysis for the static strength of the mechanical arm of a demolition robot, utilising numerical computation software to carry out detailed modelling and simulation of the mechanical arm's stress. The results demonstrated the efficacy of their method in effectively predicting the stress distribution of the mechanical arm under complex loading conditions. While significant progress has been made in kinematics, calibration, and workspace analysis, their seamless integration remains a challenge. This paper aims to address this gap by conducting a systematic research study, proposing novel methodologies, and offering theoretical underpinnings and practical guidelines for the design and implementation of robotic arms, thereby contributing to the advancement of robotic arm technology.

This study systematically examines the XB4 chockstone robotic arm by integrating kinematic analysis, workspace evaluation, and structural verification. Regarding the former, the modified Denavit-Hartenberg (D-H) parameter method is adopted to establish the linkage coordinate system of the robotic arm and determine its D-H parameters, thus providing a basis for the subsequent kinematic solution. The workspace analysis employs the Monte Carlo method to simulate and analyse the workspace of the robotic arm, thereby assessing its reachability and flexibility. For the strength calibration of key components, the base of the robotic arm—subjected to large forces—is selected as the research object. Finite element analysis is performed in SolidWorks Simulation to verify whether it meets the strength requirements. These studies provide a significant foundation for the performance optimization and reliability assessment of the XB4 chockstone robot's robotic arm.

2. Introduction to the Chiselite XB4 Robot Manipulator Arm

2.1. General Introduction to the Chiselite XB4 Robot Arm

Robotic arms are essential in modern automation, spanning industries such as manufacturing, healthcare, and services [8]. According to Universal Robots [9], robotic arms can be classified into six main types: articulated robot arms, Cartesian robot arms, cylindrical robot arms, delta (parallel) robot arms, spherical (polar) robot arms, and SCARA robot arms. Each of these robotic arms has its own advantages in terms of degrees of freedom, load capacity, speed of movement, and ability to adapt to the environment, thus satisfying diverse industrial automation needs [10].

The Chiselite XB4 robotic arm offers notable advantages over conventional robotic arms. Designed for complex and precise industrial applications, it delivers high accuracy and efficiency across diverse operational environments. The XB4 distinguishes itself through advanced servo drive technology, enhancing precision and adaptability. Its multi-degree-of-freedom joint design enhances motion flexibility, enabling precise trajectory execution. Consequently, this heightened flexibility and efficiency in motion trajectory execution contribute to an enhanced capability in terms of precision and task completion efficiency.

The XB4 robot arm is equipped with a high-precision sensor and motor system that facilitates real-time monitoring and precise adjustment of the motion attitude of each joint. This ensures continuous

stability and high efficiency during operation. Its intelligent control system dynamically adjusts operations in response to environmental changes, enhancing production efficiency.

Furthermore, the XB4 robotic arm is highly customizable, allowing adaptation to different loads, work styles, and task requirements. The robot's versatility is evident in its ability to perform both high-speed repetitive tasks and complex, high-precision operations with ease. This attribute renders the XB4 particularly well-suited for applications in precision manufacturing, assembly, handling, welding, painting and other industries.

In comparison with alternative robotic arms, the Chiselite XB4 boasts a more compact structural design, with the capacity to manoeuvre into confined workspaces while maintaining exceptional precision and stability. Its modular design reduces maintenance costs, speeds up troubleshooting and repairs, and minimizes production downtime, enhancing overall equipment availability. The specific technical parameters of the chitonite XB4 robot are detailed in Table 1.

Table 1: Specific technical parameters of the chitonite XB4 robot arm.

Product Name		XB4	XB4h
Degrees of Freedom		6	6
Drive Method		AC servo drive	AC servo drive
Maximum Working Radius		596mm	596mm
Repeat Positioning Accuracy		±0.02mm	±0.02mm
Wrist Load		4kg	4kg
Range of Motion	Axis 1	±170°	±170°
	Axis 2	+144°~-80°	+144°~-80°
	Axis 3	+54°~-194°	+54°~-194°
	Axis 4	±170°	±170°
	Axis 5	±119°	±119°
	Axis 6	±360°	±360°
Maximum Speed	Axis 1	440°/s	440°/s
	Axis 2	355°/s	355°/s
	Axis 3	440°/s	440°/s
	Axis 4	490°/s	490°/s
	Axis 5	450°/s	450°/s
	Axis 6	720°/s	900°/s
Operating Temperature		0℃~+40℃	0℃~+40℃
Storage Temperature		-10℃~+55℃	-10℃~+55℃

2.2. Composition of the Chiselite XB4 Robot Body

From Figure 1, the robot body possesses a total of six degrees of freedom, which are also referred to as six joints or six axes. Each joint motor is equipped with a brake. The body is composed of the following components:

The wrist, which possesses three degrees of freedom, is situated at the output end of the robot and comprises axis 4, axis 5, and axis 6.

The small arm is located between the large arm and the wrist joint.

The large arm is located between the small arm and the lumbar joint.

The lumbar joint is located between the large arm and the base.

The pedestal forms the foundation of the robot and contains its electrical interfaces.

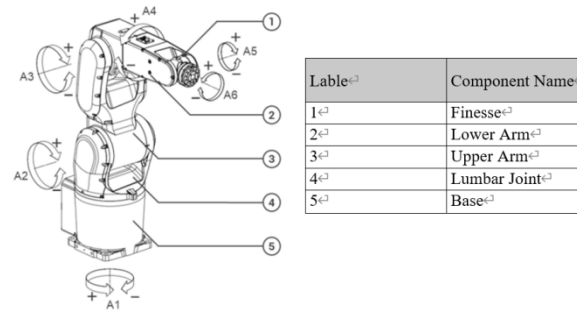


Figure 1: Chitonite XB4 Robot Body.

2.3. The working principle of the chitonite XB4 robot arm

The Chiselite XB4 robot arm is a high-performance industrial device based on a multi-degree-of-freedom joint structure, which achieves highly flexible movement capability through its six servo-driven joints. Each joint is driven by an independent servo motor and equipped with a high-precision encoder for real-time position feedback, ensuring that the robot arm's movement trajectory on complex paths is precise and smooth. The XB4's high-precision sensor network and intelligent control system enable it to quickly respond to changes in the external environment and dynamically adjust movement parameters according to actual working conditions, thus ensuring precise operation and stability. The built-in intelligent algorithms of the XB4 enable the optimisation of the path during operation, thus facilitating continuous trajectory tracking and point-to-point rapid positioning, in addition to enabling flexible operation in force-control mode. The force control function is especially suitable for complex assembly or precision docking tasks and can effectively prevent equipment damage caused by excessive external forces, thus improving operational quality. Furthermore, the XB4 is equipped with a comprehensive safety protection mechanism. In the event of an abnormal load or collision being detected by the sensor, the system will respond instantly and switch to safe mode in order to protect the equipment and its working environment. The XB4 robot arm combines flexibility, precision and intelligent control to deliver outstanding performance in complex industrial scenarios, capable of handling a wide range of demanding automation tasks while maintaining safe and reliable operation.

3. Kinematic analysis of the robotic arm of the chitonite XB4 robot

3.1. Determination of D-H parameters of the robotic arm

3.1.1. Definition of the D-H parameters

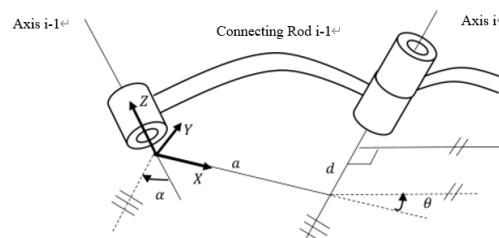


Figure 2: D-H parameter diagram of connecting rod.

As demonstrated in Figure 2, the D-H parameter is comprised of four kinematic parameters: α (connecting rod torsion angle), a (connecting rod length), d (connecting rod deflection), and θ (joint angle). Of these, The first two parameters are utilized to describe the connecting rod itself, while the

latter two describe the relationship between connecting rods. The rule for describing the relationship between the mechanism's motion and the connecting rod parameters is called the Denavit-Hartenberg method, and the corresponding parameters are called D-H parameters.

The kinematic parameters of a connecting rod are determined by the relative relationship between the joint axes at the two ends of the rod. This relationship can be described by two parameters: the length of the common perpendicular of the two joints is denoted as a , i.e. the length of the connecting rod, and α denotes the angle between the two joint axes, i.e. the angle of rotation of the connecting rod.

To establish a connection between two neighboring connecting rods, two parameters must be considered: the distance along the common axis of the two neighboring rods, known as rod deflection (denoted as d), and the angle at which the two neighboring rods rotate around the common axis. This is termed the joint angle, denoted as θ .

The D-H parameter method is divided into two distinct approaches: the standard D-H parameter method and the modified D-H parameter method. The fundamental premise underlying the standard D-H parameter method is that the position and attitude relationship between every two neighbouring coordinate systems can be fully characterised by four parameters. This approach finds application in most robotic arm systems. However, in scenarios where the robot possesses a complex geometry, exhibits significant variations in linkage dimensions, or possesses irregular relative positions between the joint axes, the definition of the standard D-H parameters may lack the requisite precision and flexibility. This can result in computational and modelling challenges. To address these limitations, the modified D-H Parameters were developed. The modified D-H parameter method refines the original system by introducing new definitions and constraints, improving accuracy in modeling robotic arms with irregular joint relationships or complex structures. The improved parameter system appears to be more efficient and flexible. Consequently, the implementation of the modified D-H parameters has the potential to not only address the limitations of the conventional D-H parameters in complex scenarios, but also enhance the modelling accuracy and computational efficiency, thereby providing a more reliable mathematical foundation for subsequent inverse kinematics solving, trajectory planning, and the implementation of control algorithms.

In the present study, the modified D-H parameter method was utilised.

The modified D-H parameter method defines a_{i-1} as the displacement from Z_{i-1} to Z_i along X_{i-1} ; α_i as the angle between Z_{i-1} and Z_i along X_{i-1} ; d_{i-1} as the displacement from X_{i-1} to X_i along Z_i ; and θ_{i-1} as the rotation from X_{i-1} to X_i along Z_i .

The aforementioned parameters are expressed in terms of Link as $L_i = \text{Link}([\theta_i, d_i, a_{i-1}, \alpha_{i-1}])$.

3.1.2. The modified D-H parameter method for the establishment of connecting rod coordinate system

- (1) Find joint axis $i-1$ and joint axis i , and label the extensions of these axes.
- (2) The common perpendicular between joint axis $i-1$ and joint axis i , or the intersection of joint axis $i-1$ and joint axis i , is to be found. The common perpendicular between joint axis $i-1$ and joint axis i , or the intersection of the intersection with joint axis $i-1$, is to be used as the origin of the link coordinate system $\{i-1\}$.
- (3) It is to be ensured that the Z_{i-1} axis points along the joint axis $i-1$.
- (4) Specify the pointing of the X_{i-1} axis along the common perpendicular to the plane in which joint axis $i-1$ and joint axis i are located if joint axis $i-1$ and joint axis i intersect.
- (5) The Y_{i-1} axis is to be determined according to the right-hand rule.
- (6) When the first joint variable is 0, specify that the coordinate systems $\{0\}$ and $\{1\}$ coincide. For the coordinate system $\{i\}$, the origin and the direction of the X_i -axis can be chosen arbitrarily; however, when choosing, try to make the linkage parameter 0.

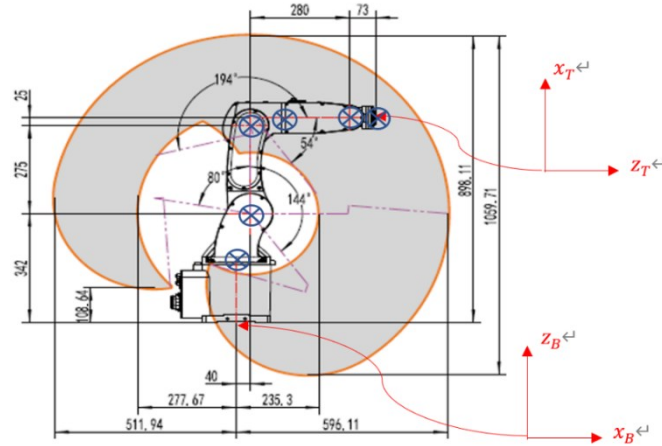


Figure 3: Parameter diagram of the chitonite XB4 robot.

The establishment of the improved D-H parametric method linkage coordinate system for this study is shown in Figure 4, based on the chitonite XB4 robot parameters in Figure 3.

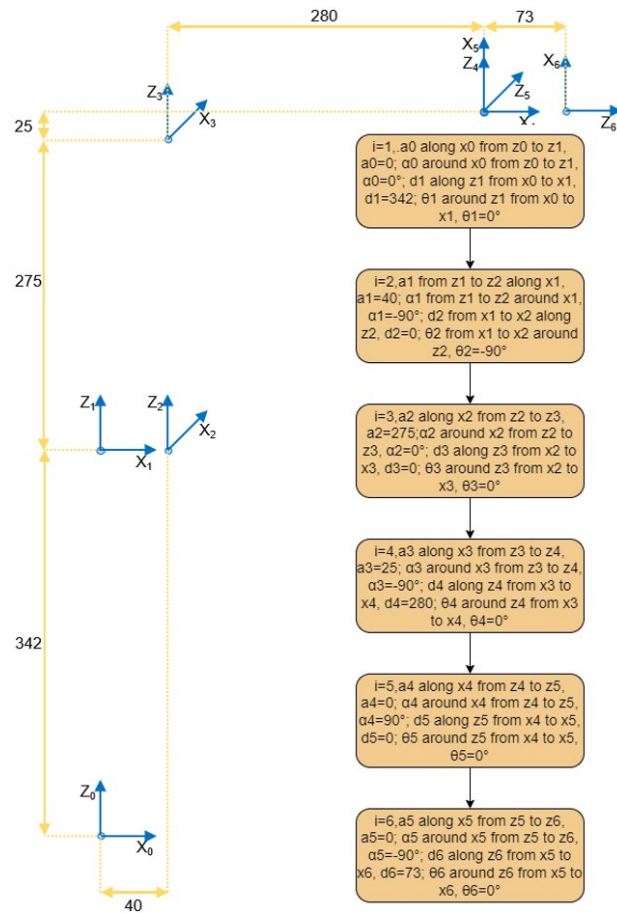


Figure 4: Linkage coordinate system established for chitonite XB4 robot using modified D-H parametric method.

Consequently, a table of the modified D-H parameters was generated, as illustrated in Table 2.

Table 2: Modified D-H parameter table.

i	α_{i-1}	a_{i-1}	d_i	θ_i
B	0	0	0	0
1	0	0	0.342	$\theta_1(0)$
2	$-\pi/2$	0.040	0	$\theta_2(-\pi/2)$
3	0	0.275	0	$\theta_3(0)$
4	$-\pi/2$	0.025	0.280	$\theta_4(0)$
5	$\pi/2$	0	0	$\theta_5(0)$
6	$-\pi/2$	0	0.073	$\theta_6(0)$
T	0	0	0	0

3.2. Workspace analysis of robotic arms

Based on the D-H parameters of the robotic arm in Table 2, the Link and SerialLink functions are used in Matlab to build the robotic arm model. The rotation angle range of each joint is defined, and the Chisel XB4 robot is a six-degree-of-freedom rotary robotic arm, with all six joints being rotary joints. Figure 5 shows the model interface when all joint variables are set to zero, where X, Y, and Z represent the position of the end-effector, and R, P, and Y represent its orientation.

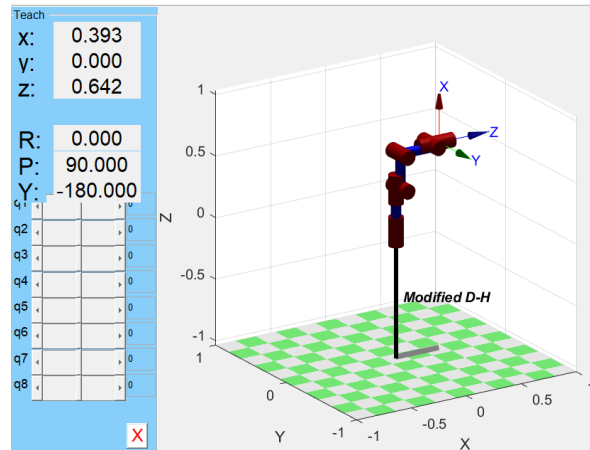


Figure 5: Chitonite XB4 robot model generated in Matlab.

3.2.1. Methods for analysing the working space of a robotic arm

Robotic arm workspace analysis typically requires researchers to evaluate the shape and size of the workspace, i.e. the range of all possible positions and poses that the robot can reach. This analysis is critical for robotic arm applications such as task planning, path planning and motion control. Common workspace analysis methods include geometric, analytical and numerical methods, each of which varies in accuracy, computational efficiency and applicability.

The geometric method is one of the most intuitive, and the boundaries of the workspace are usually derived by analysing the constraints of each joint of the robot arm and the lengths of the linkages. This method is very effective for simple robot structures or systems with clear geometric relationships, but for complex multi-degree-of-freedom robot arms, the geometric method is often difficult to accurately describe the full picture of the workspace and can become computationally expensive. Analytical methods analyse the size and shape of the workspace by building a mathematical model to describe the position and attitude of the end-effector of the robotic arm. The analytical method can provide an accurate mathematical description, but it also suffers from difficulties in solving complex

mechanical structures, especially when the system involves non-linear equations or multiple solutions, making the analytical method more difficult to apply and computationally expensive.

Compared to geometric and analytical methods, numerical methods approximate the shape and boundaries of the workspace by numerical computation. Numerical methods generally include Monte Carlo, mesh and particle methods, of which the Monte Carlo method is widely used because of its simplicity and flexibility. The Monte Carlo method uses random sampling to generate joint angle combinations, computing end-effector positions to approximate the robot arm's workspace. This method is independent of the robotic arm's geometry, efficiently handling workspaces of arbitrary shape and high-dimensional, multi-degree-of-freedom arms. The advantage of the Monte Carlo method is that it can intuitively and comprehensively assess the working capability of a robotic arm in complex environments without relying too heavily on geometric or analytical models.

3.2.2. Workspace analysis of a robotic arm using the Monte Carlo method

After establishing the spatial model of the robotic arm in MATLAB, its workspace can be analyzed. This paper applies the Monte Carlo method to analyze the robotic arm's workspace. The following are the detailed steps of the Monte Carlo analysis:

(1) Define the range of motion of the joints: Define the range of motion for each joint, i.e. the maximum and minimum angles that each joint can rotate. These ranges are used to generate random joint angles.

(2) Generate random joint angles: Use a random number generator to generate random angles within each joint's range of motion. These random angles are used to simulate the position of the robot arm in different postures.

(3) Calculate forward kinematics: For each generated combination of random joint angles, the position of the end-effector of the robot arm is calculated using forward kinematics. Forward kinematics calculates the coordinates of the end-effector in 3D space from the DH parameters and joint angles.

(4) Collect end-effector position data: Store the end-effector positions (x, y, z coordinates) obtained from each forward kinematics calculation for later analysis and visualisation.

(5) Plot workspace distribution: A 3D scatterplot is generated from the collected end-effector position data. This plot shows the distribution of the robot arm's end-effector positions in all random poses, thus visualising the robot arm's workspace.

The aforementioned steps are executed in the Matlab environment, and the resultant motion space point diagram is depicted in Figure 6.

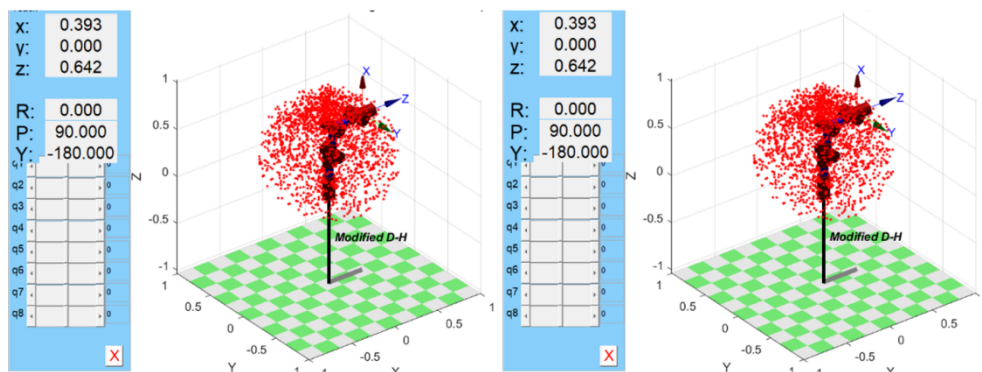


Figure 6: Spatial point plots of motions with sample sizes of 1000 (left) and 10000 (right).

As can be seen from the Figure 6, with a smaller number of samples (1000), the distribution of end-effector positions may have some irregularities or noise, especially when the workspace of the

robotic arm is more complex. The accuracy of the results is lower, but it can still roughly show the distribution of the end-effector positions of the robot arm. A larger sample size (10,000) will give a more accurate distribution of end-effector positions with less noise and random variation. The results will be smoother and closer to the real workspace, providing a more accurate analysis. However, as the number of samples increases, the computation time increases significantly. 10,000 samples require more computation and time, especially when performing forward kinematics calculations, where matrix operations must be performed and end-effector positions extracted each time. At 1000 samples, the computation time is shorter and is suitable for a quick look at the overall trend and for preliminary analysis.

From the three-dimensional scatter plot, it can be seen that the distribution of the end-effector of the robotic arm in the workspace shows a certain degree of concentration, indicating that the workspace shape of the robotic arm is more regular. The boundary of the workspace is relatively clear and there is no obvious abnormal distribution, indicating that the joint movement range of the robotic arm is reasonably set. With 10,000 random samples generated by the Monte Carlo method, the end-effector of the robotic arm has a more uniform distribution in the workspace, and there is no obvious hollow or abnormal region. The work envelope of the robotic arm is moderately large and can meet the needs of most routine tasks.

4. Strength Check of Key Load-Bearing Parts of the Robotic Arm

4.1. Strength check of major components

In this section, Finite Element Analysis (FEA) is performed in SolidWorks Simulation on the key high-stress parts of the arm to verify that the arm can meet the strength requirements. In the robotic arm, the high-load parts include the shoulder, elbow, wrist, connecting rod and base, which are subjected to various moments and loads in different directions and magnitudes under different working conditions. However, since the focus of the study is to verify the strength of the overall structure of the arm, and considering the complexity of the analysis, only the base is selected as the object of analysis for the finite element analysis. The base, as the connection between the arm and the ground or support structure, is subject to the reaction force of the whole arm, especially at high loads or high speeds, the moments and axial forces on the base are particularly significant. Therefore, the strength and stability of the base directly affects the overall performance and safety of the arm. By performing a finite element analysis on the base, its load-bearing capacity under different working conditions can be effectively evaluated.

4.2. Strength analysis of robotic arm base

The base model is imported into the Simulation module in SolidWorks, the material property is defined as 6061 aluminium alloy and the material parameters are shown in Table 3.

Table 3: Properties table for 6061 aluminium alloy.

Density (g/cm ³)	Modulus of elasticity (GPa)	Yield Strength (MPa)
2.71	69	262
Tensile Strength (MPa)	Shear Modulus (GPa)	Poisson's Ratio
310	25.94	0.33

The material definition is completed, meshing is performed and loads and constraints are added according to the data obtained from the static analysis, as shown in Figure 7.

The preparations were completed and the FEA solution was carried out and the results are shown in Figures 8 and 9.

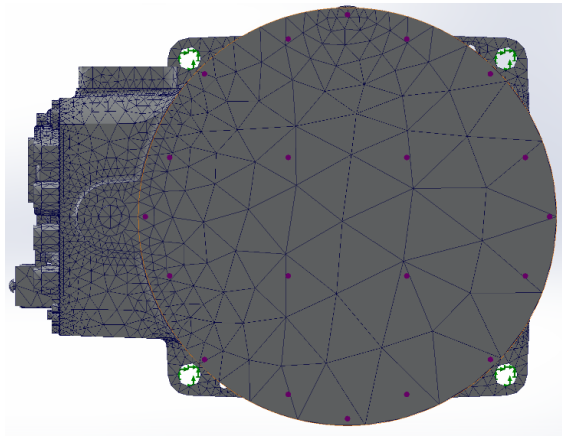


Figure 7: The effect of the chitonite XB4 robot.

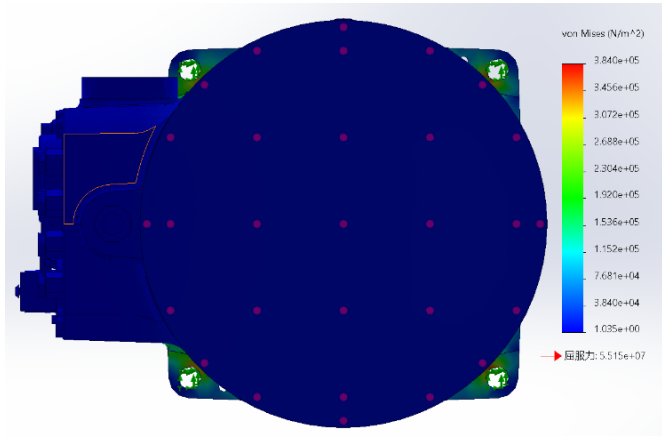


Figure 8: Stress Image.

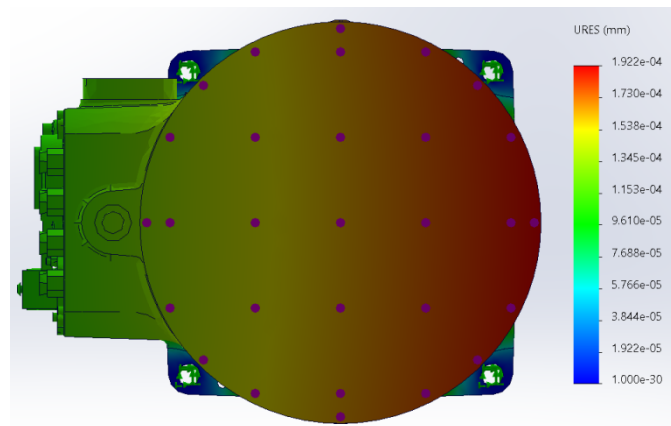


Figure 9: Displaced Image.

It is possible to draw a number of conclusions based on the results of the analyses in Figures 8 and 9.

The finite element analysis indicates that the maximum stress experienced by the model is $3.84 \times 10^5 \text{ N/m}^2$, which is significantly smaller than the yield stress of the material. This suggests that the component will not undergo plastic deformation or damage under the applied load, thereby meeting the design requirements concerning strength. Furthermore, the displacement results presented in Figure 9 indicate that the maximum displacement of the model is $1.922 \times 10^{-4} \text{ mm}$, which is significantly less than 1 mm. This suggests that the deformation of the part is negligible under the applied load, thereby ensuring the maintenance of adequate stiffness and stability. Consequently, it can be concluded that the strength and stiffness of the base meet the requirements of the design specification and can operate safely under the anticipated working conditions.

The finite element analysis results demonstrate that the studied robotic arm base exhibits adequate strength and stability under a given working load, thus satisfying the safety and performance requirements in practical applications.

5. Conclusions

In this paper, the research on kinematic analysis, working range analysis and strength calibration of key components is carried out around the robotic arm of XB4 chockstone robot, aiming to solve the problems of kinematic accuracy, working range and strength of key components encountered in the design and application of the robotic arm. In kinematic analysis, for the limitations of the traditional D-H parameter method in the complex robotic arm structure, this paper adopts the modified D-H parameter method, which solves the problem of parameter inaccuracy in kinematic modelling by establishing an accurate connecting rod coordinate system, and provides a reliable basis for precise control and path planning of the robotic arm. In workspace analysis, this paper simulates and analyses the robotic arm by Monte Carlo method, accurately calculates its reachable space and workspace range, and solves the problem of difficult to achieve accurate assessment due to the complex structure of the robotic arm in workspace calculation. In terms of strength verification, this paper carried out finite element analysis of the base of the robotic arm using SolidWorks Simulation, which solved the computational problems in strength verification of the key components of the robotic arm and ensured its safety and reliability under high load conditions. Through these works, this paper successfully verifies the kinematic characteristics, workspace and strength performance of the robotic arm of the XB4 Chockstone robot, which provides an important reference for the optimal design and practical application of the robotic arm.

However, there are some shortcomings in the study of this paper, which are mainly reflected in the strength verification. The finite element analysis used in this paper mainly focuses on strength verification under general working conditions and does not include the strength performance of the robotic arm under extreme working conditions, nor does it take into account the dynamic load changes under different working environments. Future research should incorporate dynamic load testing under various industrial conditions and explore AI-driven path optimization for enhanced real-time robotic control. In addition, although the kinematics and workspace of the XB4 robotic arm have been effectively analysed in this paper, aspects of multi-task scheduling and dynamic path planning require further exploration.

This research advances robotic arm optimization through the modified D-H parameter method and Monte Carlo approach. These methodologies enhance computational accuracy and flexibility, providing valuable insights into kinematic modeling and workspace analysis for complex robotic systems. These techniques enhance computational accuracy and flexibility, advancing kinematic and spatial analysis in robotics. From an application point of view, the research in this paper provides a theoretical basis for the design and optimisation of the robotic arm of the XB4 chockstone robot, which is of great practical significance, especially in improving the working efficiency and structural reliability of the arm. The research results not only help to improve the application effect of the robotic arm in industrial automation, but also provide technical support for the future application of the robotic arm in complex environments, which has high engineering application value.

References

- [1] International Federation of Robotics (IFR). (2024) *World Robotics 2024: Global Robot Report*. Frankfurt: International Federation of Robotics.
- [2] Zhang, X.Y., Deng, L.Y. and Wang, X.Y. (2024) Kinematic Analysis and Simulation of the Lining Replacement Robotic Arm for Ball Mill. *Mechanical & Electrical Engineering Technology*, 53(5), 38-42.
- [3] Wang, K. (2021) *Key Technology Research on Soft Robotic Arm for Surgical Robots [Ph.D. Thesis]*. University of Chinese Academy of Sciences, Changchun, 1-11.
- [4] Lou, Y. and Di, S. (2025) Time Optimal Trajectory Planning of Robotic Arm Based on Improved Sand Cat Swarm Optimization Algorithm. *Applied Intelligence*, 55(2), 123-135.
- [5] Qin, Z., Liu, Z., Liu, Y., Gao, H., Sun, C., & Sun, G. (2022). Workspace analysis and optimal design of dual cable-suspended robots for construction. *Mechanism and Machine Theory*, 171, 104763.

- [6] Kouritem, S.A., Abouheaf, M.I., Nahas, N., Hassan, M. (2022) *A multi-objective optimization design of industrial robot arms*. *Alexandria Engineering Journal*, 61(12), 12847-12867.
- [7] Xiao, J. and Wang, D.H. (2024) *Research on the Calibration and Analysis of the Demolition Robot Arm*. *Scientific and Technological Achievements*, (4), 1-10.
- [8] Niku, S.B. (2020) *Introduction to Robotics: Analysis, Control, Applications*. Hoboken: Wiley.
- [9] Universal Robots. (2022) *Types of Robotic Arms*. *Productivity Innovation*. Available at: <https://www.universal-robots.com/in/blog/types-of-robotic-arms/>
- [10] Craig, J.J. (2005) *Introduction to Robotics: Mechanics and Control*. Upper Saddle River: Prentice Hall.