DESIGN OF THE MECHANICAL ARM JOINT STRUCTURE

Lappeenranta–Lahti University of Technology LUT

Bachelor’s Programme in Mechanical Engineering, Bachelor's thesis

2026

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Examiner(s): Xinyu Jia, Associate Professor, D.Eng.

Changyang Li, University Lecturer, D.Sc. (Tech.)

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

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In co-operation with partner university Hebei University of Technology, China

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This paper investigates robotic arm joints utilizing double universal joint J structural design and structural optimization. In a robotic drive system, a standard single universal joint introduces fixed angular velocity fluctuations, leading to mechanical vibration and reduced control accuracy. To address these issues, this study focuses on double universal joints, aiming to achieve constant velocity transmission through kinematic phase compensation. The study first quantifies the inhomogeneity of velocity relative to axial angle through theoretical kinematic analysis. A comprehensive model of the three- dimensional (3D) joint assembly, including intermediate shafts, cross-threads, and sliding shoulder frames, was developed to promote the integration of rotational flexibility and axial displacement compensation. Subsequently, the structural reliability of the component was verified by finite element analysis (FEA) in an ANSYS environment. A high-quality hexahedral mesh was employed, with special attention to local refinement in the critical stress concentration zones to ensure numerical convergence and accuracy. The simulation results showed that the double universal joint effectively eliminated the periodic speed fluctuations unique to single universal joint systems. The structural analysis showed that the maximum stress under peak torque conditions was within the yield strength limit of the selected alloy steel, ensuring a sufficient safety factor for high-torque robot maneuvers. In addition, the integration of sliding forks provided effective axial compensation for structural deflection. The research results confirm that the proposed joint design provides a robust and stable solution for robotic applications requiring high loads and smooth motion trajectories.

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SYMBOLS AND ABBREVIATIONS

Greek characters

α	Angle between the input shaft and output shaft	°
β	Rotation angle of the universal joint/input shaft	°
ω_1	Angular velocity of the input shaft	rad/s
ω_2	Angular velocity of the output shaft	rad/s

Abbreviations

FEA	Finite element analysis
3D	Three dimensional
DOF	Degrees of freedom
RV	Rotary vector

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DECLARATIONS

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The originality of this thesis has been reviewed with the Turnitin similarity checking service.

AI usage

The author of the thesis, Xiping Cheng, used the following AI-tools during the preparation of the thesis:

1. ChatGPT
    a. Purpose of use: Some knowledge about the transmission method
    b. Explanation of the use of the tool: A search was conducted for three types of transmission, and carried out the study of relevant knowledge, search the picture about the relevant topic but not generate.

Responsibility

The author, Xiping Cheng, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI tools.

1 Introduction

As the industrial era enters the 4.0 era, automation technology continues to develop, and robotic arms have become efficient tools for automated production. The main application fields of robotic arms are welding, assembly, testing, handling and packing, pallet sorting and grabbing, etc. The dynamic control of robotic joints is inseparable from mechanical design, and high-precision motion trajectories rely on a stable mechanical drive foundation (Craig, 2005). In recent years, robotic arms have played an increasingly important role in human space missions, nuclear radiation areas, and special work environments (Xu and Kanade, 2012) by virtue of their ability to efficiently and reliably perform a series of difficult in-orbit missions in complex space environments. As a key part of the robotic arm, the performance of the joint structure directly determines the load capacity, movement accuracy and flexibility of the whole machine (Siciliano and Khatib, 2016).

In the research and development process of modern industrial robots, collaborative robots and special robots, the design level of the robotic arm joint, as the core execution unit to realize motion transmission and attitude control, directly determines the motion accuracy, load capacity, dynamic response characteristics and operation flexibility of the robotic arm (Patil, Vasu and Srinadh, 2023). At present, the design of robotic arm joints is facing the dual severe challenges of high integration and lightweight, which stems from the urgent need for miniaturization, high mobility and space adaptability of robotic arms in industrial scenarios - whether it is narrow working spaces (such as precision equipment assembly, minimally invasive surgical robots) or mobile robot mounting scenarios, robotic arm joints are required to achieve multi-functional integration in a limited physical space, while minimizing their own mass, so as to reduce joint drive energy consumption and improve the overall movement agility of the robotic arm.

Specifically, the core components of the robotic arm joint mainly include the transmission mechanism (typical representative of harmonic reducer and rotary vector (RV) reducer), drive unit (servo motor), perception unit (position sensor, torque sensor, speed sensor, etc.) and safety assurance unit (brake). Among them, harmonic reducer and RV reducer as the core components of joint transmission, the former is widely used in light load precision joints with the advantages of small size, large transmission ratio and stable movement, while the

latter is suitable for heavy load joints with the characteristics of high stiffness, high bearing capacity and low return error. Furthermore, the dynamic stability of these reducers is highly sensitive to the condition of internal components. For instance, localized defects in needle roller bearings can significantly alter the vibration signatures and operational precision of the joint (Li et al., 2021). As a power output source, the power density and volume size of the servo motor are directly related to the overall lightweight of the joint, how to ensure that the driving torque meets the operation needs, the selection of miniaturized, high-power density servo motors, and the compact connection with the reducer to avoid the spatial interference between components, is the key link of integrated design; The sensor needs to collect joint motion parameters (such as angle, angular velocity, torque) in real time to achieve closed-loop control, and the brake needs to quickly lock the joint under power failure or abnormal working conditions.

While pursuing a high degree of integration and lightweight, the design of the robotic arm joint also needs to simultaneously solve the three core technical difficulties of heat dissipation performance, transmission clearance and structural stiffness, which are interrelated and mutually restrictive, further increasing the design difficulty. From the perspective of heat dissipation performance, the highly integrated joint structure makes servo motors, reducers and other heat-generating components densely packaged, heat is difficult to dissipate quickly, long-term operation heat accumulation will lead to an increase in component temperature, not only reduce the output efficiency of servo motors, affect the measurement accuracy of sensors, but also may accelerate the aging of reducer grease, shorten the service life of joints, therefore, how to optimize the structural design (such as setting up heat dissipation channels, using thermal conductive materials), select high-efficiency heat dissipation components, Achieving rapid export and balanced distribution of heat inside the joint has become a key problem that must be solved in integrated design.

Transmission clearance is one of the core factors affecting the movement accuracy of the manipulator joint, which mainly stems from the internal gear meshing gap of the reducer, the component assembly gap and the wear gap after long-term operation. Therefore, in the process of joint design, it is necessary to minimize the transmission clearance by optimizing the structural parameters of the reducer (such as gear modulus and tooth profile modification), improving the machining accuracy and assembly accuracy of components, and using preload mechanisms, while taking into account the movement flexibility and

transmission efficiency of the joints to achieve a balance between accuracy and flexibility (Niku, 2020).

In addition, structural stiffness, as the core performance index (Siciliano and Khatib, 2016) of robotic arm joints under load and resistance to deformation, is easily constrained in the process of lightweight design - lightweight materials (such as aluminum alloys, carbon fiber composites) or thin-walled structures used to reduce joint mass often lead to a decrease in the overall stiffness of the joint. Therefore, based on lightweight design, how to improve the structural stiffness and deformation resistance of joints through structural topology optimization, stiffener design, reasonable material selection, and achieve the synergistic optimization of lightweight and high stiffness is a technical bottleneck that needs to be broken urgently in the field of robotic arm joint design.

The following are several representative practical application areas of robotic arms. In the medical field, surgical robots can have higher precision (Taylor et al., 2016), and doctors can control micro robotic arms with multiple degrees of freedom (DOF) through consoles to perform minimally invasive surgeries. The robotic arm can filter out subtle jitters of the human hand and perform rotational movements that exceed the limits of the human hand in a very small space, greatly reducing surgical incisions and shortening the recovery time of patients. In manufacturing, Universal Robots robotic arms can identify object positions based on vision systems to perform repetitive tasks such as grasping, placing or screwing (Villani et al., 2018). Thanks to their advanced force feedback sensors, they stop immediately when they touch a human body, ensuring safety. In the field of aerospace and deep-sea operations, the robotic arm can work normally in high-risk environments that are out of reach of human. Figure 1 shows Canadarm2, and it has autonomous crawling and precise positioning functions to assist astronauts in out-of-cabin activities, capture visiting spacecraft, and conduct maintenance and inspection of the space station's extravehicular spacecraft.

Figure 1. Canadarm2

2 Transmission mechanism analysis

In robotic systems, particularly in applications requiring precise manipulation within confined spaces—such as micro-assembly and inspection tasks in narrow industrial environments—robotic joints with multiple DOF play a critical role. These applications impose stringent constraints on joint size (≤120 mm × 100 mm × 80 mm) and weight (≤1.5 kg), while simultaneously demanding high torque output and positioning accuracy. Specifically, the joint is required to provide two DOF, including rotational motion (0°–360°) and pitch motion (−90° to +90°), with a rated torque of no less than 20 N·m and a transmission error not exceeding 0.5°. These requirements present significant challenges in achieving a balance between compactness, mechanical strength, and precision.

To solve these problems, it is necessary to conduct a systematic analysis of existing transmission technologies commonly used in robotic joints, such as planetary gear systems, harmonic drives, and worm gear mechanisms. Each of these transmission methods exhibits distinct characteristics in terms of torque density, efficiency, backlash, and structural complexity.

Based on the functional requirements and performance constraints, an appropriate transmission scheme must be selected, followed by the detailed design of the joint mechanism. This includes the design of the joint housing, shaft system, transmission components, bearing arrangements, and limiting structures. Furthermore, the transmission performance must be verified through analytical calculations to ensure that the proposed design meets the specified torque and accuracy requirements.

2.1 Planetary gear transmission

Planetary gear drives are widely used in robot joints due to their compact structure and high torque density. The system consists of sun gear, planetary gear, ring gear, and a carrier. The load is distributed between multiple planetary gears, greatly increasing torque capacity while maintaining a compact volume.

Additionally, planetary gear systems provide coaxial inputs and outputs, which is beneficial for integrated joint design. However, backlash and manufacturing tolerances can lead to transmission errors, which must be tightly controlled in precision applications. Figure 2 shows the KHK gears' structure diagram.

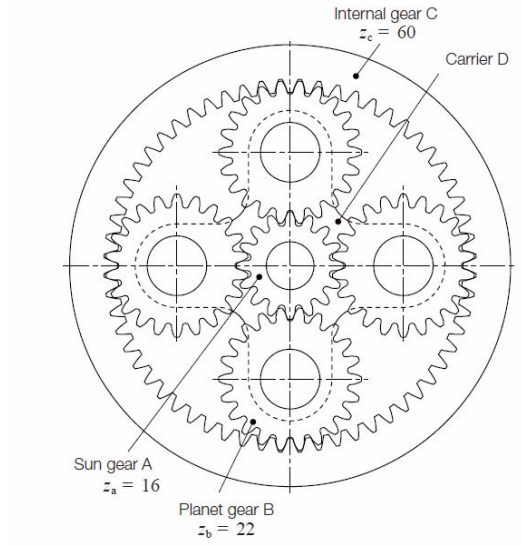

Figure 2. KHK gears

2.2 Harmonic drive

Harmonic drive is a precision transmission mechanism consisting of a wave generator, a flexible spline, and a circular spline. It works based on elastic deformation, allowing the flexible spline to engage with the circular spline in a controlled manner. Figure 3 shows harmonic drive's basic structure.

The mechanism has almost no backlash, high reduction ratio, and very high positioning accuracy, making it ideal for precision robots. Additionally, its compact construction allows for high torque density in confined spaces However, harmonic drives are costly and susceptible to assembly and material fatigue, which can affect long-term durability.

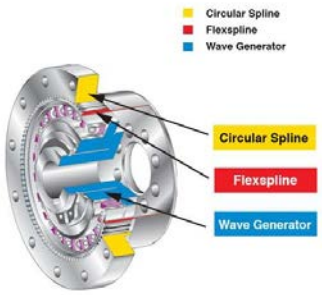

Figure 3. Harmonic drive gear

2.3 Worm gear

The worm gear drive consists of a worm and a worm gear. It can achieve high reduction ratios and has self-locking properties under specific conditions.

The self-locking properties help maintain joint position in the event of unstable input power. However, due to sliding contact between the worm and the wheel, it is less efficient and may cause wear overtime. As a result, worm gear drives are suitable for applications where high torque needs to be maintained, but not for efficient dynamic systems.

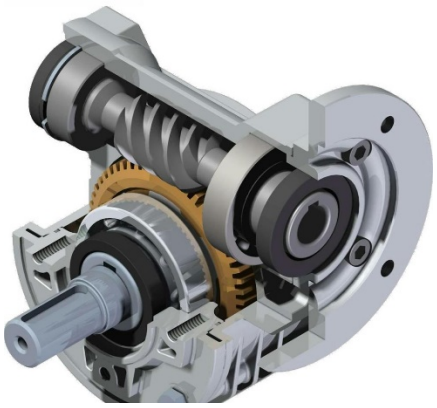

Figure 4. Worm gear

Figure 4 shows the structure of worm gear, the shaft located above resembles a thread shape is the worm, which serves as the power input end, and is located below (the golden part), and the large gear that engages with the worm is the worm gear, as the power take-off. Its external support structure is used to reduce friction between the shaft and the outer housing.

3 Joint structure analysis and design selection

3.1 Classification of robotic joints

In the mechanical design of robots, the structural characteristics of joints as the core unit connecting adjacent connecting rods and realizing relative motion directly determine the positioning accuracy, load capacity and working space of the end effector. To optimize the design objectives, this section will analyze in detail several basic and representative joint structures (rotating joints, mobile joints, and ball joints).

Robotic joints can be broadly classified into several types based on their motion characteristics, including revolute joints, prismatic joints, and spherical joints. Each type exhibits different kinds of capabilities and structural features, making them suitable for different areas.

3.1.1 Revolute joint

A rotary joint is a section of a robotic arm that rotates around an axis or a fixed point and is one of the most used joint types in robotic systems. It has a simple structure and a large load capacity. Additionally, it can achieve continuous rotation, making it suitable for applications requiring wide angular motion.

However, achieving high precision requires careful control of backlash and stiffness. The joint structure can only rotate 360° on a two-dimensional plane, and if it involves 3D movement, it will not be able to complete the task. Figure 5 shows the revolute joint working in the robotic arm, allowing the robotic arm to rotate around a fixed axis.

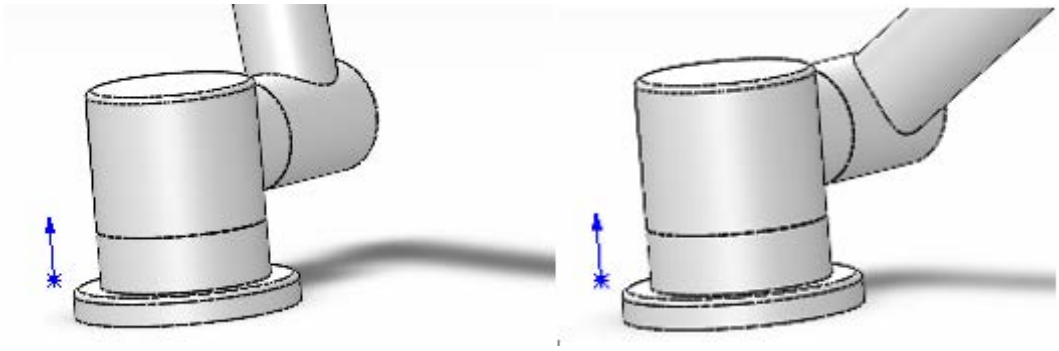

Figure 5. Revolute joint

3.1.2 Prismatic joint

A prismatic joint provides linear motion along a single axis. It is typically driven by lead screws or linear actuators. This type of joint is suitable for applications requiring precise positioning along a straight line.

However, prismatic joints generally require more space in the direction of motion and are less suitable for compact rotary systems. Therefore, the structure generally appears on the base or extension arm of the robotic arm to change the height and length, and the structure can only be moved in two dimensions. Figure 6 shows a lifting platform in a robotic arm that can move in parallel to the Z-axis.

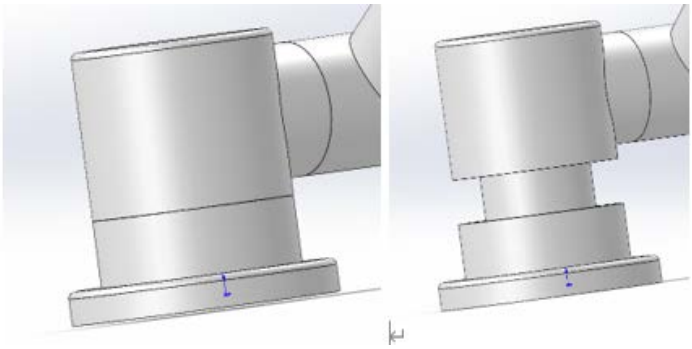

Figure 6. Prismatic joint

3.1.3 Spherical joint

A spherical joint allows rotation around multiple axes, providing high flexibility and multiple DOF. It is commonly used in applications requiring complex orientation control.

However, spherical joints are structurally complex and difficult to manufacture, especially when high torque and precision are required. Figure 7 shows a spherical joint simulating rotation in a 3D model, which shows that the joint has a high degree of freedom and is suitable for combining with the end of the robotic arm.

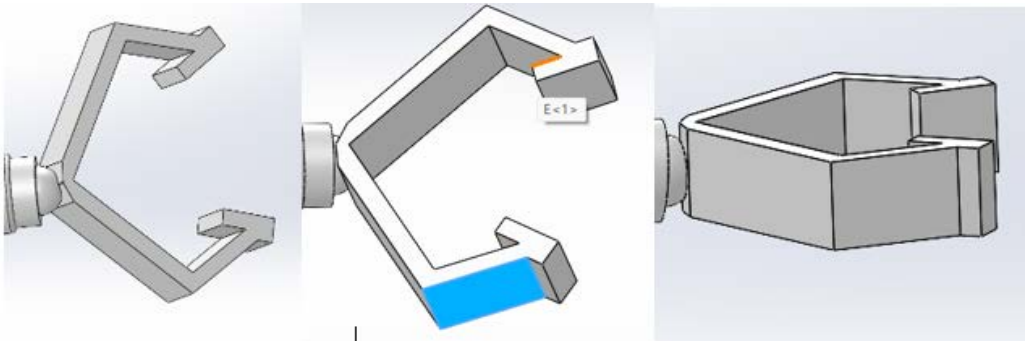

Figure 7. Spherical joint

3.2 Comparative analysis of joint types

Table1. Comparison of joint structures

Joint type	Advantages	Limitations
Revolute	Compact, high torque	Backlash issues
Prismatic	Precise linear motion	Space-consuming
Spherical	Multi-DOF flexibility	Complex structure

Choosing the right joint type is key to achieving specific motor functions. Tabel 1 shows that Revolute Joint has the advantage of being compact and capable of carrying high torque, providing stable power output in confined spaces. In contrast, prismatic joints, while excelling in achieving precise linear motion, require a large linear space for their operation, often leading to bloated overall mechanism volume. The spherical joint shows extremely high movement flexibility and can provide multiple freedom of rotation, but this flexibility comes at the cost of structural complexity, which increases the difficulty of manufacturing and control.

Considering the advantages and disadvantages of each joint, the rotating joint strikes an optimal balance between compactness and torque capacity, making it the preferred solution

for tight operating environments and high-load applications. Despite the inherent limitations of rotating the joint, such as return error, its overall performance is still better than other types. Mobile joints are not ideal in compact designs that require a high degree of integration due to their rigid requirements for space. Similarly, although ball joints have excellent spatial freedom, their complex construction often becomes a performance bottleneck in applications where high torque density and structural reliability are pursued. Therefore, when selecting joints, it is necessary to weigh the constraints of the operating environment and the dynamics of the situation.

4 Universal joints

4.1 Transmission characteristics

A universal joint is a coupling that realizes variable angle power transmission. And its basic structure consists of two fork-shaped pieces perpendicular to each other and an intermediate cross-shaft. In the field of mechanics, it is regarded as a composite joint with two DOF of rotation.

Figure 8 shows the structure of a single universal joint, the two "U" shaped parts on the left and right are fork frames, which connect the input shaft and output shaft respectively. The central core part is the cross shaft, and its four shaft heads are mounted in the holes of the two fork frames.

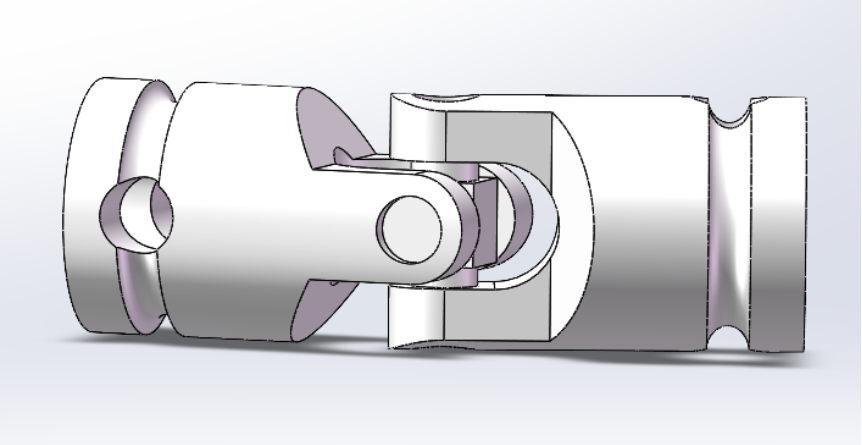

Figure 8. Universal joint

4.1.1 Non-constant velocity transmission characteristics

Single universal joint has an inherent physical limitation in engineering applications, non-uniformity. If the output shaft speed remains unchanged, the speed of the output shaft will be prone to vibration due to angular changes.

When there is an angle α between the input shaft and the output shaft, even if the input shaft rotates at a constant angular velocity ω_1, the angular velocity of the output shaft ω_2 will

fluctuate periodically with the rotation angle β. Its instantaneous transmission ratio formula is

$$\frac{\omega_2}{\omega_1} = \frac{cos\alpha}{1 - sin^2\alpha cos^2\beta} \quad (1)$$

This kind of speed fluctuation will lead to angular acceleration shock, causing the output shaft to undergo two accelerations and two decelerations per revolution. And the dynamic load and vibration at the same time, the high-frequency vibration caused by the fluctuation will accelerate the wear of the bearing and produce mechanical noise. Furthermore, the long-term cyclic stress alteration will also reduce the fatigue life of the transmission system

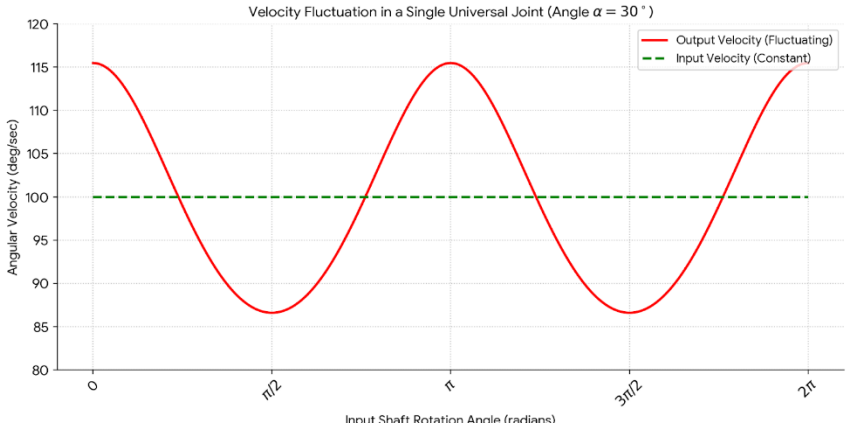

Figure 9. Comparison chart of the input/output speed

Figure 9 shows the periodic fluctuation of the angular velocity of the output shaft when there is an angle α between the input shaft and the output shaft (red line). Even if the input shaft rotates at a constant angular velocity (green dotted line), the output shaft will still generate two accelerations and two decelerations in each rotation cycle. This isokinetic nature is the main cause of mechanical vibration and noise and is the core logic of introducing double universal joints for constant velocity compensation.

To solve this problem, a double universal joint structure is used to achieve constant speed transmission through motion phase compensation. This transmission logic was validated in previous studies, which showed that “with precise geometric configuration, the motion inhomogeneity caused by the universal joint can be eliminated, thereby improving the trajectory accuracy at the end of the robotic arm”. On this basis, the importance of integrated design in modern mechanical systems, especially in the intermediate shaft with a sliding shoulder frame, has also been emphasized.

4.2 Double universal joints

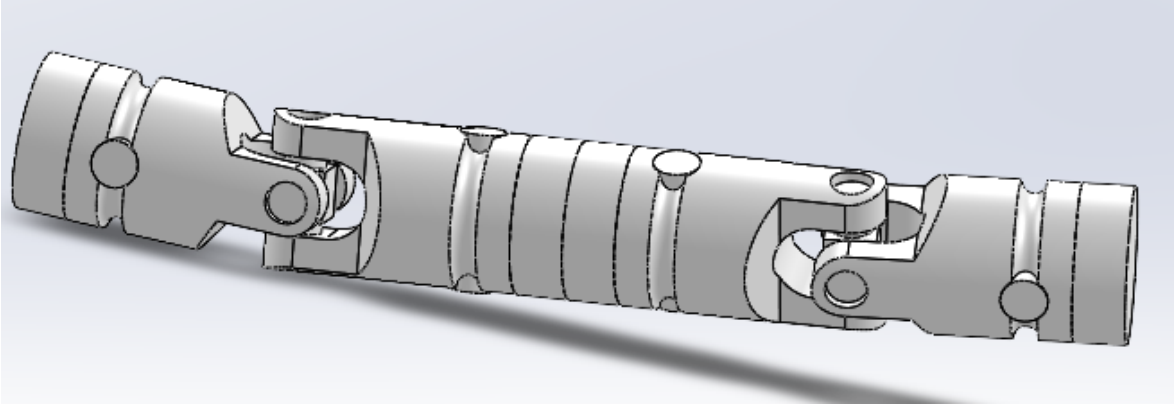

Figure 10. Double universal joints

Figure 10 shows a 3D model of the drive shaft of the double universal joint, which is more complete than the single universal joint mentioned earlier, with a cross-shaft universal joint at each end of the middle long shaft (drive shaft), and the cylindrical part in the middle. It is used to span a certain space distance, and the forks on both sides are used to connect the power source (such as the motor) and the load end respectively.

To offset the speed fluctuation of a single universal joint, a double universal joint is introduced, the core logic of which is to achieve quasi-constant velocity transmission through "phase cancellation". A double universal joint is connecting two single universal joints together in series. The basic logic of its constant velocity transmission is to use the speed fluctuation generated by the second universal joint to completely offset the fluctuation generated by the first universal joint. However, certain preconditions are required to achieve this desired result, among which symmetrical layout, consistent phase and three-axial coplanarity are very critical.

4.2.1 ANSYS analysis of double universal joints

Next, ANSYS is used to conduct a series of analyses on the design of the double universal joints, ANSYS provides a rich library of nonlinear elements and a complete constitutive model, which ensures the convergence and calculation accuracy of the finite element model when dealing with large deformations and material nonlinearity, and ensures the accuracy of our structures.

When it comes to structural strength verification, utilizing FEA for stress assessment is crucial. The failure of mechanical parts often originates at stress concentration points, particularly in the geometric transition area of the fork head. The simulations performed here with ANSYS software comply with the safety factor requirements. In addition, the power matching of the actuators is based on motor drive modeling, while the selection of the reduction system ensures high torque output and compactness of the joints.

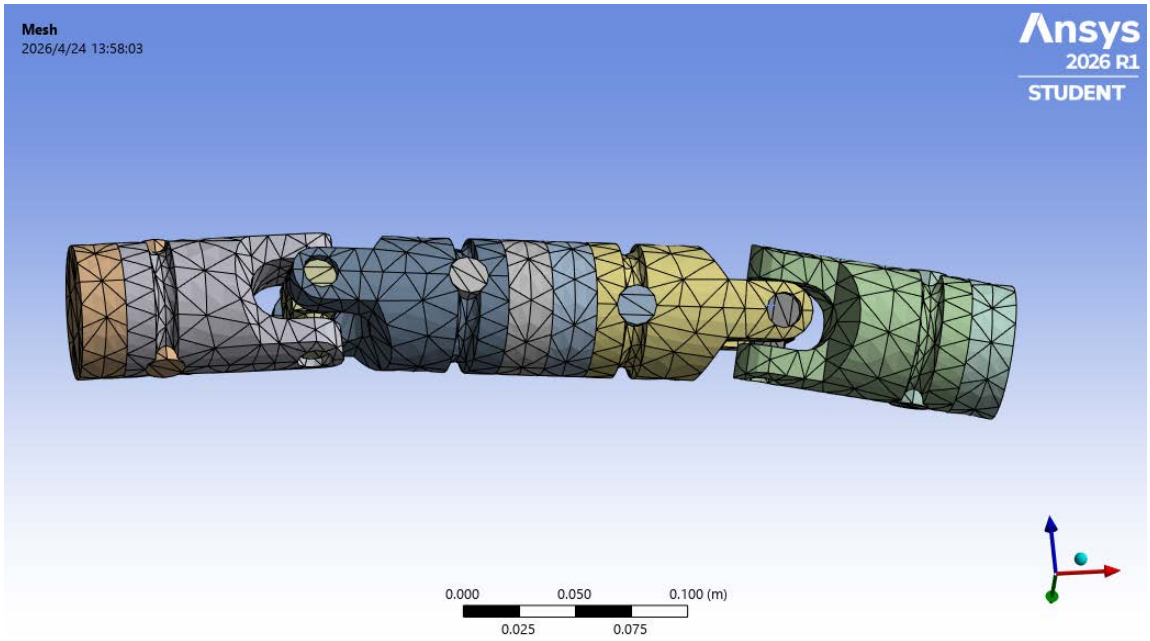

Figure 11. Mesh

Figure 11 shows the state of the mechanical universal joint assembly after finite element meshing. The assembly mainly uses tetrahedral mesh elements. These elements are highly adaptable to complex and irregular geometries

First, the geometric structure is meshed within the ANSYS environment. To enhance the fidelity and refinement of the simulation, mesh sizing is meticulously applied to the contact regions of the axes, accounting for the specific linkage mechanisms and frictional characteristics between components. Considering potential stress concentration zones, local mesh refinement is implemented on the interface between the cross-shaft journal and the fork head. This ensures a sufficient density of element layers at the contact boundaries, thereby improving the convergence and accuracy of the numerical analysis. After adding the load, can proceed with the next analysis of the designed joints.

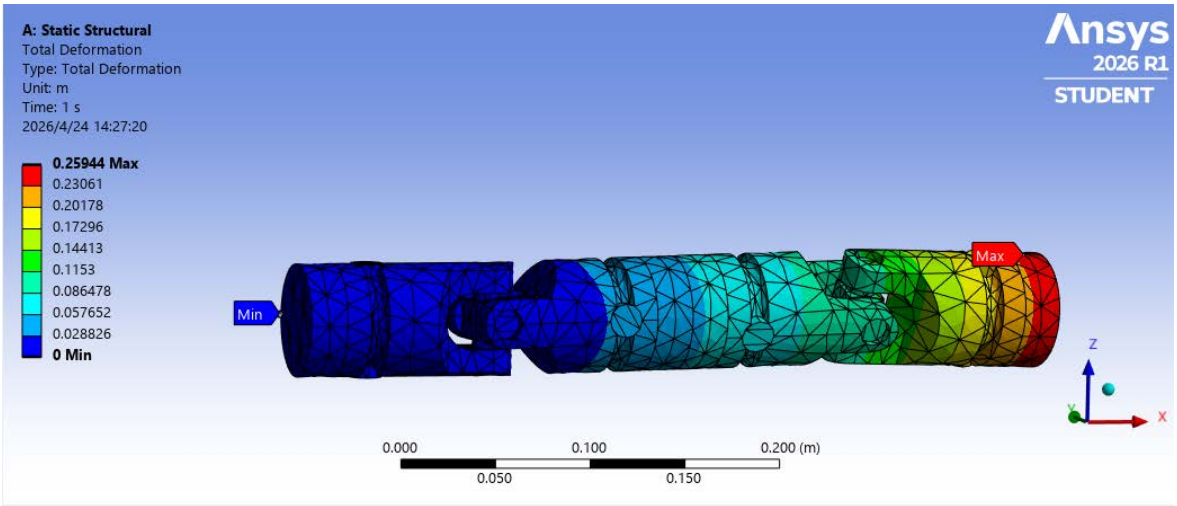

Figure 12. Total structure of steel

Figure 12 shows that the total deformation is 0.259. This relatively high value is due to the absence of modifications to the material (structure steel by default). Such a deformation is not physically logical for a universal joint drive shaft with a total length of only 0.2 meters and does not meet safety requirements.

Although structural steel dominates general machinery due to its high yield strength and mature processing technology, its excessive dead weight has become a bottleneck limiting system performance improvement in the context of modern engineering pursuing dynamic response and energy efficiency. Aluminum alloys achieve a certain degree of weight reduction by reducing density, but their fatigue resistance and stability under extreme loads are slightly inferior. In contrast, carbon fiber composites achieve the most significant weight reduction under the premise of ensuring structural safety through extremely high specific strength and designable mechanical properties. In the design of shaft parts, the logic of material selection should change from “single strength-oriented” to “comprehensive optimization with specific strength as the core” and minimize the moment of inertia and structural weight under the premise of meeting the strength safety margin by introducing composite materials or using hollow thin-walled structures. Following the modification of the component material properties, the structural configuration has been partially optimized. Specifically, the original structural steel is replaced with aluminum alloy and Epoxy Carbon Woven composites to enhance structural rigidity and specific strength. This material substitution aims to achieve a superior strength-to-weight ratio while maintaining the necessary mechanical integrity of the assembly.

Figure 13. Material details

Figure 13 shows the material attribute assignment of the universal joint drive assembly, clearly listing the three different materials used in the model, and corresponding to the specific parts in the model in color blocks, aluminum alloy (brownish-yellow part).) was mainly assigned to the middle drive shaft and part of the fork frame. Aluminum alloys are often used to lighten the weight of transmission components while maintaining sufficient strength. Epoxy Carbon Woven (230 GPa) Prepreg (off-white part) is assigned to the core connection of the gimbal, a high-performance composite material with an extremely high modulus of elasticity, used to enhance rigidity and wear resistance at critical connection points. Structural steel (gray-blue part) is assigned to the interface section and part of the connector at both ends. The steel has good impact resistance and connection reliability.

Considering that the total length of the module is about 200 mm, Figure 14 shows the maximum deformation is only 0.16 mm, indicating that the drive shaft system has high structural stiffness under current load conditions, and the deformation is in a very low order. The deformation cloud is symmetrical and stable, indicating that the geometric symmetry of the universal joint effectively cancels out some nonlinear disturbances under static action. The simulation results show that the design of the universal joint drive shaft exhibits good mechanical strength and rigidity under given working conditions, and the total deformation

is much lower than the error range allowed by the project (usually in millimeter range). The connection between parts is reliable and can achieve stable load transfer.

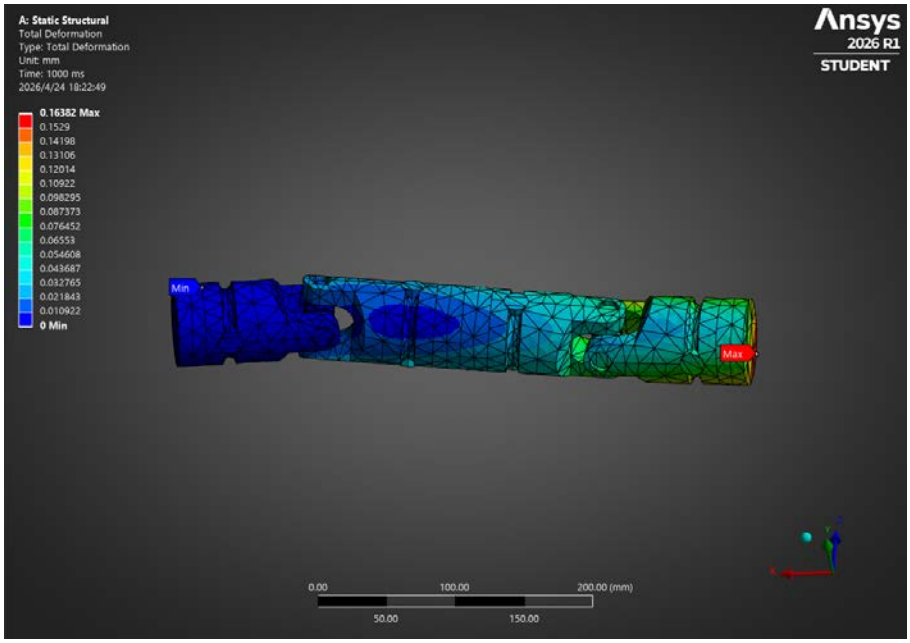

Figure 14. Total structure of components material

Next, the distribution of the equivalent effect of the drive shaft assembly under working load is evaluated, and the distribution of the equivalent effect is an important indicator to measure the plastic deformation trend of the material, which can reveal the weak parts of the structure and the core path of load transfer. Figure 15 cloud diagram shows that the maximum equivalent effect of the system becomes 0.0010759 mm/mm. The maximum strain point (red max mark in the figure) is accurately located at the contact point between the cross shaft of the universal joint and the fork head (Yoke). This is the key fulcrum point of torque transmission, and there is significant contact stress and stress concentration caused by geometric mutations. Except for the connection point, most of the shaft body is dark blue, indicating that the main part of the shaft has minimal deformation under the current load, and there is still room for optimization of material utilization. The confirmation of the equivalent strain is an important guarantee to ensure the safe operation of the universal joint. The current strain amplitude is within a safe and reasonable range, which proves that the structural design can effectively bear the given load and has a certain excess load capacity.

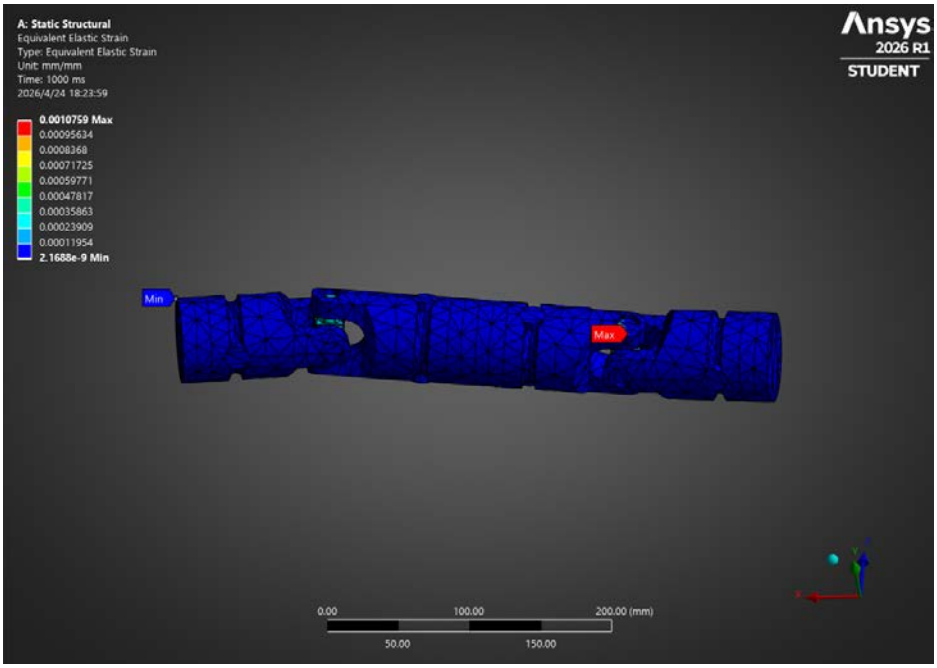

Figure 15. Equivalent elastic strain

Next, evaluate the stress state of the drive shaft assembly under load by using the Von-Mises yield criterion. Equivalent stress considers the principal stresses in three directions of space and is an important criterion for judging the structural strength of shaft parts under complex stresses (torsion, bending, and extrusion combinations). Figure 16 shows that the maximum equivalent stress force of the system is 12.983 MPa. The maximum stress point (red Max area) appears at the transition fillet where the Yoke joint is connected to the pin shaft. This is in line with mechanical expectations, as the load is transferred from the transverse pin shaft to the longitudinal fork head, and the cross-sectional mutation creates a significant stress concentration effect. The cloud diagram shows that the stress is transmitted to the shaft body through the universal joint assembly. The stress value of most areas of the shaft body (middle section) is at a low level, indicating that the size design of the shaft body is relatively conservative.

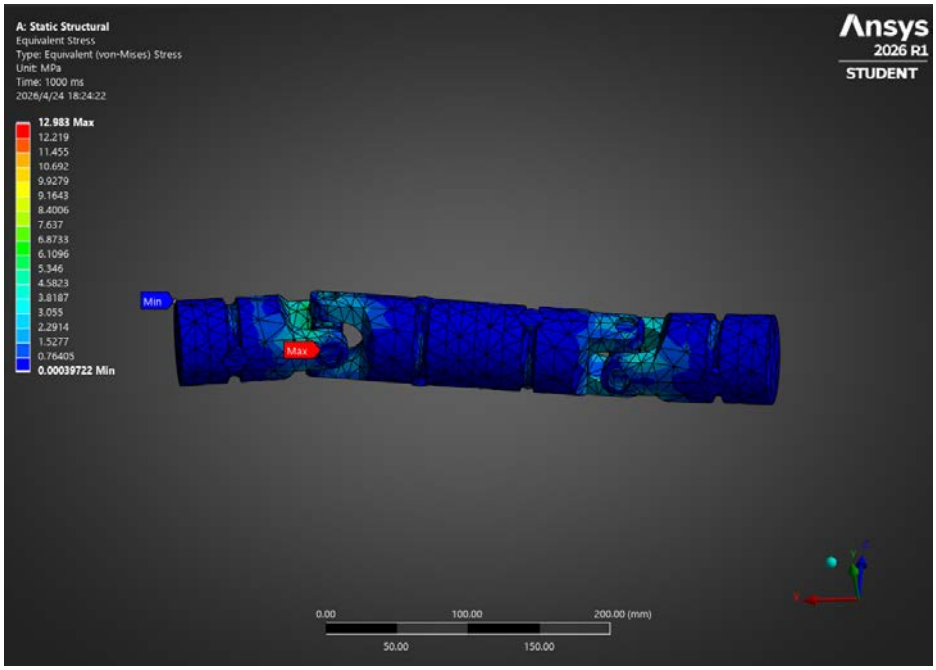

Figure 16. Equivalent von-Mises stress

4.2.2 Advantages

Double universal joints exhibit almost perfect isokinetic properties. When geometric conditions are met, this configuration eliminates most output fluctuations. At the same time, it allows for a larger deflection angle, compared with single universal joints limited by fluctuations and usually can only operate within 5 degree-10 degree. Double universal joints can handle larger axial deflection angles.

Otherwise, the structural structure is high, can withstand greater torque and shock load than ball cage universal joints of the same size. Compared with other complex structures, the structure of double universal joints is relatively simple, the heat dissipation performance is better than that of fully enclosed constant velocity joints. There is usually obvious vibration warning before damage, and safety is higher.

4.2.3 Disadvantages

Due to the internal inclusion of two cross shafts and a central centering mechanism, the axial length is significantly larger than that of a single universal joint, which is difficult to install

in a compact structure. And due to the presence of middleware, the centrifugal force generated during high-speed rotation will place higher demands on dynamic balance, and if the centering mechanism is not properly designed, it will produce secondary vibrations.

Compared with a single universal joint, the number of parts is doubled, and a precise central centering mechanism is required to ensure that the two angles are always consistent. The double universal joint is not simply a superposition of parts, but a kinematic negative feedback compensation design.

5 Conclusions

After understood and compared different mechanical joint structures, and obtained the advantages and disadvantages of each structure, and after screening, chose the joint structure of the universal joint, although the relative advantages also have many limitations, and optimized and improved on the basis of the original, from a single universal joint to a double universal joint, which is not a simple docking, but also needs to consider many factors. The kinematic analysis of the transmission system reveals the essential limitation of the single universal joint， the anisogametes of angular velocity. Theoretical calculations show that the wave amplitude increases significantly with the increase of the angle between the shafts. By adopting a double universal joint configuration, this study successfully achieves near-constant velocity power transmission. The phase cancellation effect of the second universal joint compensates for the periodic acceleration generated by the first universal joint, which is crucial for the precision control of the robotic arm. This design is used to ensure smooth and stable movement of the end effector, avoiding common high-frequency jitter. ANSYS FEA provides a critical foundation for structural reliability of joint components. The stress cloud diagram shows that the transitional trimming at the bottom of the cross journal and fork head is the primary stress concentration zone. The maximum is stress observed under peak torque load remains within the yield strength range of the selected material, providing an approximate safety factor. The high-quality hexahedral grid used in the simulation ensures that the pressure at the pin roller bearing contact interface is captured with high accuracy, validating the design's ability to withstand shock loads typical of rapid robot movements. The transmission efficiency of the joint assembly is primarily determined by friction losses within the needle bearing and the spline interface of the plain fork. Theoretical analysis shows that the twin universal joint maintains high torque transfer efficiency (typically >95%) at a small operating angle. However, as the joint angle increases, the internal axial force generated by the cross screw rises, potentially leading to increased friction and heat. The use of plain forks is crucial for actuator reliability, separating the axial displacement caused by motion from the torque transfer process. By employing an internal spline structure, the system ensures stable torque transmission while achieving smooth axial expansion and contraction, avoiding "shaft lock" situations that could damage the motor or support bearing. While dual universal joints offer superior kinematic performance, they also

present challenges in terms of axial space requirements and assembly complexity. This structure requires more precise alignment and regular lubrication of needle roller bearings than moving pairs or simple swivel joints. Considering the need for high torque density and angular flexibility, the benefits of reduced vibration and lift durability outweigh the costs associated with increased mechanical complexity. The integration of plain forks further enhances the system's robust stability by absorbing axial displacement caused by thermal expansion or structural deformation.

Secondly, it must be acknowledged that the ANSYS finite element model in this study has a certain idealization, which is mainly manifested in the fact that the connection relationship between the components is reduced to ideal direct contact, while ignoring the influence of thermal effects on structural behavior in actual conditions. Under high-speed rotation and heavy load conditions, significant frictional heat is generated between the needle roller bearing inside the universal joint and the cross-shaft journal. Since steady-state/transient thermal analysis is not introduced, the model cannot capture the stress redistribution caused by thermal expansion. Specifically, thermal effects can cause micro-expansion of the material. In the case of precision mating mechanisms such as universal joints, the thermal expansion of the cross shaft can lead to a decrease in the originally designed fit tolerance, which in turn can increase contact stress and even cause the mechanism to jam or accelerate bearing failure. In addition, the elastic modulus and yield strength of materials usually decrease with increasing temperature, which means that the actual safety factor of the structure may be lower than the theoretical values given by pure structural simulations under high-temperature conditions. Therefore, thermal stability simulation should be considered in future research. By introducing the frictional heat generation coefficient and convective heat dissipation boundary conditions, the mechanical response of the transmission system in the continuous working state can be more realistically simulated, to provide more reference data support for the design of long-life and high-reliability robotic arm joints.

This study mainly focuses on quasi-static structural analysis and ideal kinematics modeling. The limitations of current finite element models lie in the simplification of dynamic friction and thermal effects during high-speed rotation. Additionally, exploring the application of lightweight composites to fork head structures is expected to reduce the moment of inertia, thereby improving the dynamic response speed of the entire robotic system.

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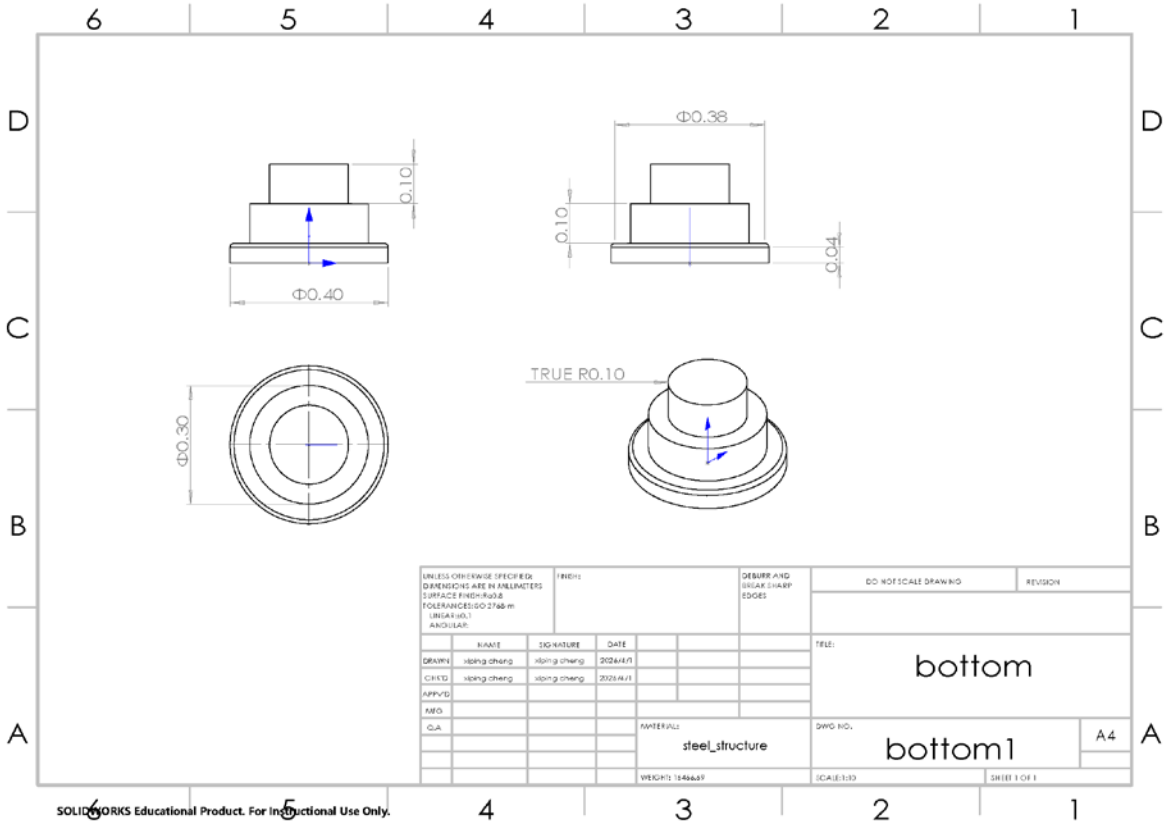
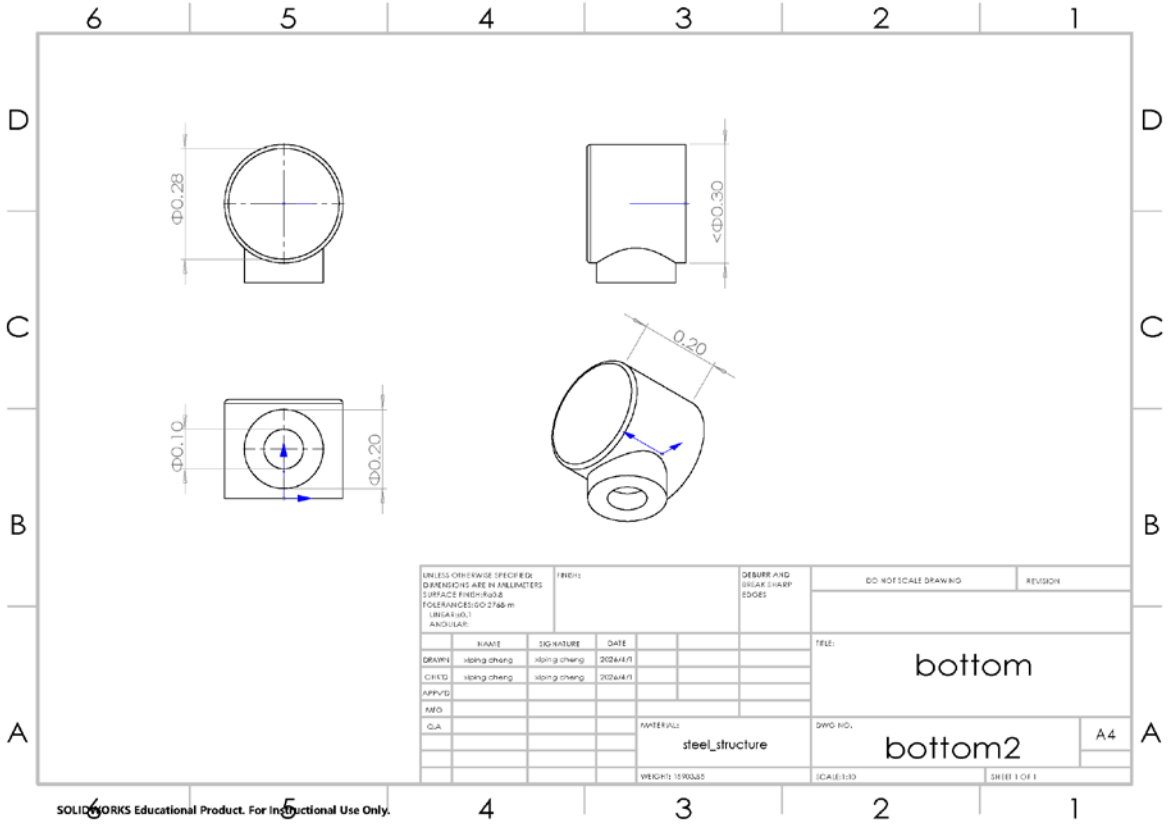
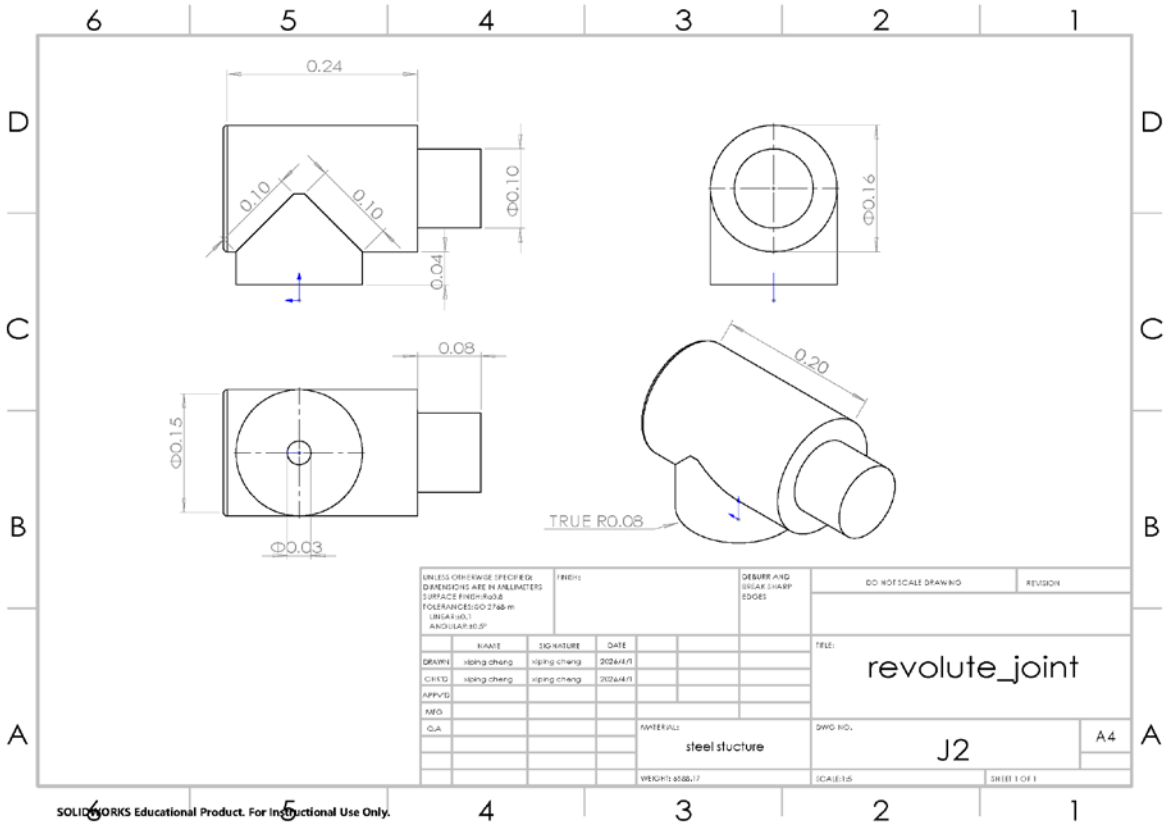
Appendix 1. 3D drawings







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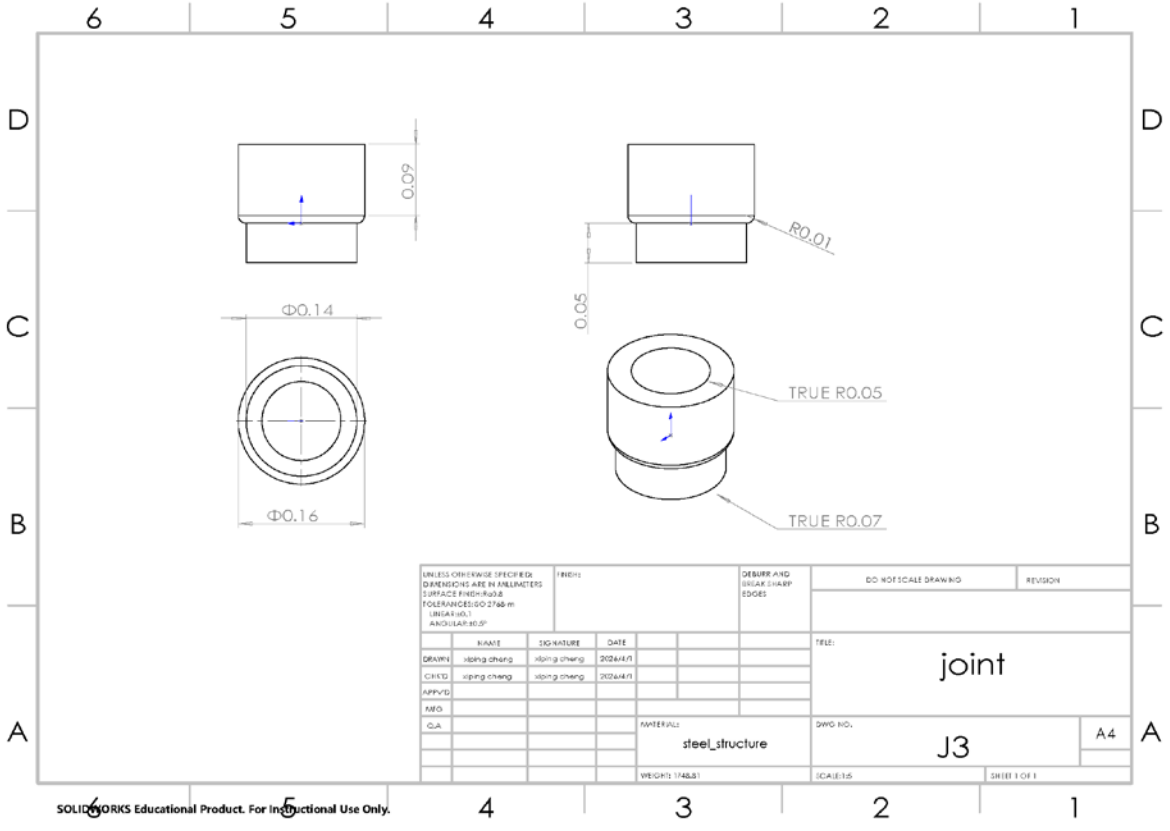

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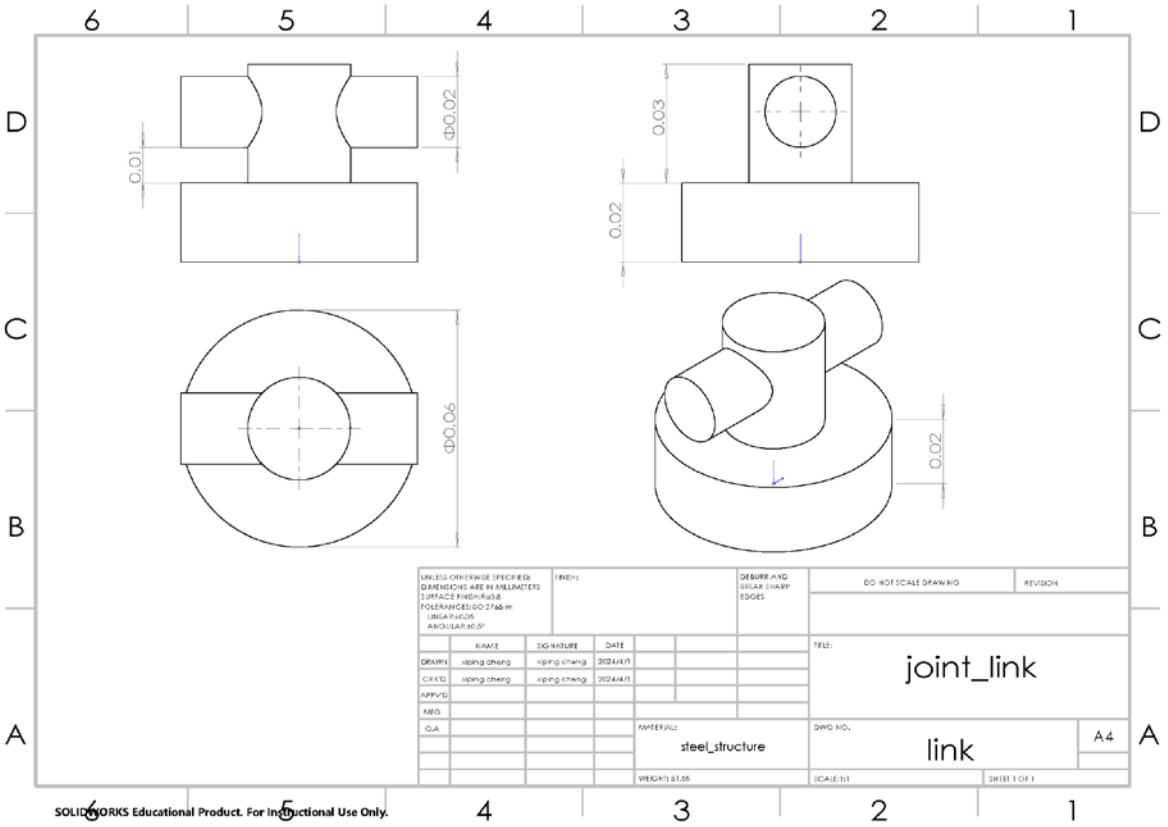
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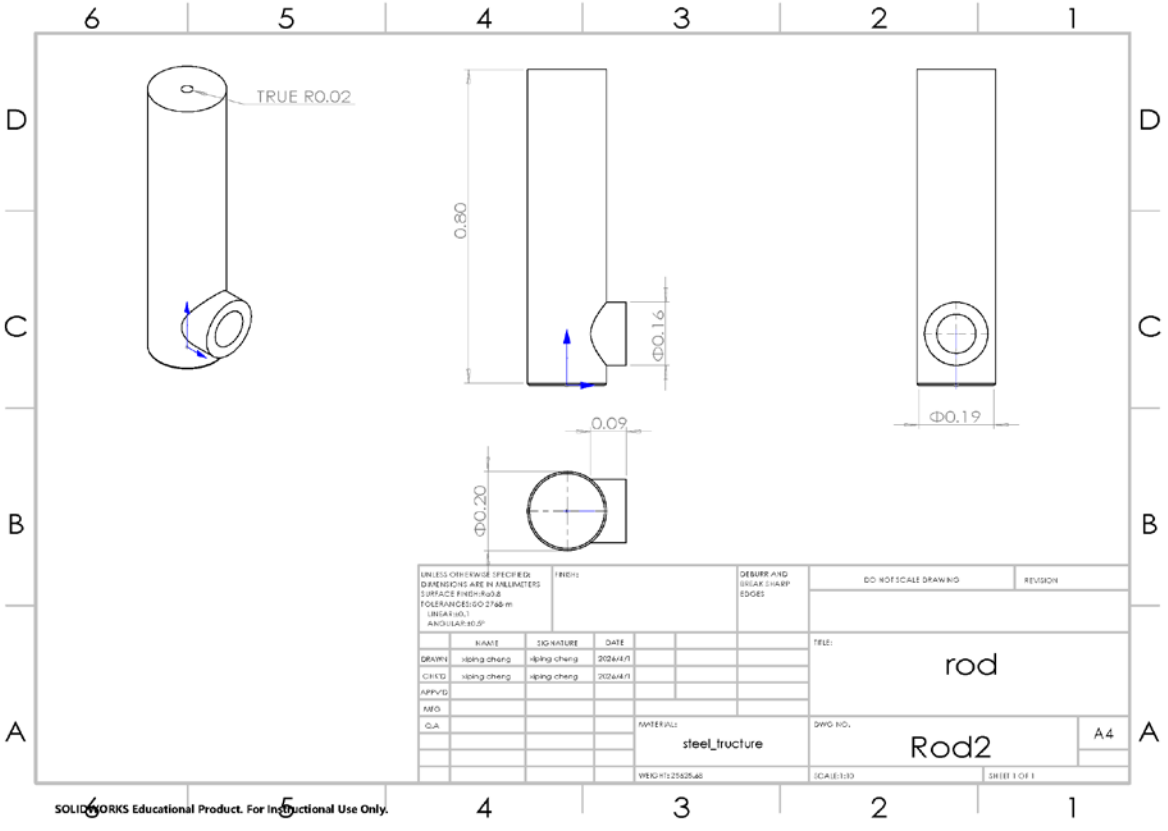
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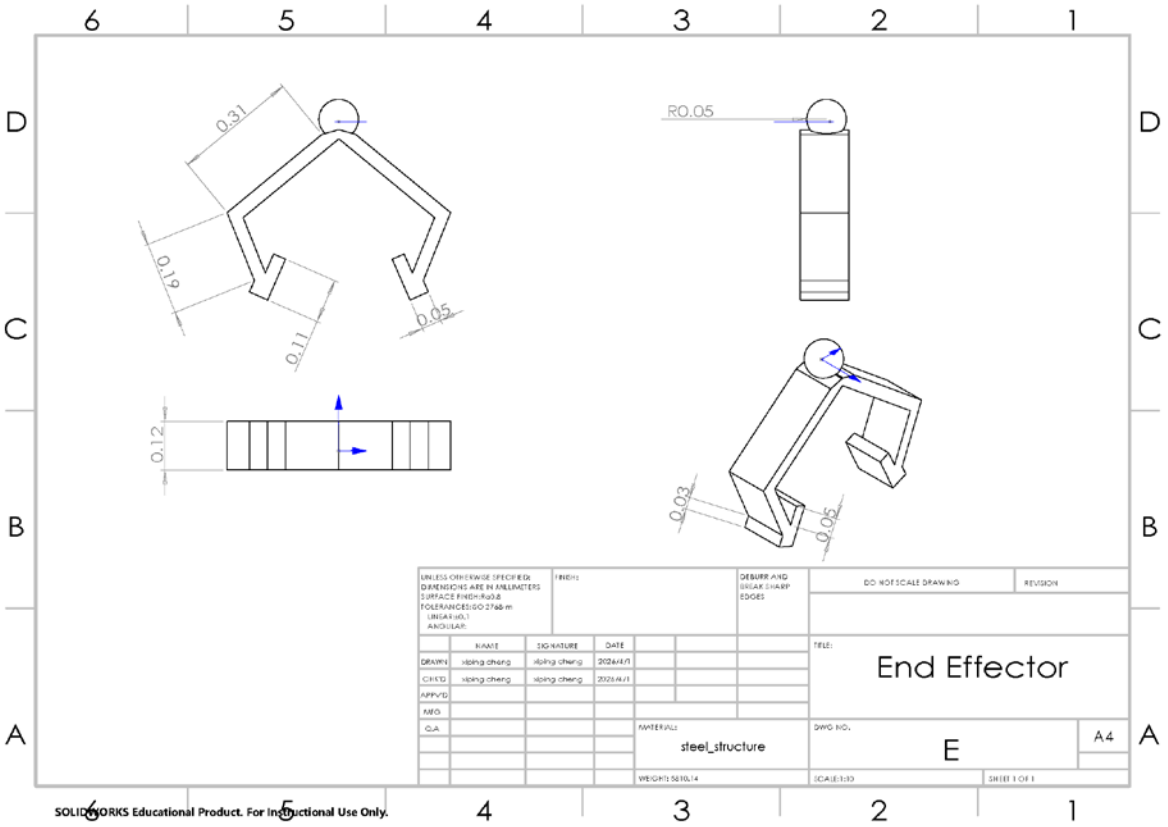
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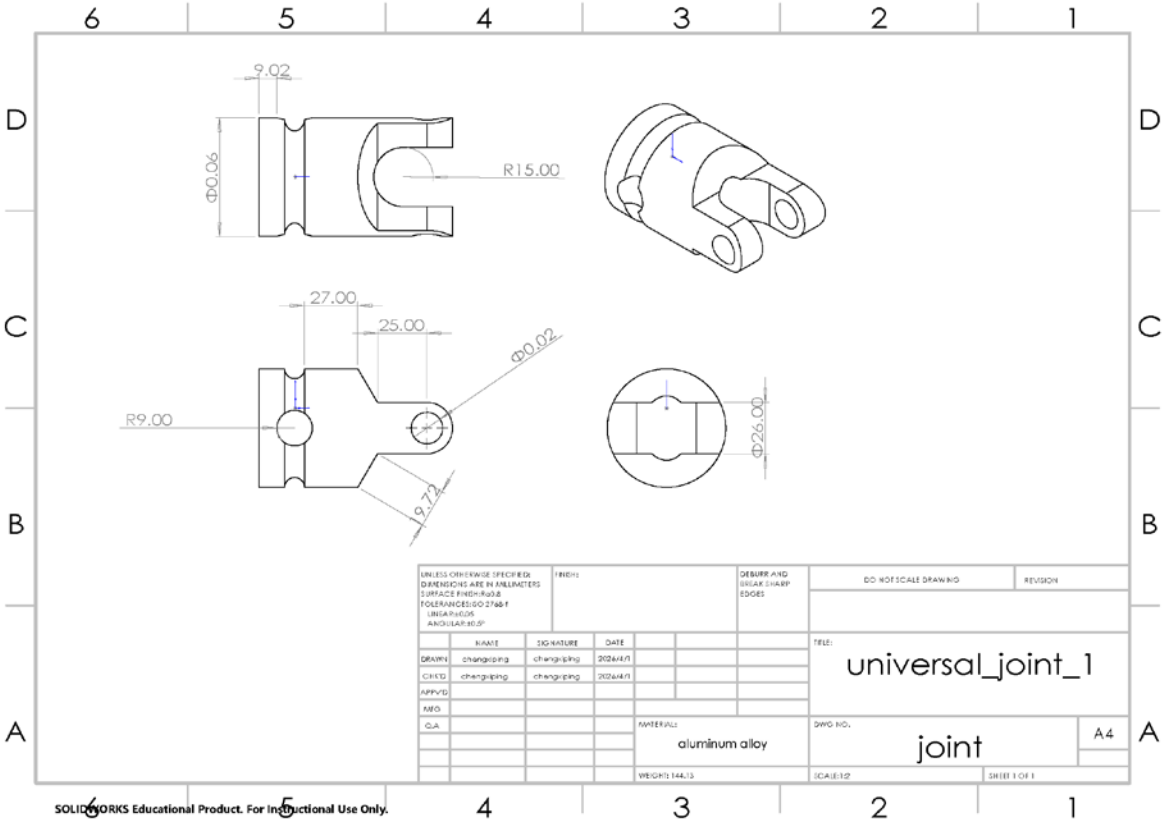
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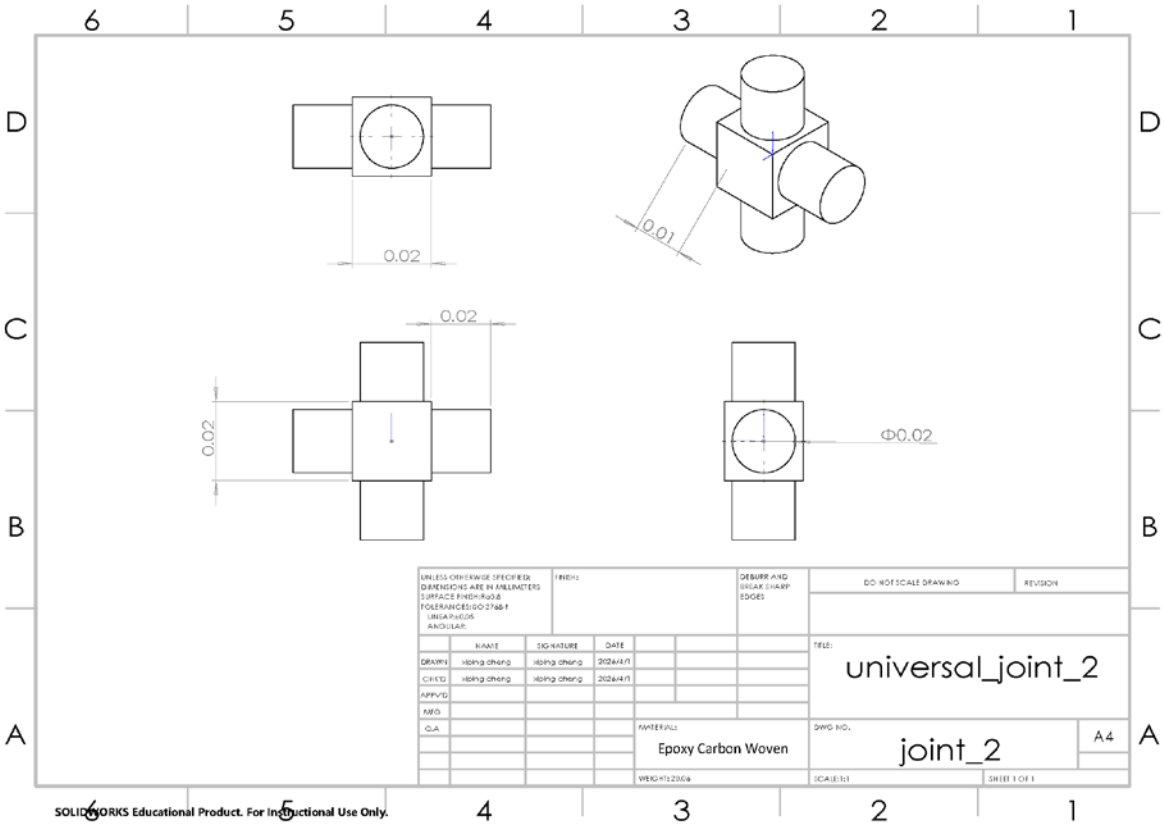

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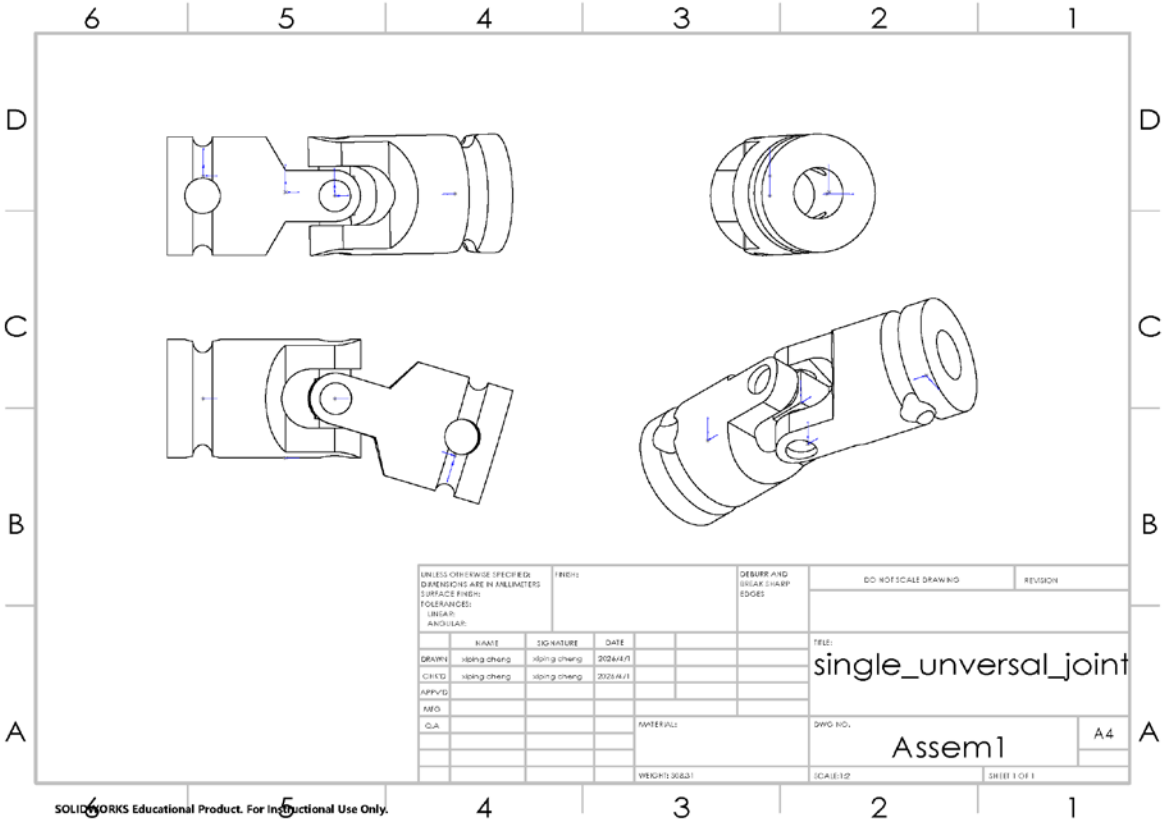

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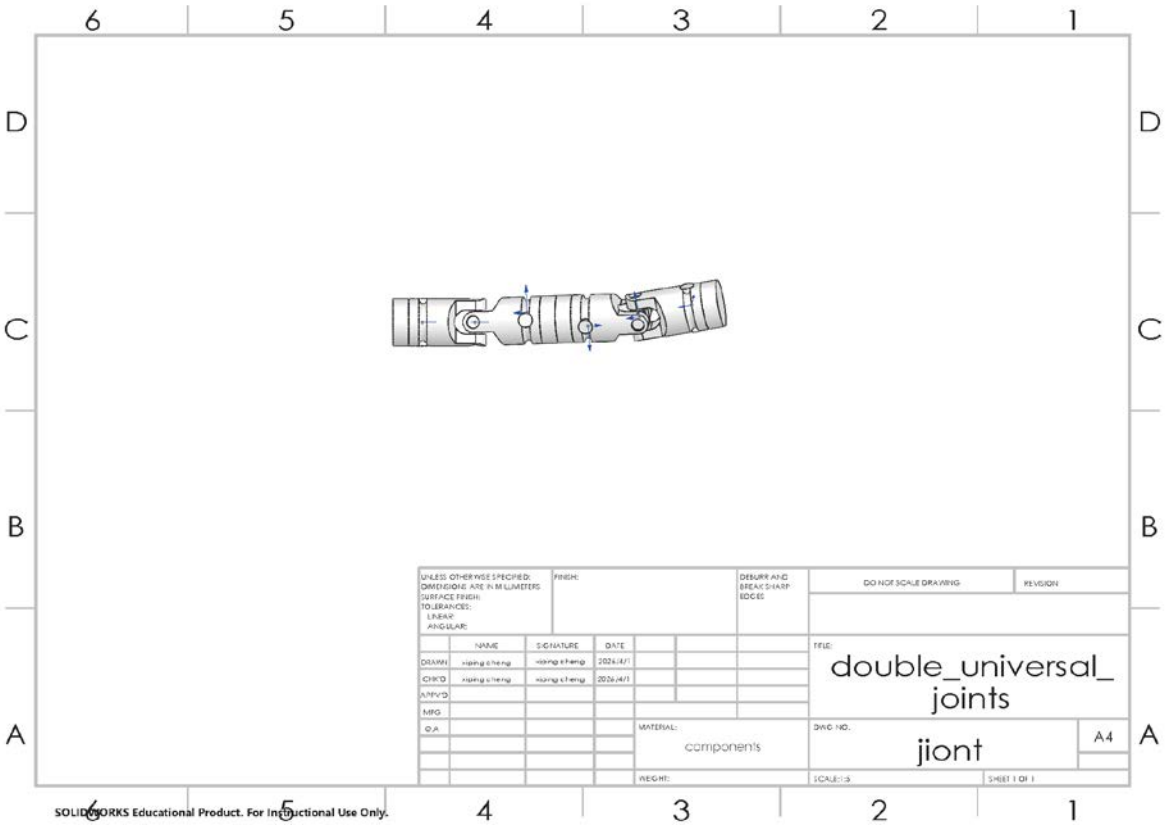
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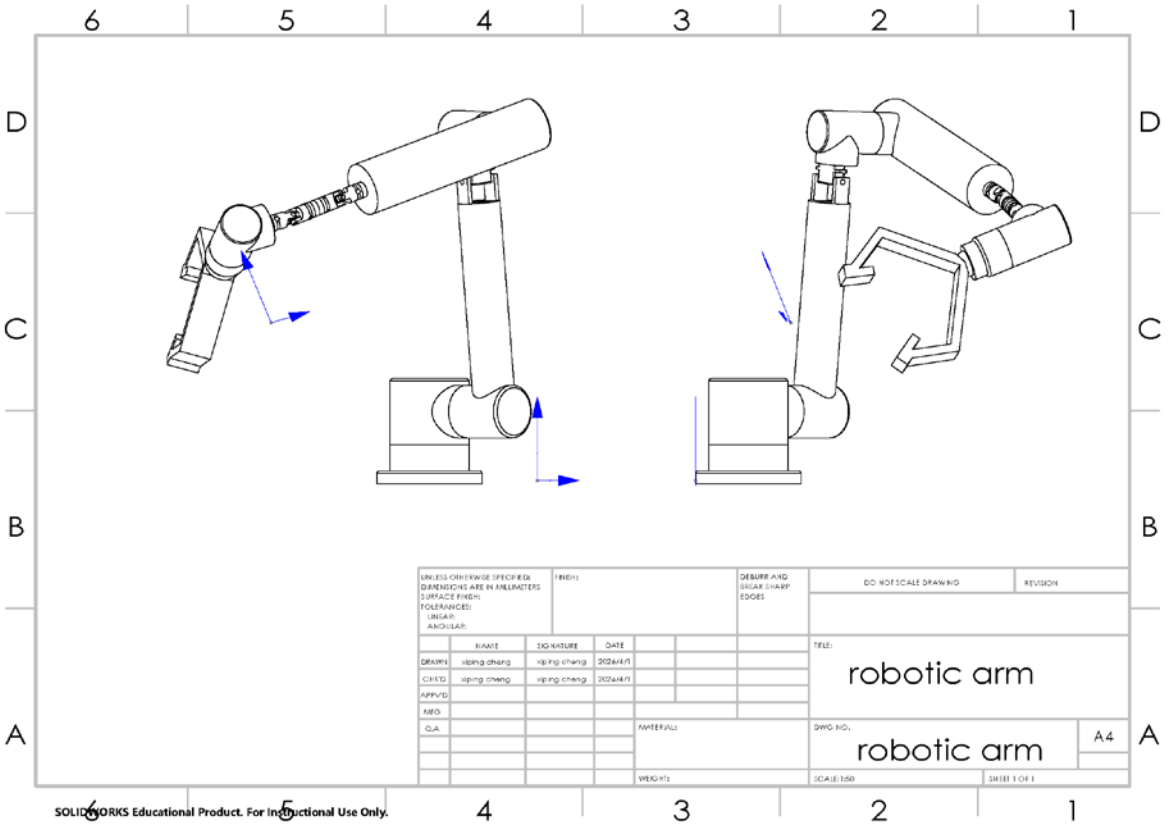
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