A Safe and Interpretable Embodied Intelligence Framework for Elderly-Care Assistive Robotic Manipulation

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Abstract

This project focuses on the mechanical design and system implementation of a lightweight assistive robotic manipulator tailored for elderly-care applications. The manipulator is designed with limited degrees of freedom, constrained workspace, and low-speed operation to ensure intrinsic safety and ease of deployment. Based on the mechanical structure, kinematic modeling, workspace analysis, and basic safety-oriented control strategies are developed. Emerging intelligent interaction technologies, including simple vision-based perception and high-level task understanding, are integrated as auxiliary modules to enhance usability without compromising mechanical safety. The proposed design demonstrates a practical and human-centered approach to elderly-care robotic manipulation, emphasizing mechanical reliability while incorporating modern intelligent technologies.

Keywords：

Assistive Robotic Manipulator; Mechanical Design; Elderly-Care Robotics; Human–Robot Interaction; Safe and Lightweight Structure; Emerging Intelligent Technologies

Content

1 Introduction

1.1 Application Scenario

1.1.1 Industry Background and Motivation

With the accelerating global trend of population aging, the number of older adults continues to rise, placing significant pressure on both institutional and home-based eldercare systems. According to the World Population Prospects: 2019 Revision, by 2050, one in six people worldwide will be aged 65 or above (16%), compared with 9% in 2019. This indicates that global society is entering an aging phase, with nearly every country experiencing growth in the size and proportion of its elderly population.

[1]From the perspective of human resources, global healthcare systems face shortages of care workers, high turnover rates, and excessive workloads. [2]It is projected that by 2060, the demand for healthcare personnel will double. The shortage of caregivers not only compromises service quality but also sharply increases the cost of care. The IFR's 2016 Global Service Robot Statistics Report shows that personal and domestic service robots are still primarily cleaning robots, lawn-mowing robots, and entertainment devices. [3]True eldercare service robots remain in their early stage of development, often limited to single-robot, single-function designs.

In 2015, the State Council of China issued the Guiding Opinions on Actively Promoting the "Internet+" Initiative, which accelerated the development of smart eldercare services in community-based and home-based contexts.[4] Meanwhile, the prevalence of chronic diseases among older adults is increasing. [5]Numerous studies show that major risks for seniors include falls, acute medical emergencies (e.g., myocardial infarction, stroke), improper medication adherence, mobility limitations, and cognitive decline. These incidents often occur when seniors are alone or at night, increasing the likelihood of delayed assistance. Currently, China's eldercare services face a severe imbalance between supply and demand. Traditional family-based eldercare and institutional eldercare models increasingly show limitations. Improving the quality of care, optimizing workflow, and reducing human labor costs have become urgent priorities. [6]Many eldercare institutions also face the contradiction of “too few caregivers, too many seniors.” A single caregiver is often responsible for more than ten older adults, making it difficult to provide continuous, high-frequency, and detailed care—especially tasks such as medication reminders, nighttime monitoring, and fall alerts. Against this backdrop, eldercare-oriented assistive robotic arms with perception, interaction, decision-making, and physical manipulation capabilities represent an important future direction. Such robotic arms can undertake large amounts of repetitive, time-sensitive, low-force caregiving tasks, while also providing rapid response in emergencies. With the advancement of embodied intelligence—integrating vision, language, and action—robots are becoming able to understand environments, follow commands, and support seniors safely and effectively. However, service robots still lack standardized and modularized research frameworks; many components are inherited from industrial robot systems, resulting in high costs. For example, there is a lack of standardized robotic arms and joints that match the anthropometric dimensions of human limbs, which is a key requirement for accelerating the development of affordable service robots.[7]

Therefore, designing a lightweight, safe, collaborative robotic arm for eldercare scenarios can help alleviate human labor constraints, improve caregiving efficiency, and provide seniors with more reliable daily assistance—offering clear social value and engineering significance.

1.2 Application Value of Eldercare Robotic Arms

1.2.1 Health and Safety Monitoring

Older adults are prone to sudden medical emergencies such as myocardial infarction, stroke, hypoglycemia, and respiratory distress—particularly during nighttime or in high-risk locations such as bathrooms, where caregivers cannot provide constant supervision. When equipped with vision sensors, microphones, or heart-rate monitoring modules, a robotic arm can periodically assess the senior’s posture, consciousness, and respiratory status, and issue alert notifications or contact healthcare personnel when abnormalities are detected. Deep learning–based fall-detection methods have demonstrated high accuracy and practicality in intelligent eldercare environments, significantly reducing rescue delay and lowering health risks.[17]

1.2.2Medication Management and Reminders

Many older adults must take multiple medications on strict schedules, such as antihypertensives, anticoagulants, and insulin. By training lightweight neural network models to recognize individual faces and various medication containers, the robotic system can combine object recognition, speech synthesis, and designated lighting indicators to perform scheduled reminders, medication delivery, and adherence monitoring. When missed or mistaken medication intake occurs, the system can issue real-time alerts, thus reducing medical risks.[19]

1.2.3 Assistance with Light Daily Tasks

Older adults frequently experience difficulty performing Activities of Daily Living (ADLs). Research indicates that mobile manipulators can assist seniors by fetching and delivering items upon request, thereby compensating for functional decline. Robots can help with household chores, personal care, and the manipulation of objects necessary for Instrumental Activities of Daily Living (IADLs). This reduces the workload on caregivers while lowering the risk of falls caused by bending or reaching overhead.[8]

1.2.4 Reducing Caregiver Workload

The eldercare industry currently faces dual challenges: inadequate staffing and imbalance in workforce structure. Caregivers in eldercare institutions often experience heavy workloads and high psychological pressure, leading to talent outflow and rising human-resource costs.[21] A robotic arm can take over large volumes of repetitive, time-sensitive, simple but time-consuming tasks, enabling caregivers to focus on high-dependency seniors who need substantial human assistance.

1.2.5 Enhancing Senior Autonomy

Through natural-language commands, visual perception, and simple motion planning, the robotic arm enables seniors to independently manage certain daily tasks—such as “bring me water” or “pass me my phone”—helping delay the decline in quality of life due to mobility limitations.

1.2.6 Emergency Response in Critical Situations

When a senior falls or shows abnormal behavior, the robotic arm can automatically execute emergency strategies such as delivering an emergency call button, turning on lights, calling the nurse station, or notifying caregivers. Traditional camera-based monitoring can only observe incidents, while a robotic arm can physically intervene—providing significantly higher practical value.

1.3 Analysis of Irreplaceabilit

1.3.1 Compared to Traditional Surveillance Systems

Cameras or wearable devices are limited to data collection and cannot perform physical interventions (e.g., delivering medicine or water, assisting in sitting up). The robotic arm possesses the capability to actively intervene in the physical world, providing direct assistance in emergencies and forming a "light-duty care" capability.

1.3.2 Compared to General Service Robots

Traditional service robots are mostly mobile platforms lacking dexterity. The robotic arm can execute precise and stable grasping and delivery tasks, making it suitable for the complex and dynamic scenarios found in elderly care.

1.3.3 Compared to Manual Care

While the number of caregivers is limited, a robotic arm can achieve 24/7 stable operation without fatigue or omission. It can handle high-frequency repetitive tasks, significantly improving the reliability of the entire care system. Furthermore, to meet care requirements, the design and control of the robotic arm must strictly comply with the General Safety Requirements for Service Robots for Household and Similar Uses [18].

1.3.4 High Scenario Specificity

Many tasks in elderly care are highly personalized, such as medicine delivery, object handover, bedside assistance, and tray placement. Traditional robotic arm systems mostly rely on predefined programs and fixed paths, lacking flexibility in operation and adaptability to environmental changes [20]. Without a visual robotic arm, these tasks would either be impossible to automate or prohibitively expensive; thus, the visual robotic arm provides unique and irreplaceable value

1.4 Advantages of the Elderly Care Scenario

Compared to industrial, warehousing, or laboratory settings, the elderly care scenario presents the following unique advantages:

Lower Structural Complexity: The requirements for structural complexity are relatively low, primarily involving light-load tasks such as pick-and-place and delivery. This is suitable for designing lightweight robotic arms oriented towards human-robot collaboration from scratch.

2. High-Frequency Rigid Demand: Tasks in this scenario address clear pain points with high frequency and strong practical significance, which is unmatched by many other scenarios.

3. Natural Fit for Embodied AI: The field has inherent value for embodied intelligence, such as using language understanding and visual recognition to assist the elderly.

4. Social Value: Robots can significantly alleviate the social contradiction of caregiver shortages, enjoying policy support and long-term development potential.

5. Ethical Controllability: The use of robotic arms in elderly care has high ethical controllability. Compared to surgery or hazardous chemical handling, this scenario is more suitable as a project for teaching and optimization.

1.5 Product Advantages

1.5.1 Existing Commercial Products (Product Survey)

i. Paro (AIST, Japan): A seal-like therapeutic robot. Shibata et al. noted that Paro is equipped with tactile, auditory, and posture sensors to interact non-verbally with the elderly by mimicking animal behavior [9]. However, it lacks physical manipulation capabilities and cannot assist with ADLs [10].

ii. ElliQ (Intuition Robotics, Israel): An active AI social robot that interacts via voice, lights, and screen animations to alleviate loneliness [11]. While excellent in cognitive support, as a desktop device, it lacks a manipulator or mobile base to intervene in the physical environment [11].

iii. Pepper (SoftBank Robotics, Japan): Carros et al. found in long-term field studies that Pepper promotes social activity through quizzes and music [12]. However, due to the lack of dexterous hands, it cannot execute physical care tasks [12].

iv. Temi (Robotemi, Israel/China): Guerin et al. identified Temi as a carrier for "remote nursing," capable of video rounds, item delivery (tray-only), and fall detection [13]. Its primary role remains a "mobile information terminal," unable to perform fine manipulation like grasping or feeding [13].

v. CareBot (GeckoSystems, USA): A mobile assistive robot designed for autonomous navigation and monitoring. It primarily relies on screens and sensors, lacking a high-precision arm for physical tasks, positioning it as a safety and reminder platform [14].

vi. Toyota HSR (Human Support Robot, Japan): Yamamoto et al. described HSR's abilities to pick up dropped objects and open curtains [15]. However, its arm speed is slow for safety, payload is limited, and high costs hinder household adoption [15].

vii. Care-O-bot (Fraunhofer IPA, Germany): A modular service robot platform. Reiser et al. noted its omnidirectional base and multi-joint arm for complex tasks in unstructured environments [16]. Similar to HSR, its complexity and high maintenance costs are barriers to commercialization

1.5.2 Limitations of Existing Products

1. Lack of dexterous manipulation; unable to perform detailed tasks like handing over objects or medicine.
2. Lack of Embodied AI capabilities; unable to execute complex actions based on natural language.
3. Excessive cost, making large-scale deployment in nursing homes unfeasible.
4. Large size or high speed poses safety concerns, making them unsuitable for close proximity to the elderly.
5. Inability to achieve 24/7 monitoring and emergency physical response.

1.5.3 Advantages of the Proposed Robotic Arm

Compared to the products above, our design offers the following advantages:

1. Specifically designed for elderly care: lightweight, low-speed, and high safety.
2. Integrates intelligent monitoring, delivery, and medication management, offering irreplaceability.
3. Compatible with Embodied AI (VLA models), executing tasks based on voice and vision.
4. Degrees of freedom (DOF) and structure are fully optimized for the elderly care workspace.
5. Significantly reduces caregiver burden and improves efficiency.
6. Cost is far lower than industrial collaborative robots, making it suitable for actual deployment.

2 Key Technologies

Based on the elderly care scenario, the robotic arm must possess capabilities in perception, understanding, interaction, and execution. The core technologies include:

2.1 Embodied AI and VLA (Vision-Language-Action) Models

Recent advancements emphasize understanding complex semantic tasks through multi-modal information. VLA model capabilities include:

1. Visual Perception: Recognizing items (medicine boxes, cups) and human states (falling, sitting up, reaching out).
2. Language Understanding: Processing voice commands like "Pass me the medicine."
3. Action Generation: Converting visual and linguistic information into executable control trajectories. Leading models (Google RT-2, OpenVLA, RT-X) demonstrate feasibility in lab settings. This project adopts their task design and planning paradigms.

2.2 Multi-Sensor Fusion

To monitor the elderly in real-time, the system integrates:

1. RGB-D Cameras: For posture and environment detection.
2. Vital Sign Interfaces: For heart rate/blood oxygen monitoring.
3. Torque and Tactile Sensors: For safe contact and anti-pinching.
4. Audio Modules: For detecting distress calls or abnormal sounds (e.g., falls).

2.3 Human-Robot Collaboration and Safety Strategies

1. Impedance/Admittance Control: Ensuring the arm yields upon contact.
2. Workspace Limits: Preventing entry into dangerous zones (e.g., head region).
3. Lightweight Design: Reducing kinetic energy through structure and speed limits.
4. Emergency Stop: Accessible mechanisms for immediate termination.

2.4 Task Planning and Decision Making

Automatic generation of grasp poses and trajectories. For example, a medicine delivery task involves: Identify location -> Grasp-> Adjust pose ->Approach user ->Hand over. This is implemented via classical motion planning (RRT, Iterative IK) combined with Behavior Trees.

3 Mechanical design

3.1 Overview

3.1.1 Degrees of Freedom(DOF)Consideration

Elderly care tasks are mostly "light tasks" (delivery, adjustment) requiring high safety and spatial flexibility rather than high force. A complex 6-DOF structure is unnecessary, but the following key actions must be guaranteed:

1. Reaching out to deliver medicine/water.
2. Picking up items from a table.
3. Vertical movement and pose adjustment at the bedside.
4. Approaching the user safely without collision.
5. Rotational capability to ensure correct grasping and handover orientation.

Analysis suggests that a 4-DOF structure balances control simplicity with functional requirements. The structure includes: Base Rotation, Shoulder Pitch, Elbow Pitch, and Wrist Roll.It can cover most daily assisted tasks of the elderly and facilitate the balance between safety and control.

Meanwhile, we also analyzed the compatibility between 3DoF and 4+DoF (5,6,7DoF) robotic arms:

Analysis of Alternatives:

i. 3-DOF: Insufficient redundancy; lacks pose adjustment (cannot keep a cup level); poor obstacle avoidance; stiff movements causing psychological discomfort.
ii. 5-7 DOF: Excessive redundancy leads to unpredictable motion paths, increasing cognitive load and fear in elderly users; higher cost and complexity hinder deployment.
iii. Selected 4-DOF Strategy: Balances reachability, pose control, and safety. The motion is concise and predictable, fostering trust.

3.1.2 Workspace Considerations

The primary operational scenarios for elderly-assisting robotic arms are around the elderly patient's bedside and adjacent work surfaces. The typical workspace covers the safety zone in front of the patient's torso (from chest to upper thighs) and areas where bedside tables and other furniture are placed. To achieve these operational ranges, the robotic arm must possess the following workspace characteristics:

Horizontal Radius: 0.2-0.4 m (bedside to table).

Vertical Range: 0-0.4 m (sitting to lying down).

Constraints: Avoid head regions; limit speed near the body. These constraints determine the link lengths and DH parameters.

3.1.3 DH Parameter Design

i. Principles

（1）Reach the chest area comfortably (approx. 300–450 mm).

（2）Cover bedside tables and floor (for dropped items).

（3）Links should not be overly long to minimize inertia.

（4）Joint ranges prioritize frontal coverage

Based on the requirements and considering ergonomic design with bedside furniture arrangement, the robotic arm's operational range is defined as follows:

Horizontal reach：0.2-0.4 m

Vertical operation range：0-0.4 m

Therefore, a compact and moderately covered linkage configuration is selected: the first link covers the main lifting range, the second link covers the forward extension range,the third link is used for fine extension and posture coordination, and the wrist is used for rotational adjustment of posture.

DH Parameter and meanings：

All joints in the robotic arm are revolute joints, modeled using standard DH (Hyperdynamics and Dexterity) rules. Specific parameters are as follows:

Joint number: i

$\alpha(i)$: Torsion angle from link i-1 to link i

a(i): Link length

d(i): Joint offset

$\theta(i)$: Joint variable (rotation angle)

Joint i	$\alpha(i)$	a(i) (mm)	d(i) (mm)	$\theta(i)$
1	-90°	0	80	θ1（Base Rotation）
2	0°	200	0	θ2（Shoulder Pitch）
3	0°	180	0	θ3（Elbow Pitch）
4	-90°	50	0	θ4（Wrist Roll）

Table 3-1 Geometry DH Parameters（SDH）

Constraint: To prevent spillage during delivery, the end-effector must remain horizontal:$\theta 4=-(\theta 2+\theta 3)$

ii. Parameter select

（1） a2 = 200 mm

Shoulder-to-elbow, reaching the chest without excess inertia.

（2） a3 = 180 mm

Elbow-to-wrist, complementing the reach.

（3） a4 = 50 mm

Tool flange/gripper interface.

（4） d1 = 80 mm

Base height, suitable for bedside installation.

iii. Joint parameter limitations

Joint	**Name**	**Scope**
θ1	Base Rotation（Yaw）	$-90° \sim +90°$
θ2	Shoulder Pitch（Pitch）	$-120° \sim +20°$
θ3	Elbow Pitch（Pitch）	$-30° \sim +120°$
θ4	Wrist Roll（Roll）	$\theta 4 = -(\theta 2 + \theta 3)$

θ1 Base rotation

- Focus interaction in front of the elderly, reducing operations in the area behind them
- Higher psychological safety
- Prevent quick rotation from sweeping past the sides of the elderly's head

θ2 Shoulder Shrugs

- -120° ensures actions at a high position above the water cup/medicine box
- +120° allows slight downward reach (such as small items on the bed)
- Avoid excessive shoulder bending downward posture pressing on the elderly person's body

θ3 Elbow extension

- +120° allows full extension when handing objects
- -30° keeps the robotic arm's elbow forward to avoid bumping the elbow into guardrails/the elderly's waist
- Supports fine approach movements

θ4 Attitude Control (Passive Constraint)

- Always maintain horizontal alignment at the end
- Deliver water precisely to prevent 'spilling'
- Visual and tactile interaction feels more natural

iv. Tasks Requirements Fulfilled by the Design

The above DH structure meets the following typical operations for elderly care assistance:

(1) Retrieving medicine from the bedside cabinet and delivering it to the elderly person’s hand;

(2) Grasping a cup of water, adjusting its angle, and delivering it;

(3) Picking up items that have fallen from the table or bed;

(4) Position of hand-to-hand interaction (handover) can be controlled and is safe;

(5) Joint configuration avoids contact with sensitive areas such as the elderly person’s head;

(6) The overall structure is lightweight, and the motion trajectory is easy to control and predict.

v. Security Advantage

Due to the shorter linkages and motion range focused on the front area, compared to general-purpose collaborative robotic arms, it has higher:

(1) trajectory predictability

(2) lower rotational inertia, making it more suitable for operation close to humans

(3) lower collision risk

(4) better compliance control performance

(5) psychological acceptance among the elderly

vi. Conclusion

This DH parameter design is tailored to the practical needs of elderly care scenarios. By reasonably setting the link lengths, joint layout, and workspace, the robotic arm achieves basic posture flexibility while remaining lightweight, safe to operate, and in line with the design intention of elderly care robotic arms to be 'light, safe, and easy to deploy.

3.1.4 Speed,Acceleration,and Materials

The primary objectives of elderly-assistive robotic arms are safety and comfort, not high-speed operation. Therefore, the design of speed and acceleration must adhere to the following principles:

（1） Strictly limited max speed (Low-Speed Mode);Avoid the risk of shock or collision

（2）smooth acceleration (S-curve profile) to prevent jerks.

（3）Compliance with ISO 10218/TS 15066.

3.1.5 Materials

Lightweight aluminum alloy structure; soft exoskeleton (silicone/rubber) to cushion impacts; rounded edges; antibacterial surfaces.

3.1.6 Weight

Total weight 2–5 kg.

3.1.7 End-Effector

Soft gripper (2-finger) with tactile feedback。

3.1.8 Consideration of Maintainability and Interaction Comfort

The elderly often need more concise interaction methods when using robots. Therefore, the design should consider:

(1) supporting voice-activated tasks for robotic arms;

(2) incorporating rich status feedback mechanisms, such as light indicators and voice confirmations.

（3）The surface of the robotic arm is treated to be soft and the color is mild to reduce fear;

（4）The structure is highly maintainable, facilitating daily inspections and maintenance by caregivers.。

3.1.9 Cost and Accessibility Requirements

To enable large-scale deployment in elderly care facilities, equipment costs must be effectively controlled. Compared with industrial collaborative robotic arms, this approach achieves cost advantages through reduced degrees of freedom, lightweight materials, fewer complex sensors, and simplified structures, making it more viable for practical implementation.

3.2 Geometry

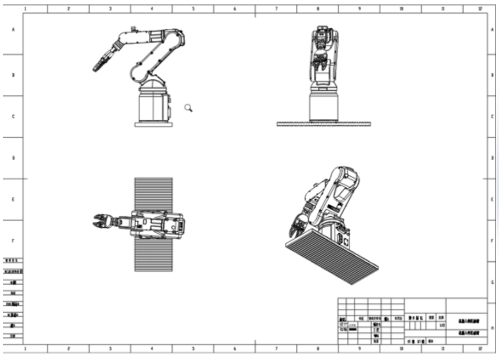
DH parameter:

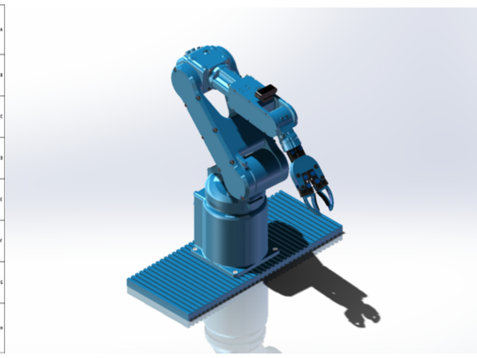
Joint i	α(i)	a(i) (mm)	d(i) (mm)	θ(i)
1	-90°	0	80	θ1（Base Rotation）
2	0°	200	0	θ2（Shoulder Pitch）
3	0°	180	0	θ3（Elbow Pitch）
4	-90°	50	0	θ4（Wrist Roll）

Coordinate System: The world frame coincides with the zero position of Joint 1. Constraint:

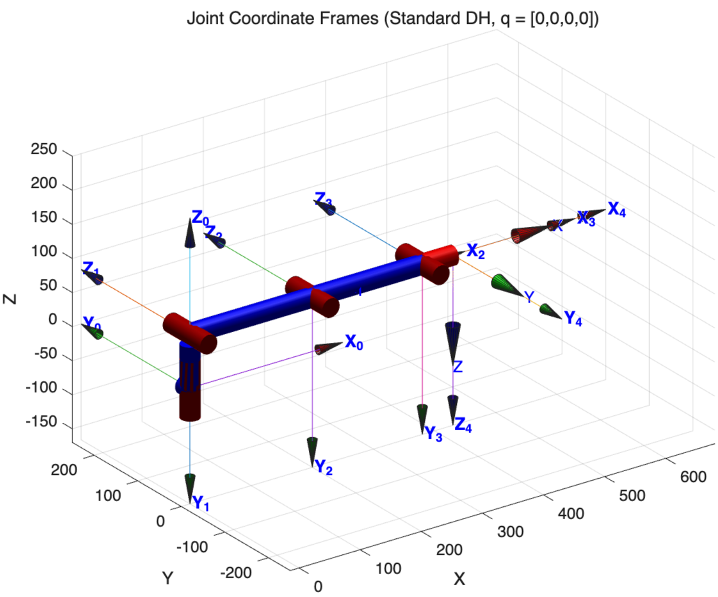
$$\theta_4 = -(\theta_2 + \theta_3)$$

2D Model and 3D Model





The Cartesian coordinate system:



3.3 Kinematics

3.3.1 Forward Kinematics

Based on the Standard DH homogeneous transformation matrix:

$$\begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Using the chain rule:

$$T_0^4 = T_0^1 T_1^2 T_2^3 T_3^4$$

Thus:

$^{0}T_4$

$$= \begin{bmatrix} \cos\ \theta_1 & \sin\ \theta_1 & 0 & \cos\ \theta_1\big(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50\cos\,(\theta_2{+}\theta_3{+}\theta_4)\big) \\ \sin\ \theta_1 & -\cos\ \theta_1 & 0 & \sin\ \theta_1\big(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50\cos\,(\theta_2{+}\theta_3{+}\theta_4)\big) \\ 0 & 0 & -1 & 80 - 200\sin\ \theta_2 - 180\sin\,(\theta_2{+}\theta_3) - 50\sin\,(\theta_2{+}\theta_3{+}\theta_4) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$x = \cos\ \theta_1\big(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50\cos\,(\theta_2{+}\theta_3{+}\theta_4)\big)$$

$$y = \sin\ \theta_1\big(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50\cos\,(\theta_2{+}\theta_3{+}\theta_4)\big)$$

$$z = 80 - 200\sin\theta_2 - 180\sin(\theta_2{+}\theta_3) - 50\,sin(\theta_2{+}\theta_3{+}\theta_4)$$

and applying the constraint:

$$\theta_4 = -(\theta_2 + \theta_3)$$

Therefore:

$$^{0}T_4 = \begin{bmatrix} \cos\ \theta_1 & \sin\ \theta_1 & 0 & \cos\ \theta_1(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50) \\ \sin\ \theta_1 & -\cos\ \theta_1 & 0 & \sin\ \theta_1(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50) \\ 0 & 0 & -1 & 80 - 200\sin\ \theta_2 - 180\sin\,(\theta_2{+}\theta_3) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$x = \cos\ \theta_1(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50)$$

$$y = \sin\ \theta_1(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50)$$

$$z = 80 - 200sin\,\theta_2 - 180sin(\theta_2{+}\theta_3) - 50$$

3.3.2 Inverse Kinematics

i. θ_1:

From:

$$x = \cos\ \theta_1(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50)$$

$$y = \sin\ \theta_1(200\cos\ \theta_2 + 180\cos\,(\theta_2{+}\theta_3) + 50)$$

We can solve for:

$$\theta_1 = \mathrm{atan2}(y, x)$$

$\theta_1$has only one solution

ii. θ_3:

From the Law of Cosines:

$$cos\theta_3 = \frac{r^2 + (80 - z)^2 - 200^2 - 180^2}{2 \cdot 200 \cdot 180}$$

Where:

$$r = \sqrt{x^2 + y^2} - 50$$

$$z = 80 - 200 \cdot sin\theta 2 - 180 \cdot sin(\theta 2 + \theta 3)$$

$$\theta_3 = \text{atan2}\left(\pm\sqrt{1 - \cos^2\theta_3}\,, \cos\theta_3\right)$$

$\theta_3$has two solutions (Elbow-up and Elbow-down)

iii. θ_2:

Starting from the robot arm joint angle position:

Wrist point horizontal component:

$$R = 200 * cos(\theta 2) + 180 * cos(\theta 2 + \theta 3)$$

Wrist point vertical component:

$$C = 200 * sin(\theta 2) + 180 * sin(\theta 2 + \theta 3)$$

Expanding:

$$cos(\theta 2 + \theta 3) = cos\theta 2 * cos\theta 3 - sin\theta 2 * sin\theta 3$$

$$sin(\theta 2 + \theta 3) = sin\theta 2 * cos\theta 3 + cos\theta 2 * sin\theta 3$$

$$R = (200 + 180 * cos\theta 3) * cos\theta 2 - 180 * sin\theta 3 * sin\theta 2$$

$$C = (200 + 180 * cos\theta 3) * sin\theta 2 + 180 * sin\theta 3 * cos\theta 2$$

Introducing:

$$K = 200 + 180 * cos\theta 3$$

$$H = 180 * sin\theta 3$$

Then:

$$R = K * cos\theta 2 - H * sin\theta 2$$

$$C = K * sin\theta 2 + H * cos\theta 2$$

We can solve for:

$$\theta_2 = \text{atan2}(CK + RH, KR - CH)$$

Where:

$$K = 200 + 180\cos\theta_3$$

$$H = 180\sin\theta_3$$

$$R = \sqrt{x^2 + y^2} - 50,$$

$$C = 80 - z$$

Note:

$R = \sqrt{x^2 + y^2} - 50$ and $C = 80 - z$(derived from the known target end-effector position) are equivalent to $R = 200 * cos(\theta 2) + 180 * cos(\theta 2 + \theta 3)$ and $C = 200 * sin(\theta 2) + 180 * sin(\theta 2 + \theta 3)$(derived from the robot arm joint angle position).

iv. θ_4:

$$\theta_4 = -(\theta_2 + \theta_3)$$

3.4 Jacobian matrix

i. Linear Velocity Jacobian Matrix:

$$x = \cos\ \theta_1 (200\cos\ \theta_2 + 180\cos\ (\theta_2 + \theta_3) + 50)$$

$$y = \sin\ \theta_1 (200\cos\ \theta_2 + 180\cos\ (\theta_2 + \theta_3) + 50)$$

$$z = 80 - 200\sin\theta_2 - 180\sin(\theta_2 + \theta_3) - 50$$

Substituting into:

$$J_v = \begin{bmatrix} \frac{\partial x}{\partial \theta_1} & \frac{\partial x}{\partial \theta_2} & \frac{\partial x}{\partial \theta_3} \\ \frac{\partial y}{\partial \theta_1} & \frac{\partial y}{\partial \theta_2} & \frac{\partial y}{\partial \theta_3} \\ \frac{\partial z}{\partial \theta_1} & \frac{\partial z}{\partial \theta_2} & \frac{\partial z}{\partial \theta_3} \end{bmatrix}$$

$$J_v = \begin{bmatrix} -(200c_2 + 180c_{23} + 50)s_1 & c_1(-200s_2 - 180s_{23}) & -180c_1 s_{23} \\ (200c_2 + 180c_{23} + 50)c_1 & s_1(-200s_2 - 180s_{23}) & -180s_1 s_{23} \\ 0 & -(200c_2 + 180c_{23}) & -180c_{23} \end{bmatrix}$$

Where,

$$c1 = \cos\theta_1, s1 = \sin\theta_1$$

$$c2 = \cos\theta_2, s2 = \sin\theta_2$$

$$c23 = \cos\ (\theta_2 + \theta_3), s23 = \sin\ (\theta_2 + \theta_3)$$

ii. Angular Velocity Jacobian Matrix:

Because

$$\theta_4 = -(\theta_2 + \theta_3)$$

here are only 3 independent joint parameters, and the Jacobian Matrix size is 6×3.

From the homogeneous transformation matrix

From the homogeneous transformation matrix

$$
{}^{0}T_4 = \begin{bmatrix} \cos\ \theta_1 & \sin\ \theta_1 & 0 & \cos\ \theta_1(200\cos\ \theta_2 + 180\cos\ (\theta_2{+}\theta_3) + 50) \\ \sin\ \theta_1 & -\cos\ \theta_1 & 0 & \sin\ \theta_1(200\cos\ \theta_2 + 180\cos\ (\theta_2{+}\theta_3) + 50) \\ 0 & 0 & -1 & 80 - 200\sin\ \theta_2 - 180\sin\ (\theta_2{+}\theta_3) \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Defining the rotation components::

$$
\begin{aligned}
&\dot{r}_{11} = -sin\ \theta_1\dot{\theta}_1,\ \ \dot{r}_{12} = cos\ \theta_1\dot{\theta}_1,\ \dot{r}_{13} = 0, \\
&\dot{r}_{21} = cos\ \theta_1\dot{\theta}_1,\quad \dot{r}_{22} = sin\ \theta_1\dot{\theta}_1, \dot{r}_{23} = 0, \\
&\dot{r}_{31} = 0, \dot{r}_{32} = 0, \qquad\qquad \dot{r}_{33} = 0.
\end{aligned}
$$

Substituting intoJ_ω:

$$
J_\omega = \begin{bmatrix} \dot{r}_{31}r_{21} + \dot{r}_{32}r_{22} + \dot{r}_{33}r_{23} \\ \dot{r}_{11}r_{31} + \dot{r}_{12}r_{32} + \dot{r}_{13}r_{33} \\ \dot{r}_{21}r_{11} + \dot{r}_{22}r_{12} + \dot{r}_{23}r_{13} \end{bmatrix}
$$

We get:

$$
J_\omega(\theta) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}
$$

Because the end-effector is always horizontal, meaning it only rotates around the Z-axis:

$$
J = \begin{bmatrix} -(200c_2 + 180c_{23} + 50)s_1 & c_1(-200s_2 - 180s_{23}) & -180c_1s_{23} \\ (200c_2 + 180c_{23} + 50)c_1 & s_1(-200s_2 - 180s_{23}) & -180s_1s_{23} \\ 0 & -(200c_2 + 180c_{23}) & -180c_{23} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}
$$

3.5 Singularities and singular configurations

In this project, the end-effector is constrained to remain horizontal ($\theta_4 = -(\theta_2 + \theta_3)$), and the main task is to control the end-effector position (x,y,z). Therefore, the effective task space is 3-dimensional, and the relevant Jacobian is the translational Jacobian $J_v \in R^{3\times3}$.

A configuration is singular if the Jacobian mapping from joint velocities to task velocities loses rank. For the 3-DOF reduced system, this happens when $\det(J_v) = 0$.

$$
J_v = \begin{bmatrix} -(200c_2 + 180c_{23} + 50)s_1 & c_1(-200s_2 - 180s_{23}) & -180c_1s_{23} \\ (200c_2 + 180c_{23} + 50)c_1 & s_1(-200s_2 - 180s_{23}) & -180s_1s_{23} \\ 0 & -(200c_2 + 180c_{23}) & -180c_{23} \end{bmatrix}
$$

$$
\det(J_v) = k\sin\ \theta_3(20\cos\ \theta_2 + 18\cos\ (\theta_2 + \theta_3) + 5)
$$

Where,

$$k = -360000$$

$\det(J_v) = 0$:

i. Elbow singularity

$$\sin \theta_3 = 0 \quad \Rightarrow \quad \theta_3 = 0° \text{ 或 } 180°$$

Implication: The second and third links are collinear (fully extended or fully folded). The end-effector's velocity along a certain direction cannot be generated independently.

ii. Arm-over-Base singularity

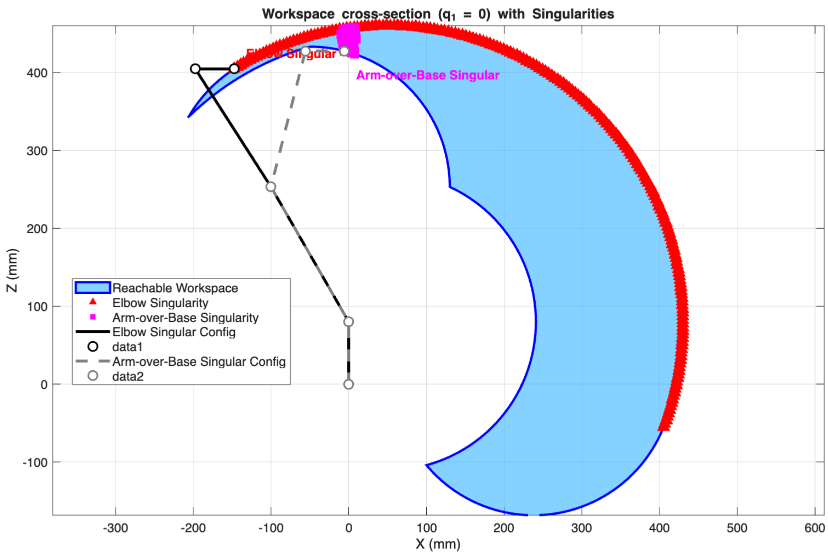
$$20 \cos \theta_2 + 18 \cos(\theta_2 + \theta_3) + 5 = 0 \Leftrightarrow 200 \cos \theta_2 + 180 \cos(\theta_2 + \theta_3) + 50 = 0$$

This expression is actually the condition for x and y to be zero in

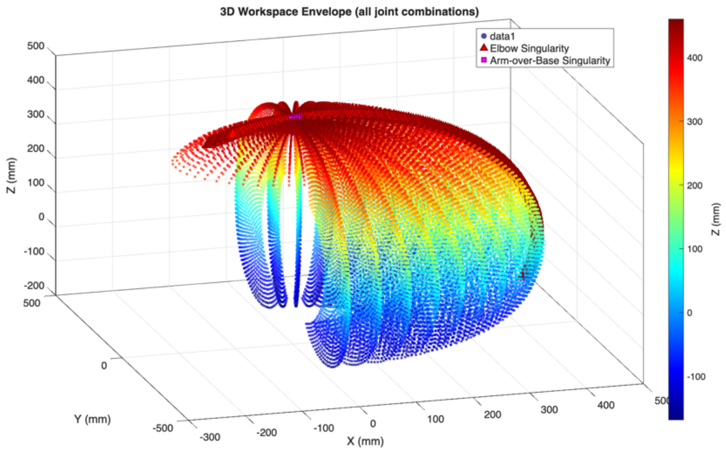
$${}^{0}T_4 = \begin{bmatrix} \cos\ \theta_1 & \sin\ \theta_1 & 0 & \cos\ \theta_1(200\cos\ \theta_2 + 180\cos\ (\theta_2+\theta_3) + 50) \\ \sin\ \theta_1 & -\cos\ \theta_1 & 0 & \sin\ \theta_1(200\cos\ \theta_2 + 180\cos\ (\theta_2+\theta_3) + 50) \\ 0 & 0 & -1 & 80 - 200\sin\ \theta_2 - 180\sin\ (\theta_2+\theta_3) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

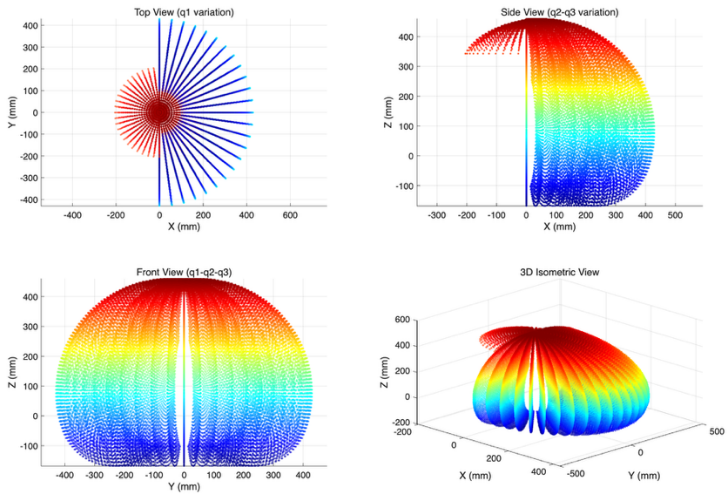
iii. Implication: The end-effector falls exactly above the base Z-axis, and rotation around θ_1 can no longer change the end-effector's (x, y), losing one dimension of independent velocity.

iv. Workspace & Singular configuration：



3D Workspace:





3.6 Static analysis

a) Static Analysis Static Modeling Assumption

Link Assumption:

Aluminum alloy hollow tubes, $D = 20\ \mathrm{mm}, t = 2\ \mathrm{mm}$

Cross-sectional area of the hollow tube:

$$A = \frac{\pi}{4}(D^2 - d^2),$$

$$D = 0.02\ \mathrm{m}, d = D - 2t = 0.016\ \mathrm{m}$$

Link Mass:

$$m_i = \rho A L_i$$

$L_2 = 0.2, L_3 = 0.18,\ L_4 = 0.05m$ get:

$$m_2 \approx 0.061 \text{ kg}$$

$$m_3 \approx 0.055 \text{ kg}$$

$$m_4 \approx 0.015 \text{ kg}$$

b) Gravity: g=9.81 m/s²

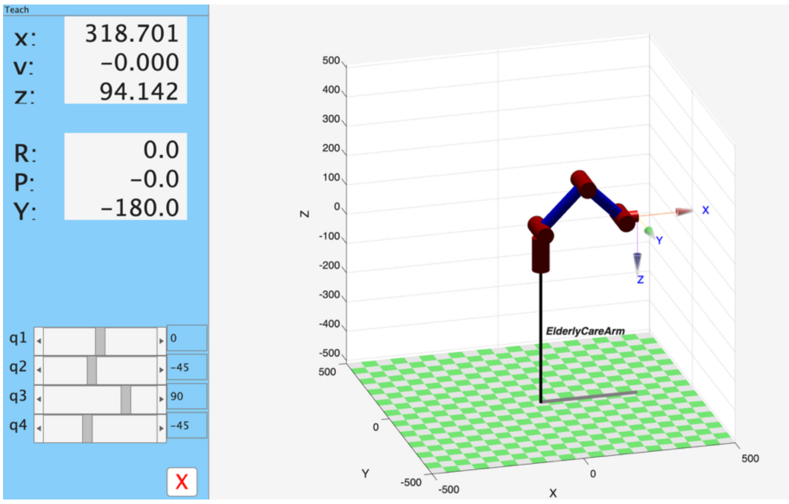
c) End-effector horizontal constraint$\theta_4 = -(\theta_2 + \theta_3)$

d) Based on the basic requirements of the elderly care scenario, the robotic arm must be capable of delivering medicine bottles and water cups. We consider end-effector payloads of 0.1 kg (medicine bottle) and 0.4 kg (water cup)。

e) Consider the joint angles at a typical operating position:

$$\theta_1 = 0°,\quad \theta_2 = -45°,\quad \theta_3 = 90°,\quad \theta_4 = -(\theta_2 + \theta_3) = -45°$$

The Pose is:



i. The torch caused by the end load

Although the derived$J_v$considers a reduced system, physically the fourth joint also experiences torque. Therefore, we expand the analysis to consider the relevant force transmission.

Given an external force \$F\$ acting at point \$p\$, the static torque generated on joint j is:

$$\tau_j = \left(p - o_{j-1}\right) \times F \ \cdot \ z_{j-1}$$

Define Jacobian Matrix:

$$J_v(:,j) = z_{j-1} \times \left(p - o_{j-1}\right)$$

Then the torque of joint j becomes:

$$\tau_j = J_v(:,j)^T F$$

$$\tau = J_v^T F$$

For link i, its center of mass position is:

$$p_i(q)$$

For joint j:

- Joint axis vector: $z_{j-1}(q)$
- joint origin: $o_{j-1}(q)$

Thus the Jacobian of the center of mass Jacobian:

$$J_{v,i}(:,j) = z_{j-1}(q) \times \left(p_i(q) - o_{j-1}(q)\right)$$

The gravity acting on the center of mass is:

$$F_i = \begin{bmatrix} 0 \\ 0 \\ -m_i g \end{bmatrix}$$

Thus the torque produced on the joint by link i is:

$$\tau_i(q) = J_{v,i}(q)^T F_i$$

Medicine bottle $m = 0.1$ kg:

$$\tau_{\text{payload}}^{(0.1)} \begin{bmatrix} 0 \\ 0.356 \\ 0.198 \\ 0.010 \end{bmatrix} \mathrm{N \cdot m}$$

Water cup $m = 0.4$ kg:

$$\tau_{\text{payload}}^{(0.4)} \begin{bmatrix} 0 \\ 1.054 \\ 0.499 \\ 0.010 \end{bmatrix} N \cdot m$$

v. Torch by link mass

Assuming there are 4 links, then:

$$\tau_{\text{gravity}}(q) = \sum_{i=1}^{4} J_{v,i}(q)^T \ (0,0,-m_i g)^T$$

Substituting the specific values, we get:

1) Link2 self-weight contribution

$$\tau_2 = \begin{bmatrix} 0 \\ 0.12694 \\ 0.04231 \\ -0.03385 \end{bmatrix} \mathrm{N \cdot m}$$

2) Link3 self-weight contribution

$$\tau_3 = \begin{bmatrix} 0 \\ 0.17931 \\ 0.10301 \\ 0.03434 \end{bmatrix} \mathrm{N \cdot m}$$

3) Link4 self-weight contribution

$$\tau_4 = \begin{bmatrix} 0 \\ 0.05058 \\ 0.02977 \\ 0.01104 \end{bmatrix} \mathrm{N \cdot m}$$

Summing the self-weight contributions of the three links:

$$\tau_{\text{links}}(q) = \begin{bmatrix} 0 \\ 0.35683 \\ 0.17509 \\ 0.01152 \end{bmatrix} \mathrm{N \cdot m}$$

vi. Total moment:

Medicine bottle:

$$\tau_{\text{total}}^{(0.1)} = \begin{bmatrix} 0 \\ 0.71283 \\ 0.37309 \\ 0.02152 \end{bmatrix} \mathrm{N \cdot m}$$

Water cup:

$$\tau_{\text{total}}^{(0.4)} = \begin{bmatrix} 0 \\ 1.41083 \\ 0.67409 \\ 0.02152 \end{bmatrix} \mathrm{N \cdot m}$$

3.7 Stiffness

i. Stiffness Modeling

Under the constraint of "keeping the end-effector horizontal"

$$\theta_4 = -(\theta_2 + \theta_3)$$

the robot possesses 3 independent degrees of freedom $(\theta_1, \theta_2, \theta_3)$。

We assume each independent joint has an equivalent torsional stiffness k_i, forming the joint stiffness matrix:

$$K_q = \mathrm{diag}(k_1, k_2, k_3) \in R^{3\times 3}$$

The relationship between small joint deflection δq and joint torque τ is

$$\tau = K_q\, \delta q$$

On the other hand, when the end-effector is subjected to an external force $F \in R^3$ the joint torque is $\tau = J_v^T F$

Eliminating τ and δq, the relationship between end-effector displacement δx and external force F is:

$$\delta x = J_v K_q^{-1} J_v^T F$$

According to the definition of Cartesian stiffness

$$F = K_x\, \delta x \quad \Leftrightarrow \quad \delta x = K_x^{-1} F$$

We have:

$$K_x^{-1} = J_v K_q^{-1} J_v^T, \qquad K_x = \left(J_v K_q^{-1} J_v^T\right)^{-1}$$

Where $K_x \in R^{3\times 3}$ is the end-effector position stiffness matrix (N/m) for a given pose

ii. Computing

From:

$$J_v = \begin{bmatrix} -(200c_2 + 180c_{23} + 50)s_1 & c_1(-200s_2 - 180s_{23}) & -180c_1 s_{23} \\ (200c_2 + 180c_{23} + 50)c_1 & s_1(-200s_2 - 180s_{23}) & -180s_1 s_{23} \\ 0 & -(200c_2 + 180c_{23}) & -180c_{23} \end{bmatrix}$$

Select typical working posture consistent with static analysis

$$q^* = [\theta_1, \theta_2, \theta_3] = [0°, -45°, 90°]$$

(corresponding to θ 4 =− 45 ∘, the end is horizontally extended and the load is maximized) 。

$$J_v(q^*) = \begin{bmatrix} 0 & 10\sqrt{2} & -90\sqrt{2} \\ 50 + 190\sqrt{2} & 0 & 0 \\ 0 & -190\sqrt{2} & -90\sqrt{2} \end{bmatrix} [\mathrm{mm}]$$

Trans to m:

$$J_v(q^*) \approx \begin{bmatrix} 0 & 0.01414 & 0.12728 \\ 0.31870 & 0 & 0 \\ 0 & -0.26870 & -0.12728 \end{bmatrix} [\mathrm{m}]$$

For stiffness estimation, we assign a set of reasonable independent joint stiffness values typical for lightweight service manipulators:

$$K_q = \mathrm{diag}(k_1, k_2, k_3) = \mathrm{diag}(300,\ 50,\ 60)\ [\mathrm{N{\cdot}m/rad}]$$

Its inverse is:

$$K_q^{-1} = \mathrm{diag}\left(\frac{1}{300}, \frac{1}{50}, \frac{1}{60}\right) \approx \mathrm{diag}(0.00333,\ 0.02,\ 0.01667)$$

Substituting into the stiffness formula, we obtain the Compliance Matrix:

$$K_x^{-1} = J_v K_q^{-1} J_v^T$$

$$K_x^{-1} \approx \begin{bmatrix} 2.74 \times 10^{-4} & 0 & 1.94 \times 10^{-4} \\ 0 & 3.39 \times 10^{-4} & 0 \\ 1.94 \times 10^{-4} & 0 & 1.71 \times 10^{-3} \end{bmatrix} [\mathrm{m/N}]$$

Taking the inverse yields the Stiffness Matrix:

$$K_x \approx \begin{bmatrix} 3.97 \times 10^{3} & 0 & -4.49 \times 10^{2} \\ 0 & 2.95 \times 10^{3} & 0 \\ -4.49 \times 10^{2} & 0 & 6.34 \times 10^{2} \end{bmatrix} [\mathrm{N/m}]$$

iii. Result Analysis

a) Diagonal Elements (Principal Stiffness)

$$K_{xx} \approx 4.0 \times 10^3\ \mathrm{N/m}$$

A 1 N force in X results in

$$\delta x \approx 1/K_{xx} \approx 2.5 \times 10^{-4}\ \mathrm{m} = 0.25\ \mathrm{mm}$$

$$K_{yy} \approx 3.0 \times 10^3\ \mathrm{N/m}$$

A 1 N force results in ~0.34 mm displacement

$$K_{zz} \approx 6.3 \times 10^2\ \mathrm{N/m}$$

A 1 N force results in ~0.34 mm displacement

This indicates that in the "horizontal extension" pose, vertical stiffness is the lowest, making the arm most prone to sagging in this direction, which is consistent with the static analysis where joints 2 and 3 bear the maximum gravitational torque.

$$K_{xz} = K_{zx} \approx -4.5 \times 10^2\ \mathrm{N/m}$$

This indicates that a Z-direction external force will induce a slight coupling displacement in the X-direction (the arm retracts slightly while sagging). The magnitude is far smaller than the principal stiffness, indicating good decoupling characteristics

b) Estimation of Deformation under Current Task Payloads

For the Water cup（0.4 kg）：

$$F_{\text{cup}} = [0,0,-3.924]^T \text{ N}$$

Displacement:

$$\delta x = K_x^{-1} F \approx \begin{bmatrix} -0.00076 \\ 0 \\ -0.00673 \end{bmatrix} \text{m} \begin{bmatrix} -0.76 \\ 0 \\ -6.7 \end{bmatrix} \text{mm}$$

Specifically, when carrying a 0.4 kg cup, the vertical sag is approximately 6–7 mm, and the horizontal retraction is less than 1 mm. This is acceptable for daily tasks like feeding water or delivering medicine.

For the Medicine Bottle (0.1 kg):

$$F_{\text{drug}} = [0,0,-0.981]^T \text{ N}$$

Displacement:

$$\delta x \approx \begin{bmatrix} -0.19 \\ 0 \\ -1.7 \end{bmatrix} \text{mm}$$

The deformation is minimal and practically imperceptible to the elderly user.

3.8 Trajectory Planning

This trajectory planning framework achieves safe, stable, and human-centered motion for elderly-care assistive tasks while maintaining mechanical and computational simplicity. By combining analytical inverse kinematics, joint-space interpolation, and a horizontal end-effector constraint, the proposed method provides a reliable motion foundation for assistive robotic manipulation. The framework is readily extensible to future enhancements such as compliant control, force sensing, and higher-level intelligent interaction.

4 Selection of actuators, sensors, and the gripper

This section selects specific actuators, sensors, and an end-effector gripper for the elderly-care robotic manipulator, building upon the preceding analyses of statics, kinematics, and stiffness, while adhering to the core principles of safety-first, cost-effectiveness, and ease of maintenance.

4.1 Actuators

Synthesizing the results of the static analysis (where the maximum total torque at Joint 2 is $\approx$1.41 N·m) with the requirements of the elderly-care scenario for low-speed, smooth, and safe operation, cost-effective digital servo motors are selected as the joint drive units. All servos support PWM control, facilitating integration with low-cost main controllers.

System integration solution:

- Drive: The system utilizes a PCA9685 16-channel PWM servo driver board, which communicates with the main controller via I2C to precisely control all servo angles and speeds.
- safe strategy ：

i. Software limit: Strict soft limit is set for each joint in the main control program (complementary to mechanical limit) to prevent dangerous posture.

ii. Speed control: All joint movements follow trapezoidal or S-shaped speed curves to ensure smooth start and stop without impact.

iii. Overload detection: By monitoring the steering motor's working current (requiring an additional current sensor or drive board feedback), it detects stalling and triggers an emergency stop.

4.2 Sensors

Sensor fusion and security logic:

- Data synchronization: All sensor timestamps are synchronized via the ROS master node.

i. Level 1 (Alert): The system detects prolonged inactivity in the elderly and triggers a voice alert.

ii. Level 2 (Alert): Detects a suspected fall posture, triggering local audio-visual alarms.

iii. Level 3 (Emergency): Both a fall posture and abnormal impact sound are detected simultaneously, automatically calling the nursing station.

4.3 Gripper

The gripper is driven by a compact servo motor and uses a linkage mechanism to open and close. The fingertips are fully covered with medical-grade silicone, making the gripper soft, safe, and easy to clean

5 Cost estimation

This cost estimation aims to verify the economic feasibility of the solution for large-scale deployment. The estimate is based on a small-batch production scale (100 units), with all pricing references drawn from prevailing e-commerce platforms in 2025.

5.1 Detailed Cost Breakdown per Unit

5.2 Market Pricing and Competitiveness Analysis

5.2.1 Market Pricing Recommendations：

- Basic Functionality Edition: ¥8,800 － ¥9,800 / unit (Includes item delivery, voice interaction, and fall detection)
- Full-Functionality Edition: ¥10,800 － ¥11,800 / unit (Adds health monitoring and medication management software)
- Annual Maintenance Service Fee: ¥500 － ¥800 / unit (Covers software upgrades, regular inspections, and spare part replacement)

5.2.2Competitiveness Comparative Analysis:

5.3 Comprehensive Competitive Advantages of the Proposed Solution:

5.3.1functional integration

This solution integrates five core functionalities into a single machine:

- Physical Assistance: Delivering medication and water, retrieving items.
- Health Monitoring: Fall detection, monitoring of vital signs.
- Medication Management: Timely reminders, medicine delivery.
- Safety Alerting: 24/7 monitoring with automatic alarm triggering for anomalies.
- Voice Interaction: Reception of and response to natural language commands.
- Compared to competing products which typically offer only 1-2 functions, this solution provides a one-stop comprehensive solution.

5.3.2 Safety-Specific Design

- Structural Safety: An optimized 4-degree-of-freedom design to avoid unpredictability from excessive redundancy.
- Material Safety: Full-body silicone soft-coating, no sharp edges, with impact-buffering properties.
- Motion Safety: Joint speed limited to 0.1-0.2 m/s, significantly lower than industrial robotic arms (0.5-1.0 m/s).
- Control Safety: Multi-layer protection (torque monitoring, tactile feedback, emergency stop button).

5.3.3Deployment Convenience

- Simple Installation: Can be mounted on a bedside table or wall, requiring no room structural modifications.
- Easy Maintenance: Modular design allows for quick replacement of key components (e.g., servos, sensors).

- Intuitive Operation: Primarily voice-controlled, eliminating the need for the elderly to learn complex interfaces.

5.3.4Scalability Potential

- Low Procurement Cost: The per-unit device cost is equivalent to only 3-4 months of a caregiver's salary.
- Low Operating Cost: Annual maintenance costs are below ¥1,000, with negligible electricity costs.
- Low Training Cost: Caregivers can learn basic operations within 2 hours.
- High Social Acceptance: Friendly appearance and gentle movements help reduce resistance from the elderly.

5.4 Innovative Business Model Recommendations

5.4.1Tiered Pricing Strategy

Version	Target Customers	Key Features	Price Point	Service Model
Entry-Level Edition	Home Users	Basic Delivery + Voice Interaction	¥8,800	One-Time Purchase
Institutional Edition	Small/Medium Care Facilities	Full Functions + Multi-Device Management	¥10,800	Annual Subscription (Includes Maintenance)
Flagship Edition	Large Care Groups	Customized Functions + Data Platform	¥12,800+	Leasing per Bed

5.4.2Revenue Projection Model

- Taking a medium-sized care facility with 200 beds as an example:
- Equipment Investment: 20 units × ¥10,800 = ¥216,000
- Annual Service Fee: 20 units × ¥800 = ¥16,000
- Labor Savings: Each unit replaces 0.3 caregivers; 20 units collectively save 6 caregivers.
- Annual Labor Cost Savings: 6 persons × ¥60,000 = ¥360,000
- Payback Period: ¥216,000 ÷ (¥360,000 - ¥16,000) ≈ 0.63 years (approximately 7.5 months)

5.5 Conclusion:

This solution, through extreme scenario-specific design, achieves comprehensive coverage of high-frequency core needs in elderly care while maintaining extremely low cost (< ¥3,000 per unit production cost). Compared to existing competing products, it fills the market gap for low-cost, multi-functional solutions, possessing the following unique competitive advantages:

i. Cost Competitiveness: The price is only 5%-15% of that of industrial collaborative arms and 2%-6% of that of specialized nursing robots.

ii. Functional Practicality: It simultaneously possesses perception, interaction, and manipulation capabilities, whereas most competitors possess only 1-2 of these.

iii. Safety Specificity: From structure and materials to control strategies, it is comprehensively optimized for the safety of the elderly.

iv. Deployment Simplicity: Installation and maintenance are straightforward, making it suitable for the existing infrastructure of elderly care institutions.

v. Business Model Flexibility: It supports various models including sales, leasing, and subscriptions, catering to diverse customer needs.

Final Value Proposition: At a cost equivalent to half a year's salary of one caregiver, this solution provides elderly care institutions with 24/7 uninterrupted, fatigue-free, omission-free standardized basic care services. It effectively alleviates the social issue of the "caregiver shortage crisis" and possesses tremendous potential for large-scale adoption and significant social value.

6 Interaction technology

6.1 Embodied Intelligence

Embodied Intelligence emphasizes that intelligent agents must acquire cognition through a **closed loop of perception, reasoning, and physical action**, rather than relying solely on abstract symbolic representations or offline computation **错误!未找到引用源。**. In elderly-care robotic manipulation scenarios, the robot is required not only to understand high-level semantic instructions, but also to safely and reliably interact with humans in close proximity under strict physical constraints.

In recent years, **Vision–Language–Action (VLA)** models have emerged as a prominent paradigm in embodied intelligence research. These models jointly learn visual perception, language understanding, and action generation, enabling robots to execute multi-step tasks based on natural language instructions [23–25]. Representative works include RT-2, which demonstrates that web-scale semantic knowledge can be transferred to robotic control policies [25], and PaLM-E, which integrates embodied perception into large language models for task planning [26].

In this project, the VLA paradigm is adopted **only at the task-decision level**, rather than directly generating low-level motor commands. Natural language instructions from elderly users are first parsed into **structured task representations**, including task type, target object, and safety constraints. Motion planning and execution are then handled by classical robotic control algorithms. This hybrid architecture combines the generalization capability of learning-based models with the safety, stability, and interpretability of model-based control, making it particularly suitable for elderly-care environments with stringent safety requirements [27].

6.1 Multisensor Fusion Technology

Elderly-care environments are characterized by confined spaces, frequent human–robot contact, and dynamic lighting conditions, making single-sensor perception insufficient. Therefore, this project adopts a **multisensor fusion framework** to ensure robust perception and safe interaction [28].

An RGB-D depth camera is used to acquire three-dimensional geometric information of the environment, enabling object recognition, spatial localization, and obstacle detection around beds, tables, and guardrails [29]. The inclusion of depth information significantly reduces perception errors caused by occlusions or illumination changes.

Interfaces for physiological monitoring data, such as heart rate and blood oxygen saturation, are reserved in the system architecture. These signals are not directly involved in motion control but are integrated at the system level to trigger task interruption or emergency alerts when abnormal conditions are detected, thereby enhancing overall care reliability [30].

Force–torque sensing at the joints and tactile sensing at the end-effector play a critical role in physical human–robot interaction. Joint torque sensors detect unexpected external forces and activate compliant control or emergency stop mechanisms, while tactile sensors are used during handover interactions to determine whether the user has securely grasped the object before release [31].

In addition, an audio sensing module is employed to detect emergency calls or abnormal sounds, serving as a redundant safety channel when visual perception is degraded, such as during nighttime or partial occlusion.

6.2 Human–Robot Collaborative Control and Safety Strategies

Elderly-assistive robotic manipulators belong to the category of physical human–robot interaction systems, where safety and comfort take precedence over speed or payload capacity. Consequently, this project incorporates well-established collaborative control and safety strategies from the robotics literature [32].

Impedance-based and admittance-based control methods are employed to achieve compliant behavior during physical interaction. These approaches allow the manipulator to behave like a mass–spring–damper system, yielding safely under external forces and minimizing the risk of injury during contact with the human body [33,34].

Workspace and motion constraints are enforced through both mechanical design and software-level restrictions. The manipulator primarily operates in the frontal region of the user and avoids sensitive areas such as the head. Motion speed and acceleration are adaptively limited based on the distance between the end-effector and the human, ensuring slow and predictable behavior in close-contact scenarios [35].

Furthermore, the system design follows the fundamental principles of the **ISO/TS 15066** collaborative robot safety standard, particularly with respect to limits on speed, force, and power during human–robot interaction [36]. Multiple emergency stop mechanisms, including voice commands, physical buttons, and sensor-triggered interruptions, are integrated to guarantee immediate intervention capability.

6.3 Task Planning and Behavior Decision-Making

To ensure reliable operation in complex elderly-care environments, this project adopts a **hierarchical task planning and behavior decision-making architecture** [37].

High-level tasks, such as medication delivery or water handover, are decomposed into a sequence of atomic actions, including object detection, grasp planning, grasp execution, pose adjustment, approach to the user, low-speed handover, object release, and safe retreat. Each atomic action is independently monitored, allowing the system to detect failures and initiate recovery strategies.

At the motion planning level, sampling-based planners such as Rapidly-exploring Random Trees (RRT) are used to generate collision-free paths in cluttered environments, while inverse kinematics and Jacobian-based control ensure smooth and continuous joint trajectories [38]. Velocity and acceleration limits are strictly enforced throughout execution to meet safety requirements.

Behavior organization is implemented using finite state machines or **Behavior Trees**, which provide modularity, readability, and fault tolerance. Behavior Trees enable the system to gracefully handle exceptional events, such as failed grasps or user hesitation, by transitioning to predefined safe states [39].

By combining embodied intelligence models for task-level decision-making with classical planning and control techniques for execution, the proposed system achieves a balance between semantic flexibility and physical safety.

7 Conclusion

This project presents the design and system-level implementation of a lightweight assistive robotic manipulator specifically tailored for elderly-care applications. Starting from the practical needs of bedside assistance, medication delivery, and object handover, the work emphasizes **mechanical safety, structural simplicity, and predictable behavior**, which are critical requirements in close human–robot interaction scenarios involving elderly users.

From a mechanical design perspective, a four-degree-of-freedom (4-DOF) manipulator architecture was carefully selected as a balanced solution between reachability, posture control, and safety. Compared with low-DOF designs, the proposed structure provides sufficient flexibility to cover typical bedside and tabletop workspaces, while avoiding the excessive redundancy, cost, and unpredictability associated with high-DOF robotic arms. The Denavit–Hartenberg (DH) parameters were designed based on ergonomic considerations of elderly users and the spatial constraints of care environments. Workspace analysis confirms that the manipulator can effectively cover the required operational region while avoiding hazardous areas such as the head and upper torso.

Kinematic modeling, inverse kinematics derivation, and Jacobian analysis were conducted under the constraint that the end-effector remains horizontal during task execution, which is essential for safe delivery of objects such as water cups and medication containers. Singular configurations were identified and analyzed, providing guidance for safe trajectory planning. Static and stiffness analyses further demonstrated that the manipulator can safely handle typical elderly-care payloads, such as water cups and medicine bottles, with acceptable deformation and torque margins. These analyses validate the mechanical feasibility and safety-oriented nature of the proposed design.

On the system level, a joint-space trajectory planning framework based on analytical inverse kinematics and smooth interpolation was implemented and validated through simulation. The use of intermediate waypoints reflecting real caregiving workflows—such as lifting, obstacle clearance, pre-handover positioning, and final delivery—ensures that the robot's motion is not only kinematically feasible but also intuitive and psychologically acceptable for elderly users.

In addition to the mechanical and control foundations, emerging intelligent interaction technologies were incorporated as auxiliary modules. Embodied intelligence concepts, including vision-based perception, simple language-driven task triggering, and hierarchical task planning, were integrated at the decision-making level without compromising the determinism and safety of low-level control. This hybrid design philosophy demonstrates that advanced intelligent interaction can be introduced incrementally on top of a robust mechanical system, rather than replacing it with opaque end-to-end solutions.

Overall, this work demonstrates that effective elderly-care robotic assistance does not require highly complex or industrial-grade robotic systems. Instead, a **task-oriented mechanical design combined with conservative control strategies and lightweight intelligent interaction** can provide a practical, affordable, and scalable solution. The proposed manipulator serves not only as a functional assistive device but also as a modular research platform for future studies in safe human–robot interaction, compliant control, and embodied intelligence in real-world care environments.

Future work will focus on physical prototyping, experimental validation with human subjects, and further refinement of compliant control and perception modules. By grounding intelligent interaction in a safety-first mechanical design, this project contributes a realistic pathway toward the deployment of robotic manipulators in everyday elderly-care scenarios.

8 References

1.United Nation. World Population Prospects 2019. New York: Department of Economic and Social Affairs Population Dynamics,2019.

[2] Leonardsen, A.-C.L., Hardeland, C., Helgesen, A.K., et al. The Use of Robotic Technology in the Healthcare of People above the Age of 65—A Systematic Review [J]. Healthcare, 2023, 11, 904.

[3] 陈亮. IFR 发布最新全球服务机器人统计报告[J]. 机器人产业，2016，18(3)：33-36.

[4]杨立春. 智慧养老产品在我国农村居家养老中的应用研究[J]. 中外企业家, 2018, 603(13): 94-95.

[5] 王文，王向佳，谢江，等.人工智能在老年慢性病共存病人自我 管理中的应用进展[J].护理研究，2022，36（5）： 869-873.

[6] 邓刚,林博,冯添毅,等.AI 智能保姆型具身机器人市场分析[J].新经济导刊,2025,(04):78-85.

[7] 赵雅婷,赵韩,梁昌勇,等.养老机器人现状及其发展[J].机械工程学报，2019，55(23):13-24

[8] Goher, K.M., Mansouri, N. & Fadlallah, S.O. Assessment of personal care and medical robots from older adults' perspective [J]. Robotics and Biomimetics, 2017, 4:5.

[9]Shibata, T. Therapeutic Seal Robot as Biofeedback Medical Device: Qualitative and Quantitative Evaluations of Robot Therapy in Dementia Care [J]. Proceedings of the IEEE, 2012.

[10]Leonardsen, A.-C.L., Hardeland, C., Helgesen, A.K., et al. The Use of Robotic Technology in the Healthcare of People above the Age of 65—A Systematic Review [J]. Healthcare, 2023, 11, 904.

[11]Pinto, J., & Rogers, W. A. ElliQ, an AI-Driven Social Robot to Alleviate Loneliness: Progress and Lessons Learned [J]. Generations Journal, 2024.

[12]Carros, F., Meurer, J., et al. Exploring Human Robot Interaction with the Elderly: Results from a Ten Week Case Study in a Care Home [C]//Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction. 2020.

[13] Guerin, D., et al. Evaluating Social Assistive Robots in Clinical Nursing Care: Mixed Method Pilot Study on Health Care Workers' Perceptions and Adoption [J]. JMIR Rehabilitation and Assistive Technologies, 2025.

[14]P.J G.L.N.M.G.N.S. A Survey of Intelligent Assistant Robots for the Elderly [J]. Aging and Disease, 2020.

[15]Yamamoto, T., Terada, K., Ochiai, A., et al. Development of human support robot as the research platform of a domestic mobile manipulator [J]. Robomech Journal, 2019, 6(1): 1-15.

[16]Reiser, U., Connette, C., Fischer, J., et al. Care-O-bot® 4: A universal mobile service robot for domestic and commercial applications [C]//2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). 2013.

[17]蔡敏雅,秦会斌 老年人跌倒检测系统及其检测方法的研究进展[D].杭州:杭州电子科技大学,2021

[18]GB/T 41527-2022.家用和类似用途服务机器人安全通用要求[S].中华人民共和国国家标准,2022

[19]范存辉,宋晓炜,徐争超.面向老年人的智能服药辅助系统[D].开封:开封大学,2023

[20]吴洪涛,蒋天宇,常天佐,等.中国机器人产业现状与创新发展趋势综述[J].机械制造与自动化,2025,54(01):1-6.

[21]周玉玲,牟洋,仇云东,等.昆明市养老机构人才需求现状调查研究:基于 56 家养老机构数据分析[J].卫生职业教育,2025,24(24)

[22].BROOKS R A. Intelligence without representation[J]. Artificial Intelligence, 1991, 47(1–3): 139–159.

[23].LYNCH C, KHANDALA V, TOMOV N, et al. Learning latent plans from play[C]//Proceedings of the Conference on Robot Learning. PMLR, 2020: 1113–1132.

[24].AHN M, BROHAN A, MCGREW B, et al. Do as I can, not as I say: Grounding language in robotic affordances[C]//Proceedings of the Conference on Robot Learning. PMLR, 2022: 287–318.

[25].BROHAN A, CHEBOTAR Y, FINN C, et al. RT-2: Vision-language-action models transfer web knowledge to robotic control[C]//Proceedings of the Conference on Robot Learning. PMLR, 2023.

[26].DRIESS D, XIA F, YANG M, et al. PaLM-E: An embodied multimodal language model[EB/OL]. arXiv:2303.03378, 2023.

[27].KROEMER O, NITSCHKE G, PETERS J. A review of robot learning for manipulation[J]. Journal of Machine Learning Research, 2021, 22(30): 1–82.

[28].LUO R C, KAY M G. Multisensor integration and fusion[J]. IEEE Transactions on Systems, Man, and Cybernetics, 1989, 19(5): 901–931.

[29].BOHG J, MORALES A, ASFOUR T, et al. Data-driven grasp synthesis—A survey[J]. IEEE Transactions on Robotics, 2014, 30(2): 289–309.

[30].MAJUMDER S, MONDAL T, DEEN M J. Wearable sensors for remote health monitoring[J]. IEEE Sensors Journal, 2017, 17(12): 3949–3960.

[31].ARGALL B D, CHERNOVA S, VELLOSO E, et al. A survey of robot learning from demonstration[J]. Robotics and Autonomous Systems, 2009, 57(5): 469–483.

[32].DE SANTIS A, SICILIANO B, DE LUCA A, et al. An atlas of physical human–robot interaction[J]. Mechanism and Machine Theory, 2008, 43(3): 253–270.

[33].HOGAN N. Impedance control: An approach to manipulation[J]. ASME Journal of Dynamic Systems, Measurement, and Control, 1985, 107(1): 1–24.

[34].KEEMINK A Q L, VAN DER KOOIJ H, STIENEN A H A. Admittance control for physical human–robot interaction[J]. International Journal of Robotics Research, 2018, 37(11): 1421–1444.

[35].HADDADIN S, ALBU-SCHÄFFER A, HIRZINGER G. Safety evaluation of physical human–robot interaction[C]//Robotics: Science and Systems. 2007.

[36].ISO. ISO/TS 15066:2016 Robots and robotic devices—Collaborative robots[S]. Geneva: International Organization for Standardization, 2016.

[37].GHALLAB M, NAU D, TRAVERSO P. Automated Planning and Acting[M]. Cambridge: Cambridge University Press, 2016.

[38].SICILIANO B, SCIAVICCO L, VILLANI L, et al. Robotics: Modelling, Planning and Control[M]. London: Springer, 2009.

[39].COLLEDANCHISE M, ÖGREN P. Behavior Trees in Robotics and AI[M]. Boca Raton: CRC Press, 2018.

9 Appendices

9.1 Actuators

Selection List and Rationale:

joint	**function**	**Maximum static torque (N • m)**	**Recommended model (brand)**	**key parameter**
1	Base rotation	≈0.0	MG996R (TowerPro)	Torque: 1.5 N • m @6V Speed: 0.1s/60° Weight: 55g
2	suppletiory movement of shoulder joint	≈1.41	DS3218 (domestic) or JX PDI-6221MG	Torque: 4.8 N • m @12V Speed: 0.15s/60° Weight: 78g
3	extension of elbow	≈0.67	SG90-HV (High Voltage Version)	Torque: 2.0 N • m @7.4V Speed: 0.2s/60° Weight: 28g
4	wrist rotation	≈0.05	SG90	Torque: 0.5 N • m @5V Speed: 0.2s/60° Weight: 20g

9.2 Sensors

To meet the requirements for environmental perception, state monitoring, and safe interaction, a low-cost, high-reliability multi-sensor system is constructed as follows.

class	function	Recommended model or solution	Key parameters/properties
visual perception	Object Recognition,Human Posture Detection and Scene Modeling	Astra Mini (Made in China)	RGB: 640x480, Depth: 640x480@30fps, USB interface, High cost-performance ratio
torque sensing	Joint load monitoring to prevent overload	HX711+Strain Gauge Self-made Bridge	Range: 0-5 N • m, Accuracy: ±0.1 N • m, Extremely low cost
tactile perception	Grasping Force Detection for Smooth Grasping	FSR402 Flexible Pressure Sensor	Range: 0-20N, thickness <1mm, flexible
Voice interaction	Receive voice commands and detect abnormal distress calls	ESP32-AudioKit V2.2	Dual microphone array with offline speech recognition (20+ core commands)
Health interface	Biometric data access (optional)	MAX30102 module	Monitor heart rate, blood oxygen, and I2C interface

9.3 Gripper

attribute	explain
design	Powered by compact servos (e.g. SG90), the device operates via a linkage mechanism for opening/closing. Both the fingertip and contact surface are fully coated with medical-grade silicone, ensuring softness and easy maintenance.
key parameter	Range: 0-60mm Maximum gripping force: 10N (adjustable via software) Weight: <60g Power supply: 5V DC
Adapter item	Medicine boxes/bottles: Silicone provides friction and is anti-slip. Water cup/dish: adaptive wrapping to avoid tight grip. Glasses, remote control: gently grab to prevent damage.
Security features	1. Mechanical flexibility: Silicone material inherently provides cushioning. 2. Force control loop: Real-time adjustment of gripping force is achieved through FSR402 feedback. 3. Anti-pinch design: The fingertips feature a smooth, rounded shape with a large contact area and low pressure.
cost advantage	The self-developed manufacturing cost (approximately 80 yuan) is significantly lower than that of commercial flexible grippers (over 300 yuan), making it suitable for large-scale promotion.

9.4 Detailed Cost Breakdown per Unit

Cost category	Details	Unit price	quantity	Subtotal (RMB)	Remarks (cost reduction/safety

		(RMB)			considerations)
A. physical construction	6061 Aluminum Alloy Connecting Rod (CNC)	200	1 set	200	Lightweight core structure
	ABS engineering plastic base/shell	80	1 set	80	Injection molding, smooth and rounded
	Bearing, fastener, silicone coating	70	1 set	70	Silica-coated is the key safety and touch cost
	subtotal A			350	
B. performer	MG996R servo (joint 1)	25	1	25	
	Steering gear DS3218 (joint 2)	75	1	75	Core Power, No Overly Cost Reduction
	Steering gear SG90-HV (Joint 3)	22	1	22	
	Steering gear SG90 (joint 4)	12	1	12	
	subtotal B			134	
C. sensor	Deep Camera (Orbitech Astra Mini)	450	1	450	With domestic solutions, costs are reduced by 40%
	FSR402 Flexible Pressure Sensor	15	4	60	For use with the jaw tip
	HX711+ Strain Gauge Torque Detection Kit	30	1	30	
	ESP32-AudioKit voice module	55	1	55	
	MAX30102 Health Module (Optional)	30	1	30	
	subtotal C			625	
D. Terminal clamping claws	Custom Silica Clamping Claw (Materials and Processing)	80	1	80	Customized in-house development with controllable costs
	subtotal D			80	
E. navar	Raspberry Pi CM4 core board (or similar domestic board)	300	1	300	master brain
	PCA9685 PWM driver board	25	1	25	
	Power module (12V/5V)	50	1	50	

	cable harness, connector, control box	50	1 set	50	
	subtotal E			425	
F. Production and Miscellaneous	Assembly and debugging labor costs	150	1	150	
	Packaging, Documents, Spare Parts	56	1	56	Accrued at 2% of the total cost
	subtotal F			206	
	Total material and production costs per unit			1820	Excluding R&D allocation
	R&D cost allocation (per 100 units)			800	Includes design, prototype, software, and certification
	Full cost per unit (accounting basis)			2620	

9.5 Code

coordinate system： coordinate_system_figure.m

workspace: Workspace.m

Trajectory Planning: tra.m