Design of human-like hand-arm for human-assisted manipulation

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**NANYANG
TECHNOLOGICAL
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**DESIGN OF HUMAN-LIKE HAND-ARM FOR
HUMAN-ASSISTED MANIPULATION**

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**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

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Design of Human-like Hand-arm for Human-assisted Manipulation

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Summary

A hand-arm system is an important module on a humanoid robot. It enables a humanoid robot to perform grasping and manipulation for many applications such as providing helps to elderly people. However, owing to limited space and weight, most humanoid robots are equipped with simple hand-arm systems, in which the hands have much lesser degrees of freedom than a human being's hands. Therefore, it is a challenge to design and implement a robotic hand-arm system which is similar to that of a human being.

In this project, a human-like hand-arm system is designed and implemented. The hand has 6 independent and 4 coupled degrees of freedom (DOFs) for its five fingers and the arm has 6 DOFs. In the design of human-like hand, each finger is assigned 2 DOFs. In this way, a hand will have 10 DOFs. However, in order to achieve the requirement of compact size, only six DOFs are actuated, and the other four DOFs will be coupled to the actuated DOFs. To realize such joint couplings, four bar linkage and rack-pinion structure are adopted.

As for the sensing and control, we have incorporated both position sensor (i.e. absolute encoders) and velocity sensor (i.e. incremental encoder) to each joint in the arm and the fingers of the hand. In addition, a 6-axis force/torque sensor is included to the wrist of an arm.

The proposed hand-arm system has been fully assembled and tested. During the implementation stage, kinematics modeling, and simulation are undertaken in MATLAB. Finally, the fully integrated and programmed hand-arm system has been installed onto the LOCH humanoid robot, which can perform vision-guided grasping and manipulation.

Chapter 1 Introduction

1.1 Significance

The world is facing a drastic change in demography. More and more countries are heading towards an aging society. In these countries, the population is aging and facing a manpower shortage, as well as a need for personal assistants for the elder people. How to cope with these problems is a pressing question hanging over the related countries.

Service robot perhaps is the most attractive solution. Being motivated by human physical functionality, service robots have developed the foundation of dexterous mechanisms, reliable sensing systems and intelligent computational algorithms. Various intelligent service robots can alleviate the burden of human tasks. It is predicted that robots will enter in every home in the future, and they will play an important role in ordinary life.

Today, humanoid robots are regarded as the most potential service robot in the future, since it can work effectively with human beings and can utilize the tools in an unmodified environment. Whereas they are developed out to provide physical assistance and even companionship for the elderly as well as replacing humans in factory, it is crucial to equip hand-arm systems as dexterous as that of humans for humanoid robots. Just like our upper limbs, the hand-arm systems play an important role for the humanoid robots. They enable the humanoid robot to perform manipulation and grasping for many tasks and applications. To some extent, the more dexterous the hand-arm module is, the more tasks it may perform. Though there is greatly progress made in robotic arms and dexterous hands, for example, industrial robot and artificial hands, a human-like hand-arm system is quite different with them in requirements. It should be considered in more aspects: it

should have human-like appearance and look friendlier, have more degrees of freedom, be safer and even do more works than human beings.

Not only for these areas, a dexterous hand-arm system can also be used in other fields that high mobility is needed, such as robotic surgery and aerospace manipulation. With the development of micro motors and advanced material technology and electronics technology, we believe that dexterous arm-hand systems will be more powerful and appear in more applications in the future.

1.2 Objective

As part of the humanoid project of “Low Cost Humanoid Robot” which aims to develop a humanoid robot with dexterous manipulators and biped mobility in service areas, such as helping people in the family or guarding in the subway stations, this project focuses on the design of the human-like hand-arm system, aiming to have the ability of grasping and performing simple gesturing.

1.3 Scope of Work

A human-like hand-arm system is the integration of mechanisms, electronics, and sensing systems. Thus, it is a challenge to design a dexterous manipulator with human-like appearance as well as humanoid functions. In this project, we mainly focus on the development of the arm-hand system of the humanoid robot as well as its implementation in manipulation and grasping. To be more specific, the main topics include:

- 1) Integration of mechanisms and electronics of hand subsystem. A human-like hand is the end-effector of the arm-hand system. It is difficult to design a dexterous hand with the

same degrees of freedom of a human being with a normal size due to the limited space. Thus, analysis should be made on the system requirements as well as the human hand in order to decide the degrees of freedom that a human-like hand should have, and then suitable mechanical structures will be designed to realize each of them. During the structure design, space for wiring and sensors mounting should be considered. Meanwhile, internal and tactile sensors should be designed to feedback the position and environment information, which are crucial for the high level control.

2) Integration of mechanisms and electronics of arm subsystem. The challenge of the design of the humanoid arm subsystem shares several aspects with that of a humanoid hand. The human-like arm module should be configured with suitable degrees of freedom to support the task performed. Meanwhile, dexterous and compact mechanisms should be designed under the limitations of dimension and weight. Attention should also be paid on the sensing system to provide enough internal and external information of the arm.

3) Kinematics of the hand-arm system. Kinematics is concerned with the mathematical relationship between the joint variables of a robot and its hand pose matrix. Based on the DOF configurations of the human-like hand and arm, the kinematics relationship will be developed to support the behaviors of manipulation and grasping.

Chapter 2 Literature Survey

Robot manipulators are considered to be the expansion of human's arms and hands. It has been a long time since people started to study artificial manipulators. Early in 15th century, a prosthetic hand was developed for a soldier who lost his hand in the war [1]. From then on, various artificial manipulators are developed and used in several fields. When entering into the 20th century, General Motors installed the first industrial robot "Unimate" for die casting handling and spot welding in 1961 [2]. Then robot manipulators started rapid development and are widely used in several fields such as military, nuclear power station, aerospace, medical surgeon and so on. In the last decades of the 20th century, robot manipulators were used to help disabled people and assist elder persons as service robots, due to the development of light micro actuators, advanced materials and various high precise sensors. Robot manipulators became more and more appearance-friendly, compact and intelligent.

Generally, there are mainly three streams in the research development of artificial manipulators, namely: a). industrial robot, b). prosthetic arm and c). intelligent dexterous manipulator, which aim to the typical applications.

a). The first one has adopted the function-oriented design for the replacement of workers in the sector of mechanical engineering industries [1]. Even though industrial robots do not imitate the human arms and hands, they can fulfill certain specific tasks with the certain precision and skills. Some keys to make the industrial robotic manipulators are: building them lighter, a minimum amount of actuators and a simple sensorial system to simplify its control.

b). The second one, of course, is used as the substitute of human upper limbs. Therefore the design of prosthetic arms is firstly determined by the four conditions of function, size, weight and appearance. The process of the prosthetic arm development can be said to be similar to that of mountain climbing tools. On the other hand, the current trend in the world is an arm-hand system similar to a real human upper limb. Many of the commercial powered prosthetic arms have one-degree-of-freedom, and can have the ability of pinching by thumb, index and middle fingers, even with five fingers for appearance. They have one degree-of-freedom only in joints between fingers and palm, but have no joints in fingers. The new trend of prosthetic arm development aims at the multiple functions, giving each finger joints, and furthermore giving the freedom of rotation as well as extension, similar to human fingers, which is trying the realization of adaptability of fingers. Using the current super micro realization technique, there are some experimental trials to locate actuators of each finger in a palm independently.

c). The third one is called intelligent dexterous manipulator. It is usually mounted on a certain kind of service robot, which may perform daily chores, help people with disabilities and serve as companions for elder people. Thus, they have combined requirements of the previous two. Especially for humanoid robot, considerations should be given on dexterity, size, weight, appearance and other aspects. It is quite a challenge to design a human-like hand-arm that completely follows a real one. Therefore, tradeoffs are made between them, which can be found in existing humanoid robots.

However, with the development of the micro-actuator, micro-sensor and high performance control system, the previous limitations are no longer difficult, and the different streams proceed toward similar targets. For example, DLR dexterous hand [3],

which is desired to be used as a space manipulator, is much more human-like. To sum up, the arm-hand system focuses on three key elements: appearance, dexterity (or DOF) and mechanics.

2.1 Appearance

A human-like appearance gives a robot a strong feeling of presence. When a robot looks much like a human being, it will be easily personified [4] and may interact with people more effectively. The more differences the appearance of a robot differs from a human being, the less humanoid it will feel. For example, it is impressive to watch dance performance of a humanoid biped robot, and it will be less attractive if a robot has two wheels. However, in Mori's "Uncanny valley" hypothesis [5], a robot is made more humanlike in its appearance and motion, the emotional response from a human being to the robot will become no long positive but a little awful. Thus, humanoid appearance is a very important factor to the robot that is faced with human beings. Figure 2.1 shows the humanoid robot from Sony Company [6]. Its personified appearance makes it lovely and friendly to the audience.

Figure 2.1 a QRIO Robot [6]

2.2 Degree of freedom of the Joints

Human arm and hand is a complex and compact organ from the engineer's point of view. If we consider a single human upper limb by modeling mechanically, then it can be expressed by the mechanism of 27 degrees of freedom. The human arm can be regarded as two rigid segments connected by three joints with 7 DOFs [7-10], while the hand can be modeled 22 degrees of freedom. Moreover, there are tremendous sensory nerve endings on the surface of the skin, which makes our arm and hands sensitive to the environment. Figure 2.2 shows the DOFs distribution of the upper limb. The shoulder joint is modeled as a ball-and-socket joint, and the elbow and wrist joints are modeled as skew-oblique joints.

Figure 2.2 DOFs Distribution of Upper Limb

It is nearly impossible to build artificial hand-arm systems equipped with so many actuators and controllers from the consideration of dimension, weight and control. Thus most of existing humanoid robots adopt only necessary DOFs for their applications and can only perform simple tasks. Table 2.1 lists the DOFs configuration of human being and some existing robots.

Table 2.1 Upper Limb DOFs Configuration of Human Being and Existing Robots

	DOF in Arm	DOF in Hand
Human Being	7DOFs: 3 in shoulder, 2 in elbow, 2 in wrist	22 DOFs
ASIMO	5DOFs: 3 in shoulder, 1 in elbow, 1 in wrist	1 DOFs
HRP2	6DOFs: 3 in shoulder, 2 in elbow, 1 in wrist	1 DOFs
QRIO	5DOFs: 3 in shoulder, 1 in elbow, 1 in wrist	5 DOFs
HUBO	6DOFs: 3 in shoulder, 2 in elbow, 1 in wrist	5 DOFs

The arms dexterity affects a lot on the manipulation ability of a humanoid robot, since it is developed out with the purpose that they could serve elderly people and patients in the future [11]. In practice, a humanoid arm with six DOFs has the minimum number of joints required for arbitrary location of its end-effector, or the hand. For this reason, a 6-DOF arm is regarded as the most general mode of robot arms [12]. For a 6-DOF robotic arm, it is able to move forward/backward, up/down, left/right (translation in three perpendicular axes) combined with rotation about three perpendicular axes (yaw, pitch, and roll). As shown in Table 2.1, HRP2 and HUBO have 6-DOF arms [13], while ASIMO has 5-DOF arms [14]. In some cases, other joints such as waist may join up to perform the tasks.

For the hands of humanoid robots, the appearance and weight are more important than functions. Thus, nearly all the existing counterparts are equipped with simple hands. For example, ASIMO has 5-DOF hands and each finger has just one DOF [14], while HRP2 has only one clamp instead [13]. Though HUBO has 5 DOFs for a single hand, the thumb lies oppositely of the other fingers [15], which makes the hand less humanlike. Obviously, a humanoid arm-hand module with limited DOFs largely restricts the motion and task it can achieve.

Passive joints are widely adopted in the design of the human-like hand. Since limited actuators can be mounted on the fingers, a passive joint can then make as supplement, and it can meet the appearance requirements of the finger joints and realize part of its function.

What is more important is that human fingers can grasp objects adaptively according to their shapes, or the fingers can move passively. This passive function makes it possible

for fingers to hold objects more accurately and to ease other handworks even without fingers moving independently and even at the expense of freedom of fingers. If it is realized by using active actuation, the control strategy would become complex and there may be limited space to mount the actuators in the palm or fingers. However, passive joints can more or less achieve the passive functions. Thus it is much common in the hand design. There are several existing methods to realize the passive joints [16-17]. Generally, the existing design of passive joints can move with the object grasped, and recover after the exterior force is withdrawn.

2.3 Mechanism

2.3.1 Actuation

Robotic hand-arm with DOFs similar to humans is hard to realize yet. One key reason is that it is not easy to develop small-sized, high power/weight ratio actuators. Till now, different driving principles can be found in the existing robotic manipulators such as hydraulic / pneumatic actuators [18~21], linear actuators [22], gearwheel motors [23, 24], shape memory alloy wire (SMA) [25] and so on.

Hydraulic or pneumatic actuators are of great practical importance in the industrial process control. They are used in a wide variety of different applications, such as heavy industries, mechanical engineering, transportation systems and in medical engineering. The advantages of these actuators are: a robust construction, a high power capacity, a high reliability and a reasonable efficiency [19]. However, conventional actuators have bulk volume and limited flexibility in their mechanical construction. Thus, a new kind of actuator namely fluidic actuator is created and used in several prototypes [18~20]. The principle is shown in Figure 2.3. The joint is driven by the fluidic actuator with a certain

angle around a stationary joint axis. A joint may be equipped with one or two active actuator elements. In the first case, the joint is moved actively in one direction only. Movement in the opposite direction takes place by a passive readjusting element, e.g. a spring. In the other case, a joint module is required that supplies an identical torque in both movement directions. The joint then is moved by adjusting the pressure of the both sides. Obviously, the advantages of this structure are a compact space, high flexibility designed into the mechanical construction, a lightweight construction and very low manufacturing costs.

Figure 2.3 Principle of Fluidic Actuator [18]

Another new type of actuator is the artificial muscle. It is a simple yet powerful device for providing a pulling force. It behaves in a way that is very similar to a biological muscle. When actuated with compressed air, it can contract by up to 40 percent of its original length. The pulling force it produces decreases as it contracts, of which the first few percent is very powerful. It is lightweight, and has high output and flexibility [26]. Several robot arms incorporating this in an actuator have been developed and the study results have been reported [27-31].

However, robot arms with pneumatic and hydraulic actuators have a fatal flaw: a compressor should be equipped to supply the high-pressure air or fluid source, and it is usually noisy and hard to be integrated in the robot arm-hand system.

Figure 2.4 Artificial Muscle and the Dexterous Hand [21]

Shape memory actuator is based on the usage of shape memory alloy (SMA) materials. When local temperature changes and/or stress state varies, a solid state phase transformation will take place. And this phenomenon is associated with a transformation strain which could be utilized for actuation. Usually, an electric current will be used to heat the material locally [32]. However, it is usually considered that the response of the SMA is too slow for actuation because it needs long heating and cooling time. What's more, it is the inherent nonlinearity of the SMA material that makes it hard to control [33]. What is worse, the SMA actuators have a limited cycle life [34]. Since heat transfer speed

is proportional to surface area of the SMA wire, smaller the SMA is, larger the surface area per unit volume becomes. So, it is suitable to be used in the robot whose dimension is smaller than normal. The figure below shows a miniature robot hand designed by SMA actuators in Japan [35].

Figure 2.5 Robot Hand Using SMA Wire [35]

Both linear motor and gear-wheeled motor convert the electricity of battery to mechanical motion. At present, the robotic arms which have realizable power outputs and which are lightest are ones using electrical motors, and there are many using lithium batteries [36], which will make the actuators more compact and efficient. Linear actuator is mainly used in the finger joints [37], where the joint space is limited to mount the gear-wheeled motor and the mating transmissions.

2.3.2 Joints and Transmission structures

In robotics, a joint connects two adjacent links together. In this way, a joint constrains the relative motion between two adjacent links. In practice, various types of joints can be designed. There are three typical joints, namely: independent joint, serial-driven joint and parallel-driven joints.

Independent joint

It refers to the most common one, to which one dedicated actuator is directly or indirectly, coupled through a coupling device. For indirectly driven there are several transmission devices. They play two key roles. One is to reduce the speed, and then enlarge the output torque. The second one is to absorb the impulse force to some extent. There are several kinds of transmission structures, such as harmonic gear, timing pulley, planetary gear. Each one has their own features and can be used in suitable cases. An independent joint is simple for the control system, and once it is broken, only the corresponding joints need to be repaired. Till now, majority of the robot joints adopt independent joints if there are no special limitations such as weight and space.

Serial-driven joint

It refers to the case that, several joints are serially deployed and driven by one dedicated actuator. It is also called a coupling joint. In this case, the movements of the joints are associated with each other. Only the proximal joint is directly driven by the actuator. The next ones are coupled with the proximal one by transmission structures, such as four-bar linkage, pulley belt, tendons and so on. Obviously, they are quite different in performance. For example, Guo etc. [38] propose a three DOF hand, in which each finger can move simultaneously by several pairs of gears. Obviously, it relies a lot on the precision of the gears mounting, or the transmission efficiency will be low and bring large friction. A

more classic method is using tendon [39] and pulleys. As shown in Figure 2.6, all the three joints are connected by pulley and pulley belt and can bend with the same velocity. In DLR dexterous hand [40, 41], the coupling joints are also be adopted on the middle and distal segments of the finger. However it uses linkage to couple the two joints. It is of high stiffness as compared to the former two methods. Thus precision grasping can be realized.

Figure 2.6 Coupling Joints Using Tendon [39]

Parallel-driven joint

It refers to the case that, several joints are independent in logical and driven by only one dedicated actuator. This is also called single-motor-driven concept [42-44] or uni-drive approach. Hamidreza etc. [45] from University of Waterloo proposed a new design for modular robot which applies the uni-drive method. In this method, the central shaft is continuously driven by a single base-mounted motor, which supplies the power to all the

modules through clutches. The engagement of clutches is controlled by using Pulse Width Modulation (PWM).

Figure 2.7 Parallel Configuration of the Uni-drive Modular Robot [45]

Chapter 3 Design of Human-like Hand

3.1 Requirements

According to the project requirements, the humanoid robot Loch is desired to have friendly outlook that is more like HRP2 and less like C3PO, and be able to perform basic biped locomotion and manipulation. To be more specific, the requirements corresponded to the humanoid hand are shown in Table 3.1.

Table 3.1 Requirements of Human-like Hand

Items	Requirements
Appearance	More like human hands instead of clamps
Dimension	Geometry of hands shall be close to human hand dimensions. The size shall have human like aspect ratio for hands.
Finger Dexterity	Fingers shall be close to human finger dimensions and dexterous enough to handle most tools built for the normal human hands
Function	Can carry up to 3 kg
	Can grasp a stick like object with single or both hands
	Can grasp objects under the guide of cameras
	To use its hand to reinforce its intended message (such as pointing at some person, showing a stop sign and stretching both hands to prevent someone from getting past)
	Can handle a glass cup (without handle) without breaking it

As described in Table 3.1, the requirements of the humanoid hand are embodied in two aspects: appearance and function. For appearance, the profile of the human-like hand

should have a palm and 5 fingers, including one thumb and four other fingers. Moreover, the length ratio between the palm and fingers, and the segments of each finger should be similar to that of the human hand. For example, the medius should be designed as the longest one, while the little finger should be the shortest. With these features, the hand can meet the requirements and look like a human hand.

The second, of course, is the function requirements. Since this human-like manipulator is desired to work in domestic environments and could serve elderly people and patients in an ordinary life, a humanoid hand must have enough ability and can perform enough tasks as the end-effector of the manipulator. Usually, the more DOFs it has, the more motions it can achieve. A human hand is so complex that totally 22 degrees of freedom are calculated by scientists. It is no need and also impossible to realize all the degrees of freedoms. However, each finger should have one degree of freedom. What is more, the thumb must have more degrees of freedom, because the thumb plays an important role in performing tasks.

When the hand is performing a certain task, it should accurately track each posture. Thus, position sensors should be mounted to detect the status of the fingers. Since the space in the finger is limited, the sensor should be small and compact. For the hand grasping function, the grasping force should be known, or the object may be damaged if the force is uncontrolled. Therefore, there ought to be some haptic sensors in the fingers or the palm. These sensors are helpful to achieve the required functions.

3.2 Specification

Based on the above discussion as well as the consideration of the limited space in the hand, the DOFs distribution of the human-like hand is determined and illustrated in

Figure 3.1. To be specific, the thumb has two degrees of freedom. The two active DOFs are orthogonal at the base point, and this enables the thumb to face towards the other fingers in grasping and align with the other fingers in initial status. For the other four fingers, each one has three segments, and connected by three joints which include one active joint, one coupled joint and one passive joint respectively. The active joint is driven by a motor and transmission mechanism mounted in the palm. The coupled joint moves with the active joint synchronously. The passive one lays between the middle and distal segments; it is driven by the exterior force instead of a motor in grasping. Normally, it will keep still. Thus, each human-like hand has 6 independent DOFs, 4 coupled and 4 passive ones in total.

Figure 3.1 DOF Sketch of Human-like Hand

Figure 3.2 Dimension Sketch of Human-like Hand

According to the digital model of humanoids in Gravez's research [46], the main dimensions of the human-like hand are decided. Subsequently, the dimensions of the palm, the thumb and other fingers are worked out and shown in Figure 3.2. In order to make the design and assembly easier, some dimensions of finger segments are modified to be identical. For example, the length of the middle segments is designed to be equal among the index, medius and ring finger.

3.3 Mechanism

3.3.1 Schematic of Hand Power Train

As described above, there are totally 6 independent DOFs, 4 coupled DOFs and 4 passive ones for each hand. To meet the requirements of function and appearance, the corresponding mechanisms are developed.

Figure 3.3 Schematic of the Overall Power Train of Hand

Figure 3.3 shows the overall power train structure of the hand. The whole power train is made of 5 independent sub-trains, and each one corresponds to one finger. For the thumb, two motors and two sets of bevel gears form a two-DOF structure. The other four fingers have the same transmission mechanism. The active joint is actuated by one motor and one set of worm/worm wheel, which converts the rotation of the motor into bending motion of

the active joint. The coupled joint is driven by a four-bar linkage and it can move with the same cadence of the active joint. The details of the coupled joint and the four-bar linkage will be analyzed later. The passive joint is achieved by using rack-and-pinion structure. It is driven by an exterior force instead of an actuator. If there is normal force acting on the button, in front of which the rack is fixed, the third segment of the finger will bend with a certain angle.

3.3.2 Structure of thumb

The thumb is assigned two independent DOFs. Usually, for a 2-DOF joint, there are several existing approaches to realize it. A typical method is differential joint type [47-49] as shown in Figure 3.4. In the sketch, gear C is connected with the roll axis of the tool or the end-effector, while gears A and B are coupled with actuators. When the gears A and B rotate with the same velocity and direction, it results in the rotation of the pitch axis; and if the gears A and B move reversely with identical speed, this will lead to the roll rotation. Normally, the rotation of the 2-DOF joint is a combination of the motions of the two axes. Though it is a commonly used structure, few reports can be found to use it on thumbs since it will face difficulty while mounting in the palm.

a. Prototype of the Mechanism

b. Principle of the Mechanism

Figure 3.4 Differential Joint Type

Another traditional approach is using independent actuators for the two-DOF joint respectively. In this method, one DOF of the joint will work as the payload of the other one. For example, the thumb of the DLR hand adopts this method [47], and the actuator and transmission structure of distal joint should be compact enough to be enclosed in the

limited space of the thumb. This is impossible for a hand with the normal size of a human hand. Though the DLR hand uses a self-designed motor [37], ultimately, it has to enlarge the size as 1.5 times as the normal one.

Figure 3.5 DLR Hand with Bigger Size than Normal One [37]

In this design, the dimension and appearance must be taken into consideration. There is another method to realize the 2-DOF mechanisms. The principle of the mechanism is shown in Figure 3.6. It is named cross-axle structure since it adopts a cross axle in the transmission. This mechanism can also move in two orthogonal orientations independently, resulting in a two-DOF structure.

Figure 3.6 Principle of Cross-axle Structure

For this type, two DC motors drive two sets of bevel gears respectively, which are connected with a cross-axle structure. The thumb tip is mounted on one arm of the shaft. The rotation of bevel gear A will make the movement of the pitch axis, but while the bevel gear D moves, it will lead to motion in both roll and pitch axes. If we define the positive directions of pitch and roll axes motion as the figure shows, the relationship of the transmission can be expressed as:

$$\theta_R = \theta_D \quad (3.1)$$

$$\theta_P = \theta_D - \theta_A \quad (3.2)$$

Where θ_P and θ_R denote the rotation angles of the pitch and roll axes respectively. The corresponding virtual model and real prototype are illustrated in Figures 3.7 and 3.8.

Figure 3.7 Virtual Model of Thumb

Figure 3.8 Mechanical Structure of Thumb

3.3.3 Structure of fingers

Usually, a humanoid hand has only one degree of freedom due to the space limitation.

However, to imitate the motion of human being, it should have the same three segments as a human. Thus most of the fingers adopt coupled structures, in which one actuator

drives all the three segments by coupling structure, such as thin steel rope, timing pulley and timing belt. Fingers using thin steel rope can cater to objects with different profiles, but it is difficult to realize precision grasping. If a finger adopts timing pulley and timing belt to connect the three joints, the bending angles of the three segments will be proportional to each other in any case. Thus they can only grasp objects with special profiles.

Figure 3.9 Illustration of Finger Structure

To overcome these problems, a new design is proposed. Figure 3.9 shows the schematic structure for each finger. A DC motor coupled with worm gear converts the rotating movement into the bending motion, and this configuration is convenient to mounting all the actuators. A four-bar linkage is used to realize the function of the coupled joint of the finger. With suitable configuration, the two joints can bend with the same velocity and position. As to the third segments, passive DOF structure is introduced to enable the hand grasping different types of objects.

Figure 3.10 Four-bar Linkage

The principle of the four-bar linkage is illustrated in Figure 3.10. Link 1 is the shortest and it is fixed on the palm, while link 2 forms the first segment, and it is fixed with the worm wheel. Thus link 2 is the active parts of the four-bar linkage. Link 3 is passive one and Link 4 consists of two segments, the shorter one of which is one element of the four-bar linkage, while the longer one denotes the second segment. When the first joint is actuated, link 2 will rotate together with the worm wheel, subsequently link 4 will be driven to bend a certain angle. To simplify the kinematics of the finger, the shorter segment of link 4 and link 1 are designed to be identical, so do links 2 and 3. In this case, the first and second segments will share the same velocity and angle displacement during finger motions.

For the third segment, it adopts rack-and-pinion structure to construct passive DOF. As shown in Figure 3.11, the rack is fixed on a button, which is constrained and can move vertically in the second segment. In case the button is pressed down by the surface of the object in grasping, it will actuate the pinion installed on the third segment of the finger,

which bends subsequently. The bending of the third segment can help the robot to hold the object much more firmly. There is also a spring mounted at the bottom of the button. When the external force disappears, the bottom will recover, and the third segment of the finger will go back to the initial status.

Figure 3.11 Sketch of Passive Structure

Figure 3.12 shows the real structure of a single finger. It is compact to be mounted in the palm. The testing shows that the maximum movement range of the first two joints is about 90 degrees. Under the imposing of exterior force, the fingertip can have a maximum bending angle of 75 degrees, which is quite close to that of a human being.

Figure 3.12 Structure of One Finger

3.3.4 Final Design and Prototype of Hand System

Figure 3.13 Detailed Mechanism of Left Hand

Figure 3.14 the Whole Mechanism of Left Hand

The above two figures show the final prototype of left hand. The four fingers as well as the motors are aligned in parallel, and the thumb module is laid above them. The whole hand is quite compact with dimensions of $165\text{mm} \times 100\text{mm} \times 40\text{mm}$ ($L \times W \times H$), and its weight is less than 3 kg excluding 6 force/torque sensors. This is quite similar to that of a human being. Since each hand has 6 independent degrees of freedom, in total 6 DC motors are required to actuate the whole hand.

3.4 Power Requirement

It is important to decide the parameters of the actuators, because the performance of motors determines the dexterity of the hand. As shown in Figure 3.15 [50], there are several types of postures in grasping. In cases a, b and c, the hand takes up the object by overcoming the gravity of the object, while in cases d and e, it is the friction between the hand and object balancing the object gravity. Obviously, the grasping force using fingertips is larger than that using palm. Thus, case d is regarded as the worst case and used for computation of the maximum grasping force.

Figure 3.15 Different Cases of Grasping [50]

Figure 3.16 shows the sketch of the largest force generated by the fingers. The force relationship between them is written as

$$G = M_L g = 2F_f \quad (3.3)$$

$$F_f = \mu F_p \quad (3.4)$$

where F_f is the friction between the fingers and the object; μ denotes the maximum static friction coefficient. Whereas the fingers will be coated with rubber to enhance the grasping capability, and the static friction coefficient between rubber and other rigid body is around 1.0~4.0, 1.0 is chosen for the value of μ as a worst scenario in the calculation. F_p denotes the normal press on the interface. M_L denotes the mass of the object, and it is desired up to 3kg.

Figure 3.16 Force Analysis of Hand Grasping

Then the normal torque of the finger is

$$T_f = \frac{M_L g}{2\mu} \times d = 0.441 N \cdot m \quad (3.5)$$

where T_f is the torque generated by the normal force and the arm of the force, and the value of d is 30mm. If we set the maximum angular velocity required (ω_f) to be $\frac{\pi}{2}$ rad/s, then the maximum power of the finger is

$$P_f = T_f \omega_f = 0.706 \times \frac{\pi}{2} = 1.11W \quad (3.6)$$

3.5 Actuator Selection

The analysis above provides the power requirement of the fingers. Actually, there would be power loss along the transmission structures since worm/worm wheel and sets of bevel gears are adopted in the finger structure. Table 3.2 shows the transmission chain of the thumb and other fingers.

Table 3.2 Transmission Chain of Thumb and Other Fingers

Parts	Transmission chain
Thumb	Planetary Reduction Gear + Bevel Gear (1:1)
Other Fingers	Planetary Reduction Gear + Worm/Worm wheel (20:1)

Usually, the efficiency (η) of worm/worm wheel with a one-tooth worm gear is about 0.7. Meanwhile safety factor should be adopted in consideration of the mounting and assembly friction. Assume that S is safety factor, and we adopt 1.2 as a rule of thumb, then the motor nominal power (P_n) is

$$P_n = \frac{S \cdot P_f}{\eta} = \frac{1.2 \times 1.1}{0.7} = 1.89W \quad (3.7)$$

Since the transmission ratios of bevel gears and worm/worm wheel are 1:1 and 20:1 respectively, two corresponding types of Maxon motor are chosen. Both are integrated with motor, gearbox and incremental encoder. The detailed parameters are shown in Table 3.3. Assume that the output torques of the thumb and fingers are T_{To} and T_{Fo} , we can get,

$$T_{To} = 0.45 * 1 = 0.45N \cdot m > 0.441N \cdot m$$

$$T_{Fo} = 2.45 \times 10^{-3} * 17 * 20 = 0.833N \cdot m > 0.441N \cdot m \quad (3.8)$$

Table 3.3 Actuator Selection for Humanoid Hand

Actuator Selection for Thumb			
Motor Code: RE-13-118637			
Assigned Power(W)	[W] 3.0	Nominal voltage (U_n)	[Volt] 12
Nominal speed (U_n)	[rpm] 10200	Nominal torque (M_N)	[mNm] 2.45
No load speed (n_o)	[rpm] 13100	Stall torque (M_H)	[mNm] 11.1
Gearhead Code: GP22C-110316			
Gear ratio	275:1	Max. Torque	0.45Nm
Incremental Encoder Code: 224702			
Counts per turn	16	No. of Channel	2
Actuator Selection for Other Fingers			
Motor Code: RE-13-118637			
Assigned Power(W)	[W] 3.0	Nominal voltage (U_n)	[Volt] 12
Nominal speed (U_n)	[rpm] 10200	Nominal torque (M_N)	[mNm] 2.45
No load speed (n_o)	[rpm] 13100	Stall torque (M_H)	[mNm] 11.1
Gearhead Code: GP22C-110314			
Gear ratio	17:1	Max. Torque	0.3Nm
Incremental Encoder Code: 224702			
Counts per turn	16	No. of Channel	2

3.6 Sensing System

There are two kinds of sensors mounted on the hand. The first is potentiometer, which is mounted on each independent joint. It is used to feedback the current position of the fingers. It is important in hand initialization and homing function.

The potentiometer is shown in Figure 3.17. The potentiometer is quite small and compact. Thus it is suitable to be mounted on fingers. Table 3.4 lists some parameters of the potentiometer. Since the movement range of the fingers are less than 90° , its rotational angle can cater to the requirement.

Table 3.4 Parameters of Potentiometer

Total Resistance (k ohm)	$10 \pm 30\%$	Linearity (%)	± 2
Dimensions (W×H×D)(mm)	11×12×2.1	Effective Rotational Angle	333.3°

Figure 3.17 Potentiometers and the Related PCB

The second one is the pressure sensor, which is used to detect the normal force between objects and fingers in grasping. It is deployed on the fingers and palm. The sensor is chosen from TekScan Company, since it is ultra-thin and the flexible printed circuit is easy for deployment. The sensor acts as a resistor in an electrical circuit. When the sensor is unloaded, its resistance is very high. If there is a force applied to the sensor, the resistance of the sensor decreases. The key parameters of the pressure sensor are listed in Table 3.5.

Figure 3.18 Pressure Sensor

Table 3.5 Specifications of Pressure Sensor

Thickness (mm)	0.2	Linearity Error (%)	± 3
Repeatability (%)	$\pm 2.5\%$	Response Time (ms)	< 5

3.7 Kinematics of Humanlike Hand

The kinematics of multi-finger hand mainly describes the motion of the fingertip and the relationship between the finger joints. In this section, we focus on expressing the position of each finger in the world coordinate system.

Firstly, the coordinate systems need to be assigned. A typical way is using D-H coordinate system [51], which is proposed by Denavit and Hartenberg in 1955. It uses a 4×4 homogeneous transformation matrix to describe the spatial relationship between two adjacent rigid mechanical links and could simplify the kinematics and dynamics problems. Thus, we adopt D-H method to configure the coordinate frames of the human-like hand which will bring convenience in further research. According to the hand DOF configuration, the coordination systems of the hand joints are defined as shown in Figure 3.19, the coordinate system of the thumb and the little finger joints are marked since the four fingers (not including thumb) have similar configuration. In the coordinate system definition, $\sum_w$ is the world coordinate system and attached on the palm of the hand, while $\sum_{Ti}$ and $\sum_{Li}$ denotes the local coordinate system of the thumb, and little finger respectively (for thumb $i \in (0,1,2)$, and little finger $i \in (0,1,2,3)$). $\sum_{T0}$ and $\sum_{L0}$ are the base coordinate systems of thumb and little finger.

After that, we can describe the thumb tip in the base coordinate system of the thumb. The D-H parameters are derived from the coordinate systems and hand dimensions as shown below.

Figure 3.19 Kinematics Model of Human-like Hand

Table 3.6 D-H Parameters of Thumb

Link	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	0	90°	$-l_{T1}$	θ_2
3	l_{T2}	0	0	0

where θ_1 and θ_2 denotes the joint angles of the thumb. The posture of thumb fingertip can be written as

$$\begin{aligned}
 {}^0T_3 &= {}^0T_1 {}^1T_2 {}^2T_3 \\
 &= \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ 0 & 0 & -1 & l_{T1} \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & l_{T2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
 &= \begin{bmatrix} c\theta_1 c\theta_2 & -s\theta_1 s\theta_2 & s\theta_1 & c\theta_1 c\theta_2 l_{T2} - s\theta_1 l_{T1} \\ s\theta_1 c\theta_2 & -s\theta_1 s\theta_2 & c\theta_1 & s\theta_1 c\theta_2 l_{T2} + c\theta_1 l_{T1} \\ s\theta_2 & c\theta_2 & 0 & s\theta_2 l_{T2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.9)
 \end{aligned}$$

To simplify the equations, $\cos\theta$ and $\sin\theta$ are denoted as $c\theta$ and $s\theta$ respectively. The transform matrix (wT_3) between the base coordinate system of the thumb ($\sum_{T0}$) and the hand coordinate system ($\sum_w$) can be derived from the configuration of the hand,

$${}^wT_3 = {}^wT_0 {}^0T_3 \quad (3.10)$$

Similarly, the D-H parameters of the little finger can be derived and listed in Table 3.7.

Table 3.7 Kinematics Configuration of Little Finger

Link	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	l_{L1}	0	0	θ_2
3	l_{L2}	0	0	θ_3
4	l_{L3}	0	0	0

where θ_1 , θ_2 and θ_3 denote the joint angles of the little finger. The posture of the little finger tip can be described in the base joint coordinate system as

$$\begin{aligned}
 {}^0_4T_L &= {}^0_1T_L {}^1_2T_L {}^2_3T_L {}^3_4T_L \\
 &= \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & l_{L1} \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & l_{L2} \\ s\theta_3 & c\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & l_{L3} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
 &= \begin{bmatrix} c(\theta_1 + \theta_2 + \theta_3) & -s(\theta_1 + \theta_2 + \theta_3) & 0 & c\theta_1 l_{L1} + c(\theta_1 + \theta_2) l_{L2} + c(\theta_1 + \theta_2 + \theta_3) l_{L3} \\ s(\theta_1 + \theta_2 + \theta_3) & c(\theta_1 + \theta_2 + \theta_3) & 0 & s\theta_1 l_{L1} + s(\theta_1 + \theta_2) l_{L2} + s(\theta_1 + \theta_2 + \theta_3) l_{L3} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.11)
 \end{aligned}$$

From the previous introduction, we know that θ_2 corresponds the angle of the coupled joint, and it is equal to the angle of the active joint. Thus

$$\theta_1 = \theta_2 \quad (3.12)$$

What is more, there are two cases in grasping. If the object is small, for example, there is a stick, then the finger tip will be used in grasping and passive joints are inactivated, and then

$$\theta_3 = 0 \quad (3.13)$$

Then Equation 3.11 can be written as

$${}^0_4T_L = \begin{bmatrix} c(2\theta_1) & -s(2\theta_1) & 0 & c\theta_1 l_{L1} + c(2\theta_1)(l_{L2} + l_{L3}) \\ s(2\theta_1) & c(2\theta_1) & 0 & s\theta_1 l_{L1} + s(2\theta_1)(l_{L2} + l_{L3}) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.14)$$

If the object is big enough and the passive finger is needed to enhance the grasping, then the second segment will firstly touch the object, meanwhile the third segment will bend owing to the force imposed on the button, and now Equation 3.11 changes

$${}^0_4T_L = \begin{bmatrix} c(2\theta_1 + \theta_3) & -s(2\theta_1 + \theta_3) & 0 & c\theta_1 l_{L1} + c(2\theta_1)l_{L2} + c(2\theta_1 + \theta_3)l_{L3} \\ s(2\theta_1 + \theta_3) & c(2\theta_1 + \theta_3) & 0 & s\theta_1 l_{L1} + s(2\theta_1)l_{L2} + s(2\theta_1 + \theta_3)l_{L3} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.15)$$

Just like the thumb, the fingertip posture of the little finger in world coordinate system ($\sum_w$) can be derived since the transform matrix form (w_0T_L) can be fixed from the hand configuration, and we get

$${}^w_4T_L = {}^w_0T_L {}^0_4T_L \quad (3.16)$$

3.8 Implementation of Human-like hand

The figures below show the implementation for the human-like hand. It can perform different kinds of tasks such as power grasping and holding. In Figure 3.20, the robot uses its four fingers to hold a plastic stick, while the thumb plays a supplementary role in this case. If the target is much more complex as shown in Figure 3.21, the thumb, index and medius should cooperate to grasp the plastic bottle, and the other two fingers help to grasp the object more firmly.

Figure 3.20 Holding a Plastic Stick

Figure 3.21 Grasping a Plastic Bottle

Chapter 4 Design of Human-like Arm

4.1 Requirements

The requirements of the human-like arm system can be divided into two aspects: appearance and function. Appearance is important for the end-users or operators, because nice appearance will make the humanoid robot friendlier and will be regarded as a partner instead of a machine with stiff outline. The second is the ability to perform some tasks. Since the manipulator aims at assisting people in activities of daily living, a human-like arm system must be capable of performing basic tasks. Usually, with more DOFs, it can achieve more complex motions. However, the weight limitation should also be considered, because a robot with heavy manipulators is dangerous to both person and the robot itself if emergence occurs. In addition, lightweight also means energy-saving, especially for the robot to carry the batteries itself. It can enable the robot to survive much longer if it has a light weight.

When the robot is performing a task, it is important to know the position of its arm-hands as well as the forces imposed on the joints. Thus, force and position sensors are required to give sensory feedback to the robot.

4.2 Specification

4.2.1 Dimensions and DOF Distribution

To make a more human-like appearance, the lengths of the humanoid arm are decided. However, the mass distribution of the human-like arm system has to be adjusted for mounting actuators and sensors. Table 4.1 presents comparison of the dimensions between a human being and a robot as well as the mass distribution.

Table 4.1 Dimensions of Human-like Arm

	Mass (kg)		Length (mm)
	Human being	Robot	
Forearm	1.4	2.5	280
Upper Arm	2.4	3	320
Whole Body	80	75~85	1.75

With full consideration of dexterity, space and weight, a 6-DOF arm is determined. Though a human being has a 7-DOF arm as shown in Figure 2.2, we reduce one DOF on the wrist to make it more compact on the end. As shown in Figure 4.1, each arm is assigned shoulder, elbow and wrist joints and each joint has 2 DOFs. This configuration enables the robot to have similar kinematics as a human being and perform majority of tasks in the ordinary life.

Figure 4.1 DOFs Distribution of Human-like Arm

4.2.2 Movement Range

For movement range of each joint, we designed it to be as close as or even wider than that of a standard human so that the humanoid robot is competent of tasks that a human being could do. Table 4.2 shows the data of movable ranges of the upper arm and forearm with comparison with those of a standard human.

Table 4.2 Joint Movement Range of Human Being and Robot

	Joints	Human being	Robot
1	Shoulder Roll	-45 deg. to 90 deg.	-180 deg. to 180 deg.
2	Shoulder Pitch	- 90 deg. to 30 deg.	- 120 deg. to 10 deg.
3	Elbow Roll	-30 deg. to 80 deg.	-180 deg. to 180 deg.
4	Elbow Pitch	-140 deg. to 10 deg.	-135 deg. to 0 deg
5	Wrist Roll	-90 deg. to 90 deg.	-180 deg. to 180 deg.
6	Wrist Pitch	- 70 deg. to 90 deg.	- 30 deg. to 90 deg.

As shown above, some joints' movable ranges, such as that of shoulder roll and wrist roll, are extended, because these roll movement joints can easily attain a wider range than a human being. However, ranges of elbow pitch and wrist pitch are slightly reduced due to the constraint of structures and safety reasons

4.2.3 Appearance Design

The appearance of the robot's upper limb is restricted by three constraints. The first is having the similar profile of that of a human being. The second is the consideration of the DOFs distribution and installment of actuators. The last is the human-like arm module should be adequate to its application and some emergency cases. The final exterior of arm and hand is shown in Figure 4.2.

Figure 4.2 Appearance of Human-like Arm

In the configuration above, the shoulder roll and pitch motions can easily attain a relative large range. The movement range of the elbow joint is limited and hard to attain that of a human being due to structural constraints. The mechanism of elbow roll joint is allocated along the upper arm, which is convenient for deployment of actuator and transmission structures. Further more, the axes of the first three joints intersect at one point, which would bring convenience for the computing of inverse kinematics. The wrist joint has two DOFs, and the wrist roll joint is allocated along the forearm the same as elbow roll joint. This will help to reduce the distal weight of the arm.

4.3 Mechanism

4.3.1 Power Train of Human-like Arm System

The power train of the human-like arm system is simpler than that of the hand. It has 6 independent joints, and each one has an independent set of transmission system. The detailed configurations are shown in Table 4.3.

Table 4.3 Power Train of Human-like Arm Joints

Joint	Movement	Reduction Gear
Shoulder	Roll	DC motor + Planetary Gear + Harmonic Gear
	Pitch	DC motor + Planetary Gear + Harmonic Gear
Elbow	Roll	DC motor + Planetary Gear + Harmonic Gear
	Pitch	DC motor + Planetary Gear + Timing Pulley & Belt + Harmonic Gear
Wrist	Roll	DC motor + Planetary Gear + Harmonic Gear
	Pitch	DC motor + Planetary Gear + Timing Pulley & Belt + Harmonic Gear

Typically, the power system of an arm joint is consisted of actuator and transmission components. DC motor is adopted for the joint actuator since it has high power/weight ratio as compared with hydraulic and other actuators. What is more, DC motor is easy for servo control and has low mechanical time constant.

There are totally two kinds of gear transmission components adopted in arm joints. The first type is the planetary gear system, which is simple and common among the reduction gears systems. It consists of one or more outer gears, revolving about a sun gear. The advantages are high power density, large reduction and compact volume. However, the planetary reduction gear system has backlash on the output shaft. Thus, we only use this reduction system at the first stage or in small error/backlash allowable joints such as finger joints. The second type is the harmonic gear (Figure 4.3). It provides unique advantages such as high reduction ratio with single stage, high torque capability and coaxial input and output shafts, and especially its zero backlash on its output side. It is widely used on the robot joints. In the human-like arm design, it is adopted as the final reduction to support high-accuracy transmission.

Figure 4.3 Harmonic Gear

In our design, the planetary gear and harmonic gear are chosen under given design conditions (e.g. space, shape, permissible power weight and so on). Meanwhile, timing pulley and timing belt are adopted in elbow pitch and wrist pitch joint, because they are used to change the transmission direction and mounting purposes.

4.3.2 Structure Design of Human-like Arm Joints

After the decision of the power train and transmission system, the detailed structure can be designed to realize the function of each joint.

Figure 4.4 Different Work Modes of Harmonic Gear

Harmonic gear is used widely as the final transmission component in all the arm joints. It consists of three components: circular spline (CS), flexspline (FS) and wave generator (WG), and it can work with several modes. In order to simplify the design of the joint structure, the principles of which are grouped based on the work modes of the harmonic gear. There are totally two kinds of structures utilized on the arm joints namely: counter-rotating structure and co-rotating structure. The first type is counter-rotating structure as shown in Figure 4.5. In this structure, the CS is fixed and FS is connected with output shaft, while the shaft of the motor and WG are coupled or connected with timing pulley and belt and work as the input. In this structure, the direction of the output rotation is opposite with that of the input.

Figure 4.5 Principle of Counter-rotating Structure

Figure 4.6 Detailed Structure of Elbow Pitch Joint

The counter-rotating structure is adopted in the shoulder roll, elbow pitch and wrist pitch joints. Figure 4.6 shows the detailed design of the elbow pitch joint. The motor is fixed on

the lateral board A, and its output shaft is connected with the WG of harmonic gear through a set of timing pulley/belt. After the transmission of the harmonic gear, the output speed slows down and the output torque enlarges. There is also a set of absolute encoder mounted on the shaft to detect the real-time position of the joints. This structure is compact-sized and easy for deployment.

Figure 4.7 Principle of Co-rotating Structure

Figure 4.8 Detailed Structure of Wrist Roll Joint

The second one is the co-rotating structure. In this structure, the output shaft rotates in same direction as the input shaft. As shown in Figure 4.4, the roles of CS and FS are exchanged as compared with the previous one. This structure is applied in wrist roll, elbow roll and shoulder pitch joints. Figure 4.8 presents the detailed structure of wrist roll joint: the output shaft of the motor is connected with the wave generator of the harmonic gear, while FS and CS are fixed with the outer frame and inner shell separately. Two angular contact bearings are connected with the inner sleeve and outer frame respectively. When the power of the motor is on, the inner shell, which works as the output of the structure, will rotate in a reduced speed. The outstanding advantage of this structure is that it can afford large spatial forces, which is useful since the arm works in an unknown environment.

4.3.3 Final Design and Prototype of Human-like Arm System

After the full design and fabrication of the individual arm joints, the whole arm module as well as the human-like hand is assembled. All the joints are tested and work in good condition. Figure 4.9 shows the final prototype of the human-like arm. The length from shoulder to wrist joint is 576 mm, and its weight is about 8 kg.

Figure 4.9 Prototype of Human-like Arm

4.4 Power Requirements

When the robot is performing object grasping, maximum torque exists at the moment that the arm extends horizontally. Assuming that the payload on the hand is 3kg, we mark the masses of upper arm, forearm, hand, and payload as M_u , M_f , M_h and M_p respectively. Based on the parameters listed in Table 4.1, the required parameters for the actuators can be derived.

Figure 4.10 Force Analysis of Human-like Arm

When the arm is fully extended horizontally, the torque of the wrist pitch joint (T_{WP}) can be expressed as

$$T_{WP} = mgl = (M_p + M_h)g \cdot \frac{L_{hand}}{2} = 3.76N \cdot m \quad (4.1)$$

where l denotes the moment arm and L_{hand} is the length of the hand.

Similar analysis can be made for elbow pitch joint

$$T_{EP} = mgl = 11.76N \cdot m \quad (4.2)$$

And for shoulder roll joint

$$T_{SR} = mgl = 34.80N \cdot m \quad (4.3)$$

In order to acquire the speed of the upper limb, we take human beings' performance as a reference. Figure 4.11 shows an experiment diagram of angular velocity of upper arm. The measurement is based on some ordinary tasks such as drinking, splashing water on face, combing hair and so on.

Figure 4.11 Angular Velocity of Upper Arm [52]

From the diagram above, we can see that the maximum angular velocity is about $1.2 \sim 1.5 \text{ rad/s}$. We assign the angular velocities of shoulder roll (ω_{SR}), shoulder pitch (ω_{SP}), elbow roll (ω_{ER}) and elbow pitch (ω_{EP}) to be $\frac{\pi}{3} \text{ rad/s}$, while wrist roll (ω_{WR}) and wrist pitch (ω_{WP}) are equal to $\frac{\pi}{2} \text{ rad/s}$.

$$\omega_{SP} = \omega_{SR} = \omega_{ER} = \omega_{EP} = \frac{\pi}{3} \quad (4.4)$$

$$\omega_{WP} = \omega_{WR} = \frac{\pi}{2} \quad (4.5)$$

And then the powers needed are

$$P_{SR} = T_{SR} \omega_{SR} = 36.42W$$

$$P_{EP} = T_{EP} \omega_{EP} = 12.32W$$

$$P_{WP} = T_{WP} \omega_{WP} = 5.90W \quad (4.6)$$

where P_{SR} means power required in shoulder roll, P_{EP} is power in elbow pitch joint and P_{WP} denotes power in wrist pitch joint.

Figure 4.12 Maximum Torque of Wrist Roll VS. Wrist Pitch

Figure 4.13 Maximum Torque of Elbow Pitch VS. Elbow Roll

Figure 4.14 Maximum Torque of Shoulder Roll VS. Shoulder Pitch

The figures above show three cases to compare the different joints while bearing the same load. In Figure 4.12, if the wrist rotates along the roll axis with the hand bending 90 degrees (left figure), then the wrist roll joint needs to overcome the almost the same maximum torque as the wrist pitch with the wrist extended horizontally (right figure), or

$$T_{WR} \approx T_{WP} = 3.76N \cdot m \quad (4.7)$$

In the same way, we can get from Figures 4.13 and 4.14 that

$$\begin{aligned} T_{ER} &\approx T_{EP} = 11.76N \cdot m \\ T_{SP} &\approx T_{SR} = 34.80N \cdot m \end{aligned} \quad (4.8)$$

Hence, from Equations 4.5 to 4.8, we can get

$$\begin{aligned} P_{WR} &= T_{WR} \omega_{WR} = 5.90W \\ P_{ER} &= T_{ER} \omega_{ER} = 12.32W \\ P_{SP} &= T_{SP} \omega_{SP} = 36.42W \end{aligned} \quad (4.9)$$

4.5 Actuators Selection

The above analysis determines the torque and power requirements of the arm joints. However, power loss will exist along the transmission chain. According to the product catalogs, the transmission efficiencies (η) of planetary gear, timing pulley/ belt and harmonic gear can be derived and they are 0.9, 0.95 and 0.8 respectively. Taking elbow pitch joint as an example, its power train contains motor, planetary, timing pulley/belt and harmonic gear. As shown in Figure 4.15, T_{EP} and W_{EP} are the assigned torque and power

for the output shaft of elbow pitch joint, while T_{EP}^i and W_{EP}^i are the corresponding torques and power required for each transmission components.

Figure 4.15 Power Analysis of Elbow Pitch Joint

Firstly, the reduction ratios of each component are determined according to the output velocity requirement and the product catalog available. The power analysis of all the transmission components is listed in Table 4.4.

Table 4.4 Power Requirements for Elbow Pitch Joint

	Torque Output (N.m)	Power Output (W)	Reduction Ratio	Transmission Efficiency (η)	Torque Input (N.m)	Power Input (W)
Harmonic Gear	11.76	12.32	100:1	0.8	0.147	15.40
Timing Pulley/Belt	0.147	15.40	1.5:1	0.95	0.103	16.21
Planetary	0.103	16.21	4.4:1	0.9	0.026	18.01

Based on Table 4.4, the brushed DC motor, timing pulley/belt and harmonic gear are chosen. The detailed specifications are listed in Table 4.5.

Table 4.5 Actuator Selection for Elbow Pitch Joint

Motor Code: RE-max 29-226815			
Assigned Power (W)	22 [W]	Nominal voltage (U_n)	48 [Volt]
Nominal speed (U_n)	5050 [rpm]	Nominal torque (M_N)	29.9 [mNm]
No load speed (n_o)	6100 [rpm]	Stall torque (M_H)	182 [mNm]
Planetary Gearhead Code: GP26B-144027			
Gear ratio	4.4:1	Max. Torque	0.8 [Nm]
Timing Pulley/ Belt			
Pitch	3 [mm]	Maximum power transferred	200 [W]
Harmonic Gear			
Model No.	CSF-14-100	Reduction Ratio	100:1
Limit for Average Torque	11 [Nm]	Limit for Repeated Peak Torque	28 [Nm]

Similarly, the transmission structure of the rest joints can be figured out. The motors and harmonic gears are grouped with three kinds, and the detailed parameters of the DC motors for arm joints are listed in Table 4.6.

Table 4.6 Actuator and Transmissions Selection for Human-like Arm Module

a). Actuator Selection and Transmissions for Shoulder Roll and Pitch

Motor Code: RE 30-310009			
Assigned Power (W)	60 [W]	Nominal voltage (U_n)	48 [Volt]
Nominal speed (U_n)	7750 [rpm]	Nominal torque (M_N)	88.2 [mNm]
No load speed (n_o)	8490 [rpm]	Stall torque (M_H)	1020 [mNm]
Planetary Gearhead Code: GP32C-166930			
Gear ratio	3.7:1	Max. Torque	1.25 [Nm]
Harmonic Gear			
Model No.	HUFD-20-160	Reduction Ratio	100:1
Limit for Average Torque	35 [Nm]	Limit for Repeated Peak Torque	50 [Nm]

b). Actuator Selection and Transmissions for Elbow Roll and Pitch

Motor Code: RE-max 29-226815			
Assigned Power (W)	22 [W]	Nominal voltage (U_n)	48 [Volt]
Nominal speed (U_n)	5050 [rpm]	Nominal torque (M_N)	29.9 [mNm]
No load speed (n_o)	6100 [rpm]	Stall torque (M_H)	182 [mNm]
Planetary Gearhead Code: GP26B-144027			
Gear ratio	4.4:1	Max. Torque	0.8 [Nm]
Timing Pulley/ Belt (Elbow Pitch Only)			
Pitch	3 [mm]	Maximum power transferred	200 [W]
Harmonic Gear			
Model No.	CSF-14-100	Reduction Ratio	100:1
Limit for Average Torque	11 [Nm]	Limit for Repeated Peak Torque	28 [Nm]

c). Actuator Selection and Transmissions for Wrist Roll and Pitch

Maxon Motor RE-max 24-222058			
Assigned Power (W)	11 [W]	Nominal voltage (U_n)	48 [Volt]
Nominal speed (U_n)	3470 [rpm]	Nominal torque (M_N)	12 [mNm]
No load speed (n_o)	5250 [rpm]	Stall torque (M_H)	35.7 [mNm]
Planetary Gearhead Code: GP22C-143972			
Gear ratio	4.4:1	Max. Torque	0.8 [Nm]
Timing Pulley/ Belt (Wrist Pitch Only)			
Pitch	2 [mm]	Maximum power transferred	100 [W]
Harmonic Gear			
Model No.	HUDEF-14-110	Reduction Ratio	110:1
Limit for Average Torque	6.0 [Nm]	Limit for Repeated Peak Torque	12 [Nm]

4.6 Sensing System

According to the functions required, the sensors mounted on the robotic arm can be divided into two categories: internal state and external state sensors. Internal state sensors deal with the information of the arm itself, such as arm joints position and velocity, which are useful for the initialization and feedback control of the joints. Meanwhile, the external state sensors detect the environment information.

For each joint of the arm, incremental encoder and absolute encoder are adopted in order to detect the position and velocity. The incremental encoder is mounted at the rear side of each motor. The key parameter is counts per turn. Table 4.7 lists the performance of different joints. The absolute encoder in usage, as shown in Figure 4.16 consists of three components: the LED, code wheel and the encoder readhead. It can provide 11 digital tracks plus 2 sin/cosine tracks generating precise 16 Gray codes. However, extra components must be used to fix and mount the encoder, and it should be of high precision.

Table 4.7 Incremental Encoder Parameters of Humanoid Arm Joint

Joint	Counts per turn
Shoulder Roll and Pitch	256
Elbow Roll and Pitch	128
Wrist Roll and Pitch	32

Figure 4.16 Absolute Encoder and the Assembly

For the external state sensors, force/torque sensors are utilized to provide force and torques data in grasping, and other tasks. Figure 4.17 shows one kind of force/torque sensors from ATI industrial Automation. It can measure the full six components of force

and torque $(F_x, F_y, F_z, T_x, T_y, T_z)$, and several advantages such as high overload protection, high signal-to-noise ratio and high-speed output make it suitable for the applications.

Figure 4.17 Force/Torque Sensors

4.7 Kinematics of Human-like Arm

The human-like arm system can be modeled as a movable chain of links interconnected by several joints. One end of the arm is attached to the base, for example the trunk of a humanoid robot, and a hand as an end-effector that can move freely in space is attached at the other end. The relative movement of the joints results in the motion of the links and the hand in a desired orientation. For the human-like hand-arm system, research is focused on the spatial description of the hand (as a whole) of the manipulator with respect to a fixed reference coordinate system.

Kinematics is concerned with the mathematical relationship between the joint variables of the robot arm and its end-effector pose matrix. Without consideration of the forces/moments that caused in motions, it deals with the analytical description of the

spatial displacement of the robot arm as a function of time, in particular the relations between the joint-variable space and the position and orientation of the end-effector of a robot arm. Kinematics mainly deals with two fundamental questions of both theoretical and practical interest in robot arm kinematics. Firstly, if the joint angle vector of a human-like arm is given, how to obtain the posture of the end-effector? On the contrary, if an objective posture and orientation is given, how to get the joint angles of the human-like arm?

The first question is usually referred to the forward kinematics problem, while the second question is the inverse kinematics problem. Whereas the joint variables are the independent variables in a robot arm and a task is usually stated in terms of the reference coordinate frame, the inverse kinematics problem is used more frequently. A simple block diagram indicating the relationship between these two problems is shown in Figure 4.18.

Figure 4.18 Forward and Inverse Kinematics Problems

Generally, forward kinematics can find pose of the end-effector (hand), and that is easy for serial manipulator. Inverse kinematic is much more complex, but there are still several approaches to deal with it.

4.7.1 Model Building

The human-like arm is a sequence of links articulated at joints. In order to mathematically represent the arm, a reference frame is normally attached to each relevant part of the arm, and each link of the robot arm is assigned a reference for the purpose of tracking the location of the link and modeling the whole robot arm. Similarly as the human-like hand, the coordinate frames are configured through D-H method as shown in Figure 4.19.

Figure 4.19 Coordinate Systems Definition of Humanoid Arm

The world coordinate system is marked as Σ_w , its Z axis points at front, Y axis points to the left side, and X axis is upward. All other local coordinate systems and object position are based on it.

The kinematics parameters of the human-like arm are then determined. Table 4.8 shows the detailed parameters of the linkages and joints. There are totally 4 parameters namely a_{j-1} , α_{j-1} , d_j and θ_j , where a_{j-1} is the length of the $(j-1)^{th}$ linkage, α_{j-1} denote the intersection angle between the linkages $j-1$ and j , which is usually measured from linkage $j-1$ to j , d_j is the displacement of linkages $j-1$ and j along the j^{th} joint axis, and θ_j denotes the rotational angle between linkages $j-1$ and j .

Table 4.8 Kinematics Parameters of the Human-like Arm

Linkage j	a_{j-1}	α_{j-1}	d_j	θ_j
1	0	0°	0	θ_1
2	0	-90°	0	θ_2
3	0	-90°	$-l_u$	θ_3
4	0	-90°	0	θ_4
5	0	-90°	$-l_f$	θ_5
6	0	-90°	0	θ_6
7	0	0°	0	θ_7
8	0	-90°	0	θ_8
9	0	-90°	$-l_u$	θ_9
10	0	-90°	0	θ_{10}
11	0	-90°	$-l_f$	θ_{11}
12	0	-90°	0	θ_{12}

Where l_u denotes the length of upper arm, l_f denotes the length of forearm and θ_j ($j=1\sim12$) corresponds the angles of the joints as defined in Figure 4.19.

4.7.2 The Forward Kinematics

The forward kinematics problem focuses on finding a transformation matrix that relates the body-attached coordinate frame to the reference coordinate frame. It usually is used on calculating center of gravity, environment confliction detection and so on. A 3 x 3 rotation matrix is used to describe the rotational operations of the body-attached frame with respect to the reference frame. The homogeneous coordinates are then used to represent position vectors in a three-dimensional space, and the rotation matrices will be expanded to 4 x 4 homogeneous transformation matrices to include the translational operations of the body-attached coordinate frames.

According to the kinematics model in Figure 4.19 and the parameters in Table 4.8, the transformation matrix between the $(j-1)^{th}$ and j^{th} local coordinate systems can be expressed as

$${}^{j-1}_jT = \begin{bmatrix} \cos \theta_j & -\sin \theta_j & 0 & a_{j-1} \\ \sin \theta_j \cos \alpha_{j-1} & \cos \theta_j \cos \alpha_{j-1} & -\sin \alpha_{j-1} & -d_j \sin \alpha_{j-1} \\ \sin \theta_j \sin \alpha_{j-1} & \cos \theta_j \sin \alpha_{j-1} & \cos \alpha_{j-1} & d_j \cos \alpha_{j-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.10)$$

By multiplying the transformation matrix ${}^{j-1}_jT$ (for left arm $i=1,2,\dots,6$) of each linkage, the transform matrix of the end-effector (hand) (0_6T) can be derived

$${}^0T_6 = {}^0T_1 {}^1T_2 {}^2T_3 {}^3T_4 {}^4T_5 {}^5T_6 \quad (4.11)$$

Since only θ_j is the unknown parameter for ${}^{j-1}T_j$ in Equation 4.10, the position and posture of the hand can be derived with a given joint angular vector of the human-like arm. Figure 4.20 shows a serial result of forward kinematics by giving a group of joint angular vectors; obviously, the manipulator can reach a lot of desired posture and positions.

Figure 4.20 Illustrations of Different Postures of the Human-like Arm

4.7.3 The Inverse Kinematics Problem

Inverse kinematics is involved in many cases such as interactive manipulation, grasping, collision avoidance and so on. Generally, the complexity of the inverse kinematics problem depends heavily on the structure of the manipulator, and the geometric arrangement of the joint axes greatly affects the complexity of the inverse kinematics. For a general structure manipulator, the inverse kinematics problem can be solved by various

methods, such as analytical [4], inverse transform [53], iterative [54] and geometric approaches [55].

If a manipulator structure is simple enough to be solved directly by algebraic method to produce an inverse kinematics solution, it is said to be solvable in closed-form. Pieper [56] figured out that any 6-DOF manipulator with three consecutive axes that are either parallel or intersecting has kinematics equations that can be expressed in closed-form.

As to the configuration of this human-like arm, the three axes of the shoulder roll, shoulder pitch and elbow roll joints intersect at a point. Hence, the closed-form solution can be obtained. Thus, the analytical method can get the solutions for any positions and postures within the task space of a six-DOF manipulator. However, several sets of solutions will be derived by this approach, and this may lead to discontinuous motions. Finally, an iterative method is adopted. Though there is disadvantage of singular problem for iterative method, improved method can be adopted to solve this problem.

Iterative Method

Iterative method is widely used in inverse kinematics problem since it has several advantages. For example, the iterative method will always find the optimized solution if there are various solutions. Figure 4.21 shows the principle of the iterative method.

Figure 4.21 Principle of Iterative Method

The algorithm consists of several steps. After the desired position P^{ref} (3×1) and posture R^{ref} (3×1) are given, the current position and posture are then computed and compared with the desired ones. The difference between them can be derived. In next step, a transform function is used to get the modified joint angle Δq (6×1) from the pose error ΔP (3×1) and ΔR (3×3). When judgment conditions are satisfied, the joint angles will become the output, otherwise the current pose will be updated through forward kinematics and the loop will repeat.

There are two key problems in the algorithm. Firstly, what are the stopping conditions? The other one is how to get the joint angles from the position and posture. The first problem is easy to be solved. The status that the error of the position and posture equals 0 can be expressed as:

$$\begin{aligned}\Delta P &= 0 \\ \Delta R &= I\end{aligned}\tag{4.12}$$

where I denotes the identity matrix.

In this case, the value of Δq will be 0. Obviously, it is an ideal situation. In practice,

an expression is adopted based on Δq itself

$$\|\Delta q\| < \varepsilon \quad (4.13)$$

If ε is smaller than 1×10^{-6} , then the objective angles are achieved.

For the second problem, the key point is to get the adjusted angle Δq to reduce the error. One method is that: a random joint angle vector is selected. If the error is reduced with the new angle vector, even though it is small, we can use this new angle vector as the current one and repeat until the error is small enough. Then the manipulator will approximate the object step by step. However, there is a widely-used approach which adopts Jacobian matrix to map between the task space variation and joint angle vector. The expression can be written as:

$$\begin{aligned} \Delta D &= J \cdot \Delta q \\ \Delta D &= \begin{bmatrix} \Delta P \\ \Delta \omega \end{bmatrix} \end{aligned} \quad (4.14)$$

where ΔD is the differential motion vector. This 6×1 Cartesian vector is the 3×1 differential translational vector and the 3×1 differential rotational vector stacked together. J (6×6) is the Jacobian matrix under the current pose. ΔP can be easily obtained by calculating the error between the desired position P^{ref} and the current position $P^{current}$ (3×1). For the differential rotational vector, $\Delta \omega$ (3×1) is derived from the orientation error (ΔR) between the desired orientation R^{ref} (3×3) and the current orientation $R^{current}$ (3×3). The expressions can be written as:

$$\Delta P = P^{ref} - P^{current}$$

$$\Delta R = (R^{current})^{-1} R^{ref} \quad (4.15)$$

Assuming that ΔR can be expressed as

$$\Delta R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \quad (4.16)$$

Then we can get $\Delta\omega$ from the expression of ΔR . The computational procedures are available in several robotic books [4, 49]. The result can be written as

$$\theta = \arccos\left(\frac{R_{11} + R_{22} + R_{33} - 1}{2}\right)$$

$$\Delta\omega = [0 \quad 0 \quad 0]^T \quad (\text{if } \Delta R = I)$$

$$\Delta\omega = \frac{\theta}{2 \sin \theta} \begin{bmatrix} R_{32} - R_{23} \\ R_{13} - R_{31} \\ R_{21} - R_{12} \end{bmatrix} \quad (\text{if } \Delta R \neq I) \quad (4.17)$$

where I is the identity matrix.

There are two main methods for obtaining the Jacobian matrix (J), namely the vector product method and the differential transformation method [50]. The latter method is adopted. Since it is a 6-DOF manipulator, the matrix has 6×6 elements, and the Jacobian matrix can be calculated as:

$$J = \begin{bmatrix} {}^w a_1 \times (p_6 - p_1) & {}^w a_2 \times (p_6 - p_2) & \cdots & {}^w a_6 \times (p_6 - p_6) \\ {}^w a_1 & {}^w a_2 & \cdots & {}^w a_6 \end{bmatrix} \quad (4.18)$$

Where ${}^w a_i (i = 1 \sim 6)$ denotes the unit rotational vector of the i^{th} joint expressed in the world coordinate system. While $p_i (i = 1 \sim 6)$ is the position vector of the i^{th} joint expressed in the world coordinate system. They are both 3×1 vectors.

Once the elements of J are decided, the adjusted angle vector can be derived from the equation by using the inverse of the Jacobian matrix.

$$\Delta q = J^{-1} \Delta D \quad (4.19)$$

And then, the modified joint angles are obtained. If the result is good enough, the output can be obtained.

Singularity Problem

In most cases, the iterative method can lead to the solution with minimum norm of Δq and result in smooth trajectory in manipulation. However, when the human-like arm is in some poses where its end-effector loses one or more degrees of mobility, the Jacobian matrix J becomes singular. In this situation, the figures in J are no longer valid. Figure 4.22 illustrates two singular cases theoretically. In both cases, the origins of shoulder, elbow and wrist joints are collinear. However, due to the physical limitation, only case (a) would happen in practice.

Figure 4.22 Singular Positions

In a practical process, we know that the singularity also exists when the sharp angle between the upper arm and forearm is small. The Jacobian matrix is then ill-conditioned or even singular. In some applications, the singular posture is avoided by changing the initial posture; for example, a biped robot bends its knees before walking. However, this is not an advisable choice for an arm, because this will narrow the work space of the manipulator. To solve this problem, an effective method named damped-least squares (DLS) is introduced. It is a local optimization method and can prevent infeasible joint velocities near singular posture [57]. Firstly, a singular value decomposition of the Jacobian matrix (J) and its inverse (J^{-1}) can be expressed as

$$J = UDV^T = \sum_{i=1}^6 \sigma_i u_i v_i^T$$

$$J^{-1} = \sum_{i=1}^6 \sigma_i^{-1} v_i u_i^T \quad (4.20)$$

Where U and V are orthogonal matrices. u_i and v_i are the columns of U and V respectively. D denotes a 6×6 diagonal matrix and σ_i is the diagonal elements. In singular posture, some values of σ_i may equal or approach 0, and J^{-1} is not available. In the DLS method, J^{-1} is replaced and Equation 4.19 is changed to

$$\Delta q = J^T (JJ^T + \lambda^2 I)^{-1} \Delta D \quad (4.21)$$

Where λ is a non-zero coefficient, and similarly, the DLS “inverse” can be expressed as

$$J^T (JJ^T + \lambda^2 I)^{-1} = \sum_{i=1}^6 \frac{\sigma_i}{\sigma_i^2 + \lambda^2} v_i u_i^T \quad (4.22)$$

Since the movement range and the length of the arm joints are limited, there would be some cases that the desired position and posture cannot reach simultaneously. There are mainly two different cases: The first is that the norm of desired position (P^{ref}) is larger than the sum of upper arm length (l_u) and forearm length (l_f). In this case, the manipulator cannot perform the desired task with the shoulder joint as the base point. One way to solve this problem is changing the base point. For example, if there is also a waist joint, the manipulator can use the waist joint to extend the movement scope. The other way is to move the whole manipulator to make the out-of-range postures reachable. For example, a biped robot with the manipulator can step towards the object first until it is

within the scope. After that, the manipulator can perform task again.

Secondly, the norm of P^{ref} is smaller than or equal to the sum of l_u and l_f , but the pose cannot be reached due to the limitation of the joint configuration. Figure 4.23 shows the movement of adduction and abduction of the wrist joint. However, the human-like arm cannot reach these postures. This will occur when Motion Capture device is used to perform tele-operation. Motion Capture is a special suit which has lots of sensors in the joints, and can capture the movement data and send them to the planning programs. One feasible method is to reach the desired position and modify the posture to its nearest reachable point. It should be judged at the beginning of the inverse kinematics problem.

Figure 4.23 Unreachable Pose

4.8 Implementation of Human-like Hand-arm System

With the full assembly of mechanical and electronic systems, some tasks are then tested such as OCU (operation control unit) based manipulation, vision-guided grasping, target tracking. Usually, a task performed by the hand-arm system can be divided into a serial of basic motions. For each step, the manipulator is planned to achieve the desired position and orientation.

a. Initial Status

b. Ready for Grasping

c. Searching Object

d. Approaching Object

e. Hand Opening

f. Touching Object

g. Hand Closing

h. Back Home Position

Figure 4.24 Illustration of Vision-guided Grasping

Figure 4.24 shows an experiment for vision-guided grasping. The whole procedure can be divided into 8 steps:

- a. Initial Status: the hand-arm system and the vision module are initialized.
- b. Ready for Grasping: the hand-arm module lifts up and is ready for grasping tasks.
- c. Searching Object: the vision module searches the target and provides position information for the next step.
- d. Approaching Object: the hand-arm system approaches the object and keeps a suitable distance.
- e. Hand Opening: the hand opens in order to grasp the target.
- f. Touching Object: the hand-arm system continues to move towards the target till they are in contact with each other.
- g. Hand Closing: The hand closes up and grasps the target.
- h. Retuning Home Position: The hand-arm module and the vision system come back to the initial status and are ready for the next tasks.

4.9 Performance Specification of Human-like Hand-arm System

After finishing the integration and initialization of the hand-arm system, its performance and key specifications are assessed.

a). Workspace of manipulator

It is required that humanoid robots can catch and carry various objects using their arms and hands. An important issue associated these applications is the range or space that a robot can reach. A reachable workspace denotes the volume of space that the origin of the

end-effector can reach in at least one orientation. To simplify the analysis, the human-like hand-arm can be regarded as a two-link manipulator with a spherical joint on the shoulder and a hinge joint on its elbow as shown in Figure 4.25.

Figure 4.25 Human-like Hand-arm Model for Workspace Analysis

Based on the model above, the endpoint P ($[P_x \ P_y \ P_z]^T$) can be expressed as

$$\begin{aligned} P_x &= -l_u \sin \theta_1 \cos \theta_2 - l_f (\cos \theta_1 \cos \theta_3 \sin \theta_4 + \sin \theta_1 \sin \theta_2 \sin \theta_3 \sin \theta_4 + \sin \theta_1 \cos \theta_2 \cos \theta_4) \\ P_y &= l_u \sin \theta_1 \cos \theta_2 - l_f (\cos \theta_1 \sin \theta_3 \sin \theta_4 - \sin \theta_1 \cos \theta_2 \cos \theta_4) \\ P_z &= -l_u \cos \theta_1 \cos \theta_2 + l_f (\sin \theta_1 \cos \theta_3 \sin \theta_4 - \cos \theta_1 \sin \theta_2 \sin \theta_3 \sin \theta_4 - \cos \theta_1 \cos \theta_2 \cos \theta_4) \\ \theta_1 &\in (-\pi \sim +\pi), \theta_2 \in \left(-\frac{2\pi}{3} \sim \frac{\pi}{18}\right), \theta_3 \in (-\pi \sim +\pi) \text{ and } \theta_4 \in \left(-\frac{3\pi}{4} \sim 0\right) \end{aligned} \quad (4.23)$$

Where $\theta_1, \theta_2, \theta_3$ and θ_4 denote the joint angles of shoulder roll, shoulder pitch, elbow roll and elbow pitch respectively, and $l_u = l_f = 288\text{mm}$. Without consideration of the joint limitation, the reachable workspace of the manipulator consists of a sphere of radius $2l_u$. However, due to hardware limitation and mechanical interference among the links, the

joints have limited range as shown in Table 4.2, the workspace is then reduced. Taking the right hand-arm as an example, its workspace becomes a seedless apple-shaped revolution body as illustrated below.

Figure 4.26 Illustration of Human-like Hand-arm Workspace

b). Design and maximum payload and velocity

The human-like hand-arm is designed to carry objects up to 3 Kg. This can be achieved under speed less than 0.1 m/s. When the hand-arm system works in its maximum velocity, the payload of the manipulator is reduced and becomes around 1 Kg. Hence, we mark 1 Kg as its maximum payload. Figure 4.27 shows grasping a hammer and moving during payload capacity testing.

Figure 4.27 Payload and velocity Testing

For parameter of maximum velocity, we measure it through indirect method. In this method, each joint is programmed to move under a fixed angle and variable duration. When the duration becomes short enough, the joint shakes during its moving toward the destination. We mark it as the average maximum velocity of this joint. The final testing results are listed in Table 4.9.

Table 4.9 Maximum Velocity of Human-like Hand-arm Joints

Joint	Maximum Velocity	Joint	Maximum Velocity
Shoulder Pitch	1.32 rad/s	Elbow Pitch	1.04 rad/s
Shoulder Roll	1.46 rad/s	Wrist Roll	0.85 rad/s
Elbow Roll	1.15 rad/s	Wrist Pitch	0.74 rad/s

c). Smallest and largest object capable of grasping

The grasping capability is firstly simulated on the virtual environment. As shown in

Figure 4.28, the thumb can move and touch the index and medius fingers. Thus, the hand is able to grasp object with very small dimensions. However, in practice, the finger tips have round corners (about 7mm in radius), and it is quite difficult to pick up small objects from a table. When the thumb and the other fingers open up to align parallelly, the hand reaches its limits of grasping, and the clearance is 55mm.

Figure 4.28 Simulation of Grasping Capability

The practical performance is also measured. As shown in Figure 4.29, the hand can grasp cylindrical objects with diameter from 10mm to 55 mm. This is regarded as the grasping capability of the human-like hand.

Figure 4.29 Grasping a Glue Stick and a Plastic Cup

d). Position accuracy and repeatability

Position accuracy and repeatability are important specifications. Some related testing methods for industrial robot are referred in measuring these parameters. Firstly, the maximum cube within the workspace is determined, the testing plane ($C_1 - C_2 - C_3 - C_4$) and five measuring points ($P_1 - P_2 - P_3 - P_4 - P_5$) are then chosen as shown in Figure 4.30.

Figure 4.30 Determination of Maximum Cube and Testing Plane in Workspace

The actual position of the manipulator is measured by a binocular vision platform as shown in Figure 4.31. This platform has two cameras and can figure out the position of static and dynamic objects. Its position accuracy is less than 0.1mm after calibration.

Figure 4.31 Binocular Vision Platform

After then, the manipulator is planned and moves along the five testing points. Totally 30 sets of data are collected, and the position accuracy and repeatability are derived.

Table 4.10 Result of Position Accuracy and Repeatability

Item	Description	Value
AP_l	Position Accuracy	3.26 mm
RP_l	Repeatability Accuracy	0.307 mm

e). Path following & trajectory tracking accuracy

For path and trajectory accuracy, we select circular trajectory for the performance measurement. The measurement devices and conditions are the same as the experiment for position accuracy and repeatability. The curve consists of two circles with different diameters located in testing plane as shown in Figure 4.32. Each circle is measured at 4 points: Q_1 - Q_2 - Q_3 - Q_4 for the bigger one and Q_5 - Q_6 - Q_7 - Q_8 for the smaller one. Finally, we collected 10 sets of testing data and the trajectory tracking accuracy is derived and shown in Table 4.11.

Figure 4.32 Determination of Testing Trajectory in Work Space

Table 4.11 Result of Trajectory Accuracy

Item	Description	Value
AT_p	Maximum Trajectory Accuracy	5.24 mm

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

A human-like hand-arm system is introduced, since there will be great potential applications in the future. The design of the prototype is mainly based on the two aspects: appearance and functions. To reach the human-like appearance, human data are taken into consideration. Then the dimensions, movement range, degrees of freedom of the humanoid hand and arm are decided respectively. For the variety of functions, the mechanism and sensory system are designed according to the requirements.

Optimization and tradeoff are made in the design of the human-like hand. Ultimately, there are totally 6 independent, 4 coupled and 4 passive degrees of freedom for each hand. To realize the two-DOF thumb, a new mechanism is introduced, which has more advantages in mounting as compared to the traditional structures. For each finger, a coupling structure is designed to reach the movement of the first two segments, and pillion-rack is adopted to realize the passive joint of the last segment. Kinematics of the humanoid hand is analyzed. Moreover, the relationship between the finger joint angles and the posture of fingertips is presented.

The human-like arm is assigned 6 degrees of freedom, which can move to arbitrary positions and postures in 3D space theoretically. Based on the force analysis of the arm, actuators are selected. What is more, two kinds of transmission structure are adopted in the arm joints. The analysis of the kinematics of the human-like hand-arm focuses on forward and inverse kinematics problems. After the model is built in the world coordination system, the forward kinematics is used to verify the variety of postures it can

attain. The inverse kinematics problem is more complex since there could be multi-solution and singular posture problems for a serial multi-DOF manipulator. Finally the iterative method and DLS algorithm are adopted, and they could cope with these problems.

5.2 Recommendations for Future Work

After completing the hand-arm prototype and going through the implementation, there are a few concepts and aspects can be paid attention on as recommendations in the future research work.

Firstly, high mounting precision is required for the worm/worm wheel transmission structure. Due to errors in fabrication and mounting, slight margin is set in order to prevent large friction during the transmission. However, it will lead to backlash of the first joint of the fingers. Possible solutions for this issue include enhancing the mounting precision and adopting small harmonic gear to replace worm/worm wheel.

There is also consideration on the refinement of the arm configuration. Although the current DOF distribution enables the robot to perform a lot of tasks, it has the problem of unachievable posture, and this will make trouble for task planning. A feasible way is to add one DOF on the current wrist, because a 7-DOF manipulator is a redundant configuration in kinematics. Actually, this configuration can model the full mechanism of the human being's arm. In this case, there will be some challenges on the structure design of a compact 3-DOF wrist.

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