Saimaa University of Applied Sciences
Name of Faculty Lappeenranta
Double Degree Program
Mechanical Engineering and Production Technology

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Design and Development of Robotic Arm for Cutting Trees

Thesis 2018

Abstract

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Mechanical Engineering and Production Technology of Faculty Lappeenranta
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The extensive use of mechanical tools does not only liberate human resources, but also greatly improves the overall work efficiency. Because the Nordic region is a famous supplier of timber in the world, it is even more essential to design a more efficient logging robot in order to accelerate the speed of cutting trees.

This thesis, through analyzes a full range of structural design and a comprehensive selection of components. It illustrates the details and key points of producing a type of robot from an idealization to actual production, as well as whether the actual design parameters will meet the actual needs (through simulation), which will build up to the automatic logging robot arm with a complete new design.

Through the calculation of the moment of inertia, torque, motor power, transmission ratio, strength (bending, yield, tensile) and safety factor, the design of the robot arm such as what material and machine elements should be used to build the robot arm is achieved. The requirements of the design like size and mechanical properties will be perfectly displayed on the actual robot arm.

Keywords: robot arm, logging robot, gearbox, structure design

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1 Introduction

Robotics involves elements of mechanical, electrical and software engineering, as well as control theory, computing and now artificial intelligence. Robotics research today is based on developing systems that exhibit modularity, flexibility, fault-tolerance, a general and extensible software environment and seamless connectivity to other machines, by providing sensor-based intelligence to the robotic arm. (1) The robotic arm is used in the automated production process, like a human arm can a certain job, the arm is in the mechanization, automation is indispensable to a new type of equipment. The robotic arm is like a person in the automatic production process using the same arm and can accomplish the operation of the equipment, the robotic arm is a kind of indispensable equipment in the mechanization and automation. With the development of social science and technology progress continuously, also it contributed to the development of robot and has been widely used, and the research and manufacture of the robot has become a hot technology in the field of robot development, promoting the development of robotic arm. Moreover, the robotic arm can be combined with mechanization and automation then can be used more widely. The goal of agricultural robots does not only apply to robotics technologies in the field of agriculture, it also applies to using agricultural challenges to develop new techniques and systems. An agricultural robot must deal with an unstructured, unknown and varying environment. In recent years, harvester robots have been among the noteworthy topics studied by researchers. First, as the modern industry has become more complex, there has been a growing need for getting work done in environments that are very dangerous for humans. As an example, work in a nuclear reactor plant often requires contact with radioactive materials. Second, as robots became more advanced and less expensive, they are being set up in industry situations where working conditions are not so much dangerous as unpleasant for various reasons. These situations typically involve high degrees of the following: heat, noise, poisonous gasses, the risk of injury by machines. (2)

Europe, the United States, Japan and other countries have studied logging machines earlier. North America and the Nordic countries are not only the big forestry countries, but also the most developed countries of forestry machinery, especially in the field of timber production, and their mechanization has been in the forefront of the world.

Back in the late 1960s, the United States, Canada, Sweden, Finland and the former Soviet Union have developed into a multi-processing machine, after 10 years of efforts, the technology is mature. In the 1970s, many countries have developed various types of machines which can complete two processes, such as the Feller buncher, logging delimber, logging skidder and skidding loading machine etc. In the early 1980s, the United aircraft was mainly used in North America, northern Europe and the former Soviet Union. By the end of the 1980s, these countries had carried out fully mechanized operation in the plains and gentle slope forest areas, accounting for about 50% of the total. In the 1990s, the United aircraft suitable for forestry in Japan developed rapidly. In 1995, Finland Plustsh launched a prototype of walking Cutting Robot; in 1997, Timberjack [2] developed a new round of more perfect robot prototype, and used for steep and soft ground harvesting operations. The machine is in normal walking speed with 6 legs to walk, according to different terrain can also be used 3 or 5 legs and balance, machine equipped with advanced control system, adjust the walking pace on the ground roughness and slope by computer and sensor, and can overcome the 120 cm high barriers, the only one machine the joystick can control the moving direction and speed regulation, working device can be set according to the procedure of automatic logging, pruning and bucking. At present, in the forest industry developed countries, the overall mechanization of forest harvesting operations has occupied a large proportion. Most of the forest harvesting and production in the plains and hills have been fully mechanized. In North America, in addition to the west mountain forest area of large diameter, chain saws have been replaced by Feller buncher and self-propelled cutting machine, and now the most popular way of logging in the forest is to use a manipulator-type robot logging.

2 Overall Structure of a Robot Arm

2.1 Design of the main content

During the design process, during first step is the establishment of the overall structure of the robot arm, followed by the specific design of each part of the structure of the program:

1) Structural design of waist slewing mechanism.

2) Structural design of swing mechanism with big arm.

3) Structural design of the swing mechanism with small arm.

2.2 Design scheme

The specific design of this topic is that the quality of disc is 0.5-2.0 kg, and taking into account the saw disc, it will produce a certain moment of inertia in the rotating process, so it must be simplified as much as possible to reduce the cost of construction and enhance the reliability. In the work process, a mechanical arm is required to complete the four degrees of freedom change, the space position and movement posture, including waist rotation, large arm rotation, small arm rotation and end rotation. In order to meet the needs of the design of this project, the degree of freedom of manipulator will be four, and the structure of articulated manipulator is adopted.

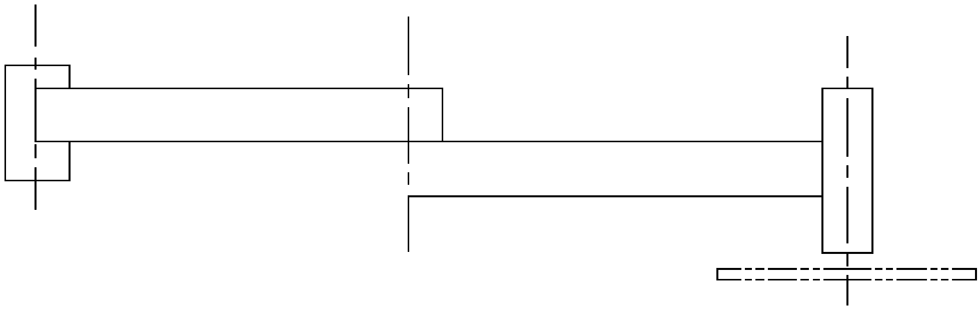


Figure 2.1. overall layout of robot arm

2.3 Design of the overall structure of robot arm

Existing mechanical arm structure types: rectangular (Cartesian) coordinates, cylindrical coordinates, spherical coordinates and joint types.

1) Cartesian coordinates manipulator

The Cartesian coordinate manipulator realizes the spatial motion by using three straight lines and 22 mutually perpendicular linear motion in the same plane. Because the Cartesian coordinate manipulator structure is the implementation of linear motion form closed-loop control, the accuracy is very high (level M). However, the size of the manipulator for space activities is relatively large. Thus, the right angle of coordinate manipulator structure layout size should be as large as possible in order to leave the mechanical arm in the Cartesian coordinate enough movement range.

2) Cylindrical coordinate manipulator

The spatial motion of a cylindrical coordinate manipulator consists of a rotating motion and two linear reentrant motions. This mechanical arm structure is relatively small with high dimension precision, commonly used in the handling process. The workspace is a circular column.

3) Spherical coordinate manipulator

The space motion of the articulated manipulator structure is composed of three rotary motions. Articulated manipulator structure has sensitive action, compact size, the small occupied space area. Due to the need to complete a certain space, motion, the size of the manipulator is relatively larger than the size of the robot body, and the workspace is relatively large. The mechanical arm structure has been widely used in various production industries.

According to the characteristics and application above, articulated manipulator structure is adopted at last.

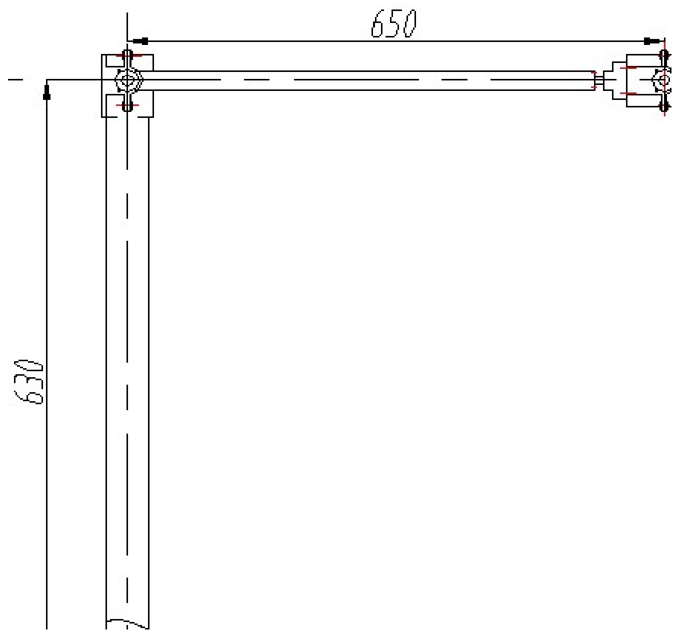


Figure 2.2. overall layout of robot arm (detail)

The specification parameters of the design project:

The maximum angle of lumbar rotation: 280 degrees

Swing maximum angle: 120 degrees

The design products need to complete the action including the rotary arm and the waist first saw disc in a plane; then the big rotary arm, adjusting the distance between the saw disc and the final felling; the saw disc touches the trees with small arm rotation, and finally cuts trees

3 Design of Waist Frame

3.1 Overall design of waist frame

The driving method of seat rotating part has two kinds: driven by the combination of motor and reducer by the hydraulic cylinder or air cylinder. Currently, the most widely used method is the motor and reducer combination drive. And because the rotation of the waist base is the most important rotary joint of the entire robot arm, the quality of the final processing of the robot will be impacted by it. Therefore, this design uses a combination of motor and reducer to drive.

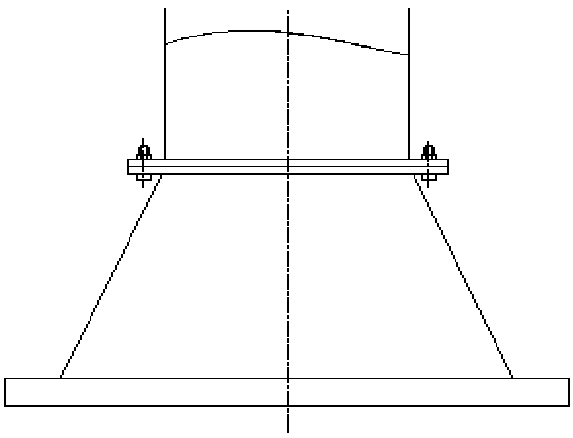


Figure 3.1. Waist frame structure layout

3.2 Design of waist frame structure

Arm of the waist machine base is a rotating cylindrical coordinate robot, ball and arm manipulator arm, belonging to the rotary base in the manipulator. Because the waist is the first rotary joint of the whole arm, most of the arm's moving parts are mounted on the waist base, it takes the weight of the whole arm. Therefore, in the design of the robot arm base layout structure, the following principles should be obeyed:

1) Waist base should have sufficient assembly space to ensure the overall reliability of the work process.

2) Waist base bears the weight of the manipulator and the load, so the selection of the base, the waist shaft and bearing the structure size should have sufficient strength and stiffness to protect against greater load strength.

3) Since the waist is the first rotating joint of the whole manipulator, it has a great influence on the overall machining quality of the manipulator. The precision and strength of the waist and the revolving part should be strengthened in the design process.

4) Waist rotation is driven by the drive device, the drive (motor, hydraulic system and pneumatic system) and reducer combination. Drives are usually equipped with speed sensors and brakes due to their extremely fast speeds.

5) Waist structure facilitates loading and unloading, adjustment. Waist and arm joints should have strong stiffness and a reliable limit plane to ensure that the relative position between the various joints. Because of the use of bearings for too long wear and tear caused by clearance and reducer rotation resulting in low quality machining, so there must be the regulation.

6) In order to reduce the moment of inertia of the rotating part of the manipulator and improve the rotating quality of the manipulator, the shell of the rotating mechanism of the waist is generally made of aluminum alloy material, while the stationary base is made of cast iron or cast steel.

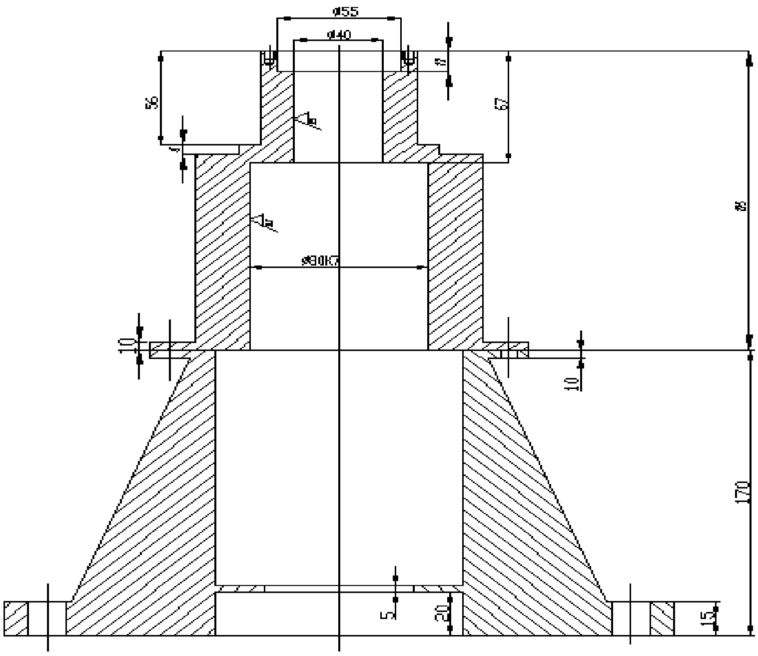


Figure 3.2. Waist base of the detailed structure

3.3 Selection of the waist motor

Basic requirements of industrial robots on the joint drive motor

1) they should have a large starting torque and inertia ratio

2) they can be started with stability

3) they have larger adjustment range (speed characteristics)

4) they are in small sizes, easy to install

5) they can work reliably in harsh environments during a longtime period

6) they should have high reliability

7) their continuity should be good

Motor Selection and Calculation:

Set the moment of inertia of the two arms for the respective center of gravity axis respectively JG1， JG2 and JG3, according to the theorem of parallel axes, we can get the moment of inertia about the axis 0 as:

$$J_{G0} = m_0 r^2 = 0.08 N.m^2$$

Moment of inertia is:

$$J_0 = m_1(\frac{l_1}{2})^2 + \frac{1}{3}m_1 l_1^{\ 2} + m_2(l_1 + \frac{l_2}{2})^2 + \frac{1}{3}m_2 l_2^{\ 2} + m_3(l_1 + l_2 + \frac{l_3}{2})^2 + \frac{1}{3}m_3 l_3^{\ 2} + J_{G0}$$

Including m0=8 kg, m1=6 kg, m2=4 kg, m3=1 kg. l_1, $l_2$and l_3 are the distances from the center of gravity to the 0 axis, and the values are 300 mm, 600 mm, 1200 mm, respectively, so the moment of inertia of the axis around 0 is:

$$\begin{aligned} J_0 &= m_1(\frac{l_1}{2})^2 + \frac{1}{3}m_1 l_1^{\ 2} + m_2(l_1 + \frac{l_2}{2})^2 + \frac{1}{3}m_2 l_2^{\ 2} + m_3(l_1 + l_2 + \frac{l_3}{2})^2 + \frac{1}{3}m_3 l_3^{\ 2} + J_{G0} \\ &= 0.135 + 0.18 + 1.44 + 0.48 + 2.25 + 0.48 + 0.08 N.mm^2 \\ &= 5.045 N.mm^2 \end{aligned}$$

When the output shaft speed is 200 degrees /s, the torque of starting torque is as follows:

$$T = J \times \omega \tag{3.1}$$

Formula detail:

T —— the torque at the beginning of rotation. （$N \cdot m$）

$\dot{w}$ —— angular acceleration. （rad/s^2）

The time required for the spindle to run from w_0=0 to w_0=200(degree) is $\Delta t = 1s$.

$$T_1 = J_1 \times w = 5.045 \times \frac{1.1\pi}{1} \approx 17.61 N.m \tag{3.2}$$

Concerning the inertia around the center of gravity of the robot arm and the friction torque, the torque makes the rotor start to rotate, which may be assumed to be $20N.m$. Motor power can be estimated by the following.

Formula:

$$P_m = (1.5 \sim 2.5)\frac{M_{LP}\Omega_{LP}}{\eta} \tag{3.3}$$

Formula detail:

Pm is Motor Power and the unit is W.

M_{LP} is load torque.

Ω_{Lp} is load speed.

η is efficiency of transmission equipment, initial value of 0.9.

Safety factor is 1.5～2.5, according to the highest safety level, choose 2.5.

$$P_m \approx 2.5 \times \frac{20\times\frac{200}{180}\pi}{0.9} = 193.93\ W \tag{3.4}$$

According to the design criteria requirements, the calculated motor power value can select the appropriate motor. The rated power P_r should:

$$P_r \geq P_m \tag{3.5}$$

Because the calculated basic requirements of motor power is 193.93W, MCS synchronous servo motors (Lenze) is a better choice. Because of MCS synchronous servo motor for precisely controlled motion. Torque range: 0.5 to 190 Nm and power range: 0.25 to 15.8 kW, particularly suitable for applications that require high dynamic performance, precision and minimal dimensions.

Advantage :

a) High overload capacity
b) Large angular accelerations
c) Plug connections for quick mounting and easy serviceability

d) Electronic nameplate for easy commissioning

e) Resolver as feedback, alternately incremental encoder or absolute value encoder

f) Increased power density using high-quality magnetic materials (SEpT technology) and specially developed pole formats

Figure 3.3. MCM synchronous servo motor (4)

Parameter table: (4)
Motor name: MCM synchronous servo motor (09E30)
Main power supply: 296V AC
Rated power (KW): 0.75
Rated speed(r/min): 3000
Rated torque (NM): 2.4
Protection degree: IP 65 (Enclosure)
Cooling: Self-ventilated

3.4 Selection of waist gearbox

Due to the overall maximum speed of 30r/min, the servo motor can adjust the required speed and the need to maintain the normal work in rated working condition. So the highest speed should be used to calculate the transmission ratio.

$$i_a = \frac{n_m}{n} = \frac{3000}{30} = 100 \quad (3.6)$$

Based on the calculated basic requirements of reduction ratio 100, and with reference to the reputation of each big reducer brand in the market, MPR/MPG planetary gearboxes (Lenze) is a better choice. The g700 planetary gearbox is an excellent solution for dynamic and cost-optimized applications, it is high-level of reliability, the long service life and excellent scalability make it a precise solution for demanding machine tasks.

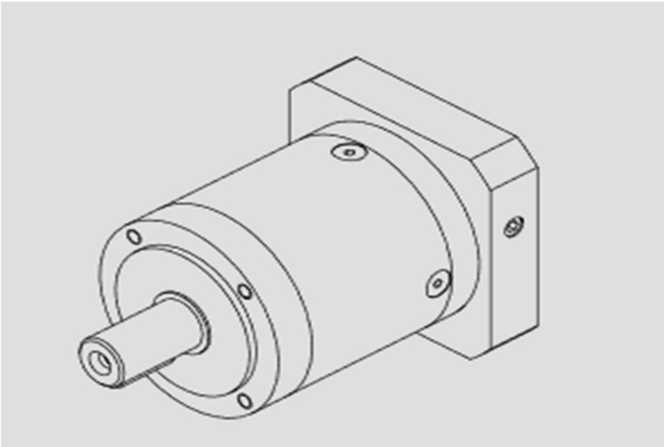


Figure 3.4. G700-P260-3 gearbox motor (4)

Parameter table: (4)
Gearbox name: g700-P260-3 (*Lenze)*
Drive end: IEC ass, with clamp, ring hub
Ratio: 100
Input speed: 3500 r/min (maximum)
Output speed: 350 r/min (maximum)
Output torque: 260 N/m
Moment of inertia: 1.515 kg/cm^2

3.5 Selection of the Key and strength check

3.5.1 How to choose key

In mechanical engineering, a key is a machine element used to connect a rotating machine element to a shaft. The key prevents relative rotation between the two parts and may enable torque transmission. The key is a standard part, the choice of the first key connection according to the characteristics of the working conditions, the strength requirements and the length of the hub to select the key, and then strength check. In summary, select the AISI 1045 (5) as the key base material, and the best way is to use quenching and tempering to improve the performance of the key.

Chemical Composition

Element	Content
Carbon, C	0.420 - 0.50 %
Iron, Fe	98.51 - 98.98 %
Manganese, Mn	0.60 - 0.90 %
Phosphorous, P	≤ 0.040 %
Sulfur, S	≤ 0.050 %

Physical Properties

Physical Properties	Metric	Imperial
Density	7.87 g/cc	0.284 lb/in^3

Mechanical Properties

Mechanical Properties	Metric	Imperial
Hardness, Brinell	163	163
Hardness, Knoop (Converted from Brinell hardness)	184	184
Hardness, Rockwell B (Converted from Brinell hardness)	84	84
Hardness, Vickers (Converted from Brinell hardness)	170	170
Tensile Strength, Ultimate	565 MPa	81900 psi
Tensile Strength, Yield	310 MPa	45000 psi
Elongation at Break (in 50 mm)	16.0 %	16.0 %
Reduction of Area	40.0 %	40.0 %
Modulus of Elasticity (Typical for steel)	200 GPa	29000 ksi
Bulk Modulus (Typical for steel)	140 GPa	20300 ksi
Poissons Ratio (Typical For Steel)	0.290	0.290
Shear Modulus (Typical for steel)	80 GPa	11600 ksi

Figure 3.5. The properties of AISI 1045 (5)

The design of the keys are the keys of the gearbox, ordinary round head A type:

Size: b*h*L=10*8*60

3.5.2 How to check the strength

When the torque is transmitted, the main failure mode is the breakdown of the working surface. Unless there is a serious overload, there will be no shear phenomenon. Therefore, the strength check calculation should be carried out according to the pressure on the working face.

It is found that the load is uniformly distributed on the surface of the key work (search in mechanical notebook), and the strength condition of the common flat key connection.

$$\sigma_P = \frac{2000T}{kld} = \frac{4000T}{hld} \leq \left[\sigma_p\right]$$

Formula detail:

T means transfer torque. (Nm)

K means the contract height of key and wheel hub. (mm)

l means working length of key, Pratt-Whitney key l =L-b and L is nominal length of key, b is key width. (mm)

D means diameter of shaft. (mm)

[σ p] means allowable extrusion stress of the weakest material in the shaft, hub and wheel. (MPa)

Check in the Mechanical Design Handbook, the allowable extrusion stress of steel and cast iron under slight impact loading is 90<<120 (MPa) and 40<<60 (MPa)respectively.

To sum up, materials used for large arm is ANSI A48-2000 No 20, and the material for rotation shaft is AISI 1045 steel. The weakest material in the two is cast iron, and there is a slight impact load in the test, so the [σ p] is 40<<60MPa, using the average [σ p] =50 MPa.

The torque delivered by the key is T=40 Nm, the contact height of the key and the keyway of the wheel is k=4 mm, the effective working length of the key is l=L-b=60-10=50 mm, and the diameter of the shaft is d=40 mm. Put these data into formula:

$$\sigma p = 10 \text{ MPa} << [\sigma p]$$

Therefore, the strength of the bond meets the conditions of use, and the key connection is safe.

3.6 Design and check of waist shaft

In the structure of the robot, the design of drive shaft in the transmission process is extremely important, and the main shaft torque moment is under load, there is a common axis straight shaft and shaft bending. According to the characteristics of the design of the mechanism, selection of drive shaft is a straight shaft, available from known conditions: n=30r/min, according to the motor shaft power transfer to P=500*0.9=45 W=0.45 kw.

The material chosen for the shaft is AISI 1045 steel is then used after quenching and tempering.

Properties (Find in website): (4)

Hardness: HBS218 ~ 255;

Limit of yield strength: σs =360MPa;

Limit of tensile strength: σb =650MPa;

Limit of bending fatigue strength: $\sigma 1$=300MPa;

According to the Mechanical Design Notebook, [σ-1] b =55MPa

The diameter of the shaft is determined by the above data, and the output diameter of the shaft is estimated according to the torsional strength (check the notebook C=1.4 ~ 126 so C=70).

$$d = \sqrt[3]{p/n}$$

$$d = 100 \times \sqrt[3]{0.45/_{30}} = 34.54\,mm$$

Then the d=35 mm.

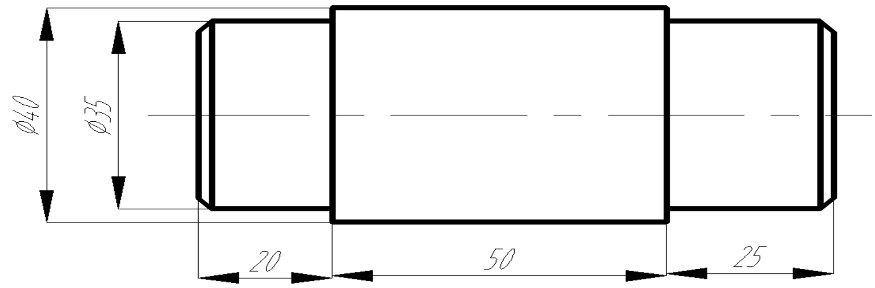


Figure 3.6. Drive shaft size

In the whole robot structure, the transmission shaft to bear the force is the largest, so the strength check calculation:

1) Judgment of dangerous shaft section

Only second segments of the load and torque are on the whole transmission shaft, so the strength check of this section is necessary.

The stress of the axial section is:

$$\sigma_b = \frac{M_m}{W} \tag{3.7}$$

The Mm unit is N / m.

The bending moment modulus is expressed by W.

The data is taken into σ_b =5Mpa.

The shear stress is as follows:

$$\tau_T = \frac{T_2}{W_T} \tag{3.8}$$

The T2 unit is N / m, indicating that the torque WT represents the modulus of torsional cross section.

Type 3-2 substituting data to get τ_T =158.42MPa.

$$\tau_b = \tau_m = \frac{\tau_T}{2} = \frac{156.25}{2} = 78\,\text{MPa} \tag{3.9}$$

The transmission shaft adopts 40Cr and should be quenched and tempered

$$\sigma_B = 735\ MPa\ , \sigma_{-1} = 386\ MPa\ , \tau_{-1} = 260\ MPa$$

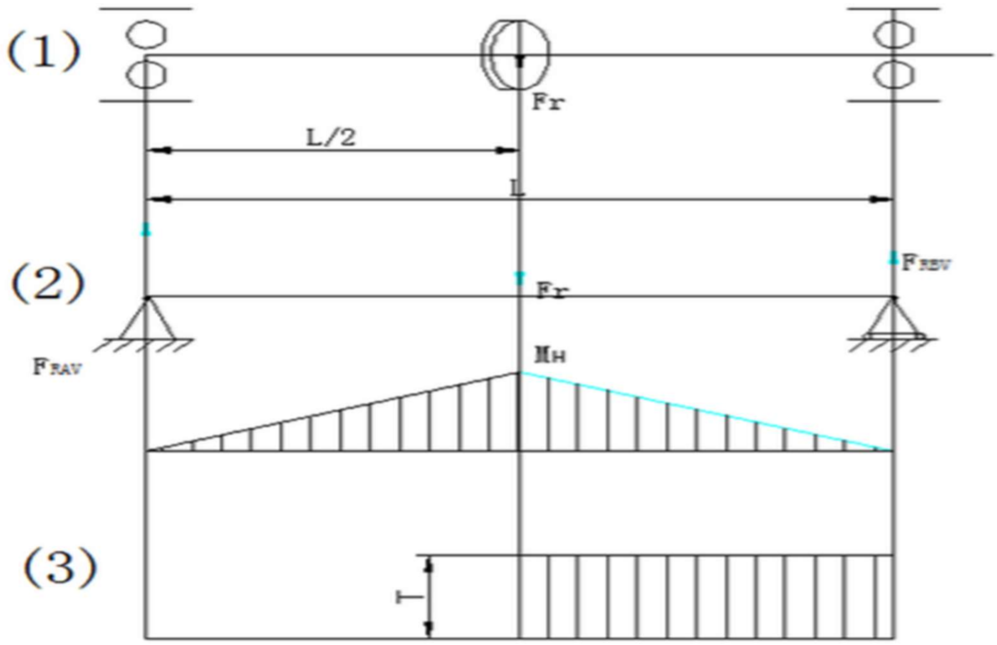


Figure 3.7. Drive shaft stress diagram

So the diameter of the shaft:

$$d = \sqrt[3]{\frac{M_e}{0.1[\sigma_{-1b}]}} = 16\,\text{mm} < d_{\min} \tag{3.10}$$

2) Calculation of safety factor

The fatigue safety factor of the shaft is:

$$S_{\sigma} = \frac{\sigma_{-1}}{K_{\sigma}\sigma_{a} + \psi_{\sigma}\sigma_{m}} \quad (3.11)$$

$$S_{\tau} = \frac{\tau_{-1}}{K_{\tau}\tau_{a} + \psi_{\tau}\tau_{m}} \quad (3.12)$$

$$S_{ca} = \frac{S_{\sigma} S_{\tau}}{\sqrt{S_{\sigma}^{2} + S_{\tau}^{2}}} \quad (3.13)$$

S_{σ} is the safety factor when considering moment only
S_{τ} is the safety factor when considering torque only.
σ_{-1} is the bending fatigue limit of material symmetric circulation.
τ_{-1} is the torsional fatigue limit of the material's symmetrical circulation.
K_{σ} is the effective stress concentration factor of the axis during bending.
K_{τ} is the effective stress concentration factor of the torsion shaft.
τ_{a} is the stress amplitude of torsional shear stress. (Mpa)
τ_{m} is the average stress that represents torsional shear stress.
σ_{a} is the stress amplitude that represents the bending stress.
σ_{m} is the mean stress that represents bending stress.
S_{ca} represents the safety factor for calculating the fatigue strength.
S indicates the safety factor of fatigue strength.

Bring the data into the formula (3-11), (3-12) and (3-13), then get the answer is $S_{\sigma} = 5, S_{\tau} = 10, S_{ca} = 4$. These safety indexes are greater than S = 1.5, so this drive shaft is safe.

4 Structure Design of Robot Arm

The robot arm is used to support the wrist and hand, and to complete a certain action. The following principles should be followed in the design process:

1. Stiffness and bearing capacity should be strong. In the process of work, the manipulator arm is equivalent to a cantilever beam. If the stiffness was poor,

the manipulator would be easy to deformation, vibration, resulting in poor machining accuracy.

2. To simplify the kinematics of the robot and facilitate the robot control, the joints should be parallel or perpendicular to each other as far as possible, and the horizontal axis should intersect as much as possible.
3. To improve the speed of the robot, it should be moderate, so as to reduce the weight of the part of the arm movement as much as possible, thus reducing the rotational inertia of the whole robot arm to the rotating shaft.
4. High positioning accuracy is required. Accuracy is one of the important indexes to measure the performance of a robot. In order to improve the accuracy, the weight of the manipulator should be reduced, and the mechanism is compact, and a buffer device should be installed.
5. The selected bearing gap should be as small as possible in order to reduce the error caused by the gap. Therefore, the joints should be equipped with materials which are easy to adjust the clearance.
6. The strength shouldered by right arm should be as symmetric as possible which reduces the additional load and enhances the flexible robot arm movement. In the design process, the control parts and devices should be evenly distributed on the mechanical arm, and if necessary, the balance mechanism should be added to adjust the uneven weight.

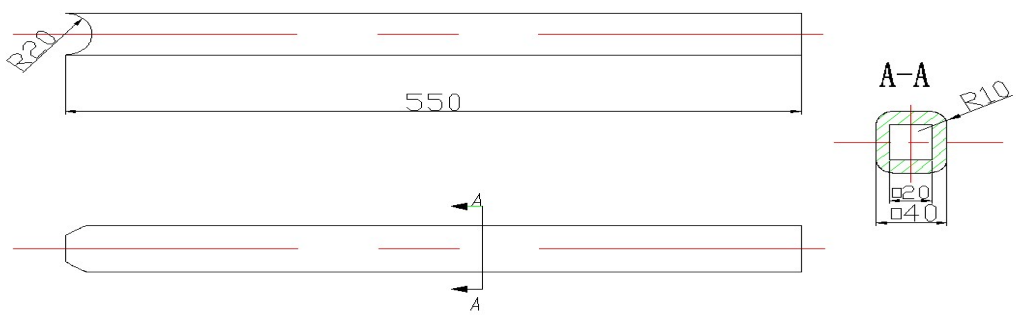


Figure 4.1. Arm structure layout drawing

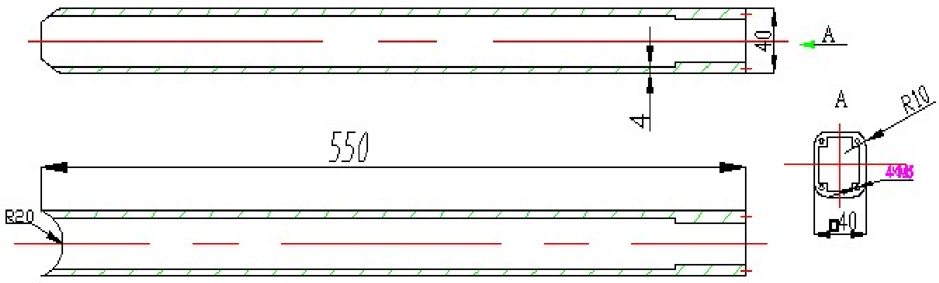


Figure 4.2. Small arm structure layout drawing

4.1 Basic design scheme

The motion of a big arm and a small arm of a robot are both slewing motion. In order to improve the movement stability and safety of the robot, the adjustment between the arms will select the motor and harmonic wave reducer.

4.2 Selection of large arm motor

The moment of inertia of the two arms for each axis of gravity are JG1 and JG2 respectively. According to the parallel axis theorem, the moment of inertia of the axis around 1 can be obtained:

$$J_{G1} = \frac{1}{3} m_1 r^2 = 0.635\ N.m^2 \tag{4.1}$$

The moment of inertia:

$$J_1 = J_{G1} + m_2(l_1 + \frac{l_2}{2})^2 + \frac{1}{3} m_2 l_2^{\ 2} + m_3(l_1 + l_2 + \frac{l_3}{2})^2 + \frac{1}{3} m_3 l_3^{\ 2} \tag{4.2}$$

Among them: m1=6 kg; m2=4 kg; m3=1 kg; L1=300 mm, L2=600 mm, L3=1200 mm; the moment of inertia around the axis 1 is:

$$J_1 = J_{G1} + m_2(l_1 + \frac{l_2}{2})^2 + \frac{1}{3}m_2 l_2{}^2 + m_3(l_1 + l_2 + \frac{l_3}{2})^2 + \frac{1}{3}m_3 l_3{}^2$$
$$= 0.635 + 1.44 + 0.48 + 2.25 + 0.48\ N.mm^2$$
$$= 5.285\ N.mm^2$$

Set the output shaft speed as $180°/S$ time required $\Delta t = 1s$:

$$T_1 = J_1 \bullet Xw = 5.285\,X\,\frac{1\pi}{1} \approx 16.5949\ N.m \tag{4.3}$$

Taking into account the inertia around the center of gravity of the robot arm and the friction torque, the torque causes the rotor to start rotating, which may be assumed to be 13 Nm.

Motor power can be estimated by pressing type:

$$P_m = (1.5 \sim 2.5)\frac{M_{LP}\Omega_{LP}}{\eta} \tag{4.4}$$

Formula detail:

Pm is the motor power (unit: W)

M_{LP} is the load torque

Ω_{LP} is the load speed

η is the transmission efficiency, initial 0.9.

The coefficient 1.5-2.5 is empirical data, so take 2.5.

$$P_m \approx 2 \times \frac{16 \times \frac{180}{180}\pi}{0.9} = 111.65\,W \tag{4.5}$$

According to the design criteria requirements, the calculated motor power value can select the appropriate motor. The rated power P_r should:

$$P_r \geq P_m$$

The same choice as the above servo motor.

Parameter table: (4)
Motor name: MCM synchronous servo motor (09E30)
Main power supply: 296V AC
Rated power (KW): 0.75
Rated speed(r/min): 3000
Rated torque (NM): 2.4
Protection degree: IP 65 (Enclosure)
Cooling: Self-ventilated

4.3 Selection of large arm gearbox

With the overall maximum speed requirements 30r / min, the servo motor is able to regulate the required speed and maintain normal operation at rated operating conditions. So calculate the gear ratio with the highest speed.

$$i_a = \frac{n_m}{n} = \frac{3000}{30} = 100 \tag{4.6}$$

So choose the same gearbox as you did before.

Gearbox name: g700-P260-3 Lenze

Parameter table: (4)
Gearbox name: g700-P260-3 (*Lenze)*
Drive end: IEC ass, with clamp, ring hub
Ratio: 100

4.4 Design of carriage for large arm motor

The carriage is used to support the motor and the gearbox.

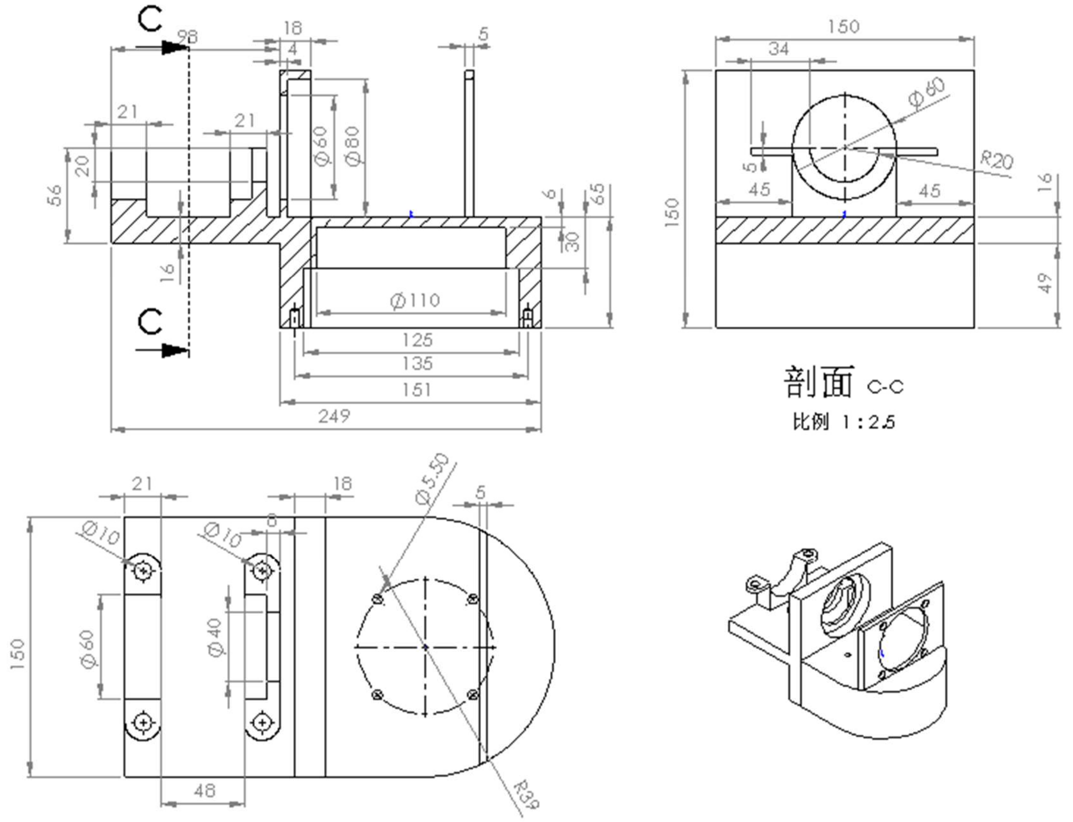


Figure 4.3. Boom motor support structure diagram

4.5 Selection of small arm motor

The moment of inertia of the two arms for each axis of gravity are JG2 and JG3 respectively. According to the parallel axis theorem, the moment of inertia of the axis around 2 can be obtained:

$$J_{G2} = \frac{1}{3} m_2 r^2 = 0.2668 \quad N.m^2 \tag{4.7}$$

The moment of inertia is:

$$J_2 = J_{G2} + m_3 (l_2 + \frac{l_3}{2})^2 + \frac{1}{3} m_3 l_3^2 \tag{4.8}$$

m2=4 kg；m3=1 kg；L2=600 mm、L3=1200 mm.

The moment of inertia J_2 around the axis 1 is:

$$J_2 = J_{G2} + m_3(l_2 + \frac{l_3}{2})^2 + \frac{1}{3}m_3 l_3^2$$
$$= 0.2668 + 1.44 + 0.48 \ N.mm^2$$
$$= 2.18668 \ N.mm^2$$

Set the output shaft speed as $100°/S$ and time required $\Delta t = 1s$.

$$T_2 = J_2 \bullet Xw = 2.1868 \times \frac{\frac{100}{180}\pi}{1} \approx 3.8147 \ N.m \tag{4.9}$$

Taking into account the inertia around the center of gravity of the robot arm and the friction torque, the torque causes the rotor to start turning, which can be assumed to be 4 Nm.

Motor power can be estimated by the following formula:

$$P_m = (1.5 \sim 2.5)\frac{M_{LP}\Omega_{LP}}{\eta} \tag{4.10}$$

Formula detail:

Pm is the motor power (unit: W)

M_{LP} is the load torque

Ω_{LP} is the load speed

η is the transmission efficiency, initial 0.9.

The coefficient 1.5-2.5 is empirical data, so take 2.5.

$$P_M \approx 2.5 \times \frac{4\times\frac{100}{180}\pi}{0.9} = 18.38 \ W \tag{4.11}$$

According to the design criteria requirements, the calculated motor power value can select the appropriate motor. The rated power P_r should:

$$P_r \geq P_m$$

Figure 4.4. MCS servo motor 06I41 (4)

Parameter table: (4)
Motor name: MCM synchronous servo motor (06I41)
Main power supply: 230V AC
Rated power (KW): 0.64
Rated speed(r/min): 4050
Rated torque (NM): 1.5

4.6 Selection of small arm gearbox

With the overall maximum speed of 20 r/min, the servo motor can adjust the required speed and the need to maintain the normal work in rated working conditions. So use the highest speed to calculate the transmission ratio.

$$i_a = \frac{n_m}{n} = \frac{4050}{20} \approx 202 \qquad (4.12)$$

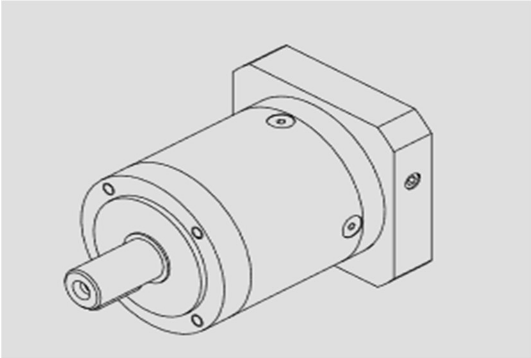


Figure 4.5. G700-P44-3 gearbox motor (4)

Parameter table: (4)

Gearbox name: g700-P44-3 (*Lenze)*

Drive end: IEC ass, with clamp, ring hub

Ratio: 200

Input speed(r/min): 4500 (maximum)

Output speed(r/min): 22.5 (maximum)

Output torque (N/m): 40

Moment of inertia: 1.435 kg/cm2

4.7 Design of carriage for small arm motor

The carriage is used to support the motor and the gearbox.

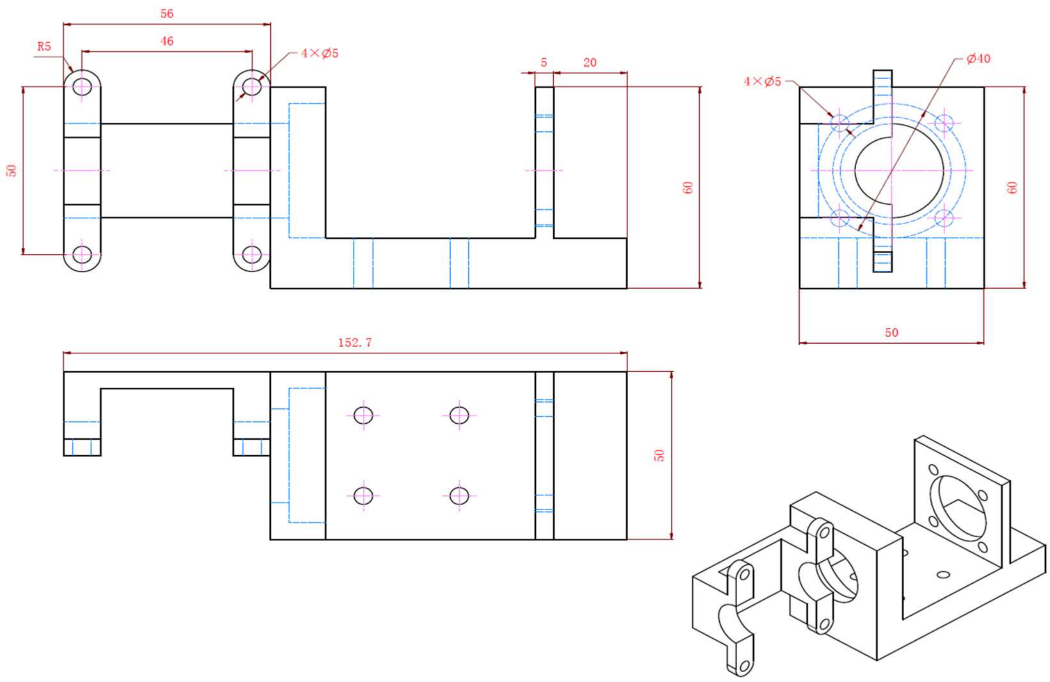


Figure 4.6. Small arm motor support frame structure

5 Structural Design of Rotor Arm End

5.1 Selection of end motor

The moment of inertia of the arm to its center of gravity is JG3. According to the parallel axis theorem, the moment of inertia around the axis 3 can be obtained:

$$J_{G3} = \frac{1}{3} m_3 r^2 = 0.000526 \quad N.m^2 \tag{5.1}$$

The moment of inertia:

$$\begin{aligned} J_3 &= J_{G3} \\ &= 0.000526 \quad N.mm^2 \end{aligned} \tag{5.2}$$

Among them: m3=1 kg.

Set the output shaft speed as $120°/S$ time required $\Delta t = 1s$:

$$T_3 = J_3 \bullet Xw = 0.000526 \times \frac{\frac{2}{3}\pi}{1} \approx 0.001101093 \quad N.m \tag{5.3}$$

Taking into account the inertia around the center of gravity of the robot arm and the friction torque, the torque causes the rotor to start rotating, which may be assumed to be 1 Nm.

Motor power can be estimated by pressing type:

$$P_m = (1.5 \sim 2.5) \frac{M_{LP} \Omega_{LP}}{\eta} \tag{5.4}$$

Formula detail:

Pm is the motor power (unit: W)

M_{LP} is the load torque

Ω_{LP} is the load speed

η is the transmission efficiency, initial 0.9.

The coefficient 1.5-2.5 is empirical data, so take 2.5.

$$P_m \approx 2 \times \frac{0.001101093 \times \frac{120}{180}\pi}{0.9} = 0.00640\,W \tag{5.5}$$

According to the design criteria requirements, the calculated motor power value can select the appropriate motor. The rated power P_r should:

$$P_r \geq P_m$$

So choose the same servo motor as you did before.

Parameter table: (4)
Motor name: MCM synchronous servo motor (06I41)
Main power supply: 230V AC
Rated power (KW): 0.64
Rated speed(r/min): 4050
Rated torque (NM): 1.5

5.2 Selection of end gearbox

With the overall maximum speed requirements 2000r / min, the servo motor is able to regulate the required speed and maintain normal operation at rated operating conditions. So calculate the gear ratio with the highest speed.

$$i_a = \frac{n_m}{n} = \frac{4050}{2000} = 2.05$$

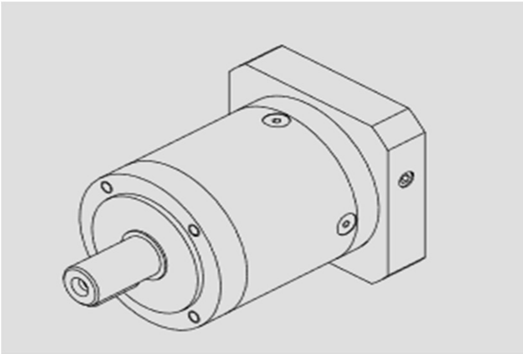


Figure 5.1. P700 P20-1 gearbox (4)

Parameter table: (4)

Gearbox name: g700-P20-1 *Lenze*

Drive end: IEC ass, with clamp, ring hub

Ratio: 8

Input speed(r/min): 5000 (maximum)

Output torque (N/m): 6

Moment of inertia: 1.435 kg/cm^2

5.3 Design of carriage for end arm motor

The carriage is used to support the motor and the gearbox.

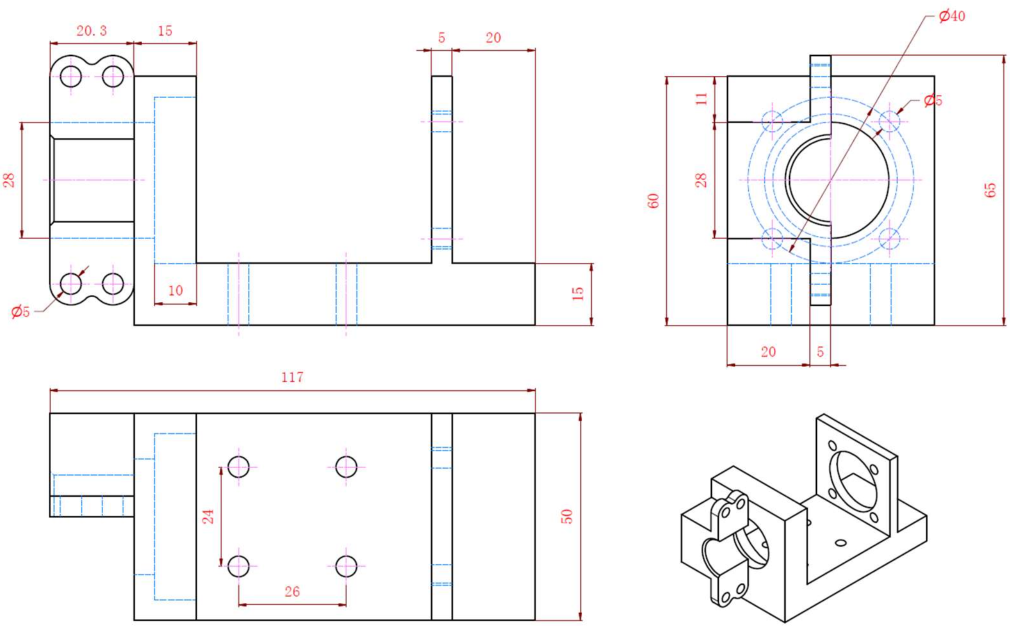


Figure 5.2. End motor support frame structure

6 Selection of Bearing

A determination of the basic bearing type, whether it is to be a slider type bearing or a rolling-element bearing, can be based logically upon a study of the several characteristics relating to the following factors: (6)

1. The mechanical requirements
2. The environmental and other conditions relative to the application
3. The relative cost (6)

To ensure the normal operation of the arm, the selected bearings must ensure quality, assembly and use of bearings to be standardized. Bearing selection of the normal operation of the arm is very important.

6.1 Selecting type and size

The general considerations of function, life, lubrication, performance, reliability, maintenance, and cost enter into the decision to select one type or the other.(7)

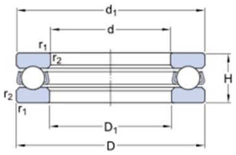
6.1.1 Selection of base bearing on the rotating shaft

Ball Thrust bearing, Single and double direction thrust ball bearings are used to accommodate pure axial loads, mostly in low-speed applications. Though their design is rather simple, these robust bearings can provide long, trouble-free service life. (8) Rated dynamic load ratio of 1, and it cannot bear the radial load, can only withstand axial load, centrifugal force at high speed, ball and cage wear, serious heat and life expectancy. Therefore, the low speed limit (45646).

According to the shaft diameter of installation the bearing segment is 30 mm, and the installation size, the basic rated load and other factors, the final selection of bearing code is 51205 Thrust ball bearings, single direction. (9)

51206

Dimensions



d		30	mm
D		52	mm
H		16	mm
d_1	≈	52	mm
D_1	≈	32	mm
$r_{1,2}$	min.	0.6	mm

Figure 6.1. Thrust ball bearings, single direction (51205) (9)

6.1.2 Selection of base bearing on the relative rotation

Tapered roller bearings, rated dynamic load ratio from 1.5 to 2.5. The axial load can be subjected to one direction axial load, and additional axial force will be produced under radial load, usually in pairs. As the contact angle increases, the axial load increases.

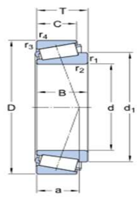
According to the shaft diameter of installation the bearing segment is 60 mm, and the installation size, the basic rated load and other factors, the final selection of bearing code is 30212 Tapered roller bearings, single row.

30212

SKF Explorer

Dimension series 3EB

Dimensions



d		60	mm
D		110	mm
T		23.75	mm
d_1	≈	80.9	mm
B		22	mm
C		19	mm
$r_{1,2}$	min.	2	mm
$r_{3,4}$	min.	1.5	mm
a		21.531	mm

Figure 6.2. Tapered roller bearings, single row (30212) (9)

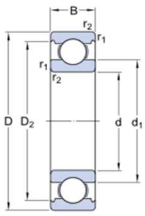
6.1.3 Selection of bearings on the large arms, small arms and end of arms

The deep groove ball bearing has a rated dynamic load ratio of 1, and the bearing capacity is small. It mainly bears radial load and also can bear small axial load at the same time. When the radial clearance of the bearing increases, it has the function of angular contact bearing, and can bear larger axial load. The friction coefficient is minimum, the limit speed is high, the weight is light, the structure is simple, and it is easy to use. No maintenance during the work. It is suitable for high speed.

Large arm bearing: according to the installation of bearing segment shaft diameter of 30 mm, and installation size, basic rated load and other factors. The final selection of bearing is 6206 (Deep groove ball bearings).

6206
SKF Explorer

Dimensions



d		30	mm
D		62	mm
B		16	mm
d_1	≈	40.36	mm
D_2	≈	54.06	mm
$r_{1,2}$	min.	1	mm

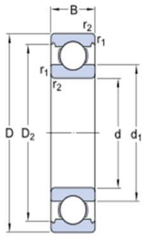
Figure 6.3. Deep groove ball bearings (6206) (9)

Small arm bearing: according to the installation of bearing segment shaft diameter of 17 mm, and installation size, basic rated load and other factors. The final selection of bearing is 6203 (Deep groove ball bearings).

6203

SKF Explorer

Dimensions



d		17	mm
D		40	mm
B		12	mm
d_1	≈	24.5	mm
D_2	≈	34.98	mm
$r_{1,2}$	min.	0.6	mm

Figure 6.4. Deep groove ball bearings (6203) (9)

End of arm bearing: according to the installation of bearing segment shaft diameter of 17 mm, and installation size, basic rated load and other factors. The final selection of bearing code is 6203 (Deep groove ball bearings). Consistent with the bearing selection of the small arm. (9)

7 Summary

Through the design of the logging robot arm, we could make a series of design, master a certain degree of mechanical design basis and simple use. Thus, this creates a solid foundation for the future work and study. The design process includes a large arm, a small arm, a waist and support structure design; servo motor, gearbox selection; bearing selection and checking. Further design and calculation of the structure and driving of the manipulator could be carried out. The whole manipulator needs to complete four kinds of motions during the working process, such as the revolving motion of the waist, the revolving motion of the large arm, the revolving motion of the small arm and the revolving motion of the arm of the end. Various rotary parts use a servo motor and a gearbox combination in such ways to achieve movement, and types and models of the required servo motor and gearbox could also be known through calculation.

Figures

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