机械与能源工程系
SUSTech Department of Mechanical and Energy Engineering

实 验 报 告

课程名称：机械设计基础

课程编号：ME303

实验题目：足式机器人

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实验成绩：

实验日期：2021 年 5 月 2 日

1 Background

The motivation of this project is to help people to finish some daily work and improve the efficiency of repetitive jobs which are considerably meaningful to human. In this project, our goals and tasks can be summarized as making a robot which can walk stably and at the same time it is strength on velocity. To reach this final target, we decided to design a robot with eight legs, four on both side to unsure the stability. In the process of design, we first searched for inspirations of references and found some traditional linkage as design base. Under an overall consideration, we chose Klann linkage as the fundamental structure of the leg and embark on drawing 3D draft of the robot. After that, we designed the gearing and did kinematic and dynamic analysis which conclude optimization of gait and reaching maximum utilization of power. Finished the above part, we process each component with 3D printing and get them fabricated. There appeared some questions, like transmission of gears and shafts. To fix this problem, we modify the hole of gears to square shape. Afterwards we did walking test and complete optimization according to the result, for example, adding friction and adjustment of main board structure. Finally, we built a robot that was more efficient, walking, and stable than before.

2 Background

2.1 Project Background

The 21st century is an era of large-scale mechanization and mechanization. According to the demand of The Times, we hope to make some robots to assist or complete some tasks independently. In our daily lives, when we need to deliver something, we want to minimize the need for human resources. Therefore, we would like to design and manufacture a connecting rod type foot robot (driven by a single motor) with a gearbox. Although this version of the design may not be able to carry a very large number of objects, we hope to enhance our capability through the design of this project. For example: practical ability, teamwork ability, communication ability, knowledge learning ability and so on.

2.2 Objectives and Tasks

The main evaluation index of this project is the straight-line moving speed of the machine on flat ground. We want to be able to reach the destination in as short a time as possible, which requires us to design as fast as possible. The tasks we need to accomplish and the schedule will be detailed in the work plan in Part 3.

3 Project Plan

3.1 Preliminary design

In this part, we will give a brief introduction on locomotion, number of feet, gait, parts layout, components connection etc.

3.1.1 Initial Conception

1) General Ideas

The robot can be divided into body, legs, and feet.

The initial concept is that the body part contains a battery and a single motor and gear transmission component, which is connected to the leg through a shaft.

2) Sports Ideas

Since we have only one motor, there is no way to use multiple motors to control each foot individually, so it is necessary to ensure static stability. Therefore, we adopted the structure of the eight-legged robot to ensure that the four legs can stand on the ground stably when at rest, so as to ensure the stability when at rest. This option definitely makes the device very stable, which is why we chose it.

In the process of movement, the device uses a connecting rod mechanism to lift the leg and push the ground forward. The legs are one-way circular movement, and the driving direction is single, which is easier to control. In order to move in a straight line when walking, the body and feet need to be symmetrical, and the center of gravity should be on the axis of symmetry. The gait adopts ordinary flat straight gait and wavy gait. The direction of motion is only a straight line, so we don't have to worry about other degrees of freedom.

3) Overall layout scheme

Place the gearbox (transmission mechanism), battery box, and motor in the same plane.

Since only need to achieve straight-line driving, the body design is long, the motor and battery are placed on the head and tail, the transmission mechanism is placed in the middle, and the plywood on both sides of the gear is added in the middle.

4) feet on each side.

The body support force is transferred from the leg linkage mechanism to the splints on both sides, and the motor provides only torque and no radial force.

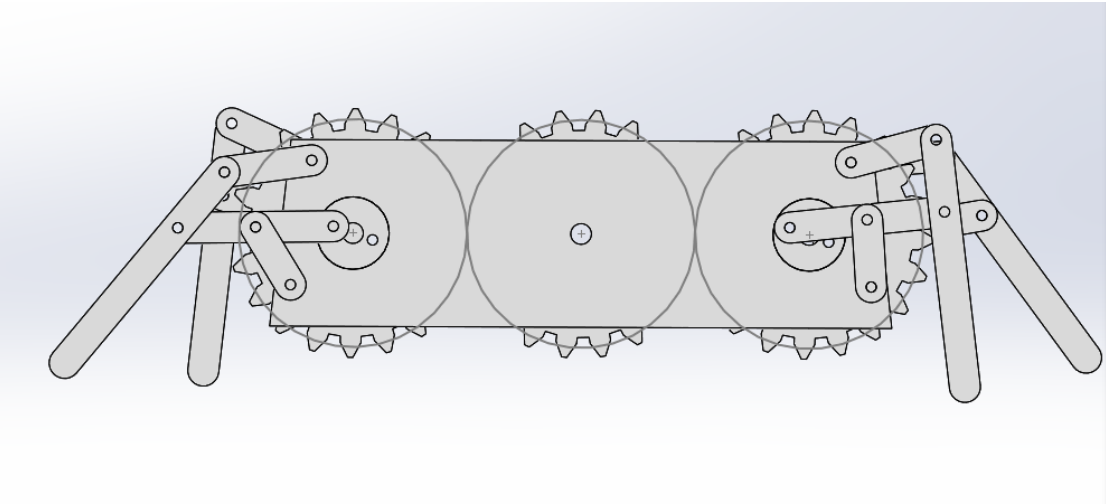
5) Body size

Main board: length--300mm width--150mm thickness--10mm

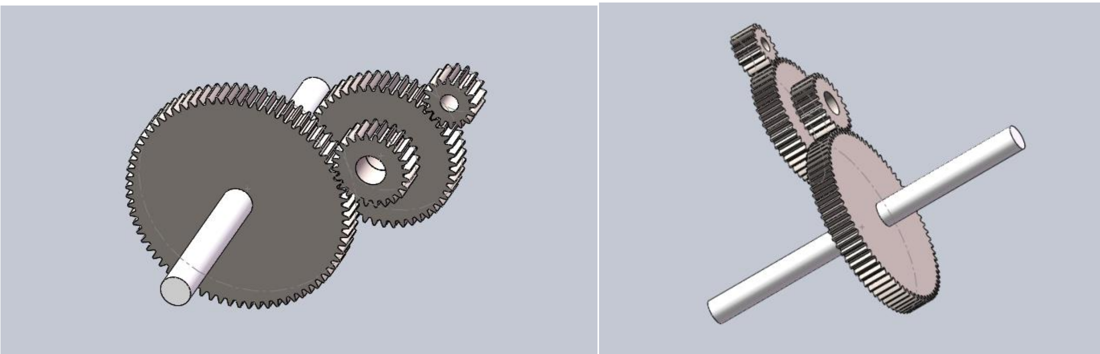
Side board: length--290mm width--80mm thickness--5mm

3.1.2 3D Preliminary Drawing of SolidWorks

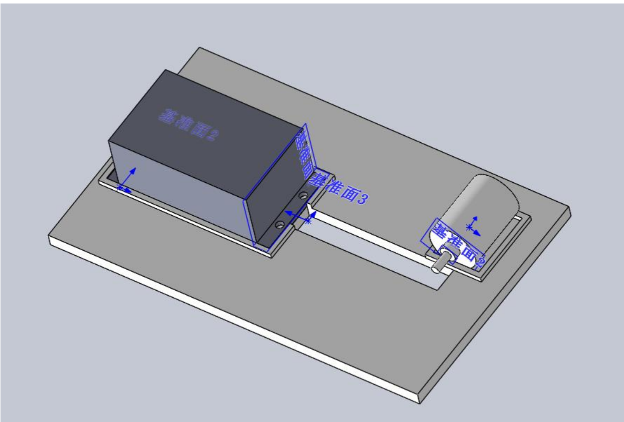
1) The sketch of the whole body.



3) The sketch of the reduction gearbox.

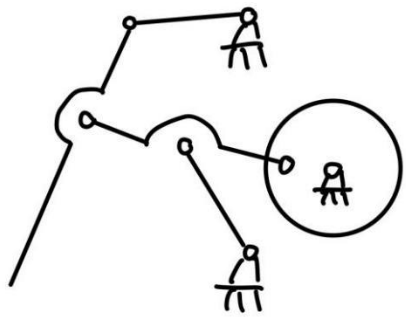


3) The sketch of the main board.



3.1.3 Mechanical Schematic Drawing

This is a schematic drawing of single-leg mechanical principles.



3.2 Task assignments

In this part, we will do the work breakdown and work assignments of each team member.

3.2.1 Hanqi Su

1) Draw some SolidWorks parts drawings

2) Motherboard design and gear transmission design

3) Aesthetic design

3.2.2 Yifan Xuan

1) Material procurement and fund management

2) Leg structure design

3) The motion scheme -- the design of the single foot connecting rod structure

3.2.3 Xingrong Diao

1) Draw some SolidWorks parts drawings

2) Motion scheme -- Multi-foot movement sequence analysis

3) kinematic analysis of motion scheme

3.2.4 Jiahui Yang

1) Part of the report preparation

2) motion scheme -- design of single - foot connecting rod structure

3) The modification and correction of the design drawing

3.2.5 Kezhou Chen

1) Part of the report preparation

2) 3D printing or parts procurement

3) The assembly of the whole structure

3.2.6 Dihan Liu

1) Part of the report preparation

2) Motion scheme -- kinematic analysis

3) Optimal design

3.3 Work schedule

3.3.1 General Layout (two weeks)

1) Confirm the overall design plan, preliminary division of labor, and work completed at each time node.

2) Preliminary motion conception, sufficient number, gait, direction of movement, etc.

3) Overall layout scheme: motor, battery box, transmission mechanism and other components layout, the determination of the overall size. The connection mode between the components: fuselage and leg, drive shaft

and body, leg connecting rod, motor and body, pin connection, key connection, glue connection, etc.

4) Preliminary drawing of SolidWorks 3D drawings and mechanical principle sketch drawing.

3.3.2 Exercise program (two weeks)

1) The choice of foot type. (e.g. 4,6,8 etc.)

2) Gait type selection. (e.g. Multi-foot moving order)

3) Single foot structure design: connecting rod structure design, design vector closed loop to calculate the connecting rod mechanism with the largest effective working stroke ratio (that is, the minimum height of lifting leg, the longest touching stroke).

4) Kinematics analysis, get better linkage mechanism, trajectory.

5) Estimate the overall weight of the robot to solve the maximum torque required by the rocker end of the connecting rod (with appropriate consideration of friction).

6) According to the torque of the given motor (300r/min) and the maximum torque of the rocker end of the connecting rod, the transmission scheme from the output section of the motor to the middle part of the foot connecting rod section is designed.

3.3.3 Overall assembly (two weeks)

1) Print parts (3D printing in the future workshop), complete assembly and debugging.

2) Summarize the completed parts, analyze the existing problems, correct the corresponding parts and re-assemble them.

3.3.4 Optimization design (two weeks)

1) Optimize the design according to the assembly process and walking effect, improve the existing problems, and reassemble.

2) Draw the 3D drawings of the whole machine, test the running state of the device, and make the final adjustment and modification.

3) Taking into account the optimization of friction, counterweight and motor output power.

4) Aesthetic optimization.

3.3.5 Report summary and report writing (one week)

1) Writing experiment report.

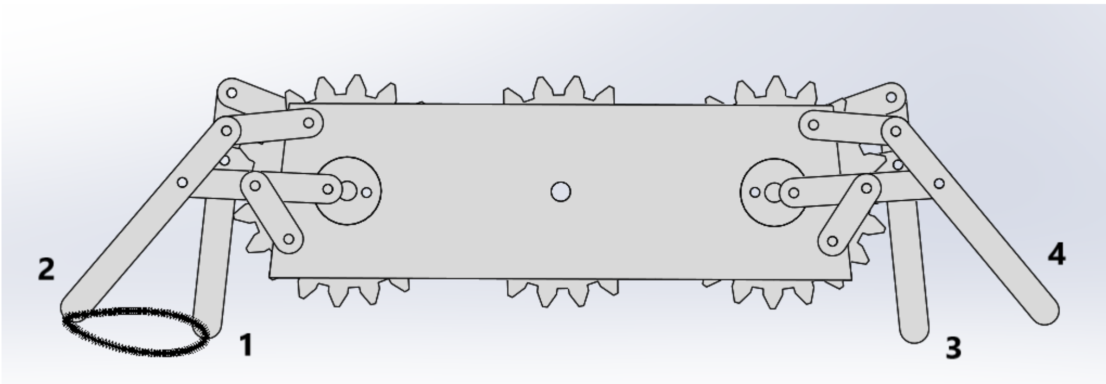
4 Conceptual design

4.1 Foot mode selection

We chose an eight-legged robot for our project. The reason is that this mode provides the best stability and load capacity. This is very important for our design of this project. After all, only if we maintain relative stability can we continue to explore whether we can run faster. For a four-legged robot, one circle of the walking gait is with two legs on the ground and two legs off the ground. However, in the state of motion, the two-point support is not stable, and it is difficult for the robot to keep balance. At this time, the robot needs relatively high speed and uniform density of materials to ensure the stability of its center of gravity. For a hexapod robot, the stability of the three-point touch is not high enough. In addition to the balancing capability, since the project only provides one motor, the six-leg gear drive will be similar to the eight-leg gear drive. This gear drive cannot achieve the efficiency of the spider walking mode. Therefore, considering the stability and weight of the motor and battery load, we chose the eight-legged robot. The eight-legged robot uses four points to hit the ground simultaneously, effectively avoiding the balance problem mentioned earlier. You can also achieve better results while walking in a straight line and carrying weights.

4.2 Gait type selection

The gait type was walking. Our robot's general structure is as shown in the following picture. It has four legs on each side, denoted as 1-8 respectively.



The order of movement is, in the set of four feet located on the ground, the back leg pushes the ground, at the same time, the front leg lifts legs forward. The other set hit the ground on all fours with the same exercise pattern. The reciprocating movement of the two sets of four legs causes the robot and the center of gravity to move forward successfully. If considered what is shown in the diagram as the initial position. The legs move in the order of 3, 7 kick the ground, leg 1, 5 lift up, 2, 4, 6, 8 pull themselves close the body and touch the ground, then it goes to 4, 8 kick and leg 2, 6 lift up, 1, 3, 5, 7 pull themselves close and touch the ground. Moreover, during the walking mode, the two legs drive gear working in clockwise rotation, and the same side leg or the same group of legs has a phase angle difference of 180 degrees, each joint moves with the drive wheel.

4.3 Single foot structure design:

First, we searched various materials on the Internet to understand the structure of various linkage mechanisms, and then analyzed them one by one in the way of vector closed loop. Finally, by comparing the vector closed-loop equations of each linkage mechanism, the Chebyshev linkage mechanism was selected as our single-legged linkage structure.

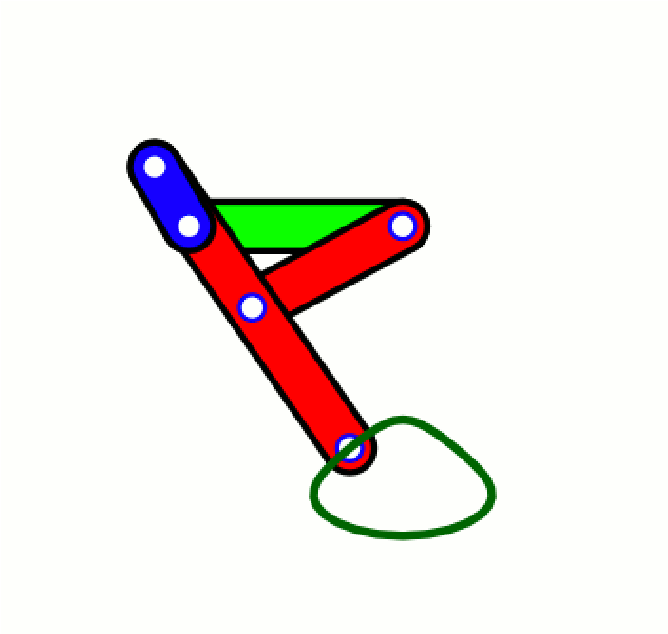
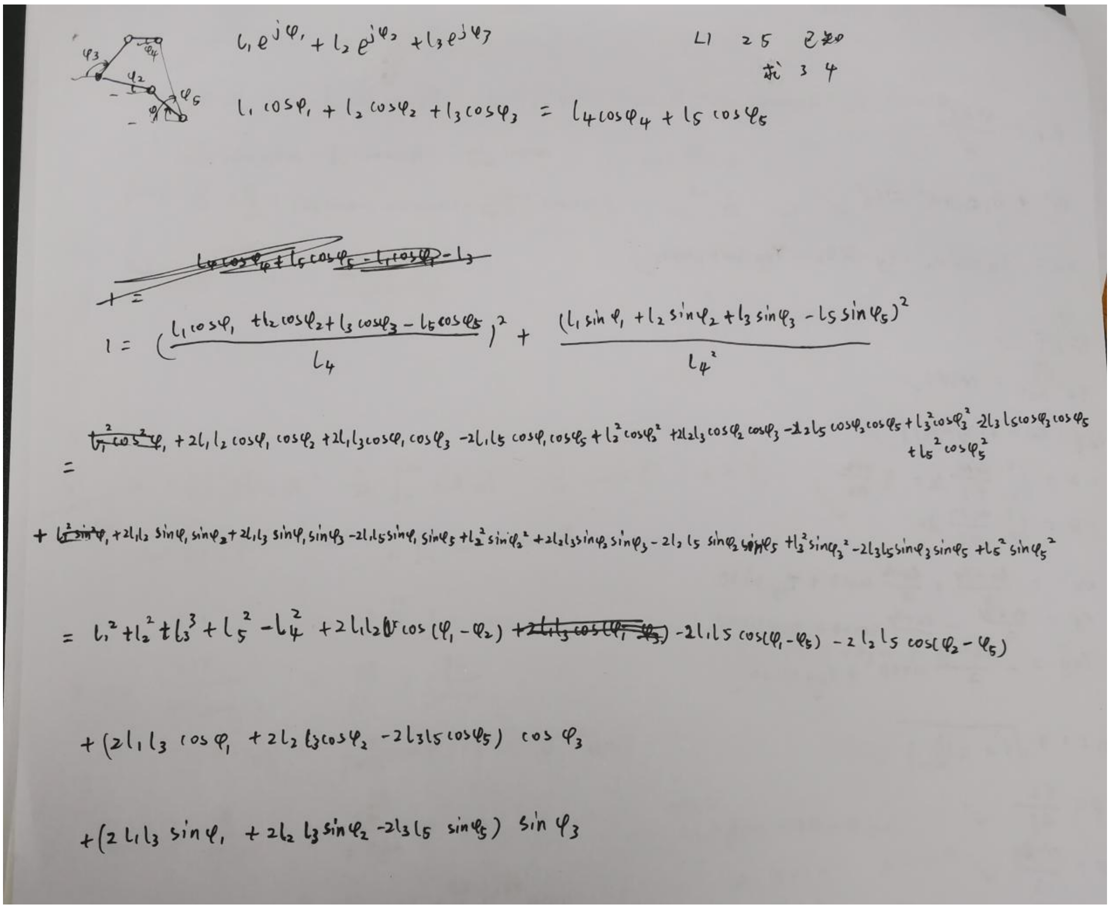


Fig. 1 (Chebyshev linkage mechanism)



$$l_1 e^{j\varphi_1} + l_2 e^{j\varphi_2} + l_3 e^{j\varphi_3}$$

L1 2 5 已知
求 3 4

$$l_1\cos\varphi_1 + l_2\cos\varphi_2 + l_3\cos\varphi_3 = l_4\cos\varphi_4 + l_5\cos\varphi_5$$

$$\cancel{l_4\cos\varphi_4 + l_5\cos\varphi_5 = l_1\cos\varphi_1 - l_3}$$

$$1 = \left(\frac{l_1\cos\varphi_1 + l_2\cos\varphi_2 + l_3\cos\varphi_3 - l_5\cos\varphi_5}{l_4}\right)^2 + \frac{(l_1\sin\varphi_1 + l_2\sin\varphi_2 + l_3\sin\varphi_3 - l_5\sin\varphi_5)^2}{l_4^2}$$

$$= l_1^2\cos^2\varphi_1 + 2l_1l_2\cos\varphi_1\cos\varphi_2 + 2l_1l_3\cos\varphi_1\cos\varphi_3 - 2l_1l_5\cos\varphi_1\cos\varphi_5 + l_2^2\cos\varphi_2^2 + 2l_2l_3\cos\varphi_2\cos\varphi_3 - 2l_2l_5\cos\varphi_2\cos\varphi_5 + l_3^2\cos\varphi_3^2 - 2l_3l_5\cos\varphi_3\cos\varphi_5 + l_5^2\cos\varphi_5^2$$

$$+ l_1^2\sin^2\varphi_1 + 2l_1l_2\sin\varphi_1\sin\varphi_2 + 2l_1l_3\sin\varphi_1\sin\varphi_3 - 2l_1l_5\sin\varphi_1\sin\varphi_5 + l_2^2\sin\varphi_2^2 + 2l_2l_3\sin\varphi_2\sin\varphi_3 - 2l_2l_5\sin\varphi_2\sin\varphi_5 + l_3^2\sin\varphi_3^2 - 2l_3l_5\sin\varphi_3\sin\varphi_5 + l_5^2\sin\varphi_5^2$$

$$= l_1^2 + l_2^2 + l_3^3 + l_5^2 - l_4^2 + 2l_1l_2\cos(\varphi_1-\varphi_2) \cancel{+2l_1l_3\cos(\varphi_1-\varphi_3)} - 2l_1l_5\cos(\varphi_1-\varphi_5) - 2l_2l_5\cos(\varphi_2-\varphi_5)$$

$$+ (2l_1l_3\cos\varphi_1 + 2l_2l_3\cos\varphi_2 - 2l_3l_5\cos\varphi_5)\cos\varphi_3$$

$$+ (2l_1l_3\sin\varphi_1 + 2l_2l_3\sin\varphi_2 - 2l_3l_5\sin\varphi_5)\sin\varphi_3$$

Fig. 2 (Vector Closed-Loop Calculation of Five-link Mechanism)

4.4 Kinematics analysis of linkage mechanism

First, the initial analysis of the problem

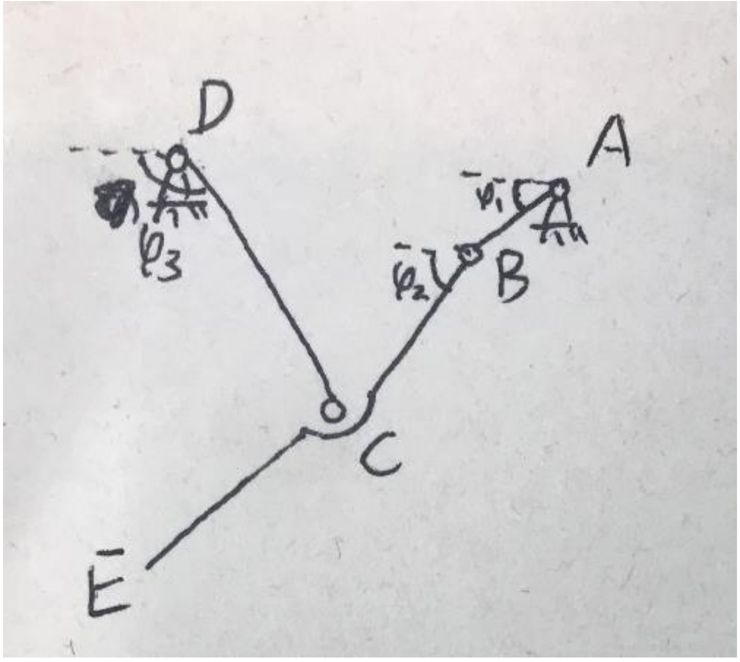


Figure 3 (mechanical diagram)

First, we draw the mechanical schematic diagram of the leg linkage mechanism (see Figure 1), and then obtain it according to the vector closed loop method. We get: $\overrightarrow{AB} + \overrightarrow{BC} = \overrightarrow{AD} + \overrightarrow{DC}$, and then we get $\Phi 3 = 2\arctan\left(\frac{B+\sqrt{A^2+B^2-C^2}}{A-C}\right)$, $\Phi 2 = \arctan\left(\frac{B+CD\sin\Phi 3}{A+CD\cos\Phi 3}\right)$, Where $\Phi 1$ is the independent variable, $A = AD - AB\cos\Phi 1$, $B = -AB\sin\Phi 1, C = \frac{A^2+B^2-BC^2-CD^2}{2CD}$(See Figure 2 and Figure 3 for the detailed solution process). Then the coordinate of E point is expressed through MATLAB. After we will again by $\Phi 1$ to 1, the interval is 0.001 to simulate the rotation of the crank AB. So we have the general solution for the trajectory of point E (Procedure is as follows):

```
angle1=0:0.001:2*pi;

A=l4-l1*cos(angle1);

B=-l1*sin(angle1);

C=(A.^2+B.^2+l3^2-l2^2)/(2*l3);

%求∠3 和∠2

angle3=2*atan((B+(A.^2+B.^2-C.^2).^0.5)./(A-C));

angle2=atan((B+l3*sin(angle3))./(A+l3*cos(angle3)));

H=l1*exp(j*angle1)+l5*exp(j*angle2);

x=real(H);

y=imag(H);
```

$AB=l_1,\ BC=l_2,\ CD=l_3,\ AD=l_4,\ AE=l_5$

$l_1 \cdot e^{j\varphi_1}+l_2 \cdot e^{j\varphi_2}=l_4+l_3 \cdot e^{j\varphi_3}$

欧拉公式展开得：

$l_1(\cos\varphi_1+j\sin\varphi_1)+l_2(\cos\varphi_2+j\sin\varphi_2)=l_4+l_3(\cos\varphi_3+j\sin\varphi_3)$

$\therefore\ l_1\cos\varphi_1+l_2\cos\varphi_2=l_4+l_3\cos\varphi_3$

$l_1\sin\varphi_1+l_2\sin\varphi_2=l_3\sin\varphi_3$

利用平方和消去φ_2得：

$l_2^2=(l_4+l_3\cos\varphi_3-l_1\cos\varphi_1)^2+(l_3\sin\varphi_3-l_1\sin\varphi_1)^2$

$=l_4^2+l_3^2\cos^2\varphi_3+l_1^2\cos^2\varphi_1+2l_3l_4\cos\varphi_3-2l_1l_4\cos\varphi_1-2l_1l_3\cos\varphi_1\cos\varphi_3$
$+l_3^2\sin^2\varphi_3+l_1^2\sin^2\varphi_1-2l_1l_3\sin\varphi_1\sin\varphi_3$

$=l_4^2+l_3^2+l_1^2-2l_1l_3\sin\varphi_1\sin\varphi_3+2(l_4-l_1\cos\varphi_1)l_3\cos\varphi_3$

$\therefore\ (l_4-l_1\cos\varphi_1)\cos\varphi_3-2l_1\sin\varphi_1\sin\varphi_3+\dfrac{(l_4-l_1\cos\varphi_1)^2+(l_1\sin\varphi_1)^2+l_3^2-l_2^2}{l_3}=0$

令$A=l_4-l_1\cos\varphi_1$

$B=-2l_1\sin\varphi_1$

$C=\dfrac{A^2+B^2+l_3^2-l_2^2}{2l_3}$

$\therefore\ A\cos\varphi_3+B\sin\varphi_3+C=0$

$\because\ \sin\varphi_3=\dfrac{2\tan(\frac{\varphi_3}{2})}{1+\tan^2(\frac{\varphi_3}{2})},\ \cos\varphi_3=\dfrac{1-\tan^2(\frac{\varphi_3}{2})}{1+\tan^2(\frac{\varphi_3}{2})}$

Fig. 4 (General solution derivation process I)

$$\therefore A\left(\frac{1-\tan^2(\frac{\varphi_3}{2})}{1+\tan^2(\frac{\varphi_3}{2})}\right)+B\frac{2\tan(\frac{\varphi_3}{2})}{1+\tan^2(\frac{\varphi_3}{2})}+C=0$$

$$\therefore (C-A)\tan^2(\tfrac{\varphi_3}{2})+2B\tan(\tfrac{\varphi_3}{2})+C=0$$

$$\therefore \tan(\tfrac{\varphi_3}{2})=\frac{B\pm\sqrt{A^2+B^2-C^2}}{A-C}$$

$$\therefore \varphi_3=2\arctan\left(\frac{B\pm\sqrt{A^2+B^2-C^2}}{A-C}\right)$$

$$\because \varphi_3=2\arctan\left(\frac{B-\sqrt{A^2+B^2-C^2}}{A-C}\right) \text{图形不符}$$

$$\therefore \varphi_3=2\arctan\left(\frac{B+\sqrt{A^2+B^2-C^2}}{A-C}\right)$$

$$\text{同理得 } \varphi_2=\arctan\frac{B+l_3\sin\varphi_3}{A+l_3\cos\varphi_3}$$

Fig. 5 (General solution derivation process 2)

Finally, we first brought in a few sets of data to look at the trajectory:

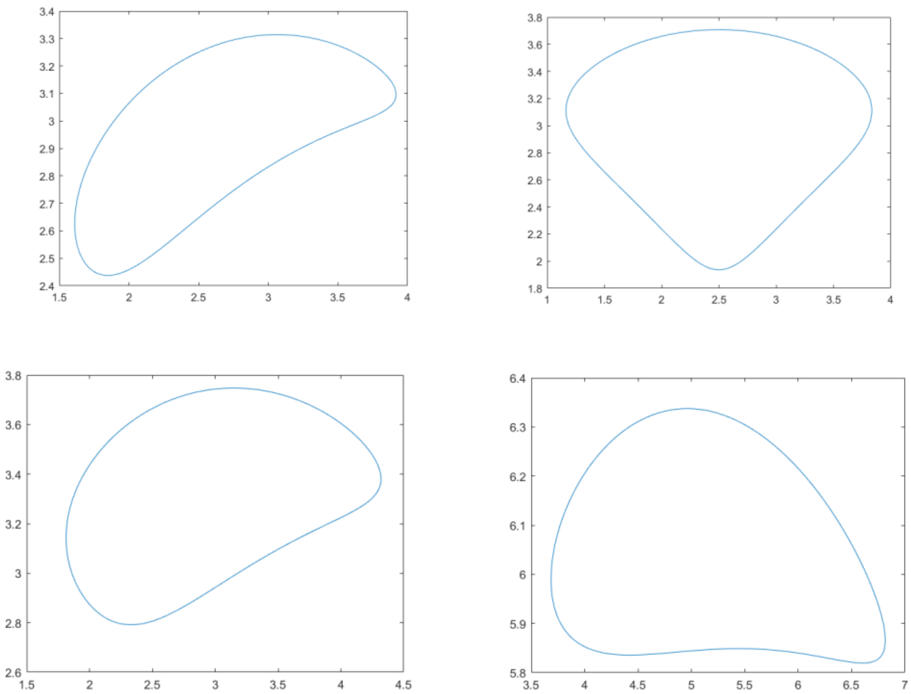


Fig. 6 (Test Track)

4.4.1 optimization method

We first set bar AB as 1, and then set the remaining bar lengths as unknowns, so that we can represent the trajectory of point E from the previous trajectory analysis.In order to obtain the minimum leg lifting height and the longest stroke touching the bottom, we first saved the maximum length in the Y direction, namely, the height of the leg lifting, and then recorded the number of points within 0.01 difference between ymin and xdistance, namely, the stroke touching the bottom. So after we've figured out all the possibilities, we take the probability that $\frac{x_{distance}}{y_{min}}$ is the most likely of all the possibilities, and that's the optimal solution.

4.4.2 the actual operation

In Matlab, set five for loops first, each for loop set a rod length, so that all the rod length possibilities are arranged. Then, in the innermost loop, the trajectory of point E of this possibility is calculated according to the formula. Then, through a for loop, the number of points within 0.01 of ymin is recorded, as xdistance.

Then, in order to exclude some special cases, some constraint conditions were added, and the data that did not conform to the constraint was removed. Finally, the data of each bar length for each possibility was recorded. After traversing the results of all possibilities, the maximum possibility of $\frac{x_{distance}}{y_{min}}$ is obtained, and the data of this possibility is extracted.

The detail procedure:

```
for l1=1
    for l2=5.5:0.1:5.7
        for l3=4.2:0.1:4.4
            for l4=4.4:0.1:4.6
                for l5=7.9:0.1:8.1
                    i=i+1;
                    A=l4-l1*cos(angle1);
                    B=-l1*sin(angle1);
                    C=(A.^2+B.^2+l3^2-l2^2)/(2*l3);
                    %求∠3 和角 2
                    angle3=2*atan((B+(A.^2+B.^2-C.^2).^0.5)./(A-
                    C));

                    angle2=atan((B+l3*sin(angle3))./(A+l3*cos(ang
                    le3)));
                    H=l1*exp(j*angle1)+l5*exp(j*angle2);
                    x=real(H);
                    y=imag(H);
                    Ymin=min(y);
                    nx=0;
                    Y(i)=max(y)-min(y);
```

```
            for n=1:length(x)
                if y(n)-0.01<Ymin
                    nx=nx+1;
                end
            end
            if -l2^2-l3^2-1.2856*l3*l4+(l1+l4)^2>0
                xtime(i)=0;
            elseif -l2^2-l3^2-1.2856*l3*l4+(l1-l4)^2>0
                xtime(i)=0;
            elseif nx>1000
                xtime(i)=nx;
            else
                xtime(i)=0;
            end

            L1(i)=l1;
            L2(i)=l2;
            L3(i)=l3;
            L4(i)=l4;
            L5(i)=l5;
        end
    end
```

```
        end
    end
end



for j=1:length(Y)
    ratio(j)=xtime(j)/Y(j);
end
[zuiyoujie I]=max(ratio);
bestL1=L1(I);
bestL2=L2(I);
bestL3=L3(I);
bestL4=L4(I);
bestL5=L5(I);
```

In order to facilitate the calculation and improve the operation efficiency, the accuracy of 1 was used to solve the solution first, and the approximate optimal solution interval was found. Then the accuracy was increased to 0.5, and then the interval of the optimal solution was reduced, and then the accuracy was increased to 0.3 and 0.1 again, and the optimal solution was finally obtained. And then I'm going to plot the trajectory of the optimal solution.

```
bestL1 =

     1


bestL2 =

    5.6000


bestL3 =

    4.3000


bestL4 =

    4.5000


bestL5 =

     8
```

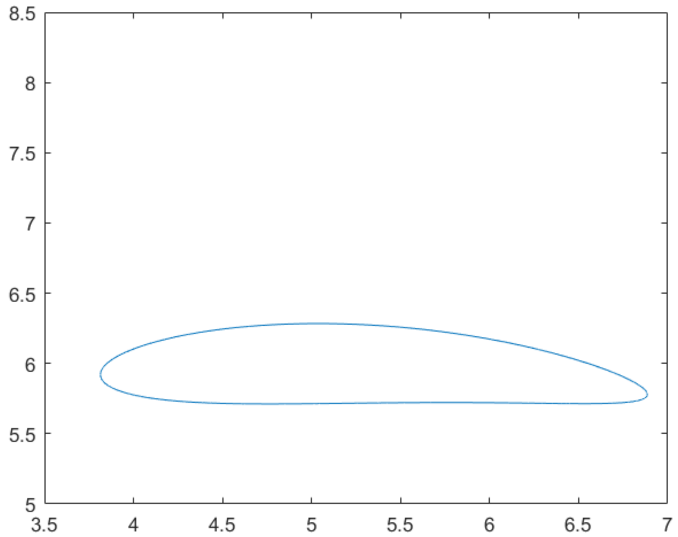


Fig. 7 (optimal solution)　　Fig. 8 (optimal solution trajectory)

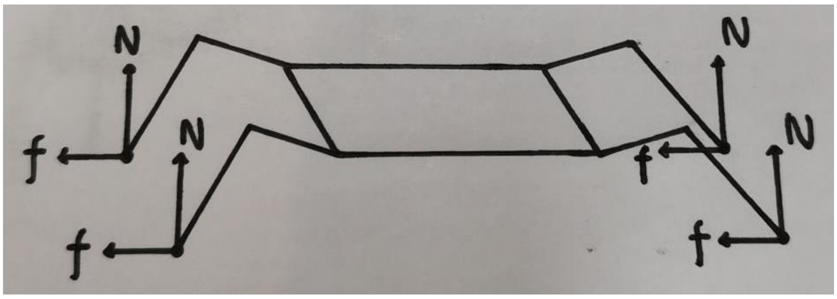
Note: It is necessary to pay attention to avoid that the trajectory of the final optimal solution is a straight line or a curve, so it is necessary to roughly estimate the length of each rod for the first calculation.

4.5 Estimate the Maximum Required Torque

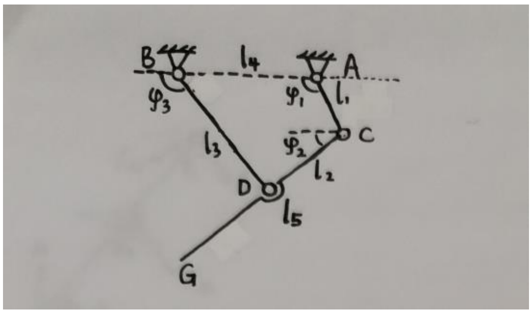
4.5.1 Step1

According to our design, we have eight legs divided into two groups. And each time there will be one entire group touching the ground. And the motion of each leg is the same, so is their free body diagram. So we could simply analysis the motion of one leg.

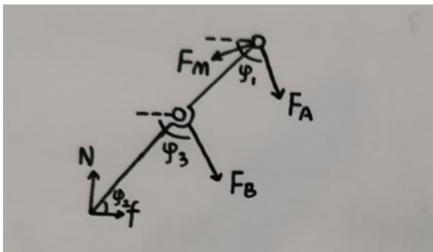
The following picture is considering the robot as a whole, so each leg is supported by a force N. We could easily give rise that 4N=Mg.



4.5.2 Step2



We analyze the motion of one specific leg. So we could draw the free body diagram of bar CDG, and establish three equations according to its three degree of freedom.

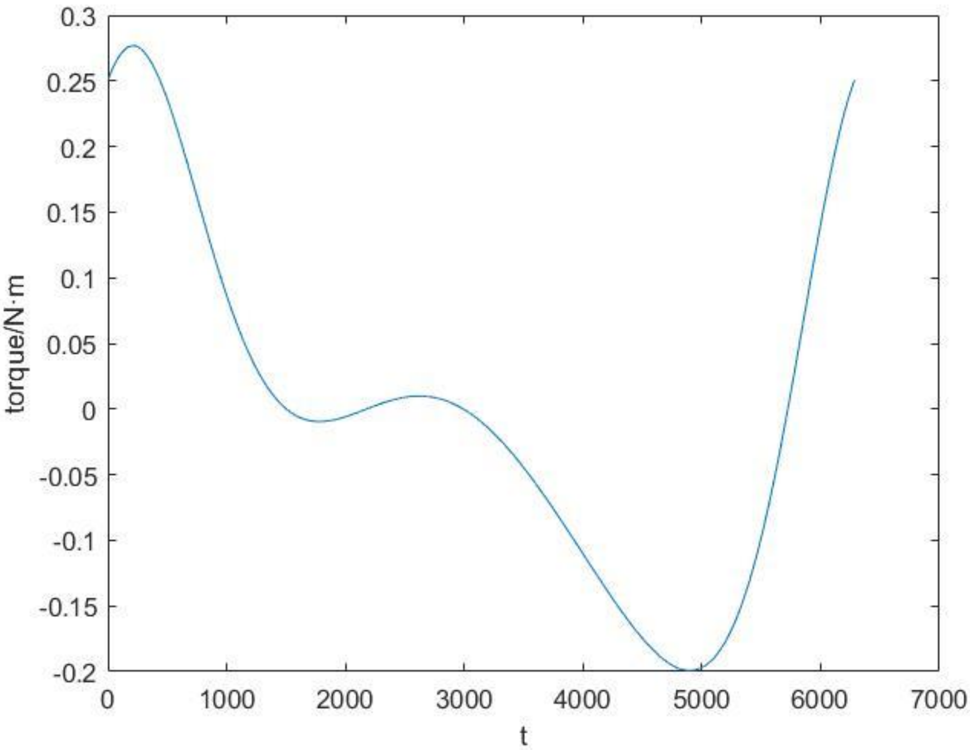


$$|F_m| = \left|\frac{T}{L_1}\right|$$

$$\begin{cases} N + \frac{T}{L_1}\sin(\frac{\pi}{2}+\varphi_1) + F_A\sin(\pi+\varphi_1) + F_B\sin(\pi+\varphi_3) = 0 \\ f + \frac{T}{L_1}\cos(\frac{\pi}{2}+\varphi_1) + F_A\cos(\pi+\varphi_1) + F_B\cos(\pi+\varphi_3) = 0 \\ F_B\sin(\varphi_3-\varphi_2)\cdot(l_5-l_2) + F_A\sin(\varphi_1-\varphi_2)l_5 + \frac{T}{L_1}\sin(\varphi_1-\frac{\pi}{2}-\varphi_2)l_5 = 0 \end{cases}$$

Remind that f is used as driven force that push the robot to move forward. So, if we set f to 0, then we could find the least maximum torque required.

The diagram below shows the distribution of required torque to keep robot moving during a period. (Notice there might be some negative values for the required torque, this mean while at this position, the robot don't need a torque. It can move by is own gravitational potential energy.)



And we calculated that the least maximum torque required is 0.2767N·m for each leg.

4.6 Transmission scheme design

4.6.1 Basic principles and design ideas

From the definition of power, and for the motor, $P = F \cdot V = F \cdot l \cdot w$ 。Where l is the radius of the motor gear connected to the motor, and w is the speed of the given motor. The product of F and l is the output torque of the given motor. Since the output power of the motor is certain and w is relatively large, the torque produced by the motor is relatively small. Since the torque of the rocker end of the connecting rod is usually large, we hope to increase the torque to meet the torque demand of the rocker end of both sides by designing appropriate transmission scheme, and meanwhile, we also hope to keep the speed of the output end suitable as far as possible.

This experiment uses gear transmission, gear transmission refers to the gear pair transmission movement and power device, it is the most widely used in modern equipment in a mechanical transmission mode. Its transmission is more accurate, high efficiency, compact structure, reliable work, long life.

In the design of our transmission scheme, the main need to take into account the gear transmission ratio. Transmission Ratio - In a mechanical transmission system, the ratio of the angular speed or speed between the starting driving wheels and the trailing driving wheels.

Transmission ratio (i)= the ratio of the angular velocity of the driving wheel (w1) to the angular velocity of the driving wheel (w2)= the ratio of the speed of the driving wheel (n1) to the speed of the driving wheel (n2)= the inverse ratio of the diameter of the gear indexing circle = the ratio of the number of teeth of the driven gear (Z2) to the number of teeth of the driving gear (Z1).

Namely: $i = w1 / w2 = n1 / n2 = D2 / D1$

$i = n1 / n2 = Z2 / Z1$

For multistage gear drives

1. The transmission ratio between each two shafts is calculated according to the above formula

2. The total transmission ratio from the first axis to the NTH axis is calculated according to the following formula: the total transmission ratio $I = (Z2/Z1) \times (Z4/Z3) \times (Z6/Z5) ...... = (n1/n2) \times (n3 / n4) \times (n5 / n6) ......$

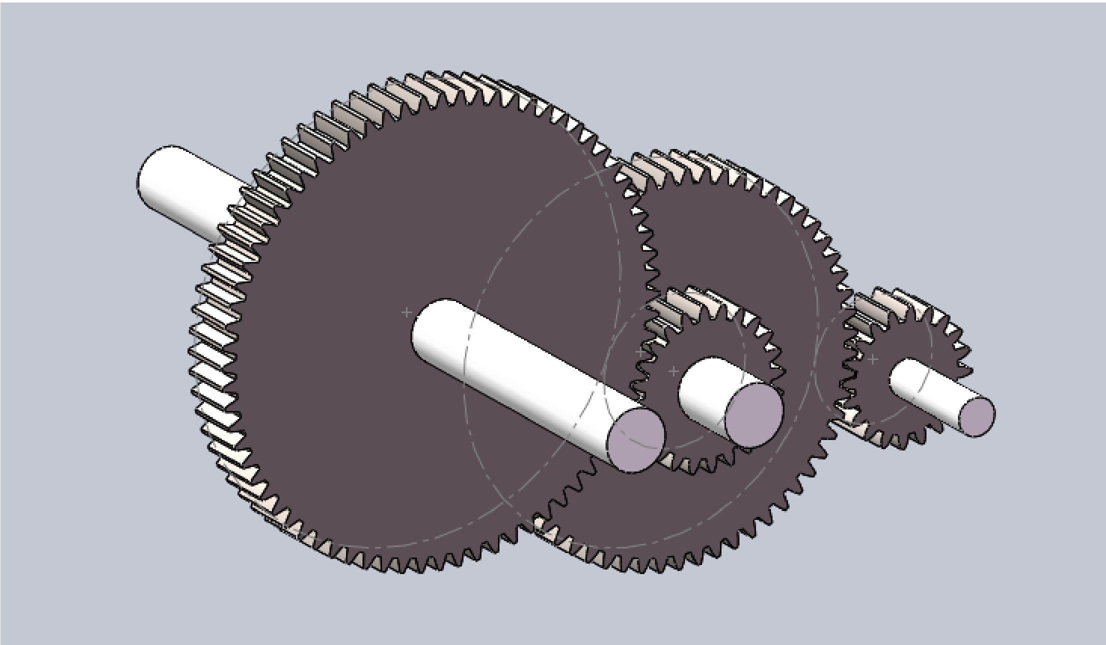
The following diagram is a schematic diagram of the multi-stage drive:

The core work of this design is to design the right transmission ratio.

If the transmission ratio is too small, the deceleration efficiency is low; If the gear ratio is too large, the maximum gear design will be large. Since the gear ratio of spur gears is generally 3-6, we use a gear ratio of 3 here.

4.6.2 Optimal results

After the same result obtained from the previous calculation, given the output power of the motor and the maximum torque of the rocker end of the connecting rod, we adopted the design scheme as shown in the figure. The diameter of the gears is 20mm,60mm,24mm.72mm (from right to left), so that the transmission ratio is (60 / 20) x (72 / 24)= 3 x 3 = 9. Thus, the torque of rocker ends on both sides can reach 2.86nm. Under the action of this transmission ratio, we can meet the design requirements for the rocker end of the connecting rod.



4.7 Connection Mode of Components

4.7.1 Body and legs, pallets of the legs

The body and legs are two important parts of this robot, and the design and assembly of these two parts are relatively independent. After completing the assembly, they need to be combined to form a complete robot. Moreover, it is necessary to be separated and assembled again in the process of improvement and optimization. If we did a non-detachable connection, it is not easy to operate in the following process, especially for the gear in the leg splint. Therefore, there will be a threaded connection between the body and the leg and legs' splints. The use of screws can not only ensure the stability and durability of the assembled robot but also provide the detachability to facilitate the improved operation.

4.7.2 Transmission shaft and body

The function of the transmission shaft in the robot structure is to synchronize the rotation of the gears on both sides and drive the leg connecting rod to propel the robot to walk straightly. During the working process, the transmission shaft needs to rotate continuously at a certain height to ensure that it is stably connected with the gears in the reduction gearbox and leg splints. The transmission shaft and the body will be connected with a hole shaft at the appropriate height, and the holes are on both sides leg splints.

4.7.3 Connecting rods of legs

The restraining relationship and the movement trajectory between the connecting rods are generated by the overall structure design, but independent of the connection structure. To achieve the desired effect to the greatest extent, the connecting parts need a structure with low friction and wear to ensure flexible rotation. Pin connection will be used for the joint of connecting rods.

4.7.4 Motor, battery, and body

There should not appear relative displacement between the motor, the battery, and the body of the robot in the process of movement, so it is necessary for these parts to maintain a stable relative position. Otherwise, the skewing of any part may lead to accidents such as the gravity deviating from the center which will cause the machine to tip over or the running direction of the leg skewed and it is unable to walk in a straight line. In addition, it is necessary to avoid the deformation of the structural parts to ensure effective working. Therefore, the motor, battery, and the body will adopt the cementing connection, a material locking mode, which will be fixed the motor and battery on the centerline of the mainboard, respectively placed at the head and tail of it.

5 Fabrication

5.1Parts selection and fabrication and assembly process

5.1.1 Selection of materials

When considering the gear, we initially wanted to use metal, because the strength of metal is high, and the gear is not easy to break teeth and other phenomena. However, because metal gears are expensive and heavy, they are not good for our machines to run. In the end, we chose to use 3D printing to solve the gear problem. (The strength of the gear printed by 3D printing is OK, and the price is not very expensive, which is in line with the principle of simple economy)

When considering side panels, motherboards, legs and other parts, acrylic panels or carbon panels have been considered. But because the acrylic plate is relatively brittle, prone to fracture, and the price of carbon plate is high, not in line with the principle of economy. Therefore, we still chose to use 3D printing to solve all the parts.

5.1.2 fabrication

We choose to outsource our parts to the factories of the future. One saves time, and the other ensures accuracy. To maximize the efficiency of the project.

5.1.3 the assembly process

Our team members worked together to assemble our device. We first assembled the leg parts and side plates in sequence, then fixed the motherboard and side plates and installed our transmission device, then fixed the motor and battery to the motherboard, and finally energized the motor to carry out relevant experimental tests.

5.2 Result analysis

At present, the first generation of products can realize the straight-line movement of the whole machine on the flat ground. Since we use an eight-legged structure, our device can run smoothly on a flat surface and reach our desired speed (1 meter per minute). But there are also some problems, such as gear easy to slip, printed parts easy to deform, part of the gear is too small, the overall device is too heavy and other problems. In 5.3, we have a further explanation of this and the corresponding solution.

5.3 Existing problem and solution

5.3.1 leg

Problem: Because early in the process of optimization excessive pursuit of linkage leg height minimum, touch the ground travel the longest, lead to the design of the leg lifts connecting rod structure height relative to touch the ground travel really is very small, but the legs every turn a circle walking distance is very short, may cause in the process of walk fast enough.

Solution: Refer to various data, redesign linkage shapes in the legs, to find the right link mechanism, in the method of using vector closed-loop calculated trajectory equation of contact point, finally use the optimal trajectory of MATLAB program to traverse the longer length to find the right length scale, gradually improve accuracy, find a relatively optimal proportion of leg structure. And according to the constraint conditions to screen out the linkage mechanism we need.

5.3.2 joint

Problem: this version of the foot robot has only two connections, one is the motherboard to the side plate, the other is the transmission rod in the gearbox to the side plate. But the transmission link cannot be subjected to greater lateral force, so the transmission link on the connection of the role is not big. Besides, as the side plate the gear occupies most of the side plate, the left and right side plates cannot be connected with the connecting block extended from the motherboard at the same time, resulting in only one side of the connection, making the stability of the side plate and the connection degree between the motherboard and the side plate greatly decreased. At the same time, there is no guarantee that the legs on the side of the motherboard will have friction with the motherboard in the process of movement, reducing the transmission power.

Solution: After discussion, we decided to perforate the lower part of the side plate and in the corresponding position of the motherboard, and then connect the two with screws and nuts using the 90 degree straight Angle code connector. In this way, on the premise of ensuring the stability of the connection, the spacing between the side plate and the main board can be controlled.

5.3.3 gear

Problem: The reducer section was originally designed with a total transmission ratio of 1:9, consisting of two 1:3 driving gears. According to the requirement that the minimum number of teeth should be greater than 17, there appears giant gears with large teeth number like 72 feet, 100 feet. Big gears mean doing the same amount of work, it rotates a smaller angle and a large torque, saving travel but labouring. During laborious conditions, the tooth root is easy to be broken or some other damage may be brought to the gears. Due to the limited output of the motor, it is also possible that the gear box failed to be driven so that the whole robot cannot moved. The design of gear transmission still needs further adjustment and improvement.

Solution: According to the torque provided by the motor, a possible solution may be reducing the transmission ratio to reduce the number of teeth under the premise of ensuring the effective driving torque. Since the gearbox and the gear drive are two relatively individual parts, the module of the gear can be changed separately, but the module of the gear in a single part needs to be the same. All the teeth of the current version are one module, changing to two or three modules may be effective in order to reduce the number of gear teeth. Along with the changing of the gears, the side panels and motherboards also need changed accordingly.

5.3.4 Beauty

The first prototype was not very beautiful, we just made a rough design of its appearance, so that it could meet the basic movement function and the need to place the items. Of course, we pursue excellence and artistic design. Therefore, in the design of the second generation of products, we will consciously consider the artistic design for the motherboard and side boards. It may adopt hollow out, carving and other means to transform the product, reflecting the basic idea that science and technology is ultimately for the realization of humanistic care.

5.3.5 Weight loss

The first prototype was actually a bit heavier. Because we did not intentionally carry out hollowed-out operations in the design of the motherboard and side panels, even if we used 3D printing, the whole device was still heavy. So at this time, we can consider the way of hollowing out to save materials. Can save a price, accord with the principle of economy. Second, to save materials, reduce the weight of the device, is conducive to better movement of the device. At the same time, it can also make the product more beautiful and reflect the humanistic and artistic care.

6 Test and Optimization

6.1Operation test

We did the first test after assembly. The stability of the robot has achieved the expected effect. The robot did not tilt or having an unstable center of gravity which result in the rollover situation, because it has eight legs and the load on the motherboard is relatively uniform . Under the normal transmission condition, the robot can move in a straight line. Moreover, the clamping effect of the side plate on the gear is compact, as a result there is no large clearance and sliding between the gears, and the phase difference is relatively small. In addition, the motion speed of the robot also reached the expectation, the speed was faster, which was expected to reach 0.5m/min. There were also some problems during the testing. When the motor just opened, because the gear module is small, the support rod will be deformed under the action of the force, and the gear of the reducer will slide relative to each other, leading to the transmission failure. What's more, due to not dealing with the motor gear hole for processing. After running for many times, the friction decreases, these two have a certain relative sliding, and the transmission effect is weakened.

6.2Evaluate the result and modify

The evaluation of the test results is that the operation effect is generally achieved, but some parts still need to be reformed to achieve better results. For the first question mentioned above, the members of project decided to modify the structure and placement of the rod after discussion. It is planned to make the support rod into an open-loop rectangle with holes in the motherboard of the corresponding size, and fix the support rod to the motherboard. In addition, the spacing between the support rods should be appropriately reduced, so that the interference fit between them can be clamped to form a stable transmission. For the failure caused by the reduction of friction of the motor gear, a careful observation of the motor's drive shaft shows that one end is cut into a plane by a small part. Taking advantage of this feature, we drilled holes in the gears and added locating pins to reduce the possibility of relative slip and failure.

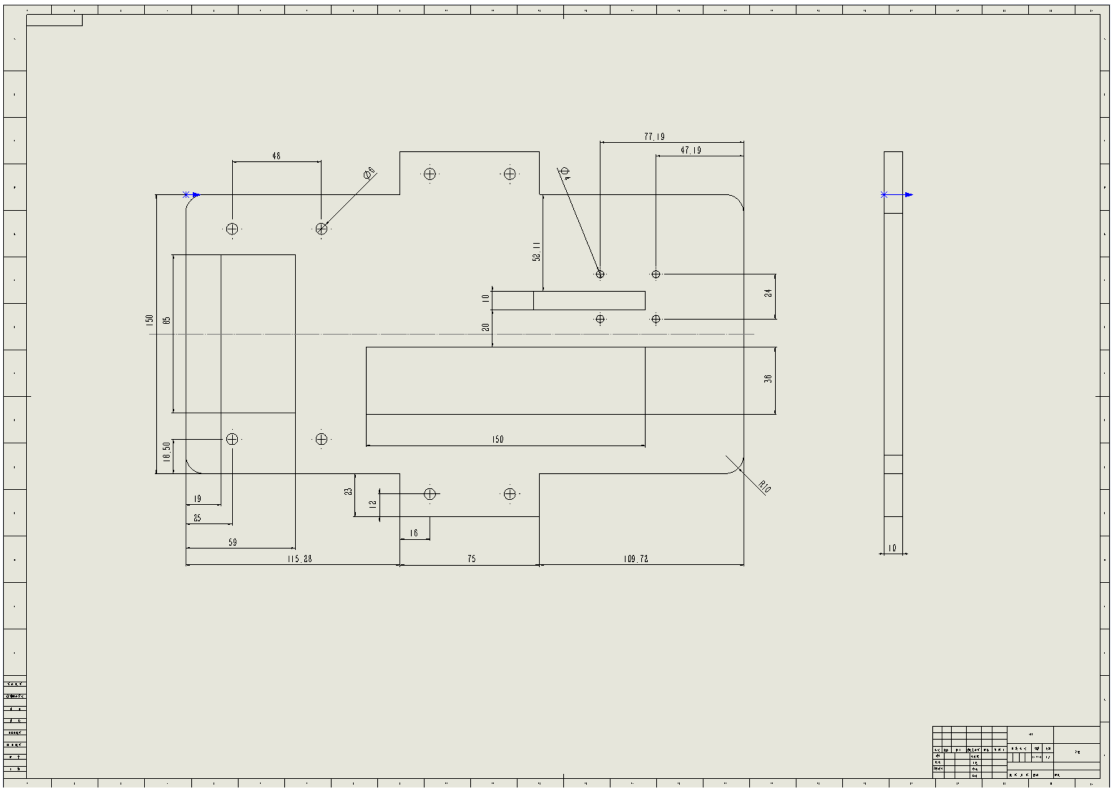
6.3Result

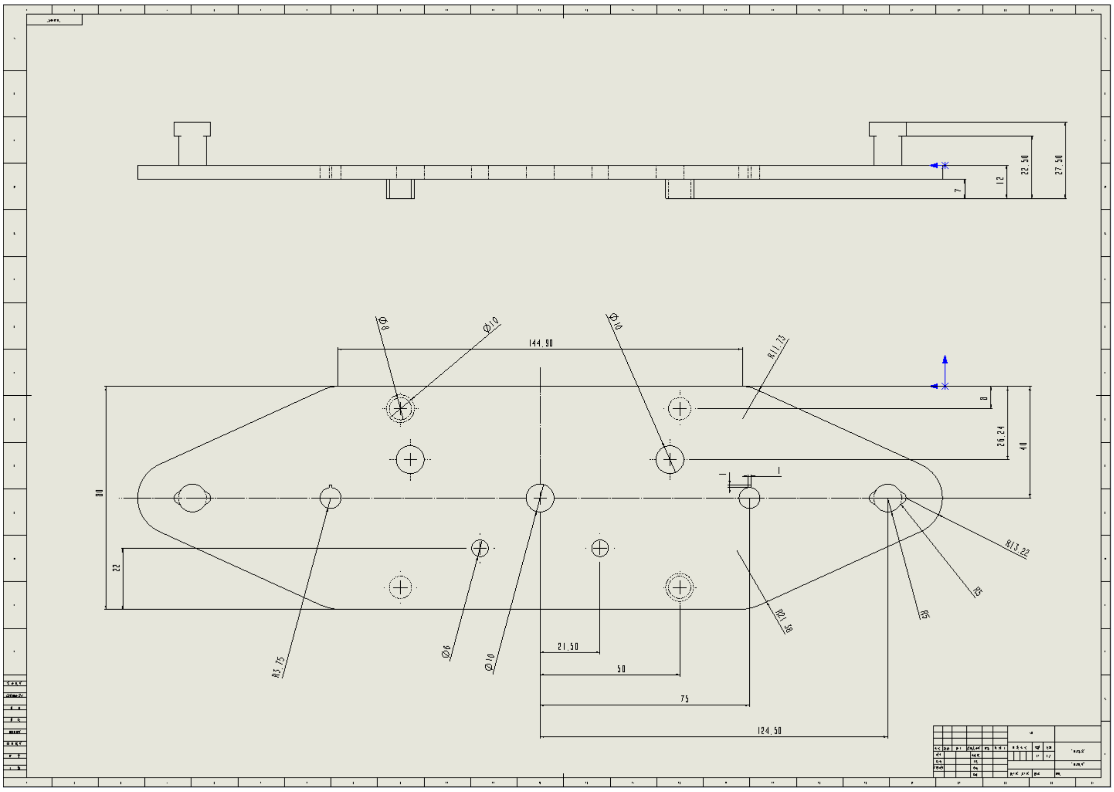
The structure replacement of the support rod is effective, and the gears of each part can be optimized for a long time stable transmission, and there will be no accident in the process of movement. The transformation of motor gear is effective. There is no significant relative sliding between motor and gear, which can provide stable power.

7 Final Design

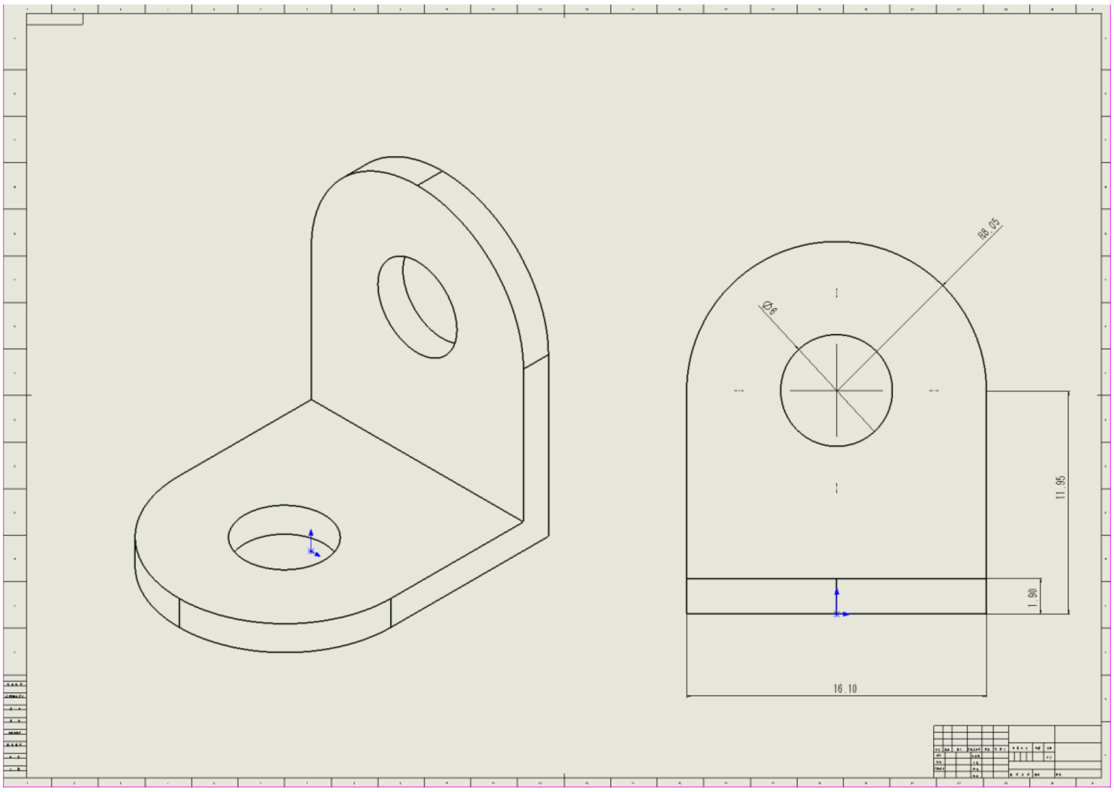
In the final optimization, the sole friction of the robot is optimized and enhanced. A prototype rubber cover matching the shape of the robot's sole is added to reduce the relative sliding between the sole and the ground in the process of movement, so that the effective step of words is reduced. A gasket is added between the connecting rods of the legs to reduce friction and improve movement efficiency. The hollow structure of the motherboard was redesigned to reduce the overall load of the robot. At the same time, the motherboard structure was guaranteed to carry the motor and battery and other components, so that the loss of vibration during movement would not occur fracture. Compared with the previous test, the robot has improved its appearance, has higher energy efficiency and forward speed, reaching about 0.6m/min. The overall mass of the robot is reduced by about a fifth, with a lower load.

8 Engineering Drawing

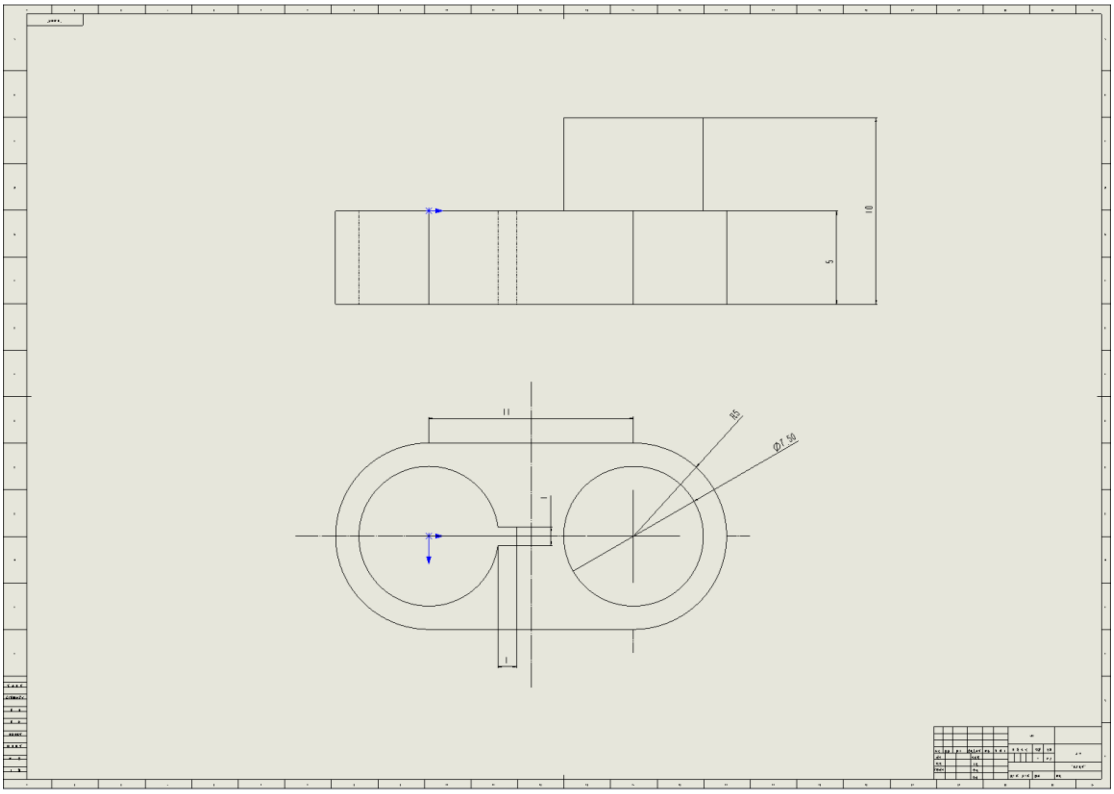


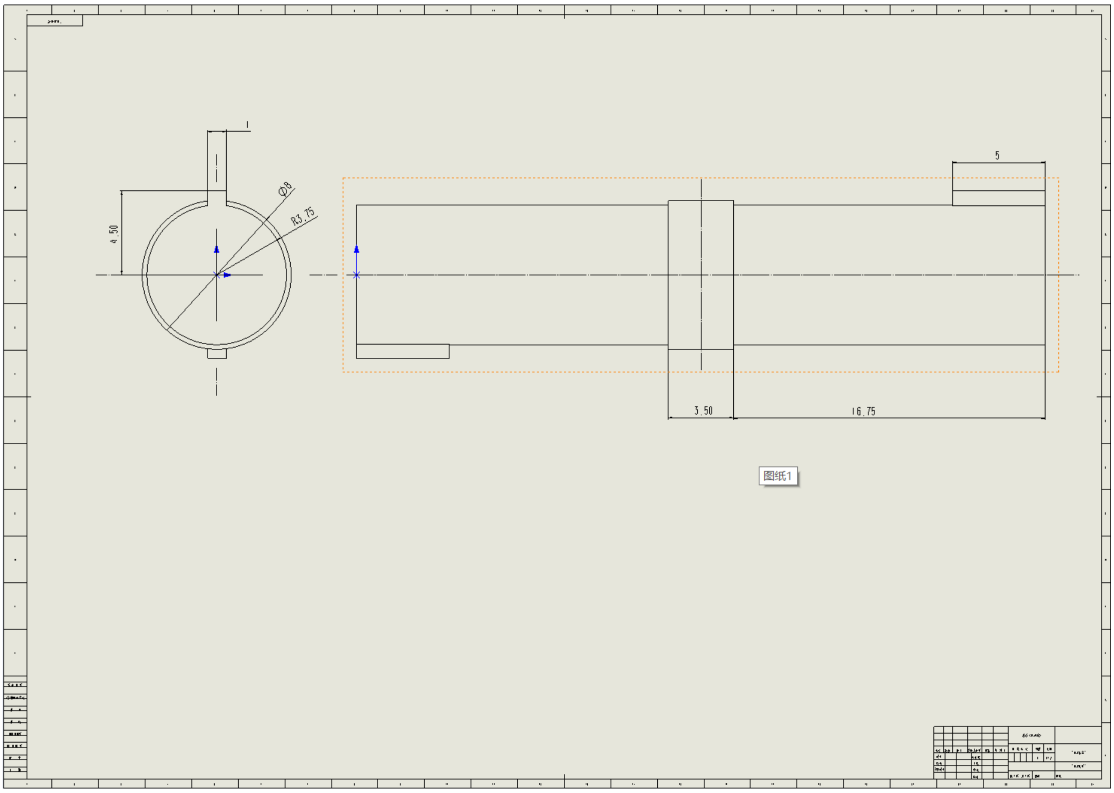


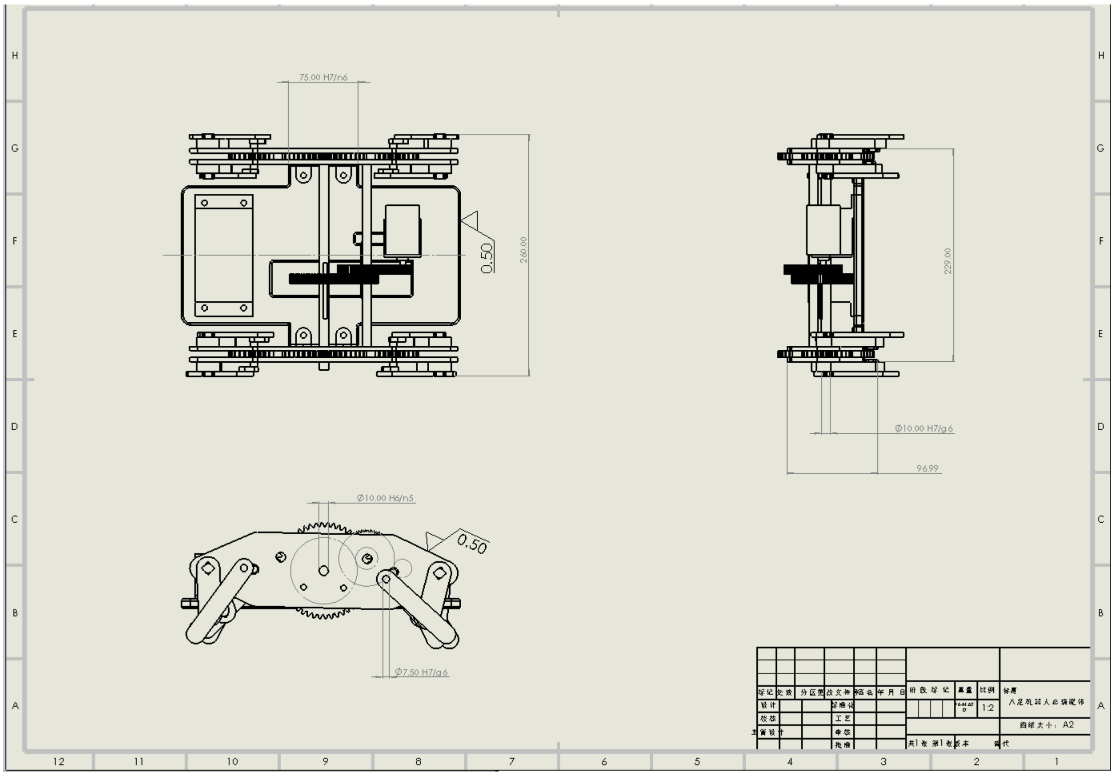
144.90
Ø8
Ø12
Ø10
R11.75
R13.22
R5
R5
R21.56
R5.75
Ø6
Ø10
21.50
50
75
124.50
22
80
26.24
40
12
22.50
27.50
7



R8.05
Ø6
11.95
1.90
16.10


10
5
11
R5
Ø7.50
1
1


1
4.50
Ø8
R3.75
5
3.50
16.75
图纸1



9 Conclusion

This project has successfully designed an eight-legged robot. It is driven by a single motor, with a main board, a geared reducer and a foot connecting linkage. The main design content is also based on the above plates. Learn and use the leg link track optimization to find the optimal path of gait. Draw 3D models and engineering drawings so that parts can be accurately machined. Perform assembly and solve practical problems caused by machining deviation from 3D model. Make revisions and resolve related issues. We have a deeper understanding of the process of mechanical design and matters needing attention in the production process. In the future, when we receive the requirements of related mechanical design, we will be able to have a complete design and thinking.

Finally, the robot has a better working effect which has a cute gait, high stability and fast speed in the process of moving. In addition, its body is relatively light and the cost is not high, moreover the manufacturing technology is simple.

10 Reference

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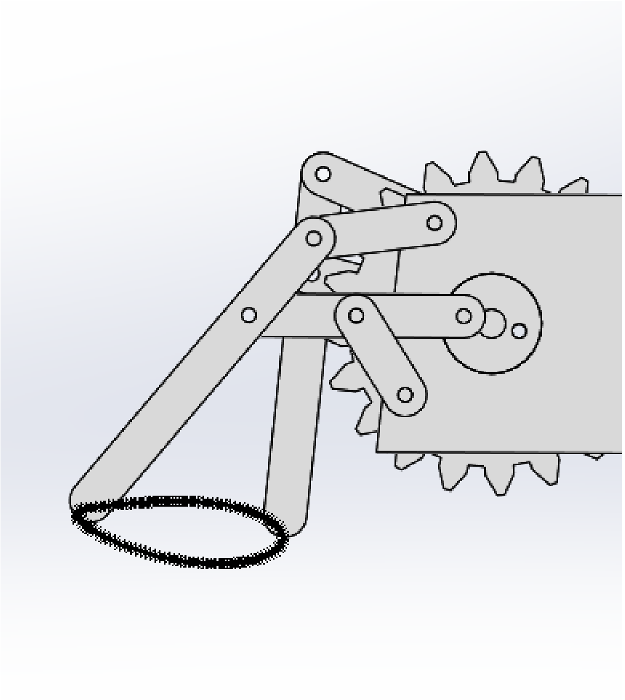
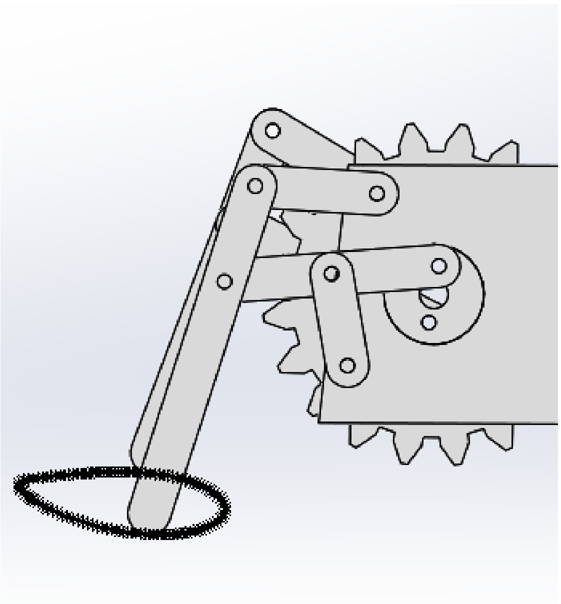
11 Appendix:

11.1 Trajectory diagram

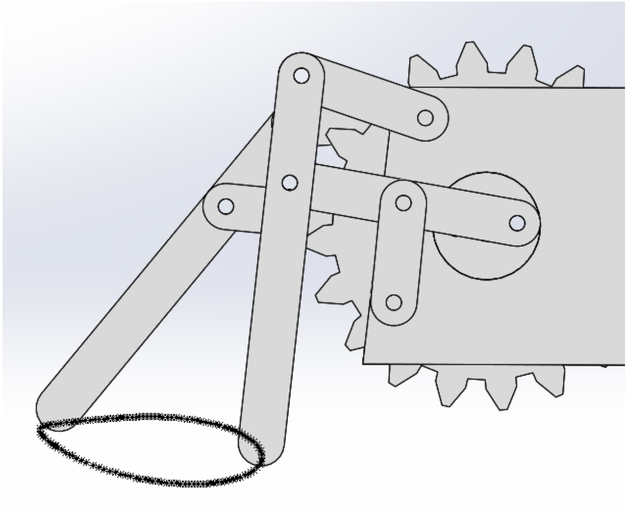
Phase one:



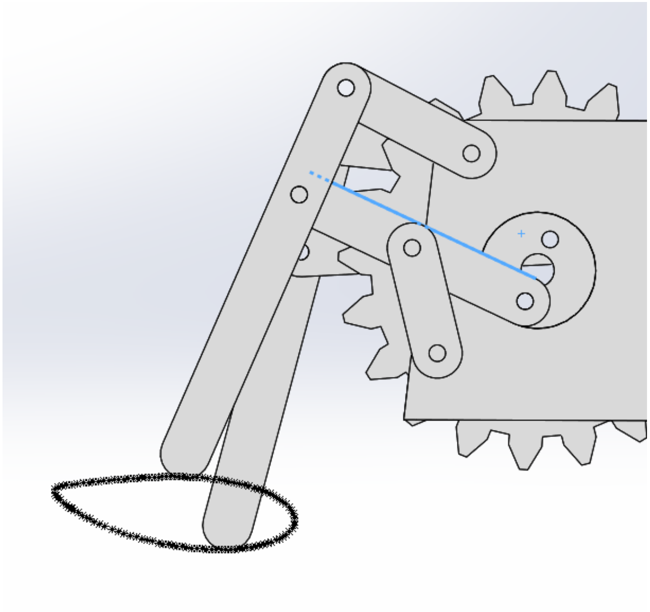
Phase two:



Phase three:



Phase four:



It goes back to phase one as follows. These four phase is considered as a rotation of a pair of legs. The moving state is shown in the video.

11.2 MATLAB Codes

MATLAB Codes for PartIV

```
clear;

clc;
```

```
%%%%%%%%%%%%L1~5%%%%%%%%%%%%
L1=0.1*1.1;
L2=0.56*1.1;
L3=0.43*1.1;
L4=0.45*1.1;
L5=0.80*1.1;

%%%%%%%%%%%%angle0~3%%%%%%%%%%%%
angle0=0;
angle1=0:0.001:2*pi;


%to solve the first 4-bar system
Z=L4*exp(i*(pi-angle0))+L1*exp(i*angle1);
temp=Z.*conj(Z)+L2^2-L3^2;
angle2=[ones(1,6284)];

    %solve for angle2
temp2_1=angle((-temp-(temp.^2-
4*L2^2*Z.*conj(Z)).^(0.5))./(2*conj(Z)*L2));
temp2_2=angle((-temp+(temp.^2-
```

```
4*L2^2*Z.*conj(Z)).^(0.5))./(2*conj(Z)*L2));
for n=1:6284
    if(temp2_1(n)>0)
        angle2(n)=temp2_1(n);
    else
        angle2(n)=temp2_2(n);
    end
end

    %solve for angle3
angle3=[ones(1,6284)];
temp3_1=angle((Z+L2*(-temp-(temp.^2-
4*L2^2*Z.*conj(Z)).^(0.5))./(2*conj(Z)*L2))/L3);
temp3_2=angle((Z+L2*(-temp+(temp.^2-
4*L2^2*Z.*conj(Z)).^(0.5))./(2*conj(Z)*L2))/L3);
for n=1:6284
    if(temp3_1(n)>0)
        angle3(n)=temp3_1(n);
    else
        angle3(n)=temp3_2(n);
    end
```

```
end

%%%%%%%%%%A,B,C,D,G%%%%%%%%%%%
A=0;
B=A-L4*exp(i*angle0);
C=L1*exp(i*(pi-angle1));
D=L3*exp(i*(pi-angle3))+B;
G=C+L5*exp(i*(pi-angle2));

%plot(real(G),imag(G)),axis([-25 0 0 25]);
%figure;
%plot(real(H),imag(H)),axis([-70 -40 80 110]);

%%%%%%%%%%Force Analysis%%%%%%%%%%
M=2;
N=0.25*9.8*M;


T=[ones(1,6284)];
Fa=[ones(1,6284)];
Fb=[ones(1,6284)];
for n=1:6284
```

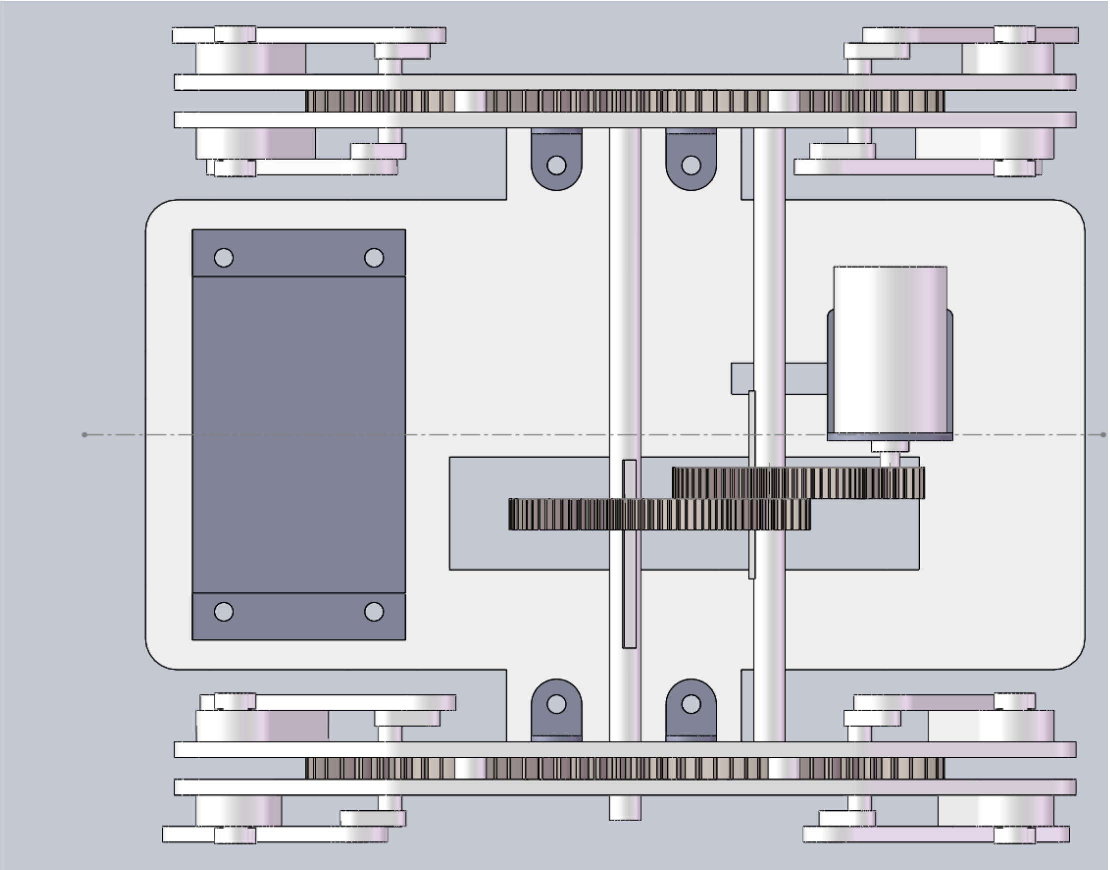
```
    MatrixA=[sin(pi/2+angle1(n))/L1 sin(pi+angle1(n))
sin(pi+angle3(n));
             cos(pi/2+angle1(n))/L1 cos(pi+angle1(n))
cos(pi+angle3(n));
             sin(angle1(n)-pi/2-angle2(n))*L5/L1 sin(angle1(n)-
angle2(n))*L5 sin(angle3(n)-angle2(n))*(L5-L2);];
    MatrixB=[-N;0;0];
    MatrixC=inv(MatrixA)*MatrixB;
    T(n)=MatrixC(1);
    Fa(n)=MatrixC(2);
    Fb(n)=MatrixC(3);
end

plot(T),xlabel('t'),ylabel('torque/N·m');

max=0;
for n=1:6284
    if(T(n)>max)
        max=T(n);
    end
end
```

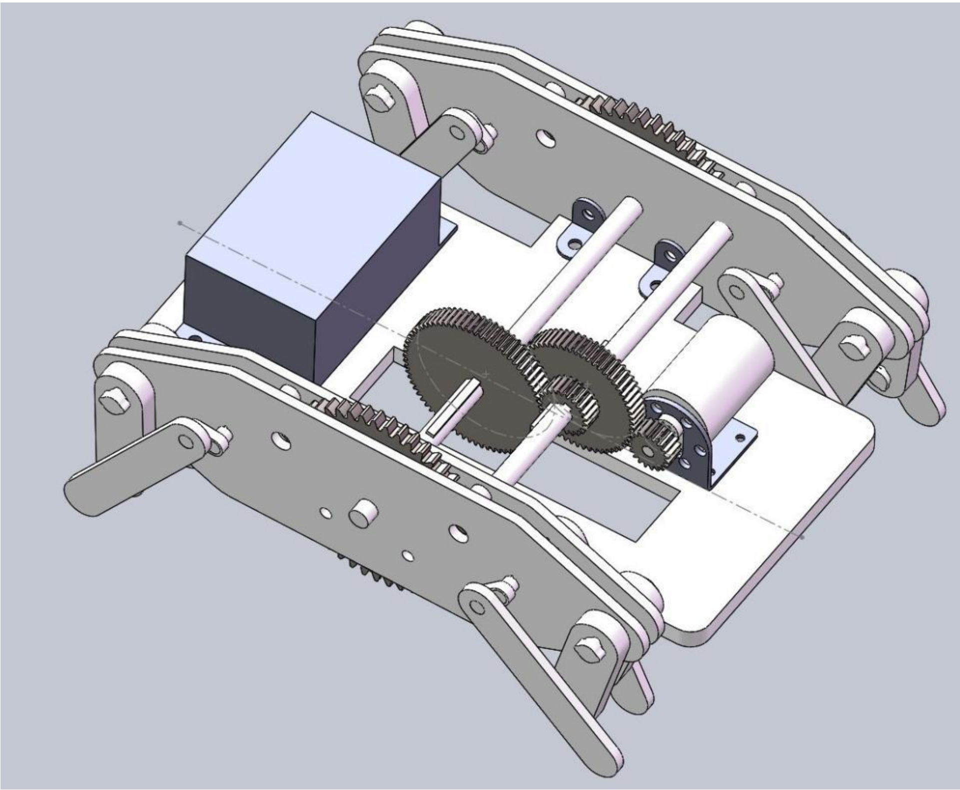
```
for l1=1
    for l2=5.5:0.1:5.7
        for l3=4.2:0.1:4.4
            for l4=4.4:0.1:4.6
                for l5=7.9:0.1:8.1
                    i=i+1;
                    A=l4-l1*cos(angle1);
                    B=-l1*sin(angle1);
                    C=(A.^2+B.^2+l3^2-l2^2)/(2*l3);
                    %求∠3 和角 2
                    angle3=2*atan((B+(A.^2+B.^2-C.^2).^0.5)./(A-
                    C));


                    angle2=atan((B+l3*sin(angle3))./(A+l3*cos(ang
                    le3)));
                    H=l1*exp(j*angle1)+l5*exp(j*angle2);
                    x=real(H);
                    y=imag(H);
                    Ymin=min(y);
                    nx=0;
                    Y(i)=max(y)-min(y);
                    for n=1:length(x)
```

```
            if y(n)-0.01<Ymin
                nx=nx+1;
            end
        end
        if -l2^2-l3^2-1.2856*l3*l4+(l1+l4)^2>0
            xtime(i)=0;
        elseif -l2^2-l3^2-1.2856*l3*l4+(l1-l4)^2>0
            xtime(i)=0;
        elseif nx>1000
            xtime(i)=nx;
        else
            xtime(i)=0;
        end

        L1(i)=l1;
        L2(i)=l2;
        L3(i)=l3;
        L4(i)=l4;
        L5(i)=l5;
    end
end
end
```

```
    end
end



for j=1:length(Y)
    ratio(j)=xtime(j)/Y(j);
end
[zuiyoujie I]=max(ratio);
bestL1=L1(I);
bestL2=L2(I);
bestL3=L3(I);
bestL4=L4(I);
bestL5=L5(I);
```

11.3 Design Sketch:





The above two pictures are the preliminary 3D renderings of the eight-legged robot.

The following is the current results after the optimization and iteration which we based on for processing.