# Walking Machine 

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## Abstract

In Project 2, we are required to build a walking machine controlled by one or two R/C servomotors to make it pass through a two-meter distance as fast as possible. To achieve this goal, we came up with three designs: the modified four-bar linkage structure, the leg walking structure and the ratchet wheel structure. For each design, we first calculated the theoretical speed and then manufactured a prototype to verify whether they could perform as expected. With plenty of trade-offs and experiments, we finally decided to use the ratchet wheel structure. The theoretical time needed to pass through the two-meter walk was about 4.4 seconds (if rolling without slipping). However, according to our test results, the time needed was about 6.12 seconds. In the competition, our final score was 6.7 seconds, which met our expectations.


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## 1. INTRODUCTION

In Project 2, we are required to build a walking machine with mechanical structure designed by ourselves and control one or two R/C servomotors with the program designed by ourselves to make it pass through a two-meter-long distance as fast as possible. To achieve this goal, we designed three structures: the modified four bar linkage structure, the analogy of human walking structure and the ratchet wheel structure. The material used to build the mechanical structure was mainly acrylic. We first designed the structure and drew the sketch with CAD software. Then we cut the material with laser cutting machine and manufactured our prototypes manually. With plenty of modifications and experiments, we finally decided to use the ratchet wheel structure.

R/C servomotor is a kind of rotary actuator that can transform electrical signal into angular speed, angular acceleration and position precisely to achieve certain control aim. ${ }^{[1]}$ It has two main advantages. One is that servomotor can react very fast to the input signal, the other is that when there is not input electrical signal, the servo motor will stop rotating simultaneously. Hence, servo motors are widely used in mechanical engineering field especially in robotics, which is also the basic knowledge we need to grasp as mechanical engineering students. In this project, servomotors are principal parts because we needed to control them to transform a half circular revolution into translation, which was the principle for us to design our mechanism.

A four-bar planner linkage is also a kind of basic structure made up of four links and four joints. Despite of only one degree of freedom, the mechanism can achieve rotation, translation and oscillation with different designs. In this project, we had a design made up of a modified four-bar linkage with a slider, which could transform the periodic half revolution into translation. However, we had to give it up due to unpermitted auxiliary parts and limited time.

A ratchet is a mechanical device that allows continuous linear or rotary motion in only one direction while preventing motion in the opposite direction, which is also widely used in mechanical engineering filed. In this project, we had a design made up of a ratchet actuated by two servomotors which could transform the periodic half revolution into continuous linear motion without singularity.

This report shows all the processes and results of our designs for Project 2 in detail.

## 2. PRODUCT DESIGN

### 2.1. Problem Statement

Project 2 requires us to design and manufacture a walking machine which can move 2meter distance as fast as possible. ${ }^{[2]}$ The major parts including servomotors, controlling board and power supply are given to us. We can also use acrylic boards, screws, pins and bearings. The most challenging thing is that the servomotor can only rotate 180 degrees. This restricts us to simply designing a machine using wheels. Therefore, we need to design a structure to turn 180-degree rotation into 360-degree rotation.

In the designing part, we should pay attention to the connection between two parts far from each other since copper columns are not allowed to use. Besides, CAD software cannot show the deformation of the structure. If the structure is designed to deform, we should carefully calculate and analyze. This is the same to the structures like gears and shafts or they may get stuck. Since the precision of the laser cutting, the joint or the connection may not be tight. Some parts may not be able to fix on others. We should leave some allowance in designing.

In the manufacturing part, the most important thing is that we should fix all the parts tightly. Since the tenon or the hole may be too large, glue is needed to stick them tightly. Spare part is required for the emergency case.

In the coding part, we should be patient. The motion of the machine must be quite complex. The angle of the servomotor need to be adjusted carefully, otherwise the machine may stuck itself or even breaks some parts.

### 2.2. Concept Generation

### 2.2.1 Leg Walking Machine

The first design we came up with is called the leg walking machine (see Figure 2.1 and 2.2). Its motion mode imitates simplified human's walk. It has two legs driven by two servomotors. When it begins to walk, the body will be raised and move forward. The bulge on the lower leg works as the knee. It keeps the leg straight when walking forward. After the body part touches the ground, the first step ends. The leg begins rotating back.

Since there is no bulge on the back of the lower leg, the leg will bend. That avoids the machine walking backward. The leg rotates to the initial position and we can have another step.


Figure 2.1: 3D model of the leg walking machine.


Figure 2.2: Prototype of the leg walking machine ( $195 \mathrm{~mm} \times 98 \mathrm{~mm} \times 145 \mathrm{~mm}$ ).
The machine is highly adjustable since we designed many spare holes. The length of the legs and body can vary within a certain range so that we can get the best performance without cutting the board again.


Figure 2.3: One step of the leg walking machine.
According to Figure 2.3, each step is 0.2381 meters and takes about 2.6 seconds. Hence, the velocity is determined to be

$$
\begin{equation*}
v=\frac{s}{t}=\frac{0.2381}{2.6}=0.0916[\mathrm{~m} / \mathrm{s}] . \tag{2.1}
\end{equation*}
$$

The time required is thus determined to be

$$
\begin{equation*}
t=\frac{s}{v}=\frac{2}{0.0916}=21.83[\mathrm{~s}] . \tag{2.2}
\end{equation*}
$$

To sum up, the leg walking machine moves at a speed of 0.0916 meters per second and it takes about 21.83 second to finish the two-meter walk. The speed is quite low since half of the rotation does not contribute to the motion at all. Increasing the length of the leg will improve the speed but will also increase the load on the servomotors. Hence, this is the best performance we can have.

### 2.2.2 Modified Four-Bar Linkage Walking Machine

Since the performance of the first design was barely satisfactory, we tried to figure out a different way. After several discussions, we finally decided to eliminate any design with legs. To largely increase the speed, wheels seemed to be a good choice. The modified four-bar linkage 'walking' machine was thus created. The idea simply came from the four-stroke combustion engine system (see Figure 2.4). The mechanism managed to transfer reciprocating linear motion into rotational motion.


Figure 2.4: Four-stroke combustion engine cycle. Retrieved from https://en.wikipedia.org/wiki/Engine\#Heat_engine.

For four-stroke combustion engine, the linear motion of the grounded prismatic joint is achieved by combustion. However, for our design, instead of combustion, the wheels were actuated by a modified four-bar linkage mechanism (see Figure 2.5).


Figure 2.5: Modified four-bar linkage mechanism.
As we can see, $\mathrm{O}_{2} \mathrm{O}_{4}$ is a ground link, Link 2 is a rocker, Link 3 is a coupler, and Link 4 is a crank. If Link 2 is controlled to oscillate within specific range, Link 4 is expected to rotate around pivot $\mathrm{O}_{4}$. The difference between our design and the traditional crankrocker four-bar linkage is joint A . If we simply use a revolute joint at A , there will be a toggle position problem when Link 4 moves to a horizontal position. However, if we apply a grounded prismatic joint, together with a loose slot at A, Link 4 will keep rotating due to inertia effect at horizontal position. This is the reason why the designed mechanism is called modified four-bar linkage.

Based on the designed mechanism, a 3D model of the modified four-bar linkage walking machine was created by SolidWorks (see Figure 2.6). Later, a corresponding prototype was made, as shown in Figure 2.7. Note that only one servomotor was used for the walking machine. The dimension is about $195 \mathrm{~mm} \times 60 \mathrm{~mm} \times 100 \mathrm{~mm}$.


Figure 2.6: 3D model of the modified four-bar linkage walking machine.


Figure 2.7: Prototype of the modified four-bar linkage walking machine.
If we rotate Link 2 at constant angular velocity, the instantaneous speed of the walking machine will change with time complexly. However, since Link 2 is doing reciprocating motion, the average speed within a single period can be calculated easily. Assume the execution time of the servomotor is 500 milliseconds within a single period. Therefore, the drive wheels can finish two revolutions within one second. Considering
the wheels are rolling without slipping, the theoretical speed of the modified four-bar linkage walking machine is thus determined to be

$$
\begin{equation*}
v=\frac{s}{t}=\frac{2 p}{t}=\frac{2 \times \pi D}{t}=\frac{2 \pi D}{t}=\frac{2 \pi \times\left(8 \times 10^{-2}\right)}{1}=0.503[\mathrm{~m} / \mathrm{s}] . \tag{2.3}
\end{equation*}
$$

Note that $p$ denotes the perimeter of the drive wheel and $D$ denotes the diameter. To finish a two-meter walk, the required time is determined to be

$$
\begin{equation*}
t=\frac{s}{v}=\frac{2}{0.503}=3.979[\mathrm{~s}] . \tag{2.4}
\end{equation*}
$$

As we can see, the calculation indicates that the modified four-bar linkage walking machine can actually have a very satisfactory performance. The reason why we didn't use it on game day lies in the fact that the prototype was made based mainly on copper column. We falsely treated it as a permitted auxiliary part. Besides, it was too late to redesign the CAD works by the time we realized the mistake.

### 2.2.3 Ratchet Wheel Walking Machine

The common concept of a walking machine that is only required to walk forward is to use the electric motor to drive the wheel. The walking machine with wheels usually owns a higher theoretical velocity than the walking machine with linkages and feet. The wheel produces simple rotational motion which is easy to analyze and calculate. In addition, the wheel can provides the machine a smooth velocity output and enhances the stability. However the RC servo motor can only rotate 180 degrees back and forth instead of rotating 360 degrees unlimited. We need to design a mechanical structure to manipulate the servo motor on the wheel that permit the wheel rotate only in one direction and prevent inversion.

The ratchet wheel is a basic mechanical device we learned from the VM350 lecture. The common mechanical structure is shown in Figure 2.8. It contains a rotational wheel of sawtooth shaped, a locking pawl and a driving pawl. It permit the ratchet wheel rotating only anticlockwise. When it is going to rotate clockwise, the locking pawl will lock the wheel as well as provide a locking torque to the ratchet wheel. This lock mechanism is achieved by the spring which always push the locking pawl towards the wheel and make the pawl insert the notch of the ratchet wheel. Since the feature of ratchet wheel that permit only one direction rotation is consistent with our design
objective to use wheels in the walking machine, we apply the ratchet wheel in our design concept.


Figure 2.8: Ratchet wheel concept. ${ }^{[3]}$
The basic idea is to connect the ratchet wheel with the servo motor. When the servo motor drives the ratchet wheel clockwise, the vehicle wheel will be driven and rotated with the ratchet wheel at the same angular velocity. When the servo motor rotates back, the locking pawl can loose and only let the ratchet wheel rotate back without driving the vehicle wheel. Moreover, we are able to rotate the vehicle wheel with no dwell with two servomotors. The principle is to drive one common vehicle wheel using two servomotors at two sides with exactly inverse rotations. For example, when the left servo motor rotates anticlockwise and drives the vehicle wheel anticlockwise, the right one rotates clockwise but do not interfere the vehicle wheel due to the locking pawl at loose condition; when the right servo motor rotates clockwise, now it turns to the left one to drive the vehicle wheel anticlockwise without interference from the right servo motor. This characteristics can make the vehicle wheel keep rotating in 360 degrees. The two servo motor work just like an electric motor and drive the vehicle wheel at a constant angular velocity.

In Project 1, we measured that the time required for the servo motor to rotate from negative 90 degrees to positive 90 degrees at the maximum angular velocity is 0.6 seconds. Therefore, the maximum constant angular velocity of the vehicle wheel is

$$
\begin{equation*}
\omega=\frac{\theta}{t}=\frac{\pi}{0.6}=5.236[\mathrm{rad} / \mathrm{s}] . \tag{2.5}
\end{equation*}
$$

We expect our walking machine to finish the two-meter walk in 10 seconds, so the required linear velocity of the walking machine is $0.2 \mathrm{~m} / \mathrm{s}(200 \mathrm{~mm} / \mathrm{s})$. In order to
achieve that goal, the minimum diameter of the vehicle wheel can be calculated. We assume no slip occurs,

$$
\begin{equation*}
D_{\min }=\frac{2 v}{\omega}=\frac{2 \times 200}{5.236}=76.4[\mathrm{~mm}] . \tag{2.6}
\end{equation*}
$$

As long as the angular velocity is confined, the larger the wheel the faster the machine. We should make the vehicle wheel as larger as possible but not exceed the dimensions limitation of $200 \mathrm{~mm} \times 200 \mathrm{~mm} \times 200 \mathrm{~mm}$. Thus the diameter of the wheel could range from 76.4 mm to 200 mm . Consider the walking machine need to include the power supply, the control board and two servomotors, the detailed distribution should be designed carefully to avoid interference and maximize the velocity performance.

## 3. FINAL DESIGN

The final design was completed using the CAD software CATIA. The overall assembly is shown in Figure 3.1. We measured and modeled the servo motor in opaque color. All transparent components are acrylics with thickness of 4 mm . The fasteners we use are entirely $\Phi 3$ screws and nuts according to the regulations of this project. We left the holes on the acrylics to mount the fasteners rather than modeled them in the assembly because it would take too much time. However, the power supply and the control board were missing in the assembly drawing. In our design concept, they should be fixed on the sides of the walking machine using screws and nuts.


Figure 3.1: Overall assembly of final design.

In order to apply the ratchet wheel structure in the machine, we designed ratchet wheel and the locking pawl made by acrylics ourselves. Figure 3.2 shows the ratchet wheel structure.


Figure 3.2: Ratchet wheel structure.
Since springs are not allowed in this project, we utilized the elasticity of acrylics to make the locking pawl. Each pawl has a length of 60 mm with 10 mm stuck to the vehicle wheel and 50 mm as a cantilever beam. In Figure 3.2 (b), the pawl is designed to be almost perpendicular to the notch of the ratchet wheel without bending when the ratchet wheel drives the vehicle wheel. When the ratchet wheel rotates inversely, the pawl can be lifted up due to the elasticity so the inversion would not interfere the vehicle wheel. In addition, we designed two wheels rotating synchronously shared by one common rotation axis. Each wheel contains four locking pawls to prevent accidental break or failure of the pawl. With one servo motor connected to one ratchet wheel on each side of the vehicle wheel, the walking machine could always be driven by one of the servo motor and the large vehicle wheel could always rotate at the constant maximum angular velocity.

In our final design, the diameter of the vehicle wheel is chosen to be $17.5 \mathrm{~cm}(0.175 \mathrm{~m})$. Assuming no slip between the wheel and the ground, the theoretical speed can be evaluated as

$$
\begin{equation*}
v=\frac{\omega D}{2}=\frac{5.236 \times 0.175}{2}=0.458[\mathrm{~m} / \mathrm{s}], \tag{3.1}
\end{equation*}
$$

This speed is able to let the walking machine finish the two-meter walk in

$$
\begin{equation*}
t=\frac{s}{v}=\frac{2}{0.458}=4.37[\mathrm{~s}], \tag{3.2}
\end{equation*}
$$

which not only satisfies our expectation but also becomes competitive in the game.
At last, the walking machine consists of three rectangle acrylics frames mounted by the screws and nuts on the corners. The middle frame fixes the rotation axis of the vehicle wheel, while the outer frames carry the servo motors, the power supply and the control board. In order to make the walking machine more stable, we added four auxiliary wheels at the under corners of the frames. The auxiliary wheels could prevent the walking machine from dumping as well as decrease friction with the ground. Finally, the dimensions of the final design are $195 \mathrm{~mm} \times 175 \mathrm{~mm} \times 152 \mathrm{~mm}$, which abide by the regulation. The orthographic views of the final design are presented in Appendix G.

## 4. MANUFACTURE

### 4.1. Manufacture Process

The manufacture process includes laser cutting and assembling process. We generated the plane views of all acrylics components and drew the CAD drawings (in Appendix E). We used the opportunity of laser cutting given by the teaching assistants to manufacture our acrylics components. For the non-acrylics components, we used $\Phi 3$ screws and nuts as the fasteners. A list of each individual component used in the walking machine is presented in Appendix A.

Firstly, we used glue to stick the pawl into the groove of the vehicle wheel. To prevent misoperations and stickum failure, we made some redundant replacements and designed some more grooves than need. For each wheel, the four pawls can be stuck every 90 degrees to make the wheel balanced. Figure 4.1 shows one wheel with four pawls stuck.


Figure 4.1: Vehicle wheel with pawls.


Figure 4.2: Application of lock nut.

To let the two wheels rotating synchronously, we used the lock nuts to fix the two wheels on a M $3 \times 40$ screw. The lock nut could lock the wheel with the screw together as well as prevent loosing (Figure 4.2). The middle frame was put in the middle and the lock nut did not clamp the frame tightly. Thus the two wheels with the screw can rotate through the hole in the middle frame freely. The completion of the wheels and the middle frame is shown in Figure 4.3.


Figure 4.3: Completion of wheel and middle frame.

The two R/C servomotors were fixed on the outer frame, and the ratchet wheels were fixed on the disks of the servo motors by screws (Figure 4.4). Besides the servomotors, the control board and the power supply were also put on the outer frame. Figure 4.5 shows the fix of the control board using two sets of screws and nuts.


Figure 4.4: Fix of the ratchet wheel.


Figure 4.5: Fix of the control board.

At the corners of the frame, we added four $\mathrm{M} 3 \times 45$ screws to connect and support the middle frame and the vehicle wheels. Moreover, each outer frame contained two auxiliary wheels at the under corners. Each auxiliary wheel used $\Phi 3$ screw as rotation axis and locknut to restrict the axial movement (Figure 4.6 and 4.7). However, since the weight of the control board and the power supply are different, the crosswise positions of the two auxiliary wheels should be different to balance the walking machine. Thus the screw of the auxiliary wheel on the power supply side was much longer than that on the control board side to prevent the walking machine from dumping Figure 4.8 shows the completion of one outer frame with the control board. The other outer frame with the power supply was established in the same way, but to choose the other four holes to mount the M $3 \times 45$ screws to avoid interference.


Figure 4.6: Auxiliary wheel on the control board side.


Figure 4.7: Auxiliary wheel on the power supply side.


Figure 4.8: Completion of one outer frame.
After the three frames were all completed, the walking machine could be assembled by simply put them together. The nuts on the screws were used to fix the frames as the Figure 4.9 shows. Make sure the pawls do not overlap the ratchet wheels. They should be embedded into the notch of the ratchet wheels appropriately as Figure 4.10 shows.


Figure 4.9: Fix of the three frames.


Figure 4.10: Correct layout of pawls and ratchet wheel.

Finally, the overall assembling of the ratchet wheel walking machine is presented in Figure 4.11. More pictures of the assembling are shown in Appendix B.


Figure 4.11: Overall assembling of the ratchet wheel walking machine.

### 4.2. Problems

Since the walking machine did not include too many components and the overall structure of the machine was not complicated, the manufacture process was actually straight forward and did not require too many efforts. However, we still found some problems during the manufacture process and these problems took us some extra efforts to fix.

Firstly, we did not model the power supply and the control board in our design and modeling process. This brought up the problem that we did not leave the correct places and fasten holes for them on the frames. We fixed this problem by drilling extra holes on the acrylics frames ourselves and found two allowable places to put them. Nevertheless, we put the power supply on the front part of the walking machine while the control board was put on the rear. From the overall assembling picture, it was obvious that the layout led to asymmetry of weight distribution and made the walking machine easy to dump and swerve during walking. That was the reason we chose different lengths of screws to be the axis of the auxiliary wheels. And apparently, we
made the walking machine look strange in crosswise direction. We should have put more efforts on the design and modeling process and fully considered the influences of the power supply and the control board. We should took the gravity center of the walking machine into account and made it more stable.

Secondly, we only left the holes on the acrylic frame during modeling but did not consider the spacing between the frames. We found that the spacing between the frames were not enough because the ratchet wheel would interfere with the rotational axis of the vehicle wheels. Hence we chose the slightly longer screws to support the frames and this led the overall dimensions become $195 \mathrm{~mm} \times 175 \mathrm{~mm} \times 160 \mathrm{~mm}$, which was 8 mm wider than design value. Although this excess did not break the dimensions regulation, we still need to think about every detailed aspects during design process. Even an overlook in length of a screw could lead to assembling difficulty or components interference.

## 5. VALIDATION

### 5.1. Tests

After the manufacture was complete, we started to do the tests and adjustments. We connected the circuits as the circuit schematic shows in Appendix D. The source code we used are presented in Appendix C. After the circuits were set up, we tested the performance of our ratchet wheel walking machine in the dormitory. We measured a runway of two meters and set up the walking machine just like it would be in the game day.

At first, the walking machine tended to swerve or turn over during walking. We found that the reason was the wires. Since the walking machine had to connect with the power supply wire and the USB wire, if we did not draw the wires as the machine was walking, the wire would be in tension and the walking machine was easy to receive an unbalanced torque which led to swerve. Then we tried to practice drawing wires simultaneously as the walking machine went forward. With several rounds of adjustments, we succeeded in finishing five tests of two-meter walk and recorded the time. The test results are shown in Table 5.1.

| Trial | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{3}$ | $\mathbf{4}$ | $\mathbf{5}$ | Average |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Time $[\mathrm{s}]$ | 5.69 | 6.18 | 6.69 | 6.18 | 6.13 | 6.17 |

Table 5.1: Test results.
From the test results, the average time required for the walking machine to finish the two-meter walk was 6.17 seconds, which was longer than the expected theoretical time 4.4 seconds in the Final Design section, though satisfied our basic requirement that was less than 10 seconds. By observation, we concluded two possible reasons that increased the time. First, the walking machine always slipped at the start, while the theoretical time was calculated assume no slip occurred. Second, although we decreased the tendency of the walking machine to swerve, it still could not run in a perfect straight line. As long as a slight swerve occurred, it would consume more time to reach the destination. In the latter tests and adjustments, we tried to avoid these two problems and prepared for the game day.

Unfortunately, our final score on the game day was 6.7 seconds which was lower than the tests. Moreover, severe accidents of dumping and swerving occurred so we only got the fifth rankings in the competition. We felt discouraged about the results because we thought our walking machine to be competitive and fast enough in the game. Finally, we analyzed our performances in tests and in competition and came up with some improvements of our design.

### 5.2. Improvement

The first improvement we could do on our design was to put the power supply and the control board at the middle position instead of putting on the sides. As we mentioned in the Problems section, the dump and swerve occurred due to the asymmetry of weight distribution. Consider the weight of power supply was heavy, it would be much better to put it in the middle at a lower position to lower the gravity center and made the walking machine much more stable. Besides, the thoughtless layout of the power supply and the control board made the two connected wires extend in different directions. According to Figure 5.1, the USB wire may pull the walking machine forward but the power supply wire may draw the walking machine backward. Any of these states would apply an unbalanced torque to the walking machine which lead to swerve. To avoid this, the two wire extension directions should be identical, either forward or backward. Then the situation of swerve can be averted a lot and the walking machine would be able to run in a straight line.


Figure 5.1: Different directions of wire extension
Another possible reason of swerve or dump was that the size of the auxiliary wheels were too small and probably made the acrylics frame touch the ground during walking. Figure 5.2 shows that the bottom of the frame was so close to the ground that even a little vibration would made them in touch. What made it even worse were the grooves between the tiles, they made the ground not flat. As long as the bottom edge of the frame stuck into the grooves, the inertia would make the walking machine swerve and even dump. This scenario did happen in our tests and in the competition. To improve, larger auxiliary wheels should be used to avoid touch in the frame and the ground. However due to the dimensions limitation, the frame size need to be reduced, which would cause the diameter of the vehicle wheels become smaller and decrease the speed of the walking machine.


Figure 5.2: Touch between the frame and the ground.

Thirdly, we could increase the friction between the wheels and the ground to avoid slip. We observed that slip always occurred at the start. The reason was that the acrylic surfaces could not provide enough grip to transmit the torque of the servo motor to the ground. One possible solution is to adhere some hot melt glue on the wheel surfaces to increase the grip. If we eliminate the slip, the acceleration period of the walking machine would be shortened and the walking machine could finish the walking always at the maximum angular velocity.

The above improvements were all to solve the problems we met, but the theoretical minimum time was still confined by the maximum angular velocity of the servo motor and the diameter of the vehicle wheel. Thus if we did not keep increase the diameter of the wheel, the walking machine could not finish the goal in less than 4.4 seconds. However, inspired by other teams in the game day, this limitation could be broken by adding the amplification structure made by gears. This improvement would probably reduce the size of the vehicle wheel because we need place to put the gears. But the gear ratio amplification would amplified the maximum angular velocity of the servo motor to the vehicle wheel and compensate the wheel diameter reduce. This improvement exists the difficulty to make the gears by acrylics and manufacture the gears by laser cutting. Any error occur would lead gears interference or gap existence. With the knowledge of gear we learned from the VM350 lectures just now, we could try to implement this improvement and test its validation.

## 6. CONCLUSION

In Project 2, we are required to design a mechatronic walking machine based on the knowledge of four-bar linkage, R/C servomotor, CAD programs, and closed-loop control system. The goal is to finish a two-meter walk as fast as possible.

To achieve the goal, we first came up with the leg walking machine. It was able to move forward step by step, but the speed was barely satisfactory. Eliminating deigns with legs, we created the modified four-bar linkage walking machine. Although its theoretical performance was considered excellent, we had to give it up due to unpermitted auxiliary parts and limited time. Luckily, the ratchet wheel walking machine was being manufactured at the same time. We thus focused on the improvement of the third design. As illustrated in VALIDATION section, we made several changes to both the mechanism and the control system according to our test results. Finally, the average time required to finish the two-meter walk was about 6.2
seconds. In the competition, our final score was 6.7 seconds, which was slightly longer than expected, probably due to smaller friction coefficient with the ground. Besides, it was really a pity that we lost the final round against Team 5.

Although Project 2 is coming to an end, we have learned a lot things, which will be beneficial to our future career. First, remember to double check the design specifications. As mentioned above, we had to give up an excellent design due to unpermitted auxiliary parts. If we had read through the design spcifications carefully, our final score might be better. Second, always have a plan B. Although we had to eliminate one design before competition, luckily, we still had the ratchet wheel walking machine. If not, our final peformance would just be a mess. Thirdly, never take others lightly. After we finished testing our final prototype, we naively believed that we were about to win the competition. Therefore, we stopped further improvement. However, it turns out that there will be always someone better than you. If we had kept making improvement, there would be no need for the final round. Fourth, try to simulate the game situation. Before the game day, we never thought of the largely different ground situation, as well as the limited operation space. If we had simulated the game situation before, we might not make unexpected mistakes during the competition.

## 7. REFERENCE

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## APPENDIX A: LIST OF COMPONENTS

| Component | Image | Number |  |
| :---: | :---: | :---: | :---: |
| Ratchet wheel |  |  |  |
| Locking pawl |  | 2 | 4 |
| Vehicle wheel |  |  |  |


| Component | Image | Number |
| :---: | :---: | :---: |
| Middle frame |  | 1 |
| Outer frame 1 |  | 1 |
| Outer frame 2 |  | 1 |
| M $3 \times 45$ screw |  | 8 |
| M $3 \times 40$ screw |  | 1 |
| M $3 \times 20$ screw |  | 10 |
| M $3 \times 12$ screw |  | 3 |
| M $3 \times 10$ screw |  | 6 |
| M3 nut |  | 52 |
| M3 lock nut |  | 17 |

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| Component | Image | Number |
| :---: | :---: | :---: |
| RC servo motor |  | 2 |
| Power supply |  | 1 |
| Control board |  | 1 |

Table A-1: List of components.

## APPENDIX B: ASSEMBLING IMAGES



Figure B-1: Front view of assembling.


Figure B-3: Left side view of assembling.


Figure B-2: Rear view of assembling.


Figure B-4: Right side view of assembling.

## APPENDIX C：SOURCE CODE

| 顺序 | 位置 | 速度 | 持续时间 |
| ---: | :---: | :---: | :---: | :---: |
| 0 | $500,500,1500,1500,1500,1500,1500,15 \ldots$ | $5000,5000,3000,3000,3000,3000,300 \ldots$ | 600 |
| 1 | $2500,2500,1500,1500,1500,1500,1500 \ldots$ | $5000,5000,3000,3000,3000,3000,300 \ldots$ | 600 |
| 2 | $500,500,1500,1500,1500,1500,1500,15 \ldots$ | $5000,5000,3000,3000,3000,3000,300 \ldots$ | 600 |
| 3 | $2500,2500,1500,1500,1500,1500,1500 \ldots$ | $5000,5000,3000,3000,3000,3000,300 \ldots$ | 600 |

Figure C－1：Source Code（GUI version）．
For Project 2，the control algorithm is quite simple．For Step 0，we let the two servo motor rotate in different directions at the maximum angular velocities．The running time was 600 ms ，which corresponded to the time of one servo motor to rotate 180 degrees．

For step 1，we let the two servo motor rotate inversely to the origin condition before Step 0 ．The other parameters of angular velocities and running time were identical as Step 0.

For Step 2 and Step 3，they were just the repeats of Step 0 and Step 1．With the set of loop execution，the code can make the walking machine keep running until we stopped the program．

The specific source code is provided below：

```
<?xml version="1.0"?>
<!--DFRobot USBSSC32 Motion File-->
<!--For any questions or problems, please contact www.DFRobot.com-->
<!--ssc32Motion.xml in /motion dir-->
<Motions Name="1a4fd768-33c2-424c-9681-7491d0ba868e" Counter="4">
```

    <Motion Index="0" Time="600">
    <PulseWidth
    $P W=" 500,500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,150$
$0,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500$, 1500,1500," />
<Speeds
SP="5000,5000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,30 00,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,300 0,3000,3000," />
</Motion>
<Motion Index="1" Time="600">
<PulseWidth
PW="2500,2500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1 \(500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,1500,15\) 00,1500,1500," />
<Speeds
SP="5000,5000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,30 00,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,3000,300 0,3000,3000," />
</Motion>

## </Motions>

## C-2

## APPENDIX D: CIRCUIT SCHEMATIC



Figure D-1: Circuit Schematic. ${ }^{[4]}$

## APPENDIX E: CONTROL DIAGRAM



Figure E-1: Control Diagram of the System.


Figure E-2: Control System Setup.

## APPENDIX F: CAD WORKS

The following figures show the CAD works of our three designs.


Figure F-1: CAD works of the leg walking machine.


Figure F-2: CAD works of the modified four-bar linkage walking machine.


Figure F-3: CAD works of the ratchet wheel walking machine.

## APPENDIX G: ORTHOGRAPHIC VIEWS

The following figures show the orthographic views of our three designs.


Figure G-1: Orthographic views of the leg walking machine.


Figure G-2: Orthographic views of the modified four-bar linkage walking machine.

(a) Front View.

(b) Right-side view.


Figure G-3: Orthographic views of the ratchet wheel walking machine.

