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3D Printing Technology-based an Amphibious Spherical Robot

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***Abstract* - It has long been recognized that the employment of underwater robots have important practical significance, which includes pipe survey, oceanic search, under-ice exploration, mine reconnaissance, dam inspection, ocean survey and so on. Owing to the limitation of underwater environment, some regular sized robots are not suitable for limited spaces. Thus some micro-robots appeared, while sacrificed important abilities such as locomotion velocity and enduring time to achieve compact sizes. Then a mother－son robot system was proposed in our previous researches, which included several micro-robots as sons and an amphibious spherical robot as the mother. The mother robot was adopted to make up for the shortages of micro-robots. This paper mainly focused on the structure and mechanism of the mother robot. The mother robot was designed with a spherical structure, which was composed of a fixed hemisphere hull and two operable quarter spherical hulls. It was actuated by four water-jet propellers and ten servomotors, capable of moving on land and in underwater environment. We developed a prototype and evaluated its walking and swimming motions in our previous experiments. Due to some problems in the process of assembly, the motion stability and reliability performed not so well. So, in this paper, we improved the structure and mechanism of the robot based on 3D Printing, which could eliminate some manufacture difficulties, shorten the production cycle, improve water-tightness, and enhance the robot's overall stability, compactness and aesthetics.**

Index Terms – 3D printing, Amphibious quadruped robot, Mother-son robot system, Bio-mimetic underwater robot, Spherical robot, Water-jet propeller.

I. Introduction

It has long been recognized that the underwater robot can implement some underwater tasks that humans deem dangerous, dull and dirty. This is mostly due to their ability of multifunction, flexibility, and high accuracy. Over the last decades, with the fast development of underwater robotics and related to all kinds of robot technology, the research of underwater robot has many remarkable achievements. Now, many countries in the world are devoted to the research of underwater robot, and underwater robot has a very wide range of applications, its applications involving industrial, fishing, exploring and military. Underwater robot has also become a significant tool for the development and utilization of sea resources [1]-[2].

As we all know, sea accounts for 71% of the total area of the earth, the biological and non-biological in the sea are the main resources to the survival of humans in the future. Therefore, the reasonable development and utilization of resources in such a vast ocean space is quite valuable. In ocean exploration and development, underwater robot has played an important role. Currently, many underwater robots mainly focus on medium-scale and large-scale, but micro-robots are also being researched all over the world because of their compact size. Micro-robots can be implemented in very limited spaces such as narrow pipelines or complicated underwater spaces full of coral reefs. But in order to realize compact size, several trades-offs have to be made and some important abilities such as locomotion and endurance time usually have to be sacrificed [3]-[6].

To combine the attributes of micro-robot and large-scale robot, we proposed a mother-son robot system, which includes several micro-robots as sons and a newly designed amphibious spherical robot as the mother [7]-[8]. When the mother robot reaches the desired location or encounters a narrow channel that is difficult to get across, it assumes a stable position and acts as a base station for the micro-robots. Then, the micro-robots exist in the mother robot, proceed to the target position and carried out their tasks. After that, micro-robots are kept in the space inside the lower hemisphere of the mother robot.

The object is to realize robot's multifunction and adaption to different environments, which is inspired by the amphibious turtles. The mother robot was designed with four legs and a spherical body, which had both a compact structure and maximum interior space. Compared with the streamlined body, it could rotate and change direction more easily, which was very important to the micro-robot in restricted spaces. The robot was actuated by using vectored water-jet propellers, which could be controlled easily with a stable thrust. In addition, this kind of actuation could generate little vortex, and it was silent and environment friendly. To expand the range of motion of the overall system, we designed the mother robot for amphibious use, which was capable of a walking motion on land and three-directional cruising motions in underwater environment. Due to some problems we encountered during installation and experiments, the robot are always unstable while walking and appear some unexpected problems, we decide to use 3D printing technology. This technology can accomplish seamless connection between some certain parts and let the robot have compact structure, perfect appearance, better waterproof and corrosion resistance, and more stable while walking on land and in underwater environment.

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The remainder of this paper is divided into five parts. First, we have reviewed the previously developed mother robot's mechanical structure and electrical design. Second, we have carried out some experiments and discussed some problems that exist. Third, we have shown the improved structure of the mother robot with 3D printing technology, and then some simulations of optimized structure by SolidWorks compared to the previous structure. Finally, we have presented our conclusions.

II. PREVIOUS PROPOSED MECHANICAL STRUCTURE

To achieve different underwater tasks, there will be requiring different shapes and size of underwater robots, for example, in deep underwater research, the robot needs to have a higher resistance to hydraulic characteristics, while for monitoring and observation underwater tasks, more attention should be paid to flexibility and stability. Mechanics, electronics and fluid mechanic are all the keys to achieve good performance for underwater robot motion control. To implement these controls it is necessary to establish some related models, with the premise of these models is to clearly know the internal structure of underwater robot. Thus this part mainly introduces the underwater robot's mechanical and electrical design of internal control circuit [9]-[11].

A. *Mechanical structure of Mother Robot*

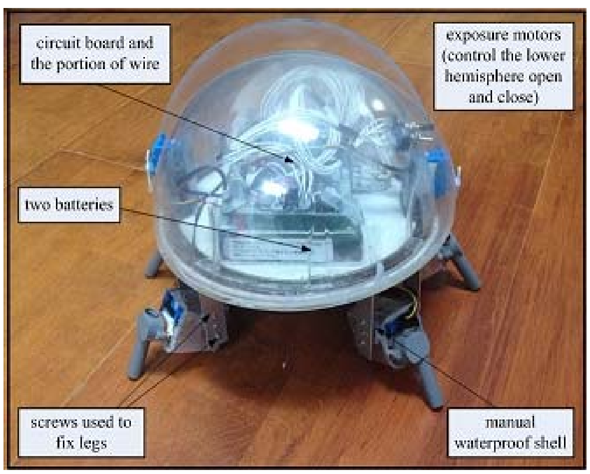


Fig.1 Previous prototype of the robot

Due to spherical structure which has the largest internal space, our mother robot is designed as spherical, and it has one hemisphere hull, and two operable quarter ball hulls. The robot has four water-jet propellers and eight servo motors. Three parts are integrated inside the robot: electrical control system, actuating system, and space for transport micro-robots. The robot can be divided into the waterproof part and the water exposure part, as shown in Fig.1.

With the consideration of downsize, we chose the power100 motor made by Raboesch as the water-jet motor, and also used the JR DS3836 servo motors, which has a compact size of 21.5*21.5*11mm, and each of them can rotate 120 degrees in max and provide a maximum torch of 2kg*cm. A water-proof box was added on each water-jet motor, water-proof was also conducted on the servo motors from inside, and stainless steel was used as the material of carrier.

B. *Electrical design of Mother Robot*

For the main control circuit board of mother robot, we adopt ATMEGA2560 as the main control board circuit; ATMEGA2560 can generate 16 channel PWM signals, fully meet requirements of some specific channels PWM signals. We can make some necessary extensions of the circuit board, add the power conversion circuit, motor drive circuit and related hydraulic propeller and serve motor to the board. Power conversion circuits mainly integrate with the linear voltage source of light emitting, diode chip, resistance and capacitance. Motor drive circuit is mainly composed of NPN transistor, diodes and resistors. Here I will not introduce these two circuits in details.

The mother robot used the motor as drive system. For mother robot's four legs, each leg is actuated by two servomotors and one water-jet propeller, in which two servomotors are perpendicularly installed in the horizontal plane and the vertical plane respectively, each water-jet propeller can be rotated by the two servomotors, and hence the direction of the jetted water which can be changed in the horizontal plane and the vertical plane either respectively or simultaneously. Two quarter spherical hulls are actuated by another two servomotors, which can implement opening and closing motion. For servo motor and battery we used in our mother robot, the relevant parameters are as follows: length is 31.0cm, breadth is 15.2cm, height is 31.0cm, the torque is 3.0kg.cm, the weight is 28.5g, and the speed is 0.18sec/60o. The servo motor itself has waterproof function, and in the experiments we did some further waterproof processing. The standard of the waterproof processing of servo motor is one of the key conditions to measure whether the underwater robot can accomplish normal operation or not. The good performance of the waterproof processing directly affects the robot's motion time in underwater environment and the poor waterproof effect leads to serve motor into the water, and light consequence of poor waterproof can let the served motor keep shaking or stopping the operation. The serious result is to let the whole control system entrance paralyzed state. In our system, we used two kinds of battery. They are all the charging battery, continuing to charging the power to circuit board. The big and small batteries working voltage are respectively 7.5V and 8.4V.

III. EXPERIMENTS AND PROBLEMS

To evaluate our mother robot's performance, we carried out some experiments on land and in underwater environment. Our mother robot can implement walking motion and rotating motion on land, ascending and descending motion in underwater environment. While walking, first, the vertical servomotor rotates to lift up the water-jet propeller; second, the horizontal servomotor actuates the water-jet propeller to swing forward; third, the water-jet propeller is dropped down and lastly it swings backward to implement one step. By changing the gait of four legs, the proposed robot can walk and rotate with different velocities. We have already presented the details of experiments results in our previous papers, and here I will not say more [12]-[14]. As a whole, the mother robot showed good performance, but there also exist some problems. For instance, because our robot’s some devices are assembled by hand, there exists some small accumulation error. The consequences of doing these could let the robot unstable and can’t walk too long time; and the reliability of the test is not too high; the fatigue life of the robot is too short; and the waterproofness is not achieve the desired results. The robot’s overall design and artistic is not good enough, and the robot's joint part is not perfect and while walking it also appear the screw loose phenomenon, so we need to find some new methods to solve these problems.

IV. IMPROVED STRUCTURE

Based on the construction of our previous mother robot, a high proportion of non-standard or customized mechanical parts and components were used, which significantly increased the prototype cost and production cycle and deceased the mate precision and waterproofness. For instance, the hemispherical upper hull was produced through injection molding, which was very expensive in small batch production, and a commercial steel bar was machined into the actuating units which needed a lot of bolts, nuts and gasket to fix motors, jets and axles.

In order to solve the above mentioned problems, we put forward a new processing method 3-D printing technology. 3-D printers seamlessly integrate with computer-assisted design software and other digital files like magnetic resonance imaging. It is a relatively rising technology which prints products on a layer-by-layer basis with material powder or beads. Compared with injection molding and cutting-based machinery, 3-D printing is able to produce custom products at relatively low prices and need no tools or molds, therefore it is more suitable for prototype production and function verification [15]. More importantly, 3-D printing is a manufacturing process which transforms mechanical drawings in computer-assisted design software to products directly, so designers can focus on designing products rather than managing production process. For a small amount of custom products, 3-D printing enables relatively low costs. At present the main application of 3-D is to establish the object's prototype and the model, a number of promising applications exist in the production of replacement parts, dental crowns, and artificial limbs, as well as in bridge manufacturing [16]-[18].

In this paper, 3-D printing technology-based an amphibious spherical underwater robot, we try our best to adopt the integration of the design and let the seamless connection between every part. This can reduce volatility in the walking process and thus will lead instability to the robot’s performance. 3-D printing can also avoid the error of manual processing, maximize the use of space and resources, and make the appearance of the whole robot looks more compact and perfect. Following we will talk about and analyze its specific design.

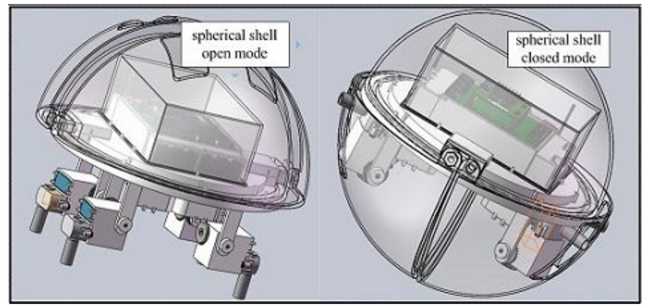


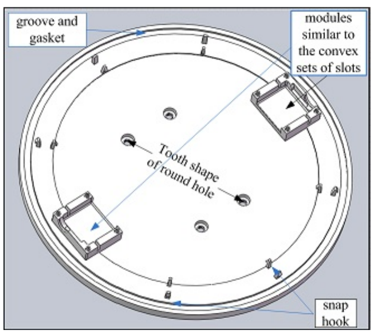
Fig.2 Overall view of the improved robot

The robot's overall appearance is shown in Fig.2, as we can see in the picture, when the robot is walking on land, the lower spherical shell is open and its four legs are vertical symmetrical. The right one shows the robot’s overall view while the lower hemisphere is closed. For the robot made by this kind of 3-D printing technology, we assembly use most parts with directly pushing method, by using the indented features generated by the grooves. This assembly way greatly reduced the inevitable cumulative error in the process of manual assembly, and for the upper hemisphere waterproof parts this assembly design can not only save more space, but also its waterproof performance more perfect. Next let us talk about the specific structure of some parts.

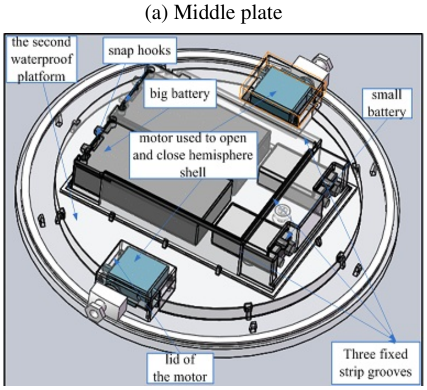
A. The design of the upper hemisphere

As we can see in the Fig.3, it shows the waterproof platform of the upper hemisphere. In order to ensure the reliability of the robot’s waterproof performance, we adopt a double diaphragm platform. The first layer platform is show on the left. It is a circular plate, with a diameter of 250mm, thickness of 8mm. We dug a slot with the distance 3.5mm of the circular platform edge, the width of the slot is 5 mm. We add 6 spring buckles near the slot, and we also put a gasket in the groove, whose thickness is 3 mm. This design ensures the soundness and integrity of the upper hemisphere shell when it is fixed on the circular plate. On the both sides of circular plate, two modules similar to the convex sets of slots, used for fixed the motors which control the lower hemispherical shell open and close. The four tooth shape of round hole in the center of the circular plate are used to fixed the four legs of the robot. Compared with many screws directly assembly before, this assembly have higher precision and better stability. In order to make full use of limited space of the upper hemispherical and better waterproof properties of waterproof components, for example the circuits and batteries, on the basis of this circular plate, we add another platform on the two platforms fixed with six snaps. The right picture in the Fig.4 shows the waterproof platform when fixed the batteries. To fix the batteries, we made a box-type structure opening at both ends. According to the size of four batteries, the box-type structures are divided into four parts. In the opening of box-type structure we have added two snaps, thus when fixed batteries we only need to push the battery directly to the corresponding slot, so that the snap can further ensure the stability. For motors used to control the lower hemispherical shell open and close, we add a lid on the convex sets of slots and use screw and gasket to ensure the motor's waterproof performance.

In order to install the circuit board, we made three fixed strip grooves above the box-type structure. Thus the circuit board can be firmly embedded in the slots and cannot get out while the robot moving, and the margin of which notches were curved to install seal washers. As we all know, for some related electronic devices of PCB and battery light, that the waterproof properties is good or bad will directly affect the overall performance. So the waterproof design is of vital importance to them, as is shown in the Fig.4, in order to further guarantee the circuit boards and battery's good waterproof performance, we added a box without covering on the top of the battery and circuit. This design enables us not only to pay attention to the battery and circuit board did double-insurance waterproof structure, but also to greatly save the space of the upper hemisphere and let the component have more compact connection between others. More importantly, such an integration of structure could enhance the shock resistance and stability of the whole robot.



(a) Middle plate



(b) Middle plate assembled with other components

Fig.3 Inner components in the upper hemisphere

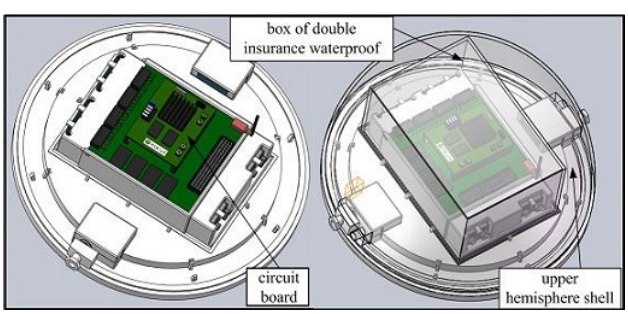


Fig.4 All components assembled in the upper hemisphere

B. The design of the lower hemisphere.

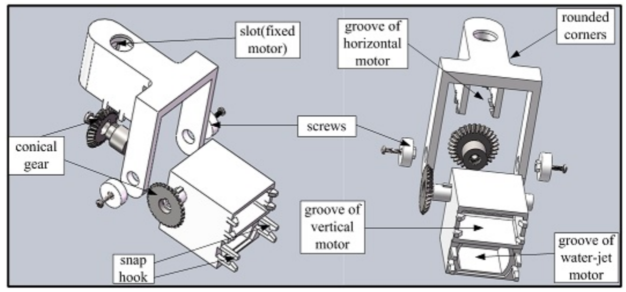


Fig.5 Explosion diagram of one leg

For assembly of robot's four legs, each leg mainly includes a vertical motor, a horizontal motor and a water-jet motor. We adopt an integrated molding stents for each leg, considering the scaffold is not only supporting the weight of the objects on upper inter hemispheric, but also bearing the pressure imposed on it by the lower three motors. We analyze the mechanical properties of leg brace and comprehensive variety of possible factors. After that we design the leg's leg brace as shown in the Fig.5. The leg braces joint is designed into a circular shape and this design can increase the strength of the scaffold and its compression performance is also stronger too. The front end of the stent not only can be used to fix the upper circular plate, but also can be used to fix the horizontal motor. The groove used to loading the horizontal motor is formed by the indented characteristic according to the related software, when the horizontal motor is pushing to the groove. The front gear is used to fix the circular plate above, at the end of the horizontal motor with two spring buckles for further strengthening. Although motor itself has waterproof function, the shell of the outside can enhance the waterproof properties further more. For vertical motor and water-jet motor, we fixed them with a whole big waterproof together. This large waterproof shell is divided into two independent spaces, one space used for fixed the vertical motor, and the other one for the water-jet motor, they all have the same installation method with the horizontal motor, namely, adopt the directly set in advance of the pressing properties of concave groove and then use the spring buckles for further strengthening.

The walking speed of our previous mother robot was severely restricted by the speed of servo motors. To solve this problem, a pair of conical gears was equipped in each joint of the actuating units to accelerate the movement of the legs. Using the occlusion feature of conical gear would have higher power transmission efficiency, while concave groove and spring buckles were also used to fix servo motors and water jets. When installing a motor, all we need to do was to insert the motor just like sliding a clip. Four thin stainless bars were installed in the flank of each leg to increase rigidity in the process of walking. Figure 6 shows the different views of the legs while assembly complete. The two quarter spherical lower hulls were fixed directly with simple screws respectively, and its opening and closing were driven by two servomotors to change the robot's motion attitudes in amphibious environment.

VI. STRESS ANALYSIS OF THE SIMULATION

In the process of the mother robot's walking, middle baffle plate part and the legs of stents suffer a relatively larger strength. The middle baffle plate not only suffers stress from the circuit board, batteries and spherical shell, but also suffers infliction from legs in the process of walking. Stress of the legs of stents also comes from different aspects, such as the tension from motor and the resistance from the conical gear. So first we made a mechanics simulation analysis for the improved structure of the middle baffle and the legs of stents.

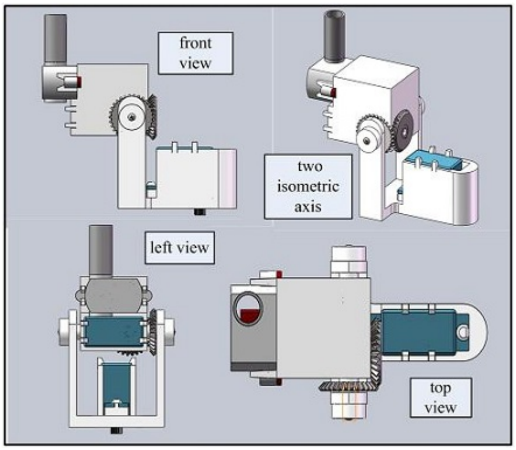
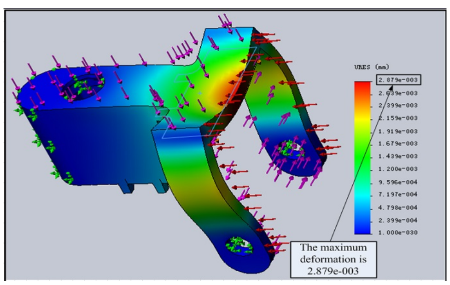
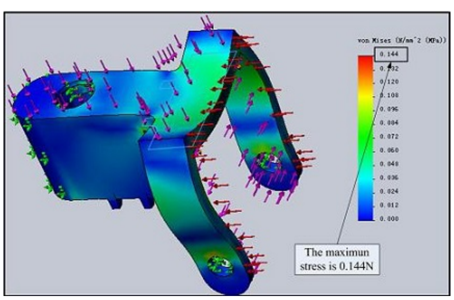


Fig.6 The leg's different views while assembly complete

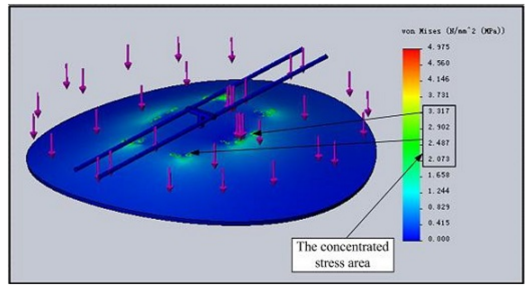


(a) The leg's deformation results

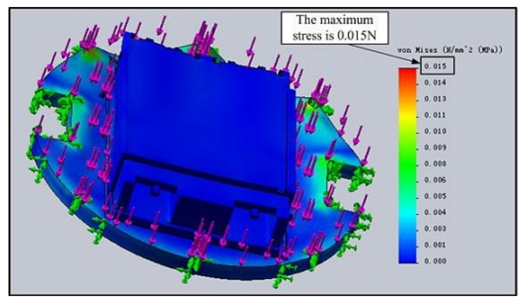


(b) The leg's support force results
Fig.7 The leg's analysis of von Misses stress

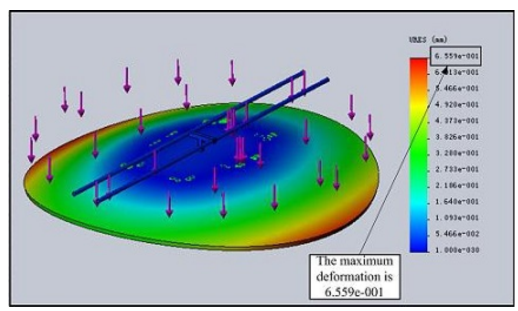
According to our assessment of overall structure stress distribution, we made a stress simulation analysis by SolidWorks. The weight of the robot was approximately 2.12 kg. Consider the resistance of legs while the robot walking and the impact force while the robot in underwater environment, ignore the friction force from the servomotor, water-jet and some tiny stress from other parts. In order to evaluate the newly designed structure's stiffness and strength, add the stress to the surface of legs and middle plate. We used ABS plastic material, and the scaffold's thickness is 4mm. Fig.7 (a) and Fig.7 (b) showed that the maximum deformation of legs was 2.897e-003mm and the maximum on Misses stress was 0.144N/m^2. The intersecting area of two vertical planes was the area of stress concentration. Figure 8 (a) and Figure 8 (b) showed the von Misses stress of the previous and current middle waterproof plate, Figure 9 (a) and Figure 9 (b) showed the maximum deformation of previous and current middle waterproof plate.



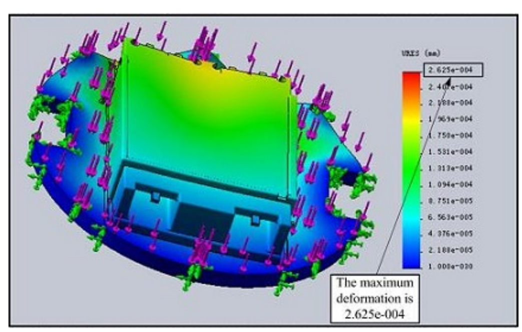
(a) The von Misses stress of the middle plate (previous)



(b) The von Misses stress of the middle plate (current)
Fig.8 Von Misses stress comparison



(a) The deformation results of the middle plate (previous)



(b) The deformation results of the middle plate (current)
Fig.9 Deformation comparison

With our previous middle waterproof plate, we adopt ordinary plastic material with the width of 3mm. Due to the overall stress comes from varies aspects, for example the weight of circuit board and batteries, and also the stress from leg while the robot is waking, the maximum deformation of plate was 6.559e-001mm, and the range of von Misses stress was from 2.073~3.317N/m^2. For our newly designed structure of middle plate, we adopt ABS plastic material with the width of 4mm. We also considered the overall von Misses stress, the maximum deformation of plate was 2.625e-004mm, and the maximum von Misses stress was 0.015N/m^2. As we can see from the simulation results, the improved structures has smaller deformation and has relatively equilibrium stress under the same condition of force, so the whole robot has better stability than the structure of before.

V. Conclusions

In this paper, in order to reduce the assembly error for our previously proposed mother robot, we proposed a technical solution and redesigned the mechanical structure of the mother robot to improve its accuracy and reliability. The whole body of the robot was designed with few components and manufactured by using 3-D printing, which is a direct and efficient process from mechanical drawings to prototypes. For there were just a few assembly connections, the number of gaps between components was observably reduced and water proof of the body was improved. Then, we analyzed the static forces and generated static deformations on the middle plate and four legs. According to comparison with previous structure, our new proposed 3-D printing prototype showed relatively better performance of the deformation and von Misses stress. Also, based on the proposed structure, the robot could eliminate some manufacture difficulties, shorten the production cycle, improve water-tightness, and enhance the robot's overall stability, compactness and aesthetics. In the future, we will implement the dynamic simulation of the whole robot, in which more factors will be considered.

Acknowledgment

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