The High-payload Manipulator Development Based on Novel Two-stage Cycloidal Speed Reducers and Hub Motors

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Abstract. Collaborative robots such as Universal Robotics and KUKA are well developed and well known throughout the world. Nowadays, the manipulator structure uses a brushless motor with an RV reducer, or a harmonic reducer, and has a built-in driver to form a joint module and is composed of a connecting rod. This paper proposes a four-axis manipulator based on the novel two-stage cycloidal reducers and hub motors. The traditional two-stage cycloidal speed reducer requires two cycloidal gears through the first-stage speed reducer. Therefore, the traditional two-stage cycloidal reducer has four cycloidal gears. The novel two-stage cycloidal speed reducer simplifies this design. The design of the secondary deceleration is achieved by connecting two different numbers of cycloidal teeth and a phase difference of 180 degrees to the intermediate central disc so that the two-stage speed reduction can be achieved, and the reduction ratio is 136. Use this type of speed reducer, with a 200W hub motor, to build a four-axis manipulator and place a driver in the rod to save space. The proposed manipulator specifications: 4 degrees of freedom, the maximum payload is 18kg, the total weight is 37kg, the maximum working space is 0.7 meters, the efficiency of the reducer is 73.657% and the backlash of the reducer is 1.135°. The features of this four-axis manipulator are lightweight, low power, low cost, high-payload, and long life. This type of reducer is also a new option in addition to RV reducer and harmonic reducer for driving manipulator's joint.

1. Introduction

Among all the core components of the robotics, the reducer is the most critical. There are two main types of reducers that are widely used in series robotics, RV reducer, and harmonic reducer. Compared with the harmonic reducer, the RV reducer has higher rigidity and life. Most robots used for automated manufacturing employ harmonic drivers for the upper two or three joints and RV reducers for the base joints. The cost of these two types of reducers has always been a problem. In the field of precision machinery, the processing technology must be tested to achieve a certain precision. Therefore, the more precise the reducer, the more expensive it is. In 2011, a new two-stage cycloid reducer [1] was proposed in an article published by Mirko Blagojevic et al., which is half the size of a conventional two-stage cycloid reducer and is similar in performance to the traditional two-stage cycloid reducer; Jyh-Jone Lee and others proposed another new two-stage cycloid reducer [2] in 2012, which has a thinner thickness than the two-stage cycloid reducer proposed by Mirko Blagojevic. The new two-stage cycloid reducer has a higher rigidity than the harmonic reducer and a smaller volume and mass than the RV reducer and seems to be suitable for high-load lightweight robots. The torques that cycloid gears can withstand and the backlash between cycloid gears and rollers have been studied in
Chiu-Fan Hsieh and Wun-Si Jian [6] analysed the key components of the new two-stage cycloidal speed reducer and RV reducer, including the distribution of stress and the relationship between backlash. Mirko Blagojevic [7] performed dynamic behavior analysis based on a new second-order cycloidal reducer. A mathematical model was established using Matlab-Simulink software to determine the parameters affecting cycloidal reducer. This paper proposes a four-axis manipulator based on a novel two-stage cycloid reducer, revising the structure published by Mirko Blagojevic et al. [1], compared to the same size RV or harmonic reducer, the novel two-stage cycloid reducer has a smaller volume and high reduction ratio makes it a place in the field of heavy load.

2. Novel two-stage cycloidal speed reducer

Typically, the cycloid drive contains two planet gears that are shifted 180 degrees from each other on the input shaft to provide dynamic balancing. It can be seen from this description of the cycloid drive that all contact within the mechanism is rolling contact as opposed to the sliding contact which occurs in a conventional gear mechanism [8], the explosion diagram of the one-stage cycloidal speed reducer of traditional design is shown in Figure 1. A single-stage reducer engages two identical cycloid discs in order to balance dynamical loads and to obtain uniform load distribution. Consequently, the traditional two-stage reducer has four cycloid discs, in total. The newly designed two-stage cycloidal speed reducer has one cycloid disc for each stage, that is, two cycloid discs in total, which means that it is rather compact. Due to its specific concept, this reducer is characterized by good load distribution and dynamic balance, and this is described in [1].

![Figure 1. A single-stage cycloidal speed reducer.](image1)

![Figure 2 A disassembled two-stage cycloidal speed reducer for hub motor.](image2)

A reducer for the hub motor is designed in Figure 2. The expression for the speed reducer ratio \( R \) is

\[
R = \frac{(N_2)(N_2+1)}{N_1-N_2}
\]  

(1)

where \( N_1 \) is the number of teeth of the first stage cycloidal gear and \( N_2 \) is the number of teeth of the second stage cycloidal gear. In this case, the first-stage cycloidal gear is 17 teeth, the number of stationary ring gear of the first-stage rollers is 18, the second-stage cycloidal gear is 15 teeth, the number of rotatable ring gear of the second-stage rollers is 16, and the transmission ratio is 136. The transmission ratio has a positive sign, which means that the output shaft rotates in the same direction as the input shaft, as shown in Figure 3 and Figure 4.

3. Hub motor

Low power hub motors are widely used in electromechanical systems such as electric bicycles and solar vehicles due to their robustness and compact structure. At the same power, the hub motor speed will be slower than the servo motor, but the torque will be higher than the servo motor, so the required
transmission ratio will be less. The motor has a power of 200 W, the rated torque is 2.35 N·m, the torque through the cycloidal reducer is approximately 320 N·m.

4. Four-axis manipulator

For the manipulator of this research, the primary task is vertical and horizontal loading and unloading, as well as handling, 4 degrees of freedom, structural design can be easily disassembled. The payload to mass ratio should be set between 0.3 and 0.5 which the manipulator with a payload of 20kg, and the total weight is controlled between 40 and 60 kg. In this paper, the total weight of the manipulator is 37 kg and payload is about 20 kg, as shown in Figure 5 and Figure 6.

5. System structure

The driver is placed in the arm of the manipulator, and one driver can drive two hub motors with a total of two drives in the manipulator. The driver uses the Hall sensor as feedback. After the
transmission ratio of 136, there are 4080 pulses in one rotation at the output, so the output has 11.33 pulses per degree. The power supply is provided by a 1500W AC-DC power. The microcontroller is using the STM32F4 and placed at the bottom, the system structure is shown in Figure 7.

![System structure](image)

**Figure 7.** The system structure of the manipulator.

6. **Backlash measurement**

The homemade reducer has obvious backlash problems due to assembly tolerances, machining tolerances, etc., so the actual backlash of the current reducer is measured. The measurement method is to use a gauge to vertically withstand a certain point of the structural member, as shown in Figure 8, and then manually pull the work-piece on the output end until it cannot be pulled, and observe the scale. The value of the scale at this time is 2.88 mm, as shown in Figure 9.

![Backlash measurement](image)

**Figure 8.** Use the gauge to withstand a point in the output. **Figure 9.** Use the hand to pull the output work-piece, and the observed value is 2.88 mm. **Figure 10.** Convert distance values to angle values.

Convert the distance value to the angle value to get the backlash value of each reducer, as shown in Figure 10 and Table 1.

| Axis | Backlash |
|------|----------|
| Axis 1 | 1.13°  |
| Axis 2 | 1.1°   |
| Axis 3 | 1.12°  |
| Axis 4 | 1.19°  |
7. Reducer noise measurement

In this part the noise measurement is described, the decibel meter is placed 10 cm away from the reducer, as shown in Figure 11, at 10 seconds to reach the output speed of 20 °/s, and maintained for five seconds. After that, the output speed reaches 35 °/s at 20 seconds, and the same is maintained for five seconds. The test result is shown in Figure 12. There is no special noise when the reducer is running, and the output is not tilted or shaken, so it can be verified that the structure is stable and the axial restraint force is greatly enhanced.

8. Payload test

The payload test process is shown in Figure 13. The weight is about 18 kg. In this part, this experiment only implements the speed response without PID control. The path planning of the manipulator is divided into 4 steps. The first step is to move the robot arm to the origin position, have a positioning groove on the robot arm, and insert the positioning fixture to achieve precise positioning. The second step is to move the second axis, the third axis, and the fourth axis to the carrying point, that is, the second axis rotates 20° (the rotation direction is defined by the DH matrix), the third axis rotates -20°, and the fourth axis rotates -33° and place the load in the end effector. The third step is to lift the load and the second axis rotates by -45° to ensure that the center of gravity of the load can be close to the inside of the arm. The fourth step is to rotate the first axis by -45° to pull the load off the work platform.

The manipulator specification is shown in Table 2. The payload is reduced to 18 kg due to the lower efficiency of the reducer than the estimated value, and the total weight is 37 kg. Since the backlash is much larger than the estimated value, the rated speed is set at 30°/s, and the rated speed can be higher when the system is stable.
Table 2. The specification of the manipulator.

| Specification                        | Value  |
|--------------------------------------|--------|
| Payload                             | 18 kg  |
| Max reach (mm)                      | 700    |
| Total weight                        | 37 kg  |
| Degree of freedom                   | 4      |
| The backlash of reducer             | 1.135° |
| Power consumption Motor spec.       | 200W*4 |

9. Conclusion

This paper proposes a combination of a novel two-stage cycloidal speed reducer with a hub motor and a four-axis manipulator. Verification and experimentation were carried out on the proposed reducer to understand that the backlash is generated by tolerance, which affects the continuity of efficiency and operation. In combination with the hub motor and the novel two-stage cycloidal speed reducer, it is very helpful for high-payload robots, especially in terms of price and volume. In the future, the problem of backlash will be solved, and the efficiency and stability of the reducer will be improved, which will provide a new direction for the future robot market.

10. References

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