Study on Robotic Differential-drive Actuator
with Parallel Velocity Control

Peng Gao, Anye Ren

Key Lab for Structure and Machinery, Aerospace System Engineering Shanghai,

Shanghai, 201109, China

pompon_gp@163.com

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Abstract. In this paper we propose a differential-drive actuator with dual-input actuation for robotic manipulation. This work is focused on mechanism design and actuation control. Based on an epicyclic gear train, the actuator uses a floating ring gear to realize two inputs and single output. Based on differential velocity control, the actuator can realize stepless speed regulation and flexible transformation. Finally, we fabricate an actuator prototype, which shows the feasibility of robotic differential-drive, but needs further experiments and tests.

Introduction

The robots normally adopt single-input and single-output driving mode, such as planetary gear reducer, harmonic gear reducer, RV reducer and so on, with relatively static dynamic response. However, the advanced robots are capable of reliable and safe manipulation, such as space robot and rehabilitation robot, which need dynamic response [1, 2]. Many approaches have been introduced in the past to achieve variable actuation capabilities. Most of all are based on dual-input actuation techniques [3]. Some actuators are based on differential drive [4, 5], some are based on antagonistic actuation [6], and some are based on series-elasticity [7, 8].

In this paper, we propose a differential-drive actuator with dual-input actuation for robotic dynamic response. Our focus is on mechanism design and actuation control. Based on an epicyclic gear train, the actuator can realize dual-input with a floating ring gear. Under the differential velocity control, the actuator can realize stepless speed regulation and fast transformation. Finally, we fabricate a prototype and give some initial tests, which show the feasibility of robotic differential-drive actuator.

Differential-drive Concept

Differential drive mixes two distinct inputs, as shown in Fig. 1. The input A and B, namely, are the velocity actuator A and the velocity actuator B, which have different dynamic velocity response. The input A can has a fixed velocity ratio, and the input B has a variable sensitivity velocity ratio. When there is no velocity difference between A and B, the output O is fixed relative to the ground; on the contrary, the output begins to move. Compared with the single input, the differential drive can realize the stepless speed regulation with high dynamic response and the fast transformation without the change of the motor rotation direction.
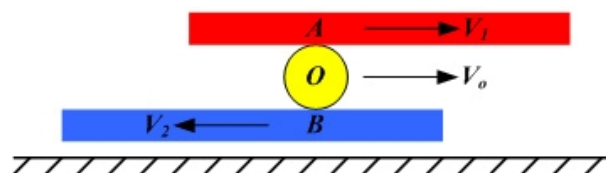

Fig. 1 Differential-drive concept

The goal of this research is to design a robotic differential-drive actuator for parallel velocity control. Based on the above differential-drive concept, the actuator adopts epicyclic gear train with two distinct inputs. Fig. 2 shows the actuator configuration. A is the sun gear of input1, B is the sun gear of

input 2, C is the fixed planetary gear, D is the floating ring gear, E is the rotary planetary gear, and F is the output framework. A and B are respectively connected with different motor, and F is the only output connected with manipulator joint.
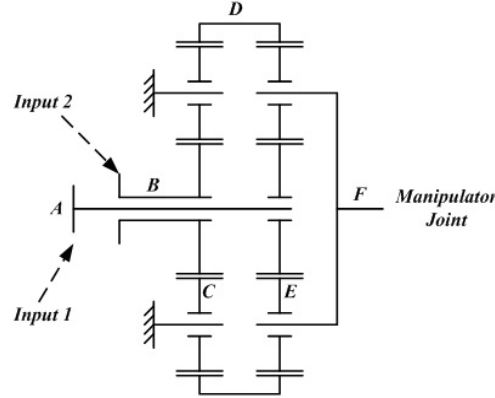

Fig. 2 Configuration of differential-drive actuator

Kinematics Analysis

The epicyclic gear train used in the above actuator is a velocity subtraction mechanism. The output velocity is a linear subtraction of the dual-input velocities.

$$v_o = \frac{1}{2}(v_1 - v_2)$$
(1)

The subscripts "1", "2", and "o" refer to the input 1, the input 2, and the actuator output. Eq. 1 shows that the actuator has two kinematic degrees of freedom. The positive direction of v_1, v_2, and v_o, are defined in the Fig.1. In theory, we can independently choose the velocity of two of the three shafts A, B, and F as two distinct inputs. In fact, we select A as input1, and B as input 2, because they have the similar structure and intensity.

When v_1 is equal to v_2, v_o is obviously equal to zero. The gear E rotates by itself, but not around the axis F. The manipulator output is zero. When v_1 is bigger than v_2, v_o has the same direction with v_1; When v_1 is smaller than v_2, v_o has the same direction with v_2. It is obvious that v_1 and v_2 do not need to change the rotation direction, and v_o can realize the flexible transformation. At the same time, the value of v_o is fixed by the relationship in Eq. 1. Therefore, we can fix the rotation ratio of any one of v_1 and v_2, and adjust the other to realize the stepless speed regulation and the flexible transformation of the manipulator joint. The differential-drive actuator not only avoids the disturbance of the rotary transformation of the electronic motor, but also improves the range and continuity of the output.

Power Flow Analysis

The power flow analysis is very important for the differential-drive actuator, because the resulting efficiency of the dual-input actuator is different from the individual input. The epicyclic gear train of the differential-drive actuator should be under power equilibrium irrespective of power losses.

$$p_o = p_1 + p_2$$
(2)

Based on a simple epicyclic gear train, the differential-drive actuator has three power ports. There are several power flow modes.

Mode 1. $p_1 > 0$, $p_2 > 0$, and $p_o > 0$. This is the normal operational mode. The actuator is expected to be in this mode, which is the two-input-one-output mode.

Mode 2. $p_1 > 0$, $p_2 < 0$, and $p_o > 0$; or $p_1 < 0$, $p_2 > 0$, and $p_o > 0$. One input backdrives the other. This is an undesirable mode.

Mode 3. $p_1<0$, $p_2<0$, and $p_o<0$. The external torque from the manipulator joint backdrives the two input. This is an undesirable mode. In this mode the external power at F shaft, is significantly more than the support by the two inputs.

Mode 4. $p_1>0$, $p_2<0$, and $p_o<0$; or $p_1<0$, $p_2>0$, and $p_o<0$. One input is backdriven by the output, while the other input is still the input. This can happen when there is external disturbance from the manipulator joint. This mode can be used to detect the external collisions.

In our analysis, the parallel velocity control should consider the power flow between the two inputs and the individual output to change the fixed rotation ratio and adjust the variable sensitivity velocity ratio.

Parallel Velocity Control

The differential-drive actuator is designed for robot high performance manipulation. The two indistinct inputs can be individually controlled under velocity control mode, which is the normal control method for DC or AC motor, and has the higher responsibility than angle control mode. In addition, the motor do not need to stop for output braking and change the rotary direction for output transformation. Therefore, the motors can continuously rotate.
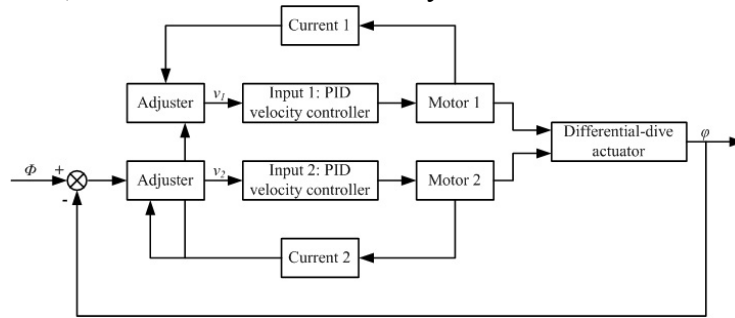

Fig. 3 Scheme of the parallel velocity control

Fig. 3 shows the scheme of the parallel velocity control. However, compared with the single-input actuator, the parallel velocity control has to detect the power flow among the three parts (two inputs and on output). The motor current can be as the inspecting condition, because the motor rotation direction is fixed. The mode 2 and 4 are similar difficult to be distinguished. However, the mode 2 can be avoided at the beginning of selecting the motors and setting the fixed velocity ratio; the mode 4 can be adapted by adjusting the fixed velocity of the other motor. The each velocity controller can adopt the classic PID method, and the output angle is tested and feedback to the outside control loop.

Fabrication and Experiment

The prototype of the differential-drive actuator is shown in Fig. 4.

Fig. 4 Prototype of the differential-drive actuator

Fig. 4(a) illustrates the main parts of the differential-drive actuator prototype. According to Fig. 2, A is the sun gear of the input 1, B is the sun gear of the input 2, C is the fixed planetary gear, D is the floating ring gear, and E is the rotary planetary gear. Fig. 4(b) shows the front output flange for the manipulator joint. Fig. 4(c) shows the back input interface with the input 1 axis and the input 2 axis. Fig. 4(d) shows the experimental platform of the prototype, where the two inputs are directly connected with two same DC brushless motors. The motors are actuated by a DC servo driver, which is communicated with a central computer by EtherCAT bus. The motor 1 is set up with a fixed velocity ratio, and the motor 2 with an adjustable velocity ratio. The output flange is connected with an angle encoder. The output angle, the velocity and current of motor 1 and 2, are feed back to the central computer.

In the initial experiments, we find that the prototype reaches an accord to realize the differential drive actuation. In addition, different velocities and load torques may lead to a complex power flow, therefore the parallel velocity control should consider the different influences under the different power flow modes. In the future study, we will further develop the optimized mechanism of the differential-drive actuator and the algorithm of the parallel velocity control.

Conclusion

In this work, we proposed a differential-drive actuator for the reliable and safe manipulation of the robot. In the paper, we have discussed the kinematic and power flow of the differential drive, based on which we introduced a parallel velocity control framework. Finally, we fabricated a differential-drive actuation prototype, and build up an experimental platform. In the future work, we will pay more attention to the mechanism optimization of the actuator and the algorithm development of the parallel velocity control.

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