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Mechatronic Dual-Redundancy Steering Gear System in Vehicle

Abstract: Mechatronic dual-redundancy steering gear system is an essential part in steer by wire system. It is not only the very important actuator in steering system, but also needed in autonomous driving car for its autonomous steering. A key point for mechatronic dual-redundancy steering gear system is its reliability and safety. To realize a kind of this system with high reliability and safety, the work on this paper proposed a kind of mechatronic dual-redundancy steering gear system, designed the mechanical architecture and controller architecture of the system, and built the redundancy management mechanism of mechatronic dual-redundancy steering gear system using redundancy theory. Simulation results verify the working ability and reliability of this system.

Keywords: mechatronic, redundancy, steer by wire, high reliability and safety

1 Introduction

Mechatronic dual-redundancy steering gear system is an essential part in steer by wire system in vehicle, which receives the steering angle information from steering wheel and executes steering operation using motors. Mechatronic dual-redundancy steering gear system is also needed in autonomous driving car for its autonomous steering. Concerning for the reliability and safety of steering, a redundant steer by wire system including a Mechatronic dual-redundancy steering gear system is came up with as vehicle steering system.

Many schools and companies have studied mechatronic dual-redundancy steering gear system while there are very less vehicles using it because the reliability and safety of the system is hard to guarantee. Yixin Yao and Brian Daugherty of Visteon

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Company [1] have proposed a structure of mechatronic dual-redundancy steering gear system by connecting two driving motor in an axis. They also did simulation study and got a good tracing performance and fault-tolerant ability. Dieter Heitzer and Alois Seewald in TRW Company [2] analyzed the mechatronic dual-redundancy steering gear system and proposed an electrical fault-tolerant structure of mechatronic dual-redundancy steering gear system and its redundant power supply system. They also proposed a HIL program of mechatronic dual-redundancy steering gear system. Yuichi Onoda and Yutaka Onuma [3] set up a kind of architecture which is based on mechatronic dual-redundancy steering gear system, and set up the model of steer by wire system. They did the assessment of the test vehicle simulation and got the steering features of steer by wire system in small steering angle. Bing Zheng and Cliff Altemare in Indiana's Purdue university [4] proposed a mechatronic dual-redundancy steering gear system with two motors and two controllers and Sohel Anwar and Lei Chen [5] optimized the two motor structure based on their study. And Mohammad Sharif-ul Hasan and Sohel Anwar [6] set up the sliding-mode observer and the method to long-run forecast and failure-tolerant control. And they used simulation to perfect system redundancy control. Also Isermann R, Schwarz R, Stolzl S [7] has their method of failure-tolerant in drive by wire system such as steer by wire system. Their works always have partial redundancy so the system may fail to work caused by one fault.

This paper proposes a structure of mechatronic dual-redundancy steering gear system with steer by wire technology in vehicle. The structure is based on redundancy theory and the system can reach once “failure/operation/warning” safety mechanism, which means that once a failure occurs in this system, the steering function is still operating as normal mode and the system will send warning information to let vehicle know that steering system has a fault.

2 The Structure of Mechatronic Dual-Redundancy Steering Gear System

Mechatronical dual-redundancy steering gear system has four modules, as shown in Fig. 1
In Fig. 1, mechatronic dual-redundancy steering gear system SG can be expressed as

$$SG = \{C, S, M, G\}$$

With elements
- C = Redundant controllers set
- S = Redundant sensors set
- M = Redundant motor driving set
- G = rack and pinion steering gear

In a mechatronic dual-redundancy steering gear system with high reliability safety, the system is formed with two steering motors, two controllers, two steering pinion angle sensors and two steering motor current sensors, which are shown in Fig. 2. In this system, the two steering motors $M_1$ and $M_2$ give the force to steer together and each motor is controlled by its controller. The same steering pinion angle information $\theta_{PA1}$ and $\theta_{PA2}$ is collected by steering pinion angle sensors $S_{PA1}$ and $S_{PA2}$, and steering motor current information $i_{SM1}$ and $i_{SM2}$ is collected by steering motor current sensors $S_{MC1}$ and $S_{MC2}$, then the information is transmitted to the corresponding
controllers. The two controllers $C_{g1}$ and $C_{g2}$ communicate with each other by redundant communication network which is consisted of CAN bus and FlexRay bus. The network is also working for the communication between mechatronic dual-redundancy steering wheel system and mechatronic dual-redundancy steering gear system.

In this architecture, the two steering motors work together to steer in normal mode. One motor, one controller, one steering pinion angle sensor and one steering motor current sensor forms one motor driving channel and the others form the other motor driving channel. The information gotten from each kind of sensors in each channel is collected by both controllers and the same two pieces of information will be arbitrated to one which is correct for normal steering. But once one of the two controllers or motors or sensors breaks, there are some measures to detect the fault and it will immediately cut the broken motor driving channel and the system will use the motor which is in normal situation to steer.

The redundant motor driving set is consisted of two motors which are connected by gears and the two motors rotate together in normal mode. The output then is reduced by worm gear reducer and drives the rack and pinion steering gear. The steering pinion and the worm are in the same axle for steering. The gear ratio between two motors is 1:1 so the two motors can output the same amount of torque and have the same rotating speed. This is shown in Fig. 2 below.

![Diagram](image_url)

- **M_s1**: steering motor of channel 1
- **M_s2**: steering motor of channel 2
- **W**: worm gear reducer
- **G**: Rack and pinion steering gear

**Fig. 2**: The structure style of redundant motor driving set
3 The Controller System of Mechatronic Dual-Redundancy Steering Gear System

The function of mechatronic dual-redundancy steering gear control system is to receive the messages of sensors and steering wheel angles in the same time drive the steering motor to execute steering operation normally. Also redundancy management is needed in the control system so the system can reach ‘failure/operation/warning’ safety mechanism so as to insure its safety and reliability.

3.1 The System Architecture Of Mechatronic Dual-Redundancy Steering Gear Control System

Fig. 3 shows the controller architecture of mechatronic dual-redundancy steering gear control system. The controller mainly consists of steering gear upper sub-controller for upper decision, steering gear information transmission sub-controller for information transmission and steering motor sub-controller for controlling the steering motor. There are angle arbitration and current arbitration to arbitrate the angle and current values which the sensors get. Steering motor sub-controller executes the current close-loop to control the motor using PWM, and steering gear upper sub-controller executes the angle close-loop to let the steering pinion angle racks the steering wheel angle.
Failure detection and failure diagnosis are both done in steering gear upper sub-controller and when failure occurs, both controllers are able to judge if the other is in a fault and use cut signal to execute channel isolation.

### 3.2 The Working Principle Of Mechatronic Dual-Redundancy Steering Gear Control System

In the mechatronic dual-redundancy steering gear system as shown in Fig. 3, the steering wheel angle message is transmitted from redundant network through redundant network information arbitration \(A_{GN1}\) and \(A_{GN2}\). Then the message is gotten by steering gear upper sub-controller \(CGU1\) and \(CGU2\) through steering gear information transmission sub-controller \(CGI1\) and \(CGI2\). Then the steering gear upper sub-controller calculates the target current of motor \(iGT1\) and \(iGT2\) to let the steering motor controllers \(CGM1\) and \(CGM2\) to execute the current close-loop of motors. So the steering motor controllers give the motor driving circus a proper PWM wave with a changed duty cycle so as to make the current of motor tracks the target current. The steering pinion...
angle sensors measure the angle $\theta_{SP1}$ and $\theta_{SP2}$ and the steering current sensors measure the current $i_{SM1}$ and $i_{SM2}$, and transmit them to the controllers.

For one motor driving channel, it will receive the current and angle message of it, and will also receive the other channel’s message through redundant network. Then both the two angle and the two current values will be arbitrated in each controller so the true angle $\theta_{SP}$ and the true current $i_{SM}$ is gotten in each controller.

This is the normal working principle of mechatronic dual-redundancy steering gear system. And when failure occurs, both controllers have the ability to judge if the other channel is right or wrong and is able to cut the motor current channel of the other.

### 3.3 The Redundancy Management Of Mechatronic Dual-Redundancy Steering Gear System

The redundancy theory demands that the system should reach once “fail-ure/operation/warning” safety mechanism that means even if there is a failure occurs, the system should keep operating and give a warning signal to upper system. So it needs failure diagnosis and failure isolation in mechatronic dual-redundancy steering gear system.

In the mechatronic dual-redundancy steering gear system, the failure diagnosis is working all the time to determine where the failure occurs. The failure diagnosis is mainly based on the angle and the current. The failure isolation mode of mechatronic dual-redundancy steering gear system is shown in Fig. 4.
Fig. 4 shows the failure isolation mode of mechatronic dual-redundancy steering gear system. For example, when CGU1 is in a failure, the CGU2 will detect the failure and give the signal s_{21} to cut the motor current channel of M_{s1}. In the same time, CGU3 will also detect the failure and give the signal s_{32} to let the current channel of M_{s2} is always on so as to prevent CGU1 cut the current channel of M_{s2} wrongly. The logic circus of the failure isolation of mechatronic dual-redundancy steering gear system is shown in Fig. 5 and its true table is in Table. 1.
As shown in Fig. 5 and Table 1. The on-off signal of current channel of $M_{s1}$ is gotten from the logic circus of signal $s_{21}$ and $s_{31}$, and $s_1 = s_{21} \cup \overline{s_{31}}$.

In normal mode, both $s_{21}$ and $s_{31}$ is equal to 1 and $s_1$ is 1, so the current channel of $M_{s1}$ is on. When the channel of $M_{s1}$ fails, $s_{21}$ will be set to 0 so $s_1$ will turn to 0 and the current channel of $M_{s1}$ is cut. And when the channel of $M_{s2}$ fails, $s_{31}$ will be set to 0 so $s_1$ will always be 0 no matter what $s_{21}$ is. Then the wrong channel $M_{s2}$ will never affect the normal channel $M_{s1}$ so can make sure the system can work normally.
4 Simulation of Mechatronic Dual-Redundancy Steering Gear System

To verify the function and redundancy ability of mechatronic dual-redundancy steering gear system, this work uses system simulation by Matlab Simulink and Carsim.

In the simulation of the system, the two motors work together to follow the steering wheel angle. The steering wheel angle is simulated by actual test from steering wheel, which can be seen in Fig. 6. (a)

![Graph showing steering wheel and gear angle comparison]

(a)

![Graph showing steering angle tracking error]

(b)

Fig. 6: steering angle tracking and tracking angle variation in normal mode
Fig. 6(a) shows that steering gear angle tracks steering wheel angle well by the two motors’ working together. And Fig. 6(b) shows that the angle variation between steering gear angle and steering wheel angle is less than $4^\circ$ every time, which is quite small. So it can be seen that the steering function plays well.

Matlab Simulink is also used to verify the redundancy ability of the system. In this test, steering wheel angle is different from that in two-motor mode. The simulation lasts almost 8 seconds and simulates a failure of one motor in the third second.

Fig. 7(a) shows steering angle tracking in this situation and it shows that the steering gear angle is tracking steering wheel angle as well as in two-motor mode after one failure occurs and there is only one motor working to track the steering wheel angle. In Fig. 7(b) it can be seen that in the third second there is little enlargement in the tracking angle variation between steering wheel angle and steering gear angle, which has no effect on the system working. And the tracking angle variation is less than $3^\circ$ all the time, so the steering function is still normal by one motor steering.
5 Conclusion

This paper presents a mechatronic dual-redundancy steering gear system, designs the mechanical architecture and controller architecture of it, and builds the redundancy management mechanism of mechatronic dual-redundancy steering gear system, including its failure diagnostician and failure isolation. The following conclusions are obtained:

(a) The proposed mechatronic dual-redundancy steering gear system not only can have good steering behavior but also can reach once ‘failure/operation/warning’ safety mechanism, having safer and more reliable steering ability.

(b) The proposed redundancy management strategy can realize failure diagnosis and failure isolation, so as to make the system keep working normally after one failure occurs.

(c) The proposed controller architecture of mechatronic dual-redundancy steering gear system can make the two motors in steering gear system work together in normal mode and change to one motor operating mode when one is failed, which makes the system work safely.
References


