Research on Fault Tolerant Strategy and Reliability of Steering-by-Wire

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Abstract—In this paper, we introduce a methodology for the reliability analysis of the redundant steering-by-wire system. With rapid development of modern automotive electronics and deep electronic degree, it is necessary to analyze the reliability of system to fully understand and quantify the failure mechanisms in order to improve the design. Several system level FMEAs are used to identify the different failure times of system and a markov model is constructed to quantify their probability of occurrence. For the safety-critical real-time system, the redundancy, failure rate and fault coverage of component are important factors to the reliability of system. It is, therefore, necessary to develop a highly dependable SBW system architecture to ensure the security of car by using redundancy, decreasing failure rate, or increasing fault coverage.

Index Terms—Steering-by-wire (SBW), failure mode and effects analysis (FMEA), markov model, redundancy.

I. INTRODUCTION

Rapid development of modern automotive electronics and deep electronic degree make the X-by-wire technology widely used in all aspects of the automobile, such as steering-by-wire, brake-by-wire, suspension-by-wire and throttle-by-wire and so on. X-by-wire technology derived from NASA in 1972 is the first to be used in telex operating system (Fly-by-wire) on space science and technology, which is an important technology of vehicle into autopilot era.

Automotive steering-by-wire system is a safety-critical real-time system. In safety-critical real-time system, the failure of a single component may cause the entire system to a standstill. Thus, fault tolerance is especially important [1]. The reliability of the electrical control system has been continuously improved in the system design, which largely introduces the concept of redundancy. In order to ensure real-time and reliability of the system, in the auto industry, there has been a large-scale Auto Union, aimed at building a scalable electronic architecture (such as AUTOSAR) and a generic, scalable communications system, such as FlexRay, which meets the needs of active safety systems. CAN bus, which is the most commonly used, has drawbacks in fault tolerance and bandwidth. Therefore, the FlexRay is used in the automotive steering-by-wire system [2].

II. SYSTEM DESIGN

In order to ensure real-time and reliability, and meet the

requirements of economic practicality, the architecture of steering-by-wire system with fault tolerance is shown in Fig. 1.

Fig. 1. Block diagram of fault-tolerant architecture of steering-by-wire system.

As shown in Fig. 1, the needs of driver's steering are achieved through three angle sensors. Two HW ECUs respectively receive data from three angle sensors, whose dates will be voted. Then ECUs transmit correct messages to the dual-channel FlexRay bus. Two FAA ECUs receive messages from the bus to control the steering motor, vice versa.

III. SYSTEM LEVEL FMEA

To facilitate the presentation, we use IN to represent sensor, and use OUT to represent motor. In order to establish the Markov model of steering-by-wire system, the first step is to develop several system level FMEAs according to the simplified logic block diagram of system. The first FMEA will help to identify first failures in the system, both catastrophic and non-catastrophic. The second FMEA will identify second catastrophic and non-catastrophic failure modes of the new non-catastrophic operational modes of the system defined by the first FMEA. The process will end when all the identified failure modes of an FMEA are catastrophic. To construct the system level FMEA, some simplifying assumptions are postulated:

- 1) Firstly, each unit is not considered transient failure and permanent failure, which is all defined as the failure rate λ .
- 2) Secondly, repair rate ρ of each unit and fault coverage c are not considered.

Define sensor failure rate as λ_{IN} , ECU failure rate as λ_{ECU} , and motor failure rate as λ_{OUT} . The FMEA tables of steering-by-wire system are shown in Table I-Table V.

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Table I corresponds to the FMEA of first fault of System. The first column of Table I lists the failures of the system state. The second column is the probability of the first column by the state described in the associated event. The third column describes the system failure times described in the first column generated, and the fourth column shows the failure rate of failure. Finally, the fifth column lists the probability of these new systems associated status. Table II corresponds to a second fault system FMEA. The first column of Table II is a non-fault state which corresponds to Table I in the fifth column. The remaining columns of Table II obtain the same manner in Table I. Table II reporting the third failure system and its construction method is same with Table II. Besides it lists the non-fault state from the fifth column of Table II. Table IV, V are constructed the same way as Table I.

TABLE I: SYSTEM LEVEL FMEA FOR FIRST FAILURES

System state with no failures	State probability	First failure	Failure rate	State probability
Sensor normal, steering motor normal, ECU node normal running	P1	Any sensor failure	$3\lambda_{IN}$	P2
		Any ECU failure	$2\lambda_{ECU}$	P8
		Any motor failure	$2\lambda_{OUT}$	P9

TABLE II: SYSTEM LEVEL FMEA FOR SECOND FAILURES

System state with one failures	State probability	Second failure	Failure rate	State probability
The remaining two sensors work properly, dual-motor normal, two-ECU normal	P2	Any sensor failure	$2\lambda_{IN}$	P3
		Any ECU failure	$2\lambda_{ECU}$	P4
		Any motor failure	$2\lambda_{OUT}$	P11
Three sensors are normal, two-motor normal, ECU single point of failure	P8	The remaining ECU node failure	λ_{ECU}	PF
		Any sensor failure	$3\lambda_{IN}$	P4
		Any motor failure	$2\lambda_{OUT}$	P10
The remaining motor instead of failing motor to provide steering, three sensors normal, two ECU normal	P9	The remaining motor failure	λ_{OUT}	PF
		Any sensor failure	$3\lambda_{IN}$	P11
		Any ECU failure	$2\lambda_{ECU}$	P10

TABLE III: SYSTEM LEVEL FMEA FOR THIRD FAILURES

System state with two failures	State probability	Third failure	Failure rate	State probability
Only one sensor is normal, two electric motors are normal, two ECU normal	P3	The remaining sensor failure	λ_{IN}	PF
		Any ECU failure	$2\lambda_{ECU}$	P5
		Any motor failure	$2\lambda_{OUT}$	P12
Two sensors work properly, dual-motor normal, ECU single point of failure	P4	Failure of any one of the remaining sensors	$2\lambda_{IN}$	P5
		Any ECU failure	λ_{ECU}	PF
		Any motor failure	$2\lambda_{OUT}$	P6
The remaining two sensors are normal, the motor single point of failure, double ECU normal	P11	Failure of any one of the remaining sensors	$2\lambda_{IN}$	P12
		Any ECU failure	$2\lambda_{ECU}$	P6
		Any motor failure	λ_{OUT}	PF
Three sensors normal, motors single point of failure, ECU single point of failure	P10	Any sensor failure	$3\lambda_{IN}$	P6
		Any motor or ECU failure	$\lambda_{ECU} + \lambda_i$	PF

TABLE IV: SYSTEM LEVEL FMEA FOR FOURTH FAILURES

System state with three failures	State probability	Fourth Failure	Failure rate	State probability
Only one sensor is normal, two-motor normal, ECU single point of failure	P5	Failure of any one of the remaining sensors or ECU	$\lambda_{IN} + \lambda_{ECU}$	PF
		Any motor failure	$2\lambda_{OUT}$	P7
Two sensors work properly, motor single point of failure, ECU single point of failure	P6	Failure of any one of the remaining sensors	$2\lambda_{IN}$	P7
		Any motor or ECU failure	$\lambda_{ECU} + \lambda_{OUT}$	PF
Only one sensor is normal, motor single point of failure, double ECU normal	P12	Any ECU failure	$2\lambda_{ECU}$	P7
		Any motor or sensor failure	$\lambda_{IN} + \lambda_{OUT}$	PF

TABLE V: SYSTEM LEVEL FMEA FOR FIFTH FAILURES

System state with four failures	State probability	Fifth Failure	System state with five failures	State probability
Only one sensor is normal, motor single point of failure, ECU single point of failure	P7	Failure of any one of the remaining sensors or ECU or motor	FAILED	PF

this paper is superior to that of traditional SBW system. The point is redundancy, which is of importance in safety-critical system.

Fig. 3. The reliability diagram of redundant and non-redundant steering-by-wire system.

Fig. 4. Reliability of triple modular redundancy and single mode systems under different failure rates.

Fig. 5. The impact on the reliability of fault coverage.

A result in this paper is the reliability analysis to study the influence of the presumed failure rates of ECU, sensor and motor. So the failure rate is a factor to the reliability of system. We set λ equal 10^{-7} and $\underline{\lambda}$ equal 10^{-8} respectively to compare the reliability between triple modular redundancy (TMR) system and single modular system to demonstrate the impact of it. The result is shown in Fig. 4.

Fig. 4 shows that, no matter what time, the reliability of triple modular redundant system is higher than that of single-mode system in the lifespan. The lower of failure rate, the higher of reliability.

Fig. 5 shows the reliability analysis for fault coverage c , which is another important factor during design.

The number 1, 2, 3, 4, 5 in the figure correspond to the fault coverage c 0.9, 0.99, 0.999, 0.9999, 0.99999. It is interesting to see that increases in the fault coverage do not produce significant changes in the reliability of system for fault coverages greater than 0.99. This analysis gives us some insight to how effective the detection algorithm should be.

VII. CONCLUSIONS

The analysis carried out on the redundant steering-by-wire system architecture shows that the influence of redundancy, failure rate and fault coverage in the overall reliability are very important. As seen, the reliability of redundant system is always higher than that of non-redundant system in the lifespan of vehicle. And the reliability of system strongly depends on the failure rate λ , which is a most important factor. Besides, the factor of fault coverage is also impact the reliability, when it is less than 0.99. Above 0.99, fault coverage is no longer influence the reliability of system any more. So, one way to improve the reliability of system is to introduce the redundancy of components. Another way is to decrease the failure rate of each unit. And we can also do it by improving the detection algorithm to have a fault coverage of 0.99 or greater.

System combined the application of FlexRay bus ensure the properties of real-time, determinacy, reliability and fault tolerance. The system is able to tolerate any failure of the sensors, ECUs and motors, therefore improving the overall stability and reliability of the system. It has certain significance to the future development of automobile technology.

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