Reliability analysis of redundant steering-by-wire system

Zhongyi Hu \textsuperscript{a,b}, Fengdeng Zhang \textsuperscript{a,b}

\textsuperscript{a} Information and Control Engineering, University of Shanghai for Science and Technology,
\textsuperscript{b} Add: No.516 Jungong Road, No.1 dormitory, 200093, Shanghai, China
zhongyihu2012@sina.com

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.

Keywords—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 \cite{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 \cite{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 Figure 1.

As shown in Figure 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:

- Firstly, each unit is not considered transient failure and permanent failure, which is all defined as the failure rate $\lambda$.
- Secondly, repair rate $\rho$ of each unit and fault coverage $c$ are not considered.

Define sensor failure rate as $\lambda_{IN}$, ECU failure rate as $\lambda_{ECU}$, and motor failure rate as $\lambda_{OUT}$. The FMEA tables of steering-by-wire system are shown in Table 1, 2.3.4.5.

Table 1 corresponds to the FMEA of first fault of System. The first column of Table 1 lists the failures of the state system. 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 2 corresponds to a second fault system FMEA. The first column of Table 2 is a non-fault state which corresponds to Table 1 in the fifth column. The remaining columns of Table 2 obtain the same manner in Table 1. Besides it lists the non-fault state from the fifth column of Table 2. Table 3 reporting the third failure system and its construction method is same with Table 2. Besides it lists the non-fault state from the fifth column of Table 2. Table 4, 5 are constructed the same way as Table 1.

### Table 1 system level FMEA for first failures

<table>
<thead>
<tr>
<th>System state with no failures</th>
<th>State probability</th>
<th>First failure</th>
<th>Failure rate</th>
<th>State probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor normal, steering motor normal, ECU node normal running</td>
<td>P1</td>
<td>Any sensor failure</td>
<td>$3\lambda_{IN}$</td>
<td>P2</td>
</tr>
<tr>
<td>Any ECU failure</td>
<td>P3</td>
<td>Any sensor failure</td>
<td>$2\lambda_{ECU}$</td>
<td>P4</td>
</tr>
<tr>
<td>Any motor failure</td>
<td>P5</td>
<td>Any sensor failure</td>
<td>$2\lambda_{OUT}$</td>
<td>P6</td>
</tr>
</tbody>
</table>

### Table 2 system level FMEA for second failures

<table>
<thead>
<tr>
<th>System state with one failures</th>
<th>State probability</th>
<th>Second failure</th>
<th>Failure rate</th>
<th>State probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>The remaining two sensors work properly, dual-motor normal, ECU single point of failure</td>
<td>P2</td>
<td>Any sensor failure</td>
<td>$2\lambda_{IN}$</td>
<td>P3</td>
</tr>
<tr>
<td>Any ECU failure</td>
<td>P4</td>
<td>Any sensor failure</td>
<td>$2\lambda_{ECU}$</td>
<td>P5</td>
</tr>
<tr>
<td>Any motor failure</td>
<td>P6</td>
<td>Any sensor failure</td>
<td>$2\lambda_{OUT}$</td>
<td>P7</td>
</tr>
</tbody>
</table>

### Table 3 system level FMEA for third failures

<table>
<thead>
<tr>
<th>System state with two failures</th>
<th>State probability</th>
<th>Third failure</th>
<th>Failure rate</th>
<th>State probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only one sensor is normal, two electric motors are normal, two ECU normal</td>
<td>P3</td>
<td>The remaining sensor failure</td>
<td>$\lambda_{IN}$</td>
<td>PF</td>
</tr>
<tr>
<td>Any ECU failure</td>
<td>P4</td>
<td>Failure of any one of the remaining sensors</td>
<td>$2\lambda_{ECU}$</td>
<td>P5</td>
</tr>
<tr>
<td>Any motor failure</td>
<td>P6</td>
<td>Failure of any one of the remaining ECU</td>
<td>$2\lambda_{OUT}$</td>
<td>P7</td>
</tr>
</tbody>
</table>

### Table 4 system level FMEA for fourth failures

<table>
<thead>
<tr>
<th>System state with three failures</th>
<th>State probability</th>
<th>Fourth Failure</th>
<th>Failure rate</th>
<th>State probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only one sensor is normal, two-motor normal, ECU single point of failure</td>
<td>P5</td>
<td>Failure of any one of the remaining sensors or ECU</td>
<td>$\lambda_{IN} + \lambda_{ECU}$</td>
<td>PF</td>
</tr>
<tr>
<td>Any motor failure</td>
<td>P6</td>
<td>Failure of any one of the remaining sensors</td>
<td>$2\lambda_{OUT}$</td>
<td>P7</td>
</tr>
<tr>
<td>Two sensors work properly, motor single point of failure, ECU single point of failure</td>
<td>P10</td>
<td>Any sensor failure</td>
<td>$2\lambda_{IN}$</td>
<td>P11</td>
</tr>
<tr>
<td>Any ECU failure</td>
<td>P12</td>
<td>Any sensor failure</td>
<td>$2\lambda_{ECU}$</td>
<td>P13</td>
</tr>
</tbody>
</table>

---

597
IV. MARKOV MODEL

Based on the above analysis of FMEA tables, we can build the Markov model on behalf of the system state. Markov model can use a linear homogeneous differential equation to represent.

\[
P(t) = \Lambda(t)P(t), \quad P(0) = \begin{bmatrix} 1 & 0 & 0 & \ldots & 0 \end{bmatrix} \tag{4-1}\]

\(P(t)\) is the state probability vector; \(P_k(t)\) (\(K = 0, 2, \ldots, 15\)) represents the probability of system state \(k\) at time \(t\). State transition matrix \(\Lambda(t)\) can be established by the table above. Each coefficient \(\lambda_{ij}\) of matrix can be obtained from the transition probabilities between states.

To facilitate the presentation, we use IN to represent sensor, and use OUT to represent motor. When the system is in good condition, there are three sensors, two ECU nodes and two motors are in operation, which using (3IN, 2ECU, 2OUT) to represent. Other states have same method of analysis. Markov model of the system is shown in Figure 2.

![Markov model of steering-by-wire system](Image)

The initial condition of differential equations is:

\[
P_1(0) = 1, \quad P_2(0) = P_3(0) = P_4(0) = P_5(0) = P_6(0) = P_7(0) = P_8(0) = P_9(0) = P_{10}(0) = P_{11}(0) = P_{12}(0) = 0 \tag{4.4-2}\]

The reliability of the system is:

\[
R(t) = P_{11}(t) + P_{12}(t) + P_{3}(t) + P_{4}(t) + P_{5}(t) + P_{6}(t) + P_{7}(t) + P_{8}(t) + P_{9}(t) + P_{10}(t) + P_{11}(t) + P_{12}(t) \tag{4-3}\]

IV. MARKOV MODEL

Based on constant differential equations \([3]\), Reliability of the system can be obtained by solving differential equations using matlab solutions.

V. MODEL PARAMETERS

According to the failure rate of ECUs, sensors and motors \([4]\) in Table 6, we can obtain \(\lambda_{IN} = 6.06 \times 10^{-7}\) (1/h), \(\lambda_{ECU} = 6.28 \times 10^{-6}\) (1/h), \(\lambda_{OUT} = 7.9 \times 10^{-7}\) (1/h).

<table>
<thead>
<tr>
<th>components</th>
<th>Failure rate (1/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sensor</td>
<td>6.06 \times 10^{-7}</td>
</tr>
<tr>
<td>HW ECU, FAA ECU</td>
<td>6.28 \times 10^{-6}</td>
</tr>
<tr>
<td>FlexRay channel</td>
<td>8.75 \times 10^{-7}</td>
</tr>
<tr>
<td>motor</td>
<td>7.9 \times 10^{-7}</td>
</tr>
</tbody>
</table>

Since the steering-by-wire system is safety-critical system, assessment of the failure rate is derived from IEC1508 standard \([3]\) (Safety Integrity Level) SIL. It provides a source to lead to random hardware failures. This is mentioned in Part V of ISO26262 \([6]\).

VI. ANALYSIS RESULT

A vehicle life time of 5 \times 10^4 hours was considered for simulations, which gives an evaluation time after 1 \times 10^5 h. Using the parameters of table 6, which correspond to the assumed nominal failure rate values of ECU, motor and sensor, the relationship between reliability and time yielded by the Markov model is shown in figure 3. To demonstrate the superiority of the designed system, we compare the reliability between the redundant steering-by-wire system and non-redundant system.

![Reliability diagram of redundant and non-redundant steering-by-wire system](Image)

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

As is shown in the figure 3, the reliability of redundant steering-by-wire system is always higher than that of non-redundant system in the lifespan of vehicle. The design in this paper is superior to that of traditional SBW system. The point is redundancy, which is of importance in safety-critical system.
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 $\lambda$ equal $10^{-7}$ and $\lambda$ 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 Figure 4.

![Figure 4 Reliability of triple modular redundancy and single mode systems under different failure rates](image)

Figure 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.

![Figure 5 the impact on the reliability of fault coverage](image)

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

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 $\lambda$, 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.

ACKNOWLEDGMENT

This work was supported by Natural Science Foundation of Shanghai under Grant No.15ZR1429300.

REFERENCES