

# Predictive Hybrid Redundancy using Exponential Smoothing Method for Safety Critical Systems

Man Ho Kim, Suk Lee, and Kyung Chang Lee\*

**Abstract:** As many systems depend on electronics, concern for fault tolerance is growing rapidly. For example, a car with its steering controlled by electronics and no mechanical linkage from steering wheel to front tires (steer-by-wire) should be fault tolerant because a failure can come without any warning and its effect is devastating. In order to make system fault tolerant, there has been a body of research mainly from aerospace field. This paper presents the structure of predictive hybrid redundancy that can remove most erroneous values. In addition, several numerical simulation results are given where the predictive hybrid redundancy outperforms well-known average and median voters.

**Keywords:** Double exponential smoothing method, drive-by-wire system, fault tolerant system, predictive hybrid redundancy, safety critical systems.

## 1. INTRODUCTION

In order to enhance the safety and convenience for both drivers and passengers, today's cars have numerous electronic components that are connected via a shared network cable [1-5]. While most electronic components are related to convenience such as power windows, the portion of safety-related electronic components such as Electronic Stability Program (ESP) is increasing rapidly. Recently, many automobile companies are replacing various mechanical links of brake and steering systems with electronic components and digital communication network, which is called drive-by-wire or x-by-wire systems in order to reduce weight, create more space, and provide more intelligent functions [6]. In general, x-by-wire systems consist of Electronic Control Units (ECUs), electrical actuators, sensors and bus systems. As an example, a steer-by-wire system can do away with the traditional steering column. In order to

convey the driver's steering command, an encoder can be attached to the steering wheel, and the sensed angle can be sent to a steering ECU via a chassis control network. Then, the ECU computes and sends the command for electronic power steering.

However, replacing rigid mechanical components with dynamically configurable electronic elements requires a higher level of fault tolerance than the traditional system based on mechanical links [7,8]. This is mainly because mechanical systems tend to warn the driver by showing deteriorated performance while electronic systems tend to fail abruptly without any warning. For the steer-by-wire example mentioned above, a sudden failure or transient faults of the encoder can bring devastating results. Because a safety-related malfunction leads to injuries and deaths of vehicle occupants, which is very critical to the car company's reputation, fault tolerance is the utmost focus of x-by-wire system development.

Fault-tolerance is usually designed by placing redundant components that duplicates the functions of the original module [9-12]. That is, a fault is isolated, and safe operation is guaranteed by replacing the faulty module with its redundant and normal module within a predefined interval. One of the most common applications is an electronic brake pedal module with duo-duplex architecture for a brake-by-wire system as shown in Fig. 1. In the brake-by-wire system, the conventional hydraulic line is replaced by an in-vehicle network. The movement of pedal or the force applied to the pedal is measured by a sensor, and then the digitized information is transmitted to four independent brake modules, one at each wheel, via the network. Therefore, the fault redundancy of the pedal sensor is very critical to the vehicle's safety. In the

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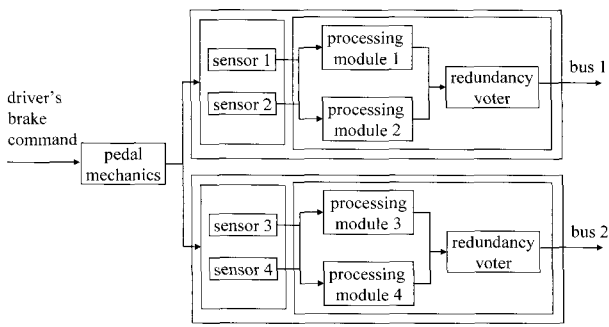


Fig. 1. Duo-duplex architecture for the brake pedal module for a brake-by-wire system.

figure, the duo-duplex pedal module consists of four sensors that measure an output value of brake pedal, four processing modules that deal with signal conditioning and processing, and two redundancy voters that determine an output value using various voting algorithms [13].

In an effort to develop better and more efficient redundancy for safety critical systems, this paper presents the structure of a predictive hybrid redundancy system with a fault detection algorithm using a double exponential smoothing method. In order to compare its performance with other methods, a MATLAB simulation model was used for a brake pedal signal. Based on the comparison, this paper shows that the predictive hybrid redundancy system has robust fault tolerant mechanism to guarantee the

reliability of the safety critical systems such as x-by-wire system because it combines the attractive features of the static redundancy and dynamic redundancy such as fault masking, fault detection, fault location, and fault recovery [9].

This paper is organized into five sections including this introduction. Section 2 gives a brief overview of the redundancy system and Section 3 presents the structure of the predictive hybrid redundancy system along with fault detection and exception handler algorithm. Section 4 describes the result of MATLAB simulation model of the predictive hybrid redundancy system. Finally, the conclusion is presented in Section 5.

## 2. OVERVIEW OF REDUNDANCY SYSTEM

In general, the hardware redundancy system, which is to add an extra hardware with the same functions implemented in the original hardware, can be classified into static redundancy, dynamic redundancy, and hybrid redundancy system according to its architecture and function. Fig. 2(a) shows the static redundancy system with multiple parallel modules. The static redundancy system requires a voter that determines the final output of the system. The voter can use majority or average rule as its fault masking algorithm to isolate any faulty input. However, the static redundancy system tends to cost more because it requires at least three parallel modules for majority voter, and it is difficult to detect faults when two or

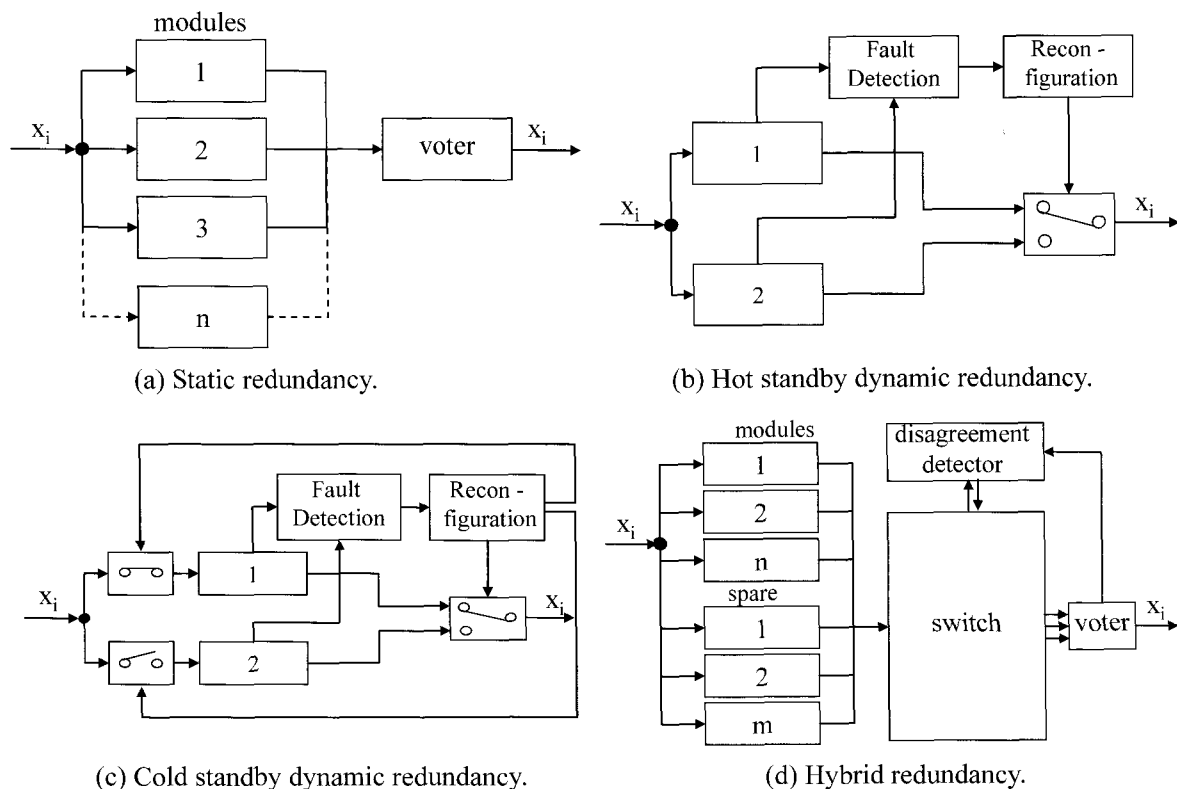


Fig. 2. Various types of hardware redundancy.

more modules are faulty [9,10].

The dynamic redundancy system achieves fault tolerance by having fault detection and reconfiguration functions instead of a voter as shown in Figs. 2(b) and 2(c). In general, the dynamic redundancy system can be classified into hot and cold standby dynamic redundancy system according to whether all modules are always operating or not. In the hot standby dynamic redundancy system as shown in Fig. 2(b), two modules are constantly sending their outputs, and the output switch is connected either of two modules. On the other hand, the cold standby dynamic redundancy system uses only one module at a time, and two switches are controlled by the reconfiguration module to block the signal from the faulty module as shown in Fig. 2(c). Here, the cold standby has a longer module life and better energy efficiency than hot standby because a single module is working at a time. But, the cold standby needs complex fault detection algorithm because it uses only one input value [14,22,23].

Fig. 2(d) shows a type of hybrid redundancy system called n-modular redundancy with spares that combines both static and dynamic approaches. It has a voter along with switch and disagreement detector. By combining two approaches, the system can mask a fault as the static approach does while it can also detect a fault and reconfigure the system just like the dynamic approach. Although this hybrid redundancy system has a certainly better reliability than the previous two, its application has been limited to safety-critical systems such as spacecraft and aircraft due to high cost and complexity. However, by virtue of inexpensive microcontrollers with high computing power, the hybrid redundancy becomes a promising approach to wider range of safety-critical application.

### 3. STRUCTURE OF PREDICTIVE HYBRID REDUNDANCY

To have redundancy for products like intelligent vehicle, we propose a structure called predictive hybrid redundancy shown in Fig. 3. The rationale for having the structure shown in the figure is that we cannot afford too many redundant sensors on a system such as a passenger car. Therefore, the use of static or n-modular redundancy with spares is hard to justify their cost and complexity. Alternatively, we can consider the hybrid of hot standby dynamic redundancy and static redundancy along with a capability to forecast the input value. The predictive hybrid redundancy makes use of high computing power of a microcontroller to forecast the change from the last value of the system output using a double exponential smoothing method. The predicted change is used to judge if there is a fault in the current value of the sensor signal by checking whether the

new inputs lie within the predicted interval. This forecasting is based on the assumption that the input signal usually changes gradually without large fluctuations.

Fig. 3 shows five modules of the predictive hybrid redundancy: a threshold predictor, a fault detector, an exception handler, a reconfigurator, and a voter. First, the threshold predictor forecasts a threshold, which is essentially the expected change in the output signal. This threshold is calculated by using an algorithm called exponential smoothing algorithm to be explained later. Second, the fault detector judges whether a fault exists in two inputs using the forecasted threshold. If an input value lies within an interval centered on the system output in the previous step, it decides that the input is error free. The interval's width is directly proportional to the predicted threshold. The third component, i.e., the exception handler determines an output value when the fault detector decides that both input values are unreliable. When some unexpected external disturbance affects the plant, the fault detector judges that both inputs are erroneous and that an output cannot be determined. At this time, the exception handler determines an output value by incrementing the last output value to prevent abnormal operation due to the absence of an output signal. The reconfigurator activates or deactivates control switches to pass or isolate the input value, respectively. Finally, the voter calculates an output value using an averaging method.

The threshold predictor must first forecast a threshold value for judging whether a fault exists in the values given to the fault detector. To forecast a threshold in the hybrid redundancy system, the double exponential smoothing method, which is a representative method of time series forecasting methodology, was chosen. In general, the exponential smoothing method is a forecasting method that assigns exponentially decreasing weights as the observations get older [15]. In other words, recent observations are given relatively more weight than

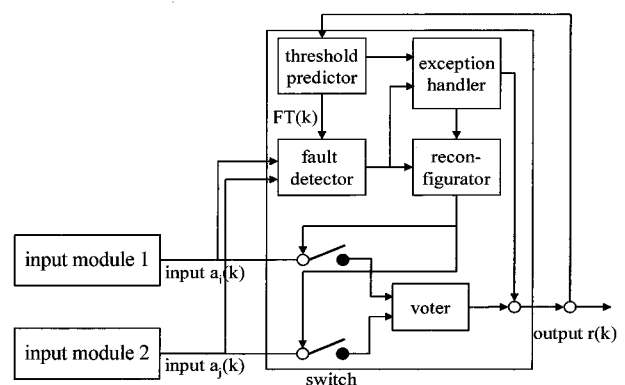


Fig. 3. Structure of the predictive hybrid redundancy.

older observations in forecasting. The double exponential smoothing method removes random variation and shows trends and cyclic components in forecasting [15]. Since the encoder output signal or actuator input signal may follow a trend such as a sine wave or step response form in real industrial applications, the double exponential smoothing method may be appropriate for forecasting the patterns of these signals [16,17]. For forecasting the  $k$ -th threshold  $FT(k)$  of a hybrid redundancy system, the double exponential smoothing method can be expressed as follows:

$$\begin{aligned} FT^{[1]}(k) &= \alpha RT(k) + (1 - \alpha) FT^{[1]}(k - 1), \\ FT^{[2]}(k) &= \alpha FT^{[1]}(k) + (1 - \alpha) FT^{[2]}(k - 1), \\ FT(k) &= \left(2 + \frac{\alpha}{1 - \alpha}\right) FT^{[1]}(k) - \left(1 + \frac{\alpha}{1 - \alpha}\right) FT^{[2]}(k), \\ RT(k) &= r(k - 1) - r(k - 2), \end{aligned} \quad (1)$$

where  $FT^{[1]}(k)$  and  $FT^{[2]}(k)$  are the first and second step forecast thresholds determined using the exponential smoothing method in the  $k$ -th cycle, respectively, and  $RT(k)$  is the real threshold in the  $k$ -th cycle. In addition,  $r(k)$  is an output value in the  $k$ -th cycle, and  $\alpha$ , which is generally selected to be from 0.05 to 0.3, is the double exponential smoothing parameter.  $FT(k)$  is the forecasted change in the input signal, which is used as a threshold to judge whether a fault exists in the values input to the fault detector, in the  $k$ -th cycle using  $FT^{[1]}(k)$  and  $FT^{[2]}(k)$ . Here,  $r(-1)$ ,  $r(-2)$ ,  $FT^{[1]}(0)$ , and  $FT^{[2]}(0)$  are initialized as zero;  $r(0)$  is assumed to be the average of the first input values

of the two modules and is assumed to be error-free. Fig. 3 shows five modules of the predictive hybrid redundancy: a threshold predictor, a fault detector, an exception handler, a reconfigurator, and a voter.

After forecasting the threshold  $FT(k)$  in the threshold predictor, the fault detector judges whether a fault exists in the two input values using  $FT(k)$ , as shown in Fig. 4. In the figure, if the difference between the  $k$ -th input value  $a_i(k)$  and the  $(k - 1)$ -th output value  $r(k - 1)$  is within the range  $(1 \pm \beta)FT(k)$ , the fault detector determines that  $a_i(k)$  is error-free. Conversely, if  $a_i(k)$  exceeds a permitted limit of the forecasted input value, the corresponding input is considered erroneous. If at least one input is determined to be error-free, the reconfigurator is called upon to generate the  $k$ -th output value  $r(k)$  of the hybrid redundancy system. Here, it is necessary to determine the appropriate value of  $\beta$  based on the features of the system. However, if both inputs are determined to be erroneous, the fault detector calculates  $d_{ij}(k)$ , which is defined as the difference of the  $k$ -th values  $a_i(k)$  and  $a_j(k)$  of two input modules. Here, if  $d_{ij}(k)$  is within the range  $\pm FT(k)$ , the two input values are regarded as error-free and the reconfigurator is called upon to calculate  $r(k)$ . That is, if both inputs exceed a permitted limit of the forecasted input value and the difference between the two inputs is smaller than an allowable error, the two inputs are considered to be varying rapidly due to an unexpected external disturbance. Conversely, if  $d_{ij}(k)$  exceeds the range of  $FT(k)$ , the two inputs are considered erroneous and the exception handler is called upon to determine the output value.

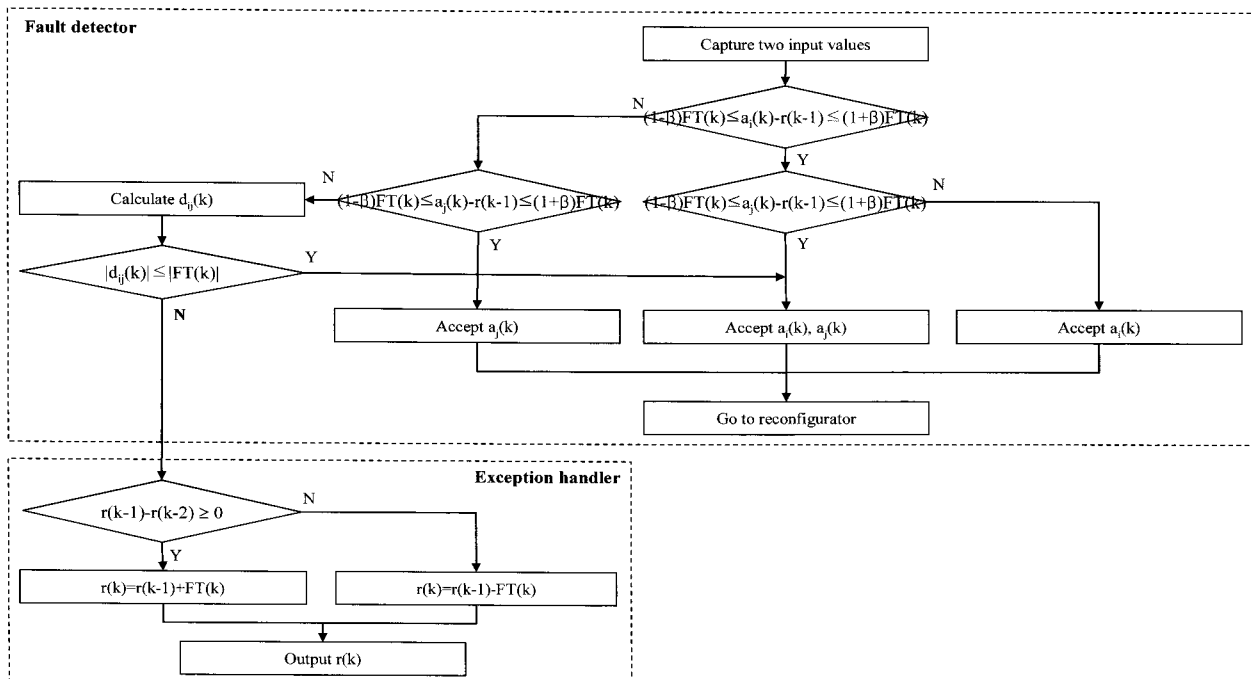


Fig. 4. The algorithm used in the fault detector and exception handler of the predictive hybrid redundancy.

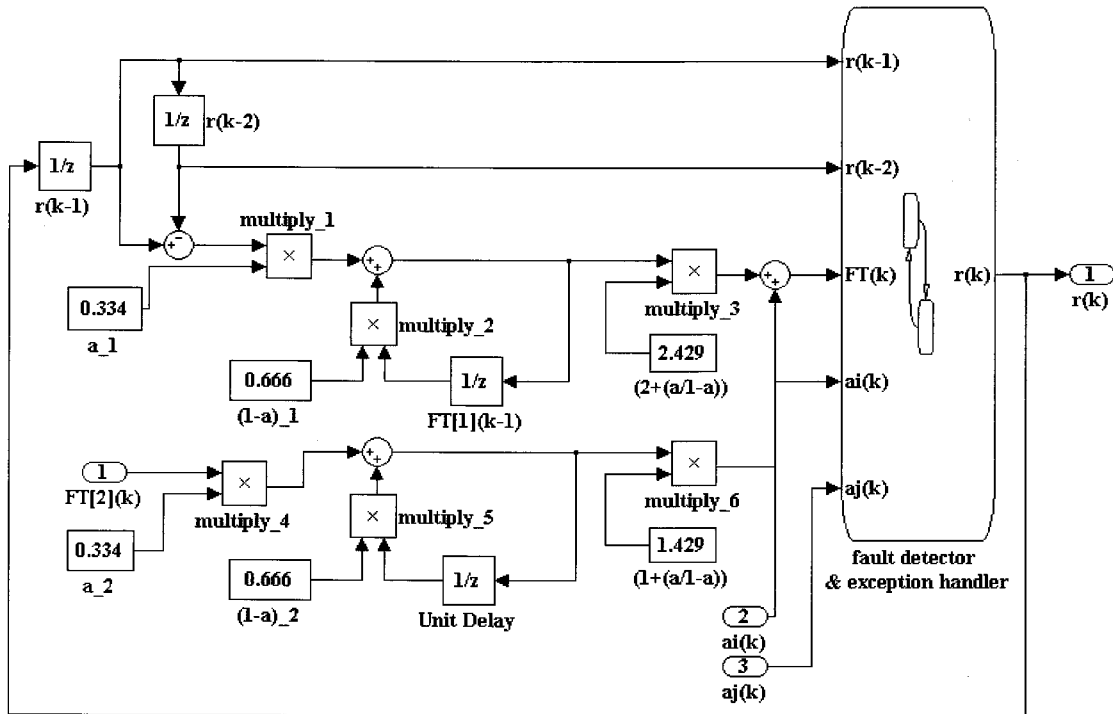


Fig. 5. MATLAB simulation model of the predictive hybrid redundancy.

When the two inputs are determined to be erroneous, the exception handler calculates a feasible output to prevent malfunction of the hybrid redundancy system. To determine the output value  $r(k)$ , the exception handler calculates the difference between the  $(k-1)$ -th output and the  $(k-2)$ -th output. If the difference is positive, the exception handler judges that the input value is increasing and determines the output as the sum of  $r(k-1)$  and  $FT(k)$ . If the difference is negative, the output is determined as the difference of  $r(k-1)$  and  $FT(k)$ . Using this method, because the output can be determined as the second best value even if both inputs are erroneous, it is possible to prevent abnormal operation of the system that may occur due to the absence of output.

Finally, if at least one input is error-free, the reconfigurator activates a control switch to convey the corresponding input to the voter. The reconfigurator isolates the erroneous input using a deactivating control switch, and the voter calculates the output value by averaging the passed input values.

#### 4. PERFORMANCE EVALUATION OF PREDICTIVE HYBRID REDUNDANCY

This section evaluates the performance of the predictive hybrid redundancy along with implementation details for the MATLAB simulation model. In the MATLAB simulation, the threshold predictor is implemented using the general function block of MATLAB Simulink using MathWorks, as shown in Fig. 5. The fault detector, exception handler,

reconfigurator, and voter are implemented using MATLAB Stateflow, which adds finite state machines to the Simulink model, as shown in Fig. 6 [18]. Then, to compare the performance of the predictive hybrid redundancy, we implemented an average and median voters which are commonly used voting algorithm in triple modular redundancy (TMR) systems, using the MATLAB Simulink function block.

In the simulation of the predictive hybrid redundancy, we generated a virtual brake pedal signal, which represents the brake force sensor output of a brake pedal in a brake-by-wire system, as shown in Fig. 7(a), using the general function block of MATLAB Simulink. The model simulates a brake pedal signal by rapidly increasing the pedal signal with a sampling period of 1 ms to 4.5 V over 400 ms

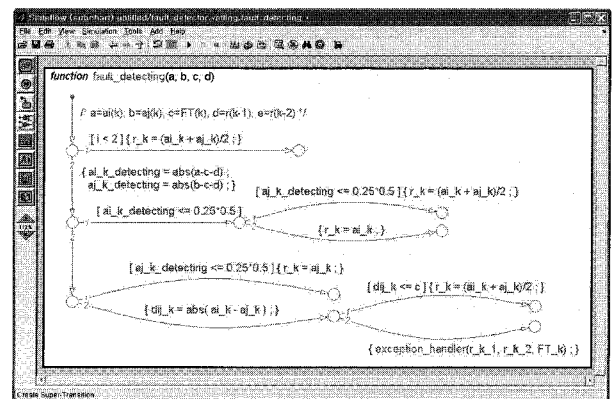
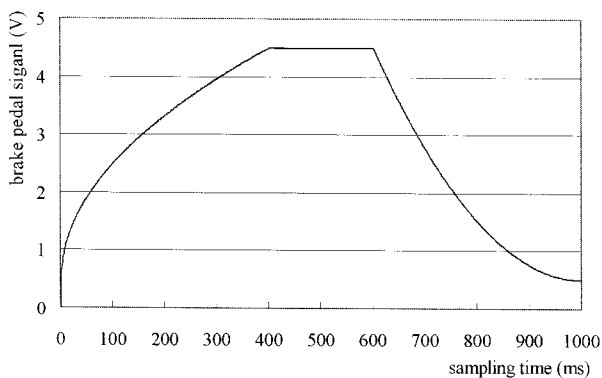


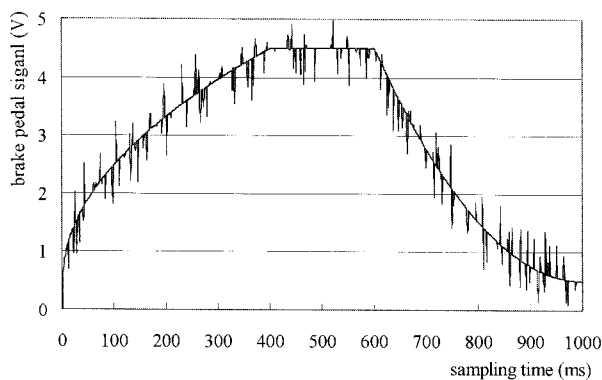
Fig. 6. MATLAB Stateflow diagram of the fault detector.

to represent slamming on the brake. Then, it maintains a constant voltage. Finally, the signal is decreased rapidly to 0.5 V over an interval of 400 ms to represent taking the foot off the brake.

To generate a signal with faults, we added an impulse-type fault, which can appear and disappear within a very short period of time [9,11], to the original brake pedal signal based on the fault rate and fault value. The simulation model generated a fault signal by adding faulty value to the original brake pedal value of the  $t$ -th sample determined by a Gaussian distribution based on the indicated fault rate. Here, to determine whether a brake value of the  $t$ -th sample is fault, a value of Gaussian distribution with mean of 0 and variation of 1 is generated. And then, if an absolute value of this value is larger than '1-fault rate', it is assumed that the brake signal of this sample is faulty. Also, the faulty value is the product of three values, i.e., pre-assigned fault value, the maximum output value of the brake pedal signal (5V), and value generated by uniform distribution probability (minimum of -1 and maximum of 1). Fig. 7(b) shows the result of injecting an impulse-type fault with a fault rate of 15% and a fault value of 15% to the brake pedal signal shown in Fig. 7(a). For example, the



(a) Signal of a brake pedal without a fault.



(b) Signal of a brake pedal with a fault rate of 15% and a fault value of 15%.

Fig. 7. Examples of simulated brake pedal signals with and without faults.

42nd sample of the brake pedal signal in Fig. 7(a) was 1.796 V while the value in Fig. 7(b) was changed to 2.517 V by adding 0.721 V, which is a random value between 0.75 and -0.75 V (i.e., the fault value of 15% times the maximum output of 5 V). To run simulations of the average, median, and predictive hybrid redundancy, we generated three different fault signals similar to that in Fig. 7(b) by varying the fault rate and fault value. Here, the predictive hybrid redundancy uses two input signals while the average and median voters need three input signals.

In order to select appropriate double exponential smoothing parameter  $\alpha$ , we defined the mean square prediction error (MSE) as follows:

$$MSE = \frac{\sum_{k=1}^n (RT(k) - FT(k))^2}{n}. \quad (2)$$

We compared the MSE with different values of  $\alpha$ . Fig. 8 shows the MSE between the original brake pedal signal and the estimated brake pedal signal with  $\alpha$  ranging from 0.05 to 0.3, which is the suggested range [19,20]. Hence, we have chosen the value of 0.3 for  $\alpha$ .

In order to determine an appropriate value for the fault detection parameter  $\beta$ , we defined the integral of the absolute magnitude of the error (IAE) as follows [21]:

$$IAE = \sum_{k=1}^n \Delta T \cdot |e(k)|, \quad (3)$$

where  $e(k)$  is the difference between the original brake pedal value and the fault-masked brake pedal processed, and  $\Delta T$  is the sampling time of the brake pedal signal.

Fig. 9 shows the IAE performance index of predictive hybrid redundancy for varying fault values with a fixed fault rate of 10%. From simulation results, we have chosen the value of 0.0625 for  $\beta$ .

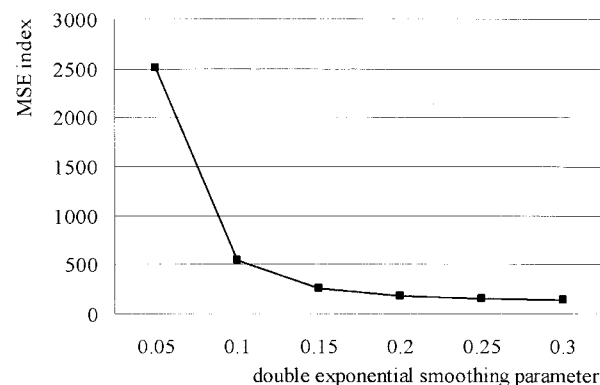


Fig. 8. MSE performance index for double exponential smoothing parameter.

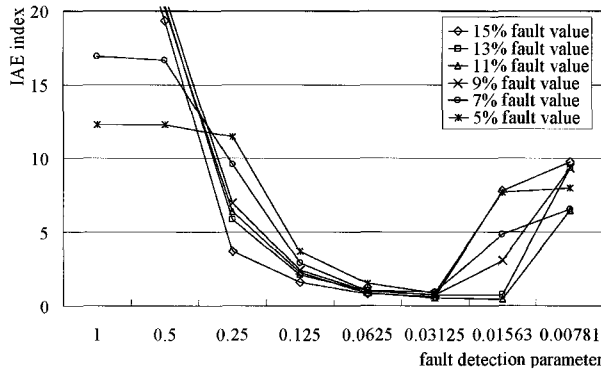


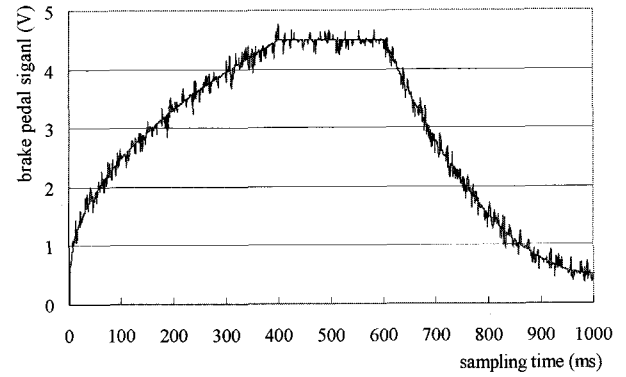
Fig. 9. IAE performance index for fault detection parameter for varying fault values with a fault rate of 10%.

With these values of  $\alpha$  and  $\beta$ , the predictive hybrid method is compared with the average and median voters. The comparison is made based on the IAE given by (3). Fig. 10 shows the simulation results of the average and median voters using three different signals, and that of the predictive hybrid redundancy using two different signals with a fault rate of 15% and a fault value of 15%. In Fig. 10(a), after processing by the average voter using three different signals with faults, we can see that the output signal still includes a great deal of instantaneous fluctuation compared to the original signal, as shown in Fig. 7(a). This is because the average voter always uses all the signals no matter whether a signal contains some fault or not.

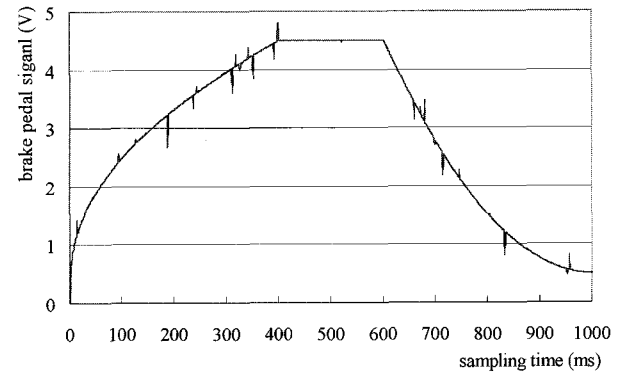
On the other hand, it seems that the median voter almost eliminated the faults, as shown in Fig. 10(b). The IAE performance index for the median voter (5.596) is far better than that of the average voter (47.538). Nevertheless, some faults still affect the output when two or more values are faulty. This simulation shows that it may not be suitable for fault tolerance of safety critical systems like a vehicle x-by-wire system.

Fig. 10(c) shows the system output of predictive hybrid redundancy. It looks almost identical to the original signal. As expected, the IAE performance index is 0.729, which is better than the value for the median voter. This simulation indicates that the predictive hybrid redundancy can be an appropriate algorithm for safety critical systems because the exception handler determines a feasible output for safe operation even if both input values are temporarily faulty.

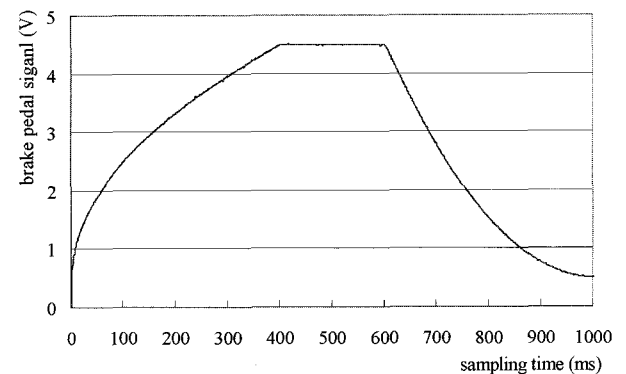
Fig. 11(a) shows the IAE performance indices of the average, median voters, and predictive hybrid redundancy for varying fault rates with a fixed fault value of 10%. In the figure, the IAE performance index of the average voter increases linearly with the fault rate. The IAE performance index of the median voter increases to 5.785 for a fault rate of 15%. In



(a) Signal of brake pedal using the average voter.



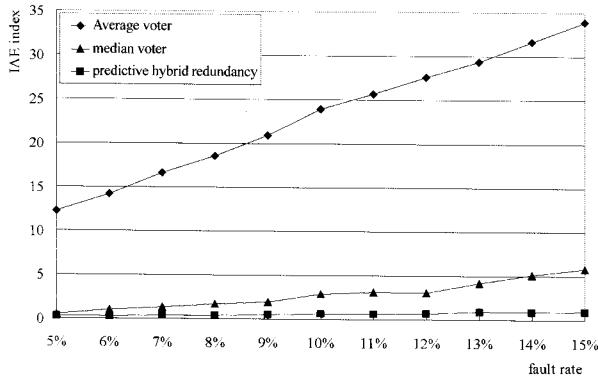
(b) Signal of brake pedal using the median voter.



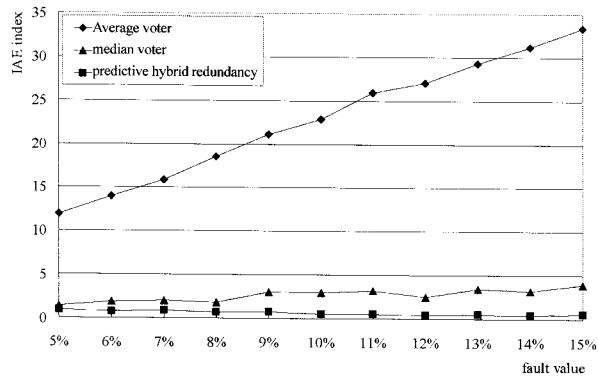
(c) Signal of brake pedal using the predictive hybrid redundancy.

Fig. 10. Signals of brake pedal using average, median voters and predictive hybrid redundancy with a fault value of 15% and a fault rate of 15%.

contrast, the IAE performance index of the predictive hybrid redundancy remains relatively low, and reaches 1.722 for a fault rate of 15%. Fig. 11(b) plots the IAE performance indices for varying fault values at a fixed fault rate of 10%. The trends in the IAE performance indices of the average, median voters and predictive hybrid redundancy are similar to those in Fig. 11(a). In particular, the IAE performance index of the predictive hybrid redundancy, which is 0.965 for a fault value of 15% and a fault rate of 10%, remains



(a) AE performance index for varying fault rates with a fault value of 10%.



(b) AE performance index for varying fault values with a fault rate of 10%.

Fig. 11. IAE performance index for varying fault rates and fault values.

relatively constant.

These results indicate that the performance of the predictive hybrid redundancy is superior to those of the average and median voters. In addition, since the average and median voters use three sensors while only two sensors are necessary for the predictive hybrid redundancy, it is possible to implement a redundant system with less redundant sensors. This may imply less expensive system because a sensor may cost more than a microprocessor we need to execute the algorithm.

## 5. SUMMARY AND CONCLUSIONS

This paper presents the predictive hybrid redundancy along with a fault detection algorithm using the double exponential smoothing method for safety critical systems such as the x-by-wire system of intelligent vehicles. To verify the feasibility of the predictive hybrid redundancy, we developed a MATLAB simulation model using the Simulink function block and Stateflow, and compared the performance of the predictive hybrid redundancy with those of the average and median voters.

We can draw two conclusions. First, the MATLAB simulation results showed that the predictive hybrid redundancy can eliminate faults far better than the general voting method used for a TMR system. The fault-masked signal was very similar to the original signal without faults. The simulation demonstrated that the predictive hybrid redundancy can be very effective for safety critical systems.

Second, since the average and median voters require three sensors while the predictive hybrid redundancy needs only two, it may be possible to implement a redundancy system more cost-effectively. By virtue of inexpensive microcontrollers and improved implementation technology, the predictive hybrid redundancy can be applied to various industrial systems that are very sensitive to costs.

The natural extension of this research is to compare the performance of the predictive hybrid redundancy with those of other dynamic and hybrid methods along with experimental demonstration of its efficacy. Furthermore, other methods to handle the prolonged faults at both sensors should be developed because the proposed method may become inadequate in such situation.

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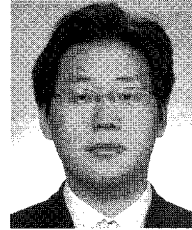
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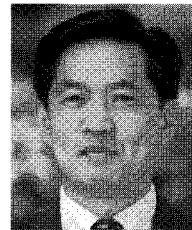
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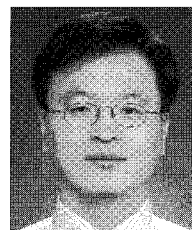
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