Experiment of Sensor Fault Tolerance Algorithm combined with Cyber System for Coil Tilter on the Smart Hybrid Powerpack

Jaegwang Lee
Department of Mechanical Engineering
Sungkyunkwan University
Suwon, Korea
email: leejkcool@gmail.com

Janggeol Nam, Buchun Song, Hyeonwoo Kim, Iksu Choi and Hunmo Kim
Department of Mechanical Engineering
Sungkyunkwan University
Suwon, Korea
email: mystic777@skku.edu, theme7749@gmail.com, 88jamesk88@gmail.com, cis326@naver.com, kimhm@me.skku.ac.kr

Abstract — This paper presents a Smart Hybrid Powerpack (SHP) for the sensor failure recovery algorithm for coil tilter and cyber system for control and monitoring. The SHP is combined with all advanced technologies: an Electro Hydraulic Actuator (EHA), fault tolerant control, intelligent control, and Graphic User Interface (GUI) based remote control and monitoring. The proposed algorithm for the sensor failure recovery uses a Kalman filter for noise caused by electric currents and temporary failures caused by a disturbance. In addition, sensor hardware that becomes damaged due to external impact, fails due to aging, or permanently fails due to damage, uses the Sliding Mode Observer (SMO) for normal waveform estimation and recovery. The proposed algorithm for the sensor failure recovery was implemented using an experiment. The performance of the proposed algorithm is verified through an alarm and monitoring of the cyber system in the event of failure of the coil tilter system.

Keywords — Coil tilter; Smart Hybrid Powerpack (SHP); Electro Hydraulic Actuator (EHA); fault tolerance; Machine GUI; Office GUI; Mobile GUI.

I. INTRODUCTION

Hydraulic actuators are widely used in various industries where high actuating forces are required. In order to enhance the performance of the hydraulic system, disturbances due to the external environment and effects of interference should be minimized [1]. In addition, Electro Hydraulic Actuator (EHA) systems were developed to compensate for the disadvantages of the conventional hydraulic actuator, such as low energy efficiency, limited installation spaces, heavy weight of components, and fluid leakage [2]. The EHA system has high energy efficiency due to a two-way fluid pump and an electric motor directly connected to each pump. The existing remote system was only possible for fault diagnosis through system monitoring [3][4]. The newly proposed Smart Hybrid Powerpack (SHP) combined with the cyber system are shown in Fig.1. Unlike the existing remote system, the EHA system is applied to the control and monitoring through a ECU control board and Graphic User Interface (GUI) by wireless communication and wire network. The cyber system includes an intelligent fault tolerance control, such as real time feedback of sensor signals, software filter, and sensor observer detecting and recovering from sensor faults. [5][6].

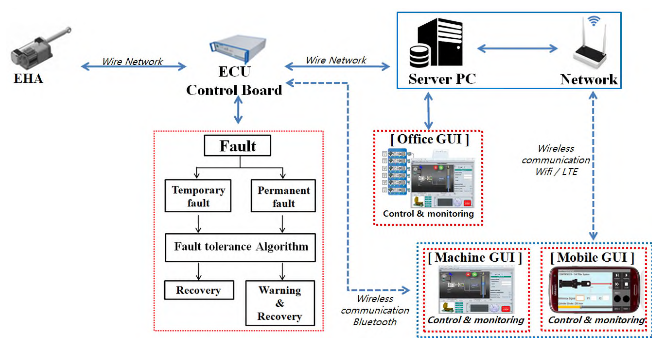

Figure 1. The SHP structure combined with cyber system

The various sensors in the SHP are applied by intelligent control systems for its safety and reliability, for the remote control system with monitoring, and for precision and accuracy of control. The sensors applied to the SHP are the LVDT (Linear Variable Differential Transformer) for tracking the change of the position of the cylinder, pressure for controlling the thrust, and encoder for motor speed. The LVDT sensor is mounted onto the cylinder rod, and the pressure sensors are attached to the cylinder head and rod. When a fault occurs in the SHP sensors, it is difficult to control the cylinder due to inaccurate sensor values. If a transient noise occurs due to an electrical malfunction, the noise can be recovered by using hardware methods, such as a coil filter. Also, the noise can be recovered by using software methods, such as a Kalman filter. If a permanent failure occurs in sensors attached to the SHP, such as disturbances, vibration, internal hardware problem in the sensors, or aging equipment, a rapid recovery is required because it can cause serious problems with the control. When a permanent failure occurs in the SHP, the original sensor signal is estimated and recovered by the Sliding Mode Observer (SMO). The prototype is operated through the (Office/Machine/Mobile) GUI, and the failure recovery algorithm is performed through a MATLAB Simulink [5].

The rest of the paper is structured as follows. In Section 2, two types of faults (temporary and permanent) are presented, and the design and analysis of the SMO algorithm for failure recovery are discussed. In Section 3, the experimental results of fault recovery are shown. We conclude in Section 4.

II. DESIGN OF FAULT TOLERANCE ALGORITHM

A. *Classification of fault types*

Sensor fault modes are classified in two categories, as shown in TABLE I. Once electronic noises are generated due to external factors, there is a possibility that normal signal accompany sensor errors or failure can occur. If the normal sensor signal is blended with a temporary fault caused by an electric current or outer high-voltage surge, it can generate instantaneous errors on account of high frequency noise. Permanent fault (Failure) can be caused by a sensor hardware problem, such as physical force, heat, deterioration of equipment, or being a defective product. It can generate permanent failure of the sensor [6].

TABLE I. THE CLASSIFICATION

Faults	Cause	Effects
Temporary fault (Error)	Noise	Error value by transient noise
Permanent fault (Failure)	Breaking of wire, Short circuit	Output Voltage 0V
	Fixation	Fixed voltage output
	Zero drift	Offset change

Fig 2. shows the characteristics of the sensor waveform in the event of the two types of sensor faults (temporary and permanent) [6].

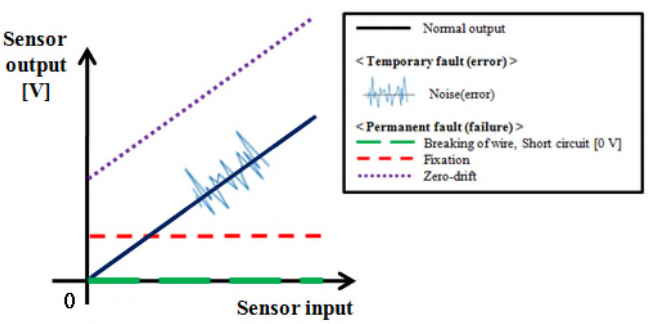

Figure 2. Four types of sensor faults

In case of a temporary fault (Error), instantaneous errors will appear in the sensor data output line in case of unstable voltage (power) supply or disturbance. This is shown in Fig. 2 by the irregular blue line (noise). In the case of a permanent fault, such as disconnection of a wire or a short circuit during the operation of the EHA, it is impossible to receive both data of the current cylinder position and sensor status due to the physical breakdown of the data line. This is shown in Fig. 2 by the wide dashed green line. Eventually, the output signal goes to zero voltage. When the output signal is constant (see middle dashed red line in Fig. 2), it is defined as fixation. When fixation occurs, the SHP will not recognize the stop command and will operate the EHA continuously; the EHA may cause a malfunction of over output exceeding the reference input. Also, the pump continues to rotate due to wrong information coming from the sensors. Eventually, pressure inside of the pump increases and it can become a serious threat to the safety of the system. In the case of zero-drift, an offset occurs because of the addition of an initial signal and jumping voltage signal (see the short dashed purple line in Fig. 2). Offset signal occurs with a permanent fault.

B. *Analysis of fault tolerance algorithm*

Sensor errors caused by noise are recovered by the Kalman filter. The Kalman filter estimates the current sensor signal value from past sensor signal values based on the system model [7].

$$K_{t+1} = C^{-}_{t+1} H^{T} (H C^{-}_{t+1} H^{T} + R)^{-1} \quad (1)$$

$$C_{t+1} = C^{-}_{t+1} - K_{t+1} H C^{-}_{t+1} \quad (2)$$

$$\hat{x}_{t+1} = \hat{x}^{-}_{t+1} + K_{t+1} z_{t+1} - K_{t+1} H \hat{x}^{-}_{t+1} \quad (3)$$

Equation (1) calculates the Kalman gain K_{t+1} by using system model H, R, prediction error covariance C^{-}_{t+1}. Kalman acts as a scale for the calculation of estimated value $\hat{x}_{t+1}$ which is the final output in the Kalman filter algorithm. In (2), the error covariance C_{t+1} is calculated by using the Kalman gain, system model H, and prediction error covariance C^{-}_{t+1}. Error covariance is used to determine how accurate is the estimated value in the prediction equation. The error covariance is larger than the largest error. Equation (3) calculates the estimated value of current time by using predicted estimated value $\hat{x}^{-}_{t+1}$, input z_{t+1}, K_{t+1} as the weighting and system model variable H. According to previous situations and system model, Kalman filter tunes a Kalman gain each time by repeating equation. So, it can correct the estimated value within the normal margin of error in the face of rapid waveform variations due to noise [7].

In order to control the output of the cylinder, we have to know the position of the rod and the internal pressure of the cylinder. If the position sensor has a permanent fault, ECU cannot control the cylinder because the exact position of the cylinder rod cannot be detected. If the pressure sensor has a permanent fault, ECU cannot obtain the information for the precise axial control because ECU cannot detect the internal pressure of the system. In order to estimate the output of the sensors, we should be aware of the change of discharge flow

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rate in the pump to be input to the system and system dynamics model of the EHA [8][9].

Through dynamic cylinder models, SMO estimates a signal of the position sensor or pressure sensor, which requires a repair by using the input flow rate variation. The SMO model for estimating the position sensor is expressed as follows [10].

$$\dot{\hat{y}} = g_1 \operatorname{sgn}(\hat{y} - y) - y + \left\{ \frac{\beta_e Q}{(V_H + S_H y)} \right\} \tag{4}$$

where, Q is the discharge flow rate of the pump, S_H is the cross section of the cylinder head, y is the location of the cylinder rod, V_H is the volume of the cylinder head, and β_e is the effective bulk modulus of the hydraulic fluid. In the (4), $\dot{\hat{y}}$ is the estimated output speed of the cylinder rod, $\hat{y}$ is the estimated location of cylinder rod, and g_1 is an arbitrary constant of the signum function (sgn). The SMO algorithm has characteristics that estimate the original sensor signals and vibration with signum function of difference between the output value of the sensor and the estimated value. The signum function compares the difference between the location of the cylinder rod and the estimated location of the cylinder rod based on the system model and reduces their error range. The SMO can quickly recover the permanent fault of the sensor because it has a robust characteristic for the disturbance and a succinct model equation [10].

III. EXPERIMENT OF THE FAULT TOLERANCE ALGORITHM COMBINED WITH CYBER SYSTEM

The coil tilter SHP is composed of three main parts that include the EHA system, the fault tolerance in ECU, and the cyber system.

The cyber system consists of the Office GUI, the Machine GUI, and the Mobile GUI. The Mobile GUI of the cyber system is connected to the ECU and exerts its control over the SHP by wireless network communication. The Machine GUI and the Office GUI are connected to the ECU by a wire network. The GUI sends the reference input signal to the ECU and the ECU sends command signals to the EHA.

In this experiment, we consider a fault that may occur while operating the SHP through the cyber system shown in Fig. 3. The sensor fault occurs through a function generator and relay. The object of this experiment is to determine whether the fault tolerance algorithm can make the cyber system detect the fault, send an alarm for the fault, and recover from the fault by using the fault tolerance algorithm.

Fig. 4 shows the SMO algorithm of the LVDT sensor by using the function blocks from MATLAB Simulink.

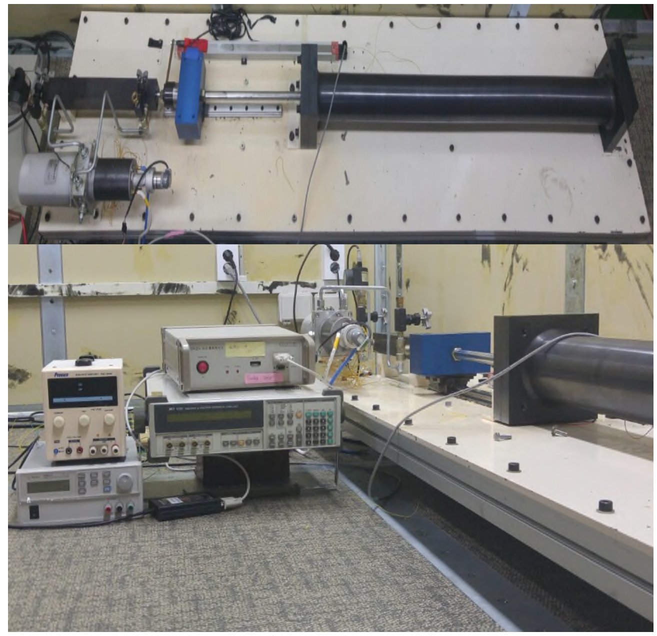

Figure 3. The experiment equipment

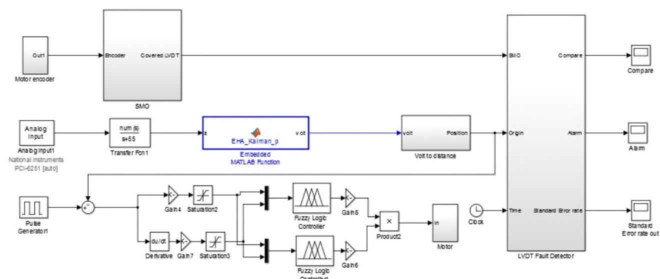

Figure 4. Fault tolerance algorithm of LVDT

The fault tolerance algorithm indicates that the SMO algorithm used as an input of the flow rate change by using speed of the motor is combined with the dynamic equation of the SHP model. When the temporary fault happens, a Kalman gain changes in real time in the Kalman filter and it calculates estimated value of the sensor. So, the ECU can correct the estimated value within the normal margin of error. When a fault occurs (temporary or permanent), a comparison is done between the reference input signals and the SMO signal calculated by the SMO formula, and the fault input signal is replaced with the recovered sensor input signal through a fault detector in the fault tolerance algorithm.

IV. RESULTS

When a fault does not happen, the normal position value of the cylinder rod is shown in Fig.5.

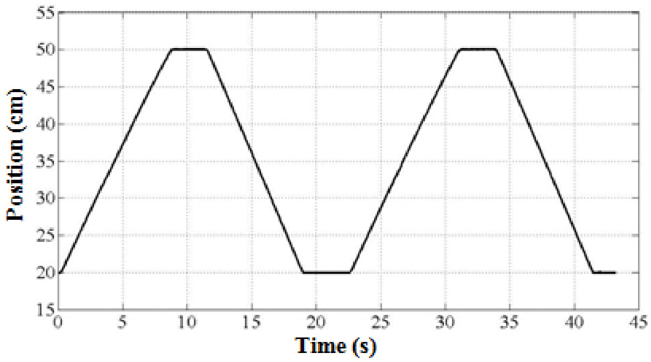

Figure 5. Normal signal of LVDT

To get the temporary fault, a function generator was used to give random noise signals. Fig. 6 shows the estimation of the LVDT sensor output using the Kalman filter and the threshold predictor. Mixed noise signals (see the dashed line in Fig. 6) were recovered through the Kalman filter.

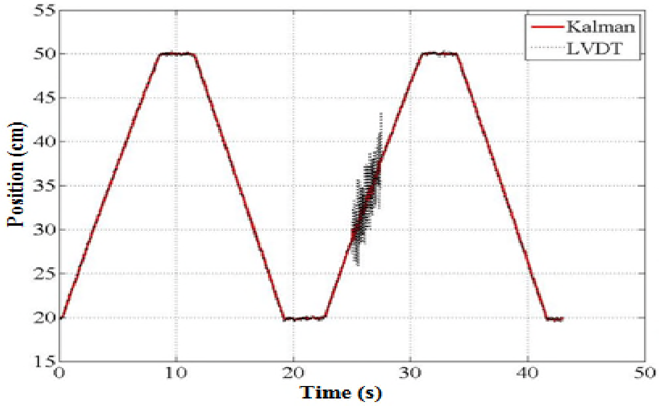

Figure 6. Noise signal and recovered signal by using Kalman filter

To generate the LVDT sensor signal with a permanent sensor fault, the experiment used a relay which is an electromagnetic switch to generate the sudden permanent fault (breaking of the wire and short circuit). After a fault occurs (relay operated), the voltage of the LVDT goes to 0V. When the relay is electrically switched at time 27 seconds, the LVDT signal goes to 0V due to breaking of the wire and short circuit. When the signal is over the allowable error range, the LVDT signal is replaced to threshold predictor signal from encoder related to motor rpm. Estimates of the LVDT sensor outputs by using the SMO model and recovered signal are shown in Fig. 7.

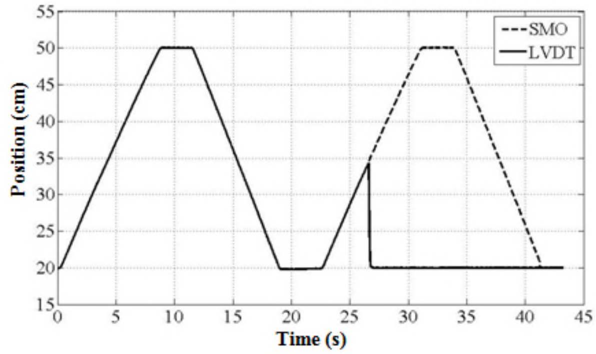

Figure 7. Short circuit / Disconnection of wire fault signal and recovered signal by using SMO

The position of the cylinder rod follows the recovered signal into the reference error based on the SMO model. After that, the alarm output is switching from 0 to 1 as shown in Fig. 8. Also, the cyber system alarm is warning on the display and the (Office/Machine/Mobile) GUIs show that LVDT is under recovery while the alarm goes on.

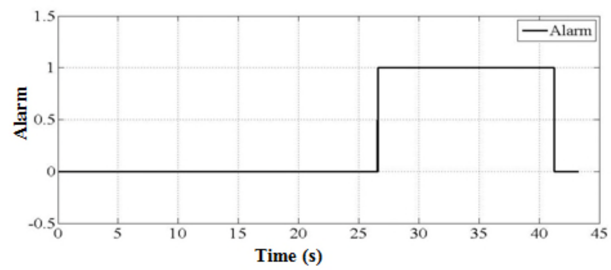

Figure 8. Fault detection alarm of Short circuit / Disconnection of wire

To find out the error rate of the SMO, by comparing the LVDT signal with the SMO threshold predictor signal, it shows that the recovered signal is well operated because the maximum of the reference error is under an allowable range. If the LVDT signal exceeds the allowable signal, the fault detector gives an alarm during recovery. Also, the LVDT sensor signal is replaced by the SMO signal in parallel. If the fault persists, the signal may be considered as a permanent fault, as indicated in the fault classification shown in TABLE I. Following the previous experiments, two sudden permanent fault experiments (fixation, zero-drift) will be applied.

To generate the LVDT sensor signal with a permanent fault, we use a relay for sudden operation and power supply to engender fixation. After the fault occurs, the voltage of the LVDT goes to a fixed voltage (3V). When the signal exceeds the allowable error range, the LVDT signal is replaced by a threshold predictor signal from encoder related to motor rpm. Estimates of the LVDT sensor outputs by using the SMO model and recovered signal are shown in Fig. 9.

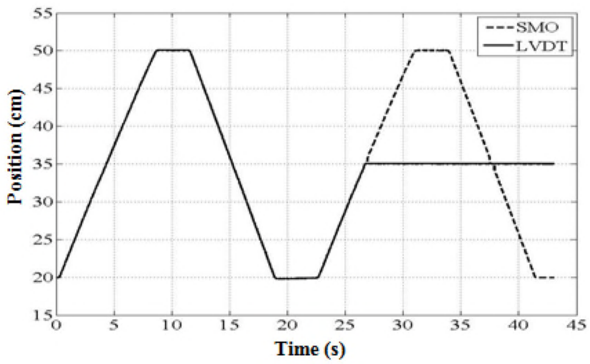

Figure 9. Fixation fault signal and recovered signal by using SMO

After that, the alarm output is switching from 0 to 1, as shown in Fig. 10. We see a fault where chattering occurred near time 27 seconds during the alarm, but the duration of the alarm is too short to determine the presence of the permanent fault. Also, the cyber system alarm is warning in display and the (Office/Machine/Mobile) GUI shows that the LVDT is under recovery while the alarm operates.

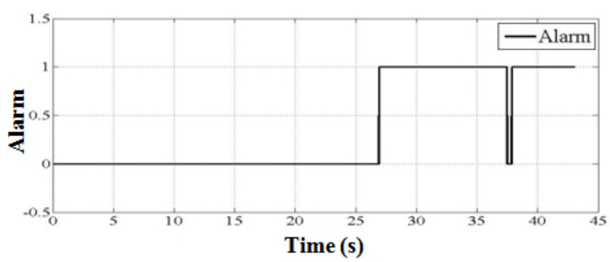

Figure 10. Fault detection alarm of fixation

To generate the LVDT sensor signal with a permanent fault, we use a relay for sudden operation and power supply to make zero-drift. After the fault occurs, the voltage of LVDT will be lower offset. When the signal exceeds the allowable error range, the LVDT signal is replaced by a threshold predictor signal from encoder related to motor rpm. Estimates of the LVDT sensor outputs by using the SMO model and the recovered signal are shown in Fig. 11.

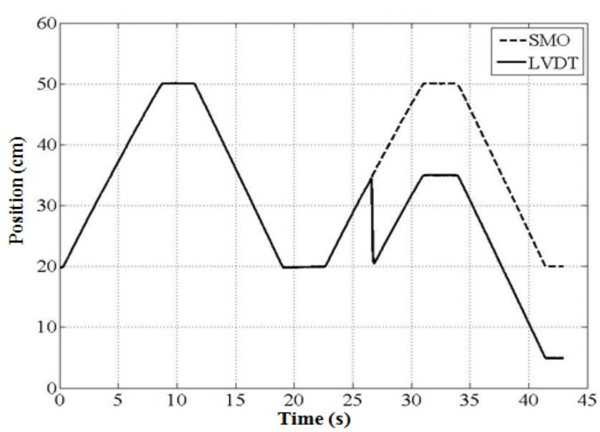

Figure 11. Lower zero-drift fault signal and recovered signal by using SMO

After that, the alarm output is switching from 0 to 1 as shown in Fig.12.

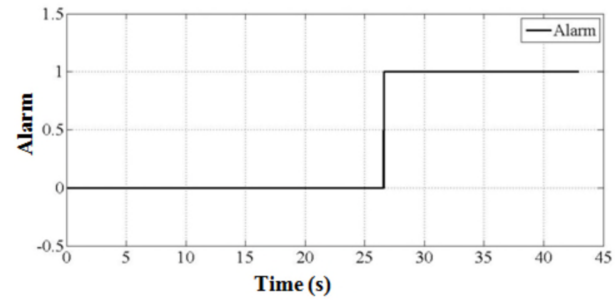

Figure 12. Fault detection alarm of lower zero-drift

After a fault occurs, the voltage of LVDT will be upper offset. Estimates of the LVDT sensor outputs by using the SMO model and the recovered signal are shown in Fig. 13.

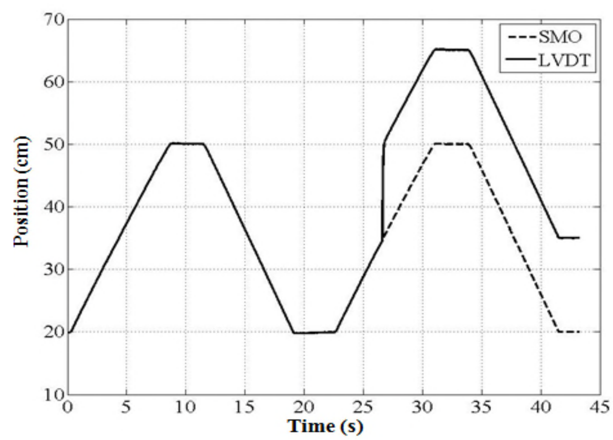

Figure 13. Upper zero-drift fault signal and recovered signal by using SMO

After the permanent fault occurs, the alarm output is switching from 0 to 1, as shown in Fig. 14.

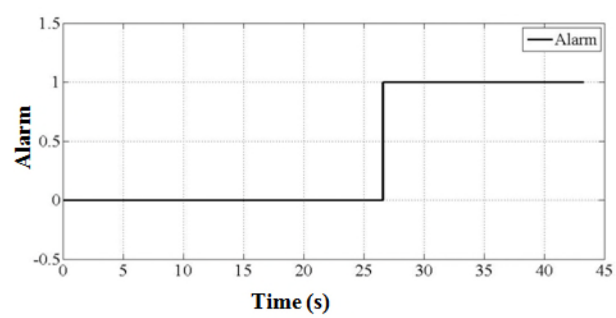

Figure 14. Fault detection alarm of upper zero-drift

During the whole process of permanent fault experiment, the cyber system alarm is warning in the display and the (Office/Machine/Mobile) GUI shows that the LVDT is under recovery while the alarm operates, as shown in Fig. 15.

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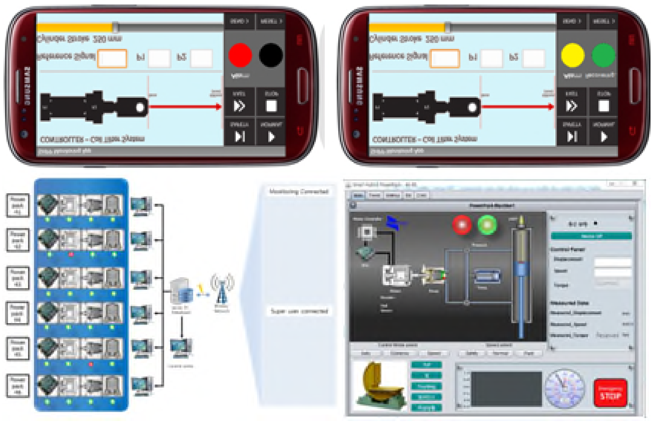

Figure 15. Fault detection alarm of cyber system

Fig.16 shows the overall configuration of the coil tilter system.

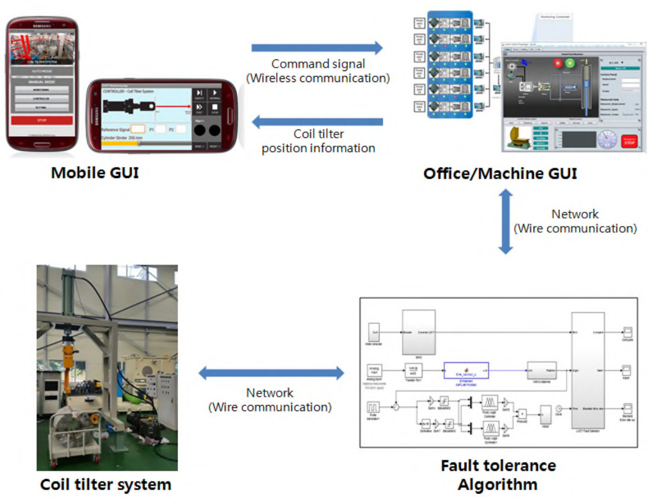

Figure 16. The structure of coil tilter SHP

When operating without a fault, the command signal is given to the coil tilter SHP through (Office/Machine/Mobile) GUI. If the coil tilter SHP in not the normal operation due to the fault, the fault tolerance algorithm will be operated and (Office/Machine/Mobile) GUI are verified through an alarm to users and recover the fault. After the fault is returned to normal waveform, the alarm will turn off and the coil tilter SHP will operate normally.

V. CONCLUSION

In this paper, SHP system uses the sensor fault tolerance algorithm combined with the cyber system for the coil tilter. When a fault happens in the coil tilter SHP, a proposed fault tolerance algorithm verifies the fault type and recovers the (temporary or permanent) fault and the (Office/Machine/Mobile) GUI observes the recovering procedure through a monitoring display. In consideration of the fault that may occur during control through the cyber system, the importance of a sensor fault tolerance technology is emphasized. When sensors do not detect the fault properly, the fault tolerance algorithm automatically and simultaneously operates with the prototype. If one sensor does not operate properly, the fault tolerance algorithm replaces a broken signal to estimate signal from Kalman filter or SMO related to other sensor signals. The proposed fault tolerant algorithm is designed and performed for temporary or permanent faults with the LVDT sensor as an experiment. Also, monitoring and alarming in the cyber system confirms the performance. As a result, a sensor fault tolerance technology with the cyber system is suitable for coil tilter SHP. In the future, all experiments will be applied to new prototypes.

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