The Fault-tolerant Control System Based on Majority Voting with Kalman Filter

Vit Danecek and Pavel Silhavy

***Abstract*—The article deals with the Fault-tolerant control system which is based on majority voting with the Kalman filter. The reader is made familiar with the Fault tolerant systems and requirements on them at the beginning. The voters, the majority voting principle and the Kalman filter equations are subsequently described. The reader is made familiar with the Fault-tolerant control system which is based on majority voting with the Kalman filter after then. That Fault-tolerant control system is described in detail, including the experimental simulation results. The conclusion of the article contains a detailed description of the Fault-tolerant control system which is based on majority voting with the Kalman filter and it assess experimental results.**

***Index Terms*—Fault Tolerant system, Fault detection, Kalman filter, Majority voter unit, Robust control**

I. Introduction

TODAY electronic control devices are becoming increasingly more sophisticated and functionally are part of larger systems. These systems are used in all fields of human activity. They are used as in a few critical applications, as well as critical applications in aerospace [1], submarines, medical devices, chemical [2] and nuclear industry [3]. Today's objective in the design of sophisticated systems, it is necessary to ensure not only the correct functionality, but to ensure that in case of the failure is introduced themselves to a predefined safe state.

The steady safe state achieving in less critical systems is relatively easier in comparison with the Fault tolerant systems. The less critical systems appear to the first time as cheaper solutions but this fact changes during the whole working period.

For critical systems is difficult to achieve a safe state and the system is usually designed so that it can continue to operate in reduced mode in the event of one or more error (Fault tolerant systems [4]). The example of system controlled by the fault-tolerant-robust-control system is shown in Fig.1. We use example for better explanation. In aviation safety can arise when suddenly turning off the power electronic devices in flight in the event of failure. It is possible, however, switch to a backup power source. Self-switch should do the electronic system itself, but that will inform the person. Informing people is generally carried out audiovisual form. However, for special systems are used as well as other signalization forms (e.g. mechanical movement of your seat). Older and less sophisticated method is in this case, waiting for a command operator. This form is less demanding on both hardware and software primarily to the proposal. Another option is to input a preset sequence of operator program commands in case of the failure.

Fig. 1. The example of The Fault-tolerant-robust-control system.

The Fault-tolerant control systems used for its activity measured data obtained from number of sensors. To increase the reliability of the data, the sensor is to use a redundant technology. It is a technique in which a one physical quantity is sensed by a number of sensors. In practice, most sensors are used in the Triple modular redundancy. The basic principle of the Triple modular redundancy is shown in Fig. 2 [5].

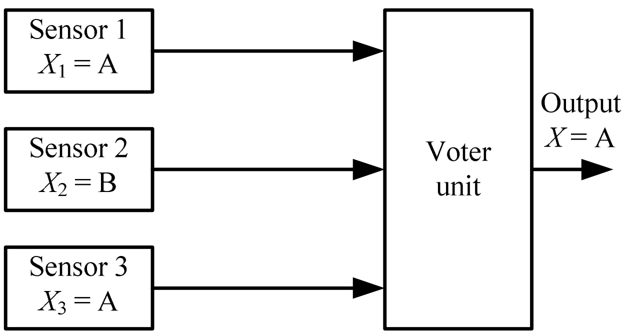

Fig. 2. The basic principle of the Triple modular redundancy.

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The Triple modular redundancy has an optimal ratio of availability on the reliability of the data. Among its drawbacks, unfortunately, it is economic inefficiencies during the physical implementation. This method also requires the sophisticated voter unit for proper function. The sophisticated Voter unit must determine the correct output value from a member of a group of measured data from sensors. General requirements for the Voter are discussed in the Section III. The present main objective in this area of science is to reduce the number of physical sensors, while maintaining the same ratio to the optimum ratio of the availability of reliability. Fulfilling this objective would have been a drastic decline in overall economic cost of fault tolerant systems. To this end, use the predictive element and replace it by one or more physical signals from sensors. The Predictor is used to predict present value of the S2 sensor signal. The previously mentioned concept is shown on Fig. 3.

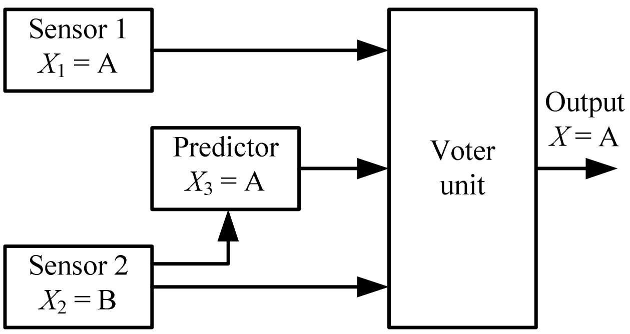

Fig. 3. The Triple modular redundancy with the Predictor.

The article introduces the possibility of using the Kalman filter, as a predictor with the formal majority Voter unit. This method upgrades the current scientific knowledge of an attempt to switch the input signals from the sensors into the Kalman filter.

The paper is organized as follows. After this introduction section, we try to summarize the general voter function in Section II. The general principles of formal majority voting with priorities are explained in Section III. The Kalman filter equations are described in Section IV. In Section V, we try to introduce own Fault-tolerant control system which is based on majority voting with the Kalman filter. In Section VI, we try to present simulation results. The final section, which is Section VII, includes concluding remarks and probable future directions of the researches regarding advance Fault-tolerant control system.

II. The General Voter Function

The Voters, sometimes called Adjudicators [6], are elements that determine two or more input options. The Adjudicator determines the correct output and the correct result. There are a number of voter algorithms. In a specific implementation, used specially modified algorithms based on the principle of majority rule are used. They stand out above all by their simplicity. Generally, all types of the voter work on a similar principle. The General principle features of voters are shown in Fig. 4. The first is voter initialization. If it contains special internal variables, they are activated. The current initialization always depends on target implementation. The voter subsequently receives input variations of all inputs.

Adjudication algorithms are applied to these variants. The Adjudication algorithm returns a correct output and adjusts the status results [7], [8].

There are four possible states of the result:

1) All input variants from the set X are acceptable. One of them is chosen as the output.
2) At least one input variant from the set X is acceptable. This variant is selected as the output value.
3) No input variants from the set X are acceptable. The output value is selected at random. Status outcome is set to result not found.
4) No input variants from the set X are acceptable. The output value is selected at a predefined default value. Status outcome is set to the result not found with default output.

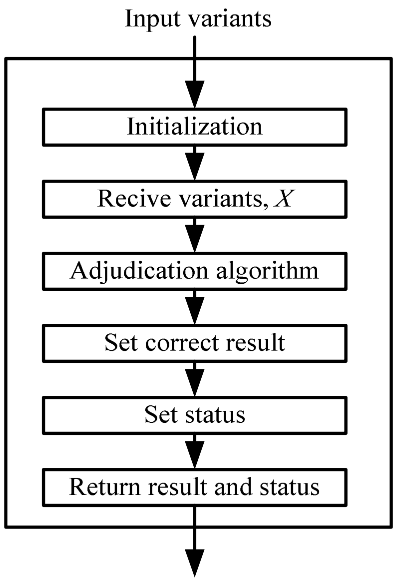

Fig. 4. The General principle features of voters.

III. Majority Voting without Priorities

The fault tolerant system needs to know the source of output value from voter unit in every time. For these cases we introduce a new type of voter algorithm. This new type of majority voter unit with priorities is shown in Fig. 5.

The Basic principle is very similar to the traditional majority voting principle, but after setting of possible correct Xs a Table of Priorities of inputs is used. Based on this table the output value and output result from the majority voter unit with priorities are sets. The Table of priorities of the Majority voter unit with priorities is predefined by the operator. In this case there is no undefined output value. In disputable cases the predefined default value or predefined input X_n is used.

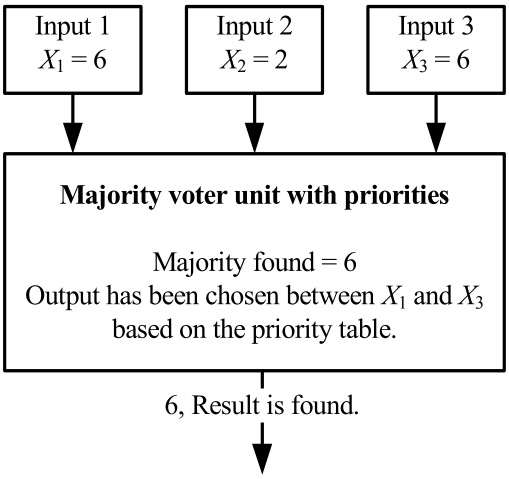

Fig. 5. The principles function of majority voter unit with priorities

IV. The Kalman Filter Equations

The Kalman filter is one of the best predictor in present days [9-10]. It could be used as predictor for output value or input values based on previous measurement of the system.

The basic idea of Kalman filter is based on update filter parameters during the time and correction present measured value. The Kalman filter equations are (1)–(5). The initial conditions $x_{k\text{-}1}$, $P_{k\text{-}1}$, the system process noise covariance Q and measurement noise covariance R matrices must be set before first usage. In practice, Q and R matrices might change with each time step or measurement. We assume they are constant for purpose of this article. The Kalman filter time update equations are follows

$$x_k = Ax_{k-1} + Bu_{k-1} \text{ and} \quad (1)$$

$$P_k = AP_{k-1}A^T + Q \,. \quad (2)$$

The x_k represents estimated state, the A matrix includes model process data. The B matrix relates the optional control input u. The posterior estimate error covariance is P_k. The Kalman filter measurement update equations are follows

$$K_k = P_k H^T (HP_k H^T + R)^{-1} \,, \quad (3)$$

$$x_k = x_k + K_k (z_k - Hx_k) \text{ and} \quad (4)$$

$$P_k = (I - K_k H) P_k \,. \quad (5)$$

The Kalman gain K_k is defined by equation number three. The H matrix represents the measurement model data. The z_k represents present measured data. The I matrix is standard mathematic identity matrix.

The state prediction of input signal is based on continuously repeats of equations (1)–(5).

V. The Fault-tolerant Control System Based on Majority Voting with Kalman Filter

The Fault-tolerant control system based on majority voting with the Kalman filter includes all previous mentioned basic ideas. The present model is divided into three basic parts in general.

The first part of them is the Kalman filter. The Kalman filter is based on equations which are mentioned on previous section. The values in the matrixes of Kalman filter directly depends on target designed systems in general way. The following values are sets into the Kalman filter (The full model values of the MATLAB program are presented for better possible reconstruction. The syntax of the MATLAB program is used in following sentences in the text.). The Initial condition for estimated state is set to 1. The Initial condition for estimated error covariance is set to 1*eye(1). The State transition matrix is sets to 1. The Process noise covariance is sets to 1*eye(1). The Measurement matrix is set to 1. The Measurement noise covariance is set to 0,01*eye(1). The Kalman filter measurement input is the Z signal. The estimate output of the Kalman filter is represented by the *X_Est* signal. The *X3* input signal of the Voter unit is represented by previously mentioned signal.

The second part is the Multiport switch which provide switching between inputs *X1*, *X2* and *X3* into the *Z* input signal of the Kalman filter. The *X3* is feedback signal from the Voter unit. The present value of the *KC* control signal drives switching in the Multiport switch via input C.

The third part is the Voter unit which sets correct output y, voter status result E and the switch control signal KC. The digital input signals from sensors are defined as *X1* and *X2.* The both signals must be digital signals. The *X_est* prediction signal of the Kalman filter which works as predictor is connected to input *X3*. The default value is connected to *Y_Default* input of voter. The Default value will be used in case of the Voter unit malfunction. The maximal allowed differences between input signals *Xs* is defined by *ed* input signal. The Default value is set in simulation in the value 0,04. The present value is based on static setting of that value. In future research we should improve the model for dynamic setting threshold approach.

The Voter unit creates decision based on condition and it also creates output signals. The Condition table and the Action table of the Voter are presented at Table I and Table II. The unique idea of this system is use the Switch unit to real-time changing input signal to Kalman filter. We try to introduce this method. The Fault-tolerant control system based on majority voting with Kalman filter is shown on Fig. 6.

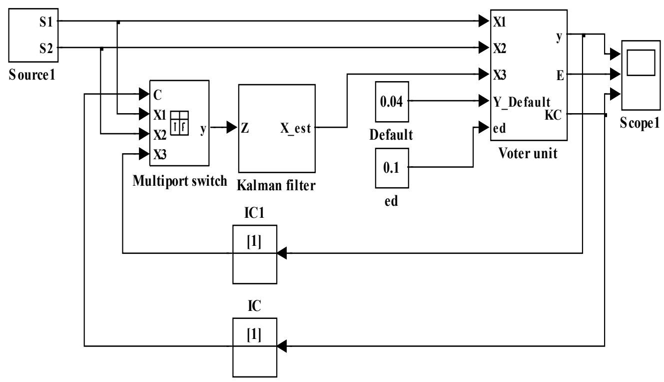

Fig. 6. The Fault-tolerant control system based on majority voting with Kalman filter.

TABLE I
CONDITION TABLE OF VOTER UNIT

Condition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	20	21	22	23	24	25	26
(X1+abs(ed)) > (X3-abs(ed))	T	F	T	T	T	T	F	T	F	T	-	-	-	-	T	T	-	T	-	T	T	T	-	-	-
(X2+abs(ed)) > (X3-abs(ed))	F	T	F	T	T	F	T	T	T	T	-	-	-	-	T	T	-	T	T	T	T	T	-	-	-
abs(X3-X1) < abs(X3-X2)	T	F	T	T	F	T	F	F	F	F	-	T	F	-	T	T	-	F	F	F	F	T	F	-	-
((X3-ed)<X1) && (X1<(X3+ed))	T	F	T	T	T	T	F	F	F	F	F	T	T	F	T	T	-	F	F	F	T	T	-	F	-
((X3-ed)<X2) && (X2<(X3+ed))	F	T	F	F	T	F	T	T	T	T	F	T	T	F	F	F	-	T	T	T	T	F	-	F	-
((X2-ed)<X1) && (X1<(X2+ed))	F	F	F	-	T	F	F	-	F	F	T	-	-	T	F	F	-	F	F	F	T	-	T	F	-
(X2+ed) == (X3+ed)	F	T	F	F	T	F	F	F	F	F	F	-	F	F	F	F	T	T	F	F	T	F	F	F	-
(X1+ed) == (X3+ed)	T	F	F	F	T	F	F	F	F	F	F	-	F	F	F	T	F	F	F	F	F	F	F	F	-
(X1+ed) == (X2+ed)	F	F	F	F	T	F	F	F	F	F	F	-	F	F	F	F	F	F	F	F	F	F	T	F	-
X1>X3	-	F	F	F	F	T	F	F	F	F	F	-	-	T	-	F	F	T	T	T	T	T	-	-	-
X2>X3	-	F	-	-	F	-	F	F	T	T	F	-	-	T	-	-	F	F	F	T	F	T	-	-	-
Actions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	20	21	22	23	24	25	26

The T symbol represents true value. The F symbol represents false value. The dash symbol represents not used condition.

TABLE II
ACTION TABLE OF VOTER UNIT

#	Description	Action
1	The X1 input is chosen. The X2 input is not correct. The X1 equals to X3.The high error border of X2 is lower than lower error border of X3.	y = X1; E=1; KC=1
2	The X2 input is chosen. The X1 input is not correct. The X1 input is lower than X3.	y = X2; E=2; KC=2
3	The X1 input is chosen. The X2 input is not correct. The X1 input is lower than X3.The high error border of X2 is lower than low error border of X3.	y = X1; E=3; KC=1
4	The X1 input is chosen. The X2 input is not correct. The X1 input is lower than X3.The high error border of X2 is higher than low error border of X3.	y = X1; E=4; KC=1
5	The all inputs are correct. The X1 is chosen. The X1=X2=X3	y= X1; E=5; KC=1
6	The X1 input is chosen. The X2 input is not correct. The X1 input is higher than X3.The high error border of X2 is lower than low error border of X3.	y = X1; E=6; KC=1
7	The X2 input is chosen. The X1 input is not correct. The X2 input is lower than X3.The high error border of X1 is lower than low error border of X3.	y = X2; E=7; KC=2
8	The X2 input is chosen. The X1 input is not correct. The X2 input is lower than X3.The high error border of X1 is higher than lower error border of X3.	y = X2; E=8; KC=2
9	The X2 input is chosen. The X1 input is not correct. The X2 input is higher than X3.The high error border of X1 is lower than lower error border of X3.	y = X2; E=9; KC=2
10	The X2 input is chosen. The X1 input is not correct. The X2 input is higher than X3.The high error border of X1 is higher than lower error border of X3. The X3 is higher than X1.	y = X2; E=10; KC=2
11	The correct output does not exist. The X1 and X2 are in range. The X3 is out of range X1.The X2 is lower than X1. The X3 is higher than X1.	y= X1; E=11; KC=1
12	The X1 input is chosen. All inputs are correct. The X1 is closer to the X3 than X2.	y= X1; E=12; KC= 1
13	The X2 input is chosen. All inputs are correct. The X2 is closer to the X3 than X1.	y= X2; E=13; KC= 2
14	The X3 is not correct. X1 and X2 are similar. The X1 is chosen as correct input.	y= X2; E=14; KC= 2
15	The X1 input is chosen. The X2 input is not correct. The X1 input is higher than X3.The high error border of X2 is higher than higher error border of X3.	y= X1; E=15; KC= 1
16	The X1 input is chosen. The X2 input is not correct. The X1 input is equal to the X3.The high error border of X2 is higher than higher error border of X3.	y= X1; E=16; KC= 1
17	The X2 input is chosen. The X1 input is not correct. The X2 input is equal to the X3.The high error border of X1 is higher than low error border of X3.	y= X2; E=17; KC= 2
18	The X2 input is chosen. The X1 input is not correct. The X2 input is equal to the X3.The high error border of X3 is lower than low error border of X1.	y= X2; E=18; KC= 2
19	The X2 input is chosen. The X1 input is not correct. The X2 input is lower than the X3.The X2 is on range. The high error border of X1 is lower than low error border of X3.	y= X2; E=19; KC= 2
20	The X2 input is chosen. The X1 input is not correct. The X2 input is higher than the X3.The X2 is on range. The high error border of X1 is than low error border of X3.	y= X2; E=20; KC= 2
21	The X2 input is chosen. The X1 input is not correct. The X2 input is higher than the X3.The X2 is on range. The low error border of X1 is higher than high error border of X3.	y= X2; E=21; KC= 2
22	The X2 input is chosen. The X2 input is equal to the X3.The X1 is on the range of the X3.	y= X2; E=22; KC= 2
23	The X1 input is chosen. The X2 input is not correct. The low error border of X2 is higher than low error border of X2.	y= X1; E=23; KC= 1
24	The X1 input is chosen. The X1 and X2 are equal. The X3 is somewhere on space.	y= X1; E=24; KC= 1
25	All inputs are out of range. The borders are out of range.	y=Y_Default; E=25; KC=3
26	The Voter is not able set proper output. The Default output is set.	y=Y_Default; E=26; KC=3

VI. THE SIMULATION RESULTS

This chapter introduce the simulation results of present research which is still in progress. The separate testing of all block of system was successfully done. The simulation results of combined blocks are shown on follows Fig. 7 up to Fig. 10.

The digital value of input voltage of the sensor S1 is represented by the X1 signal. The digital value of input voltage of the sensor S2 is represented by the X2 signal. The present value of the X3 signal is generated by the Predictor. It is the Kalman filter in this model. The all input voltages as function of time are shown in Fig.7.

The output voltage as function of time is shown on Fig. 8. The status of the Voter unit as function of time is shown on Fig 9. The *E* signal values are explained in Table II in details at second column.

The Switch status as a function of time is shown in Fig. 10.

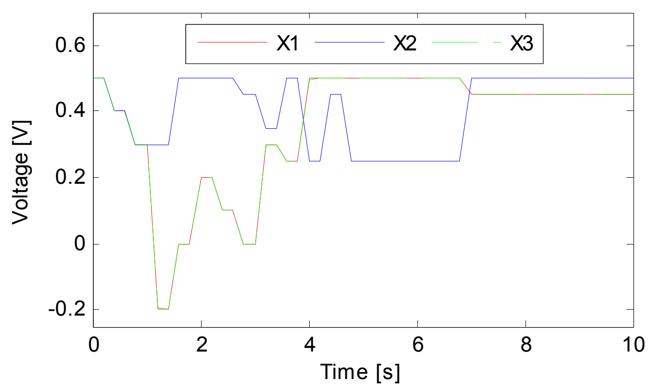

Fig. 7. The input voltages as a function of time.

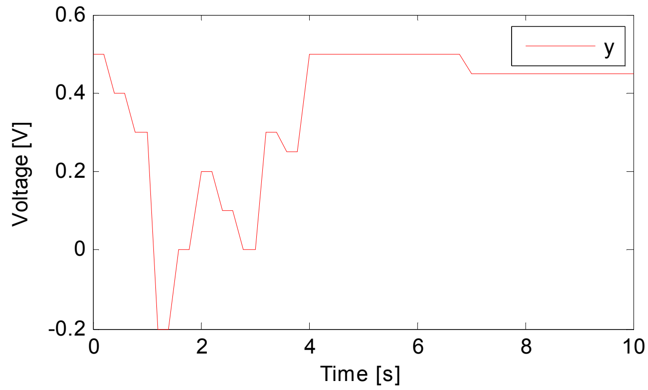

Fig. 8. The output voltage as a function of time.

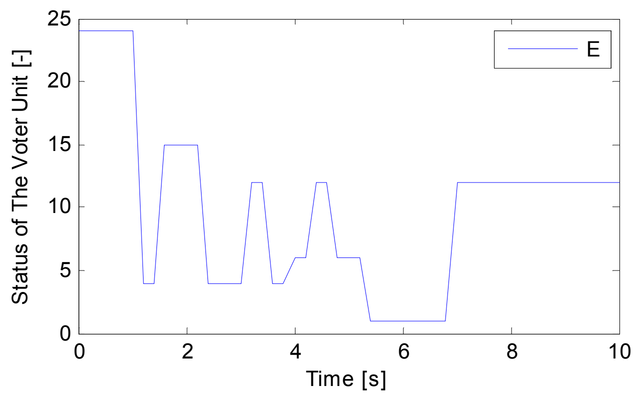

Fig. 9. The Status of Voter Unit as a function of time.

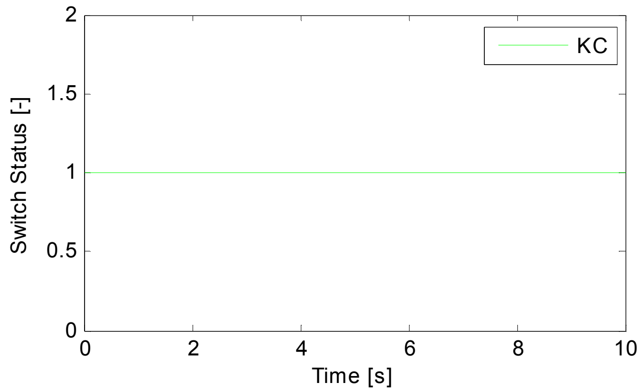

Fig. 10. The Switch status as a function of time.

The present simulation result shows only particularly success. The knowledge of the present research is following. The Voter unit works fine, but Kalman Filter is able precisely predict also wrong input. The Voter is able to find match between wrong inputs in this case. The Attempt to find proper solution for previous mentioned problem is still evolving.

VII. CONCLUSION

Nowadays there is a dynamic aviation industry growth. The aircrafts are devices that require a high degree of availability and reliability. Three physical redundant safety channels are obviously used for reach previously mentioned requirements. Unfortunately each safety channel takes usefully space and increases the overall weight of the aircraft. Also it is necessary to test them on every service operations. The every safety channel in general way increase overall cost of airplanes. It is very uneconomical.

The article deals with the Fault-tolerant control system which is based on majority voting with Kalman filter. The basic idea of the whole system is try to reduce one physical channel by using informational redundancy. The informational redundancy is represented by the Predictor unit, the Switch unit and Voter unit in the model. The Kalman fitter is sets as the Predictor unit. The two physical channels are switched to the Predictor unit. The control signal for the Switch unit is generated by the Voter unit. The System meets all the requirements for the Voter, which are defined in the Section II. The article also presents the current scientific developments of The Fault tolerant control system which is based on majority voting with the Kalman filter.

The System difficulties arising in the previous section will be eliminated in future. The Attempt to find proper solution for previous mentioned problem is still evolving.

Our research will be focused in future to replace the existing the Voter unit in model by some type of the neural network. This change will directly reduce complexity of the design in case of addition or removing input signals. The new problems will arise in future research with the neural networks.

The neural network must be trained by some train vector for example. Also we would like implement the Verify and

Validation unit of the input sensors into model in future. The many possibilities exist in future research but the basic idea of function of whole system is presented in this paper.

After that, the system should be used as part of aircraft control systems.

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