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Light Tracking Fault Tolerant Control System

J. Florescu*, T. Vinay, L. Wang

***Abstract*—**A fault detection and identification (FDI) technique is presented to create a fault tolerant control system (FTC). The fault detection is achieved by monitoring the position of the light source using an array of light sensors. When a decision is made about the presence of a fault an identification process is initiated to locate the faulty component and reconfigure the controller signals. The signals provided by the sensors are predictable; therefore the existence of a fault is easily identified. Identification of the faulty sensor is based on the dynamics of the frame. The technique is not restricted to a particular type of controllers and the results show consistency.

***Keywords*—**algorithm, detection and diagnostic, fault-tolerant control, fault detection and identification.

I. Introduction

CONTROL systems are using sensors to detect the state of the system and provide the necessary feedback. The light tracking system has to change the position of a frame in such away to receive the maximum light from a source [1] [2]. The frame is fitted with a sensor module to detect the intensity of the light located in the same plane. For a spatial tracking system a similar system is located in a perpendicular direction [3]. For each direction the sensor module is composed of four light sensors (phototransistors) for each direction. The sensors are distributed on a semi-circle as shown in the Figure 1.

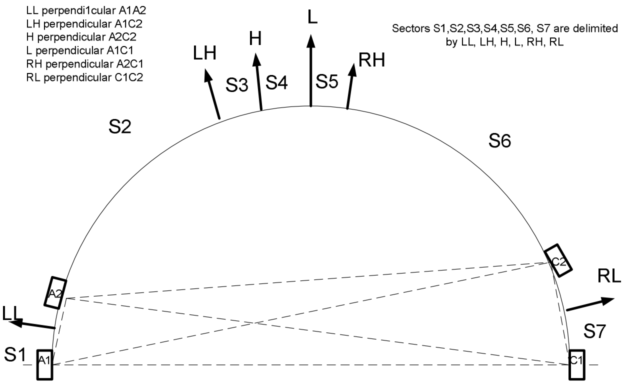

Fig. 1 The sensors location

The asymmetric location of the sensors is very important to create redundant information about the location of the light source. In a symmetric geometry the signal H and L overlap. It is considered that the frame is orientated towards the light source if the later is in the sectors S3, S4 or S5.

*John Florescu is with the Royal Melbourne Institute of Technology, Australia and is doing research in fault-tolerant system control (e-mail: florescujohn@gmail.com). Employed by Australian College of Kuwait.
Professor Liuping Wang is with the Royal Melbourne Institute of Technology, Head of Discipline, Electrical Energy and Control Systems
Dr. Thurai Vinay is with the Royal Melbourne Institute of Technology, Senior Lecturer
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A system operates satisfactory until a fault occurs. The controller moves the frame around until the source of light is in sector 3, 4 or 5. The actions upon the frame are: LEFT, RIGHT and STOP. The light source moves to the left (MOVE_L) or to the right (MOVE_R). Six comparators compare the ooutput signals of the following pairs of photo sensors: A1-A2, A1-C2, A1-C1, A2-C2, A2-C1 and C2-C1. The outputs of the comparators are: LL, LH, H,L, RH and RL. The states of the system are shown in Figure 2.

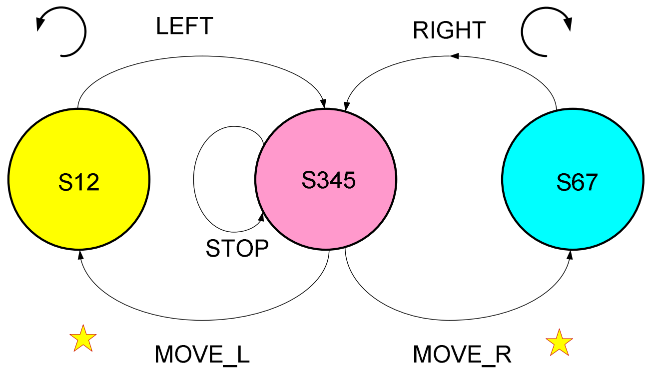

Fig. 2 State diagram

There are five different scenarios: no faulty sensor (NF), sensor A1 faulty (A1), sensor A2 faulty (A2), sensor C1 faulty (C1), and sensor C2 faulty (C2). The tables 1 to 5 shows the relations between the signals, the position of the light source (sectors) and the detected sector.

TABLE I
NO FAULT (NF). RELATIONS BETWEEN SIGNALS AND SECTORS

	LL	LH	H	L	RH	RL	DETECTED
S1	1	1	1	1	1	1	S1
S2	0	1	1	1	1	1	S2
S3	0	0	1	1	1	1	S3
S4	0	0	0	1	1	1	S4
S5	0	0	0	0	1	1	S5
S6	0	0	0	0	0	1	S6
S7	0	0	0	0	0	0	S7

To position the frame in sector S4, the signals H and L are sufficient.

TABLE II
A1 SENSOR IS FAULTY

	LL	LH	H	L	RH	RL	DETECTED
S1	0	0	1	0	1	1	X
S2	0	0	1	0	1	1	X
S3	0	0	1	0	1	1	X
S4	0	0	0	0	1	1	S4
S5	0	0	0	0	1	1	S5
S6	0	0	0	0	0	1	S6
S7	0	0	0	0	0	0	S7

As shown in Table II, when A1 is faulty the signals LL, LH and L are corrupted and the signals to be used are H and RH.

The frame would be oriented to sectors S4 or S5.

An X suggests that the position can't be detected.

If the frame is moving to the right (RIGHT) the source of light would be crossing from sector S7 towards the centre. If the frame is moving to the left (LEFT) the source of light would be crossing from sector S1 towards the centre.

When the frame moves RIGHT signals located to the left changes its state from 0 to 1. The frame should reverse direction and stop (STOP) when the same signal is 0 again.

When the frame moves LEFT signals located to the right changes its state from 1 to 0. The frame should reverse direction and stop (STOP) when the same signal is 1 again.

In Table II it is assumed that the corrupted signals have the value 0. The situation doesn't change when the value is 1.

TABLE III
C1 IS FAULTY

	LL	LH	H	L	RH	RL	DETECTED
S1	1	1	1	0	0	0	X
S2	0	1	1	0	0	0	X
S3	0	0	1	0	0	0	X
S4	0	0	0	0	0	0	S7
S5	0	0	0	0	0	0	S7
S6	0	0	0	0	0	0	S7
S7	0	0	0	0	0	0	S7

TABLE IV
A2 IS FAUL

	LL	LH	H	L	RH	RL	DETECTED
S1	0	1	0	1	0	1	X
S2	0	1	0	1	0	1	X
S3	0	0	0	1	0	1	X
S4	0	0	0	1	0	1	X
S5	0	0	0	0	0	1	S6
S6	0	0	0	0	0	1	S6
S7	0	0	0	0	0	0	S7

As shown if Table III when C1 is faulty the signals used are LH and H and the corrupted signals are L, RH and RL.

When A2 is faulty LH and L are the controlled signals and the corrupted signals are LL, H and RH. The frame can be oriented to have the light source either in sector S3 or S4.

Table V shows the situation when the sensor C2 is faulty.

The corrupted signals would be LH, L and RL. The signals used by the controller are L and RH. The frame would be located in sector S5

TABLE V
C2 IS FAULTY

	LL	LH	H	L	RH	RL	DETECTED
S1	1	0	0	1	1	0	X
S2	0	0	0	1	1	0	X
S3	0	0	0	1	1	0	X
S4	0	0	0	1	1	0	X
S5	0	0	0	0	1	0	X
S6	0	0	0	0	0	0	S6
S7	0	0	0	0	0	0	S6

Notes:

1. The moving frame is fitted with limit switches to avoid overshooting.
2. In each of the five situations there are only two signals considered to control the move. These signals are named X and Y as shown in the Table 6.
3. Signals LL and RL are not considered by any of the controllers. Their extreme position eliminates them from the competition.
4. It is less complicated to monitor the four pairs of signals than the four signals. Another advantage is that when a pair is validated to be the signals X,Y the faulty signals is identified.

TABLE VI
THE DISTRIBUTION OF THE CONTROLLER SIGNALS X, Y

	NF		A1		C1		A2		C2	
	X	Y	X	Y	X	Y	X	Y	X	Y
	H	L	H	RH	LH	H	LH	L	L	RH
S1	1	1	1	1	1	1	1	1	1	1
S2	1	1	1	1	1	1	1	1	1	1
S3	1	1	1	1	0	1	0	1	1	1
S4	0	1	0	1	0	0	0	1	1	1
S5	0	0	0	1	0	0	0	0	0	1
S6	0	0	0	0	0	0	0	0	0	0
S7	0	0	0	0	0	0	0	0	0	0

Model-based mechanisms are the most popular methods in detecting faults. The variables used by observers are the system variables. In the book Diagnosis and Fault-Tolerant Control [4] various observers are available.

Fault detection is base on collecting the data from the sensors, processing and evaluate residuals or other expressions.In this case the process of FDI is driven mainly by events [5].

II. Fault Diagnosis And Identification

It is common sense that the source of light must be in one sector, therefore only one the following expressions are true:

$$S1 = LL\&LH\&H\&L\&RH\&RL \quad (1)$$
$$S2 = \overline{LL}\&LH\&H\&L\&RH\&RL \quad (2)$$
$$S3 = \overline{LL}\&\overline{LH}\&H\&L\&RH\&RL \quad (3)$$
$$S4 = \overline{LL}\&\overline{LH}\&\overline{H}\&L\&RH\&RL \quad (4)$$
$$S5 = \overline{LL}\&\overline{LH}\&\overline{H}\&\overline{L}\&RH\&RL \quad (5)$$
$$S6 = \overline{LL}\&\overline{LH}\&\overline{H}\&\overline{L}\&\overline{RH}\&RL \quad (6)$$
$$S7 = \overline{LL}\&\overline{LH}\&\overline{H}\&\overline{L}\&\overline{RH}\&\overline{RL} \quad (7)$$

A faulty sensor is detected when none of the expressions is true or more than one are true.

The equations 1 to 7 can be used only to point out that a sensor is faulty.

Identification of the fault is achieved by monitoring the movements of the frame.

As mentioned earlier when the frame moves to right the light source will change the sector location on direction S7 – S1 (from bottom to the top of the Table 1). The table shows that all signals change their value only once from 0 to 1.

When the frame moves left the light source will change the sector location on direction S1 – S7 (from top to the bottom of the Table I). The table shows that all signals change their value only once from 1 to 0.

The actuator has three different actions on the frame:

- RIGHT when the light source is in the right sectors S6 and S7
- LEFT when the light source is in the left sectors S1 and S2
- STOP when the light source is in the centre sectors S3, S4 or S5

The location of the light sensor is given by the value of the expressions S1 to S7. When the light source crosses into the next sector, only one of the signals changes, therefore one of the expression S1 to S7 true.

The algorithm of identifying the faulty component is as follows:

Step 1

Move the frame to one of the extreme, for example to the right and reverse the direction.

Step 2

Start monitoring the vector with the signals LH, H, L, RH.

Note: the signals LL and RL were eliminated from the competition due to their extreme location.

Step 3

The vector [LH, H, L, RH] changes only two elements, from 1 to 0 if the move is from right to left (top to bottom in the tables).

Step 4

When the second change is recorded, the frame is moves back until the last element change back.

The first element identify the first signal and the second the second signal.

Step 5

Make a decision according to Table VII.

Table VII

Relations between faulty components and control signals

First signal (X)	Second signal (Y)	Faulty sensor
H	RH	A1
LH	H	C1
LH	L	A2
L	RH	C2

After the faulty component is identify the controller signals X, Y become:

X = First signal

Y = Second signal

From now on the controller is using the new X, Y signals as shown in Figure 3

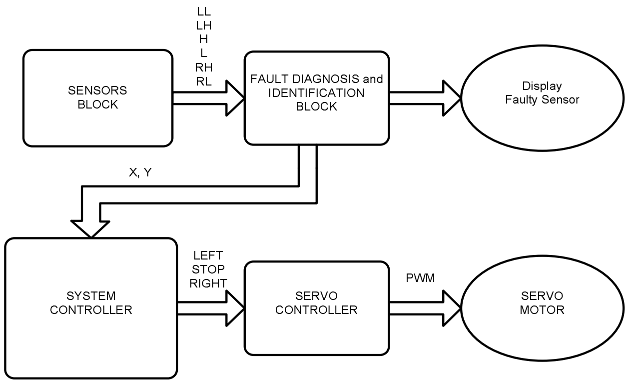

Fig. 3 Fault Tolerant Control Block Diagram

III. Simulation

The FDI process has been verified by creating VHDL project, generate a bit file and program NEXYS 2 board from Digilent.

The board is fitted with Xilinx Spartan 3E-500 and has onboard buttons, switches and LEDs.

There is an onboard clock of 50 MHz and for the experiment is divided by 30 000 000, to allow a monitoring the behavior of the model (Figure 4).

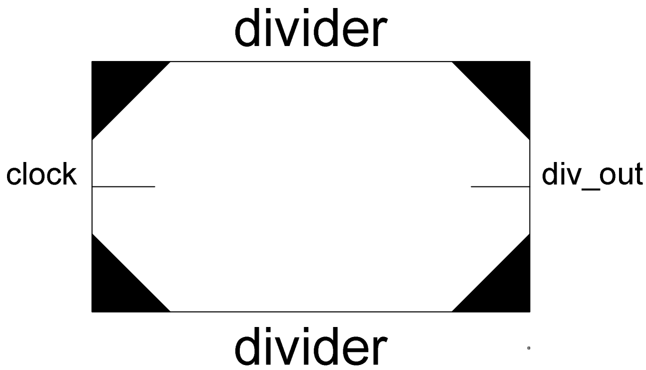

Fig. 4 Clock divider VHDL module

The output of the divider is used to drive a module to generate the signals required for simulation. It also has four inputs that can change the generated pattern to simulate one of the possible faulty components: A1, C1, A2, and C2. The output is the six signals that can identify the sectors and the directions left (L) or right (R). The Xilinx module is shown in Figure 5.

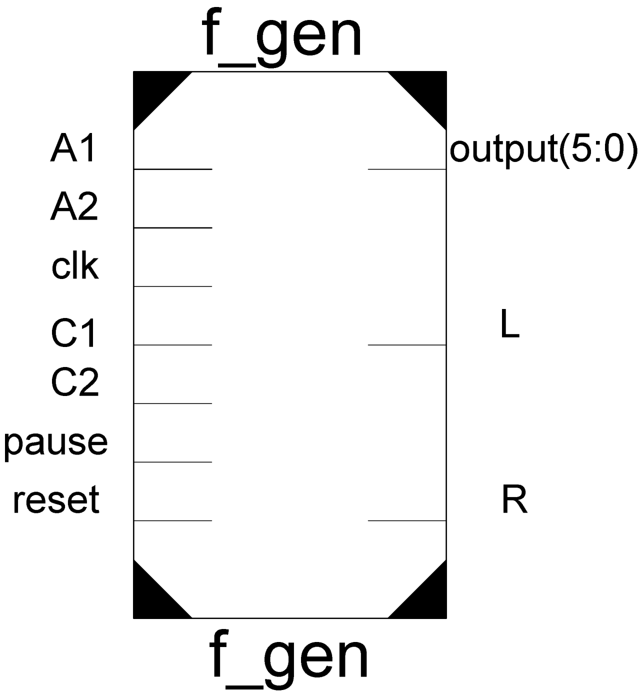

Fig. 5 Fault signal generator module

The next module is an array of D flips flops to memorize the previous values of the signals.

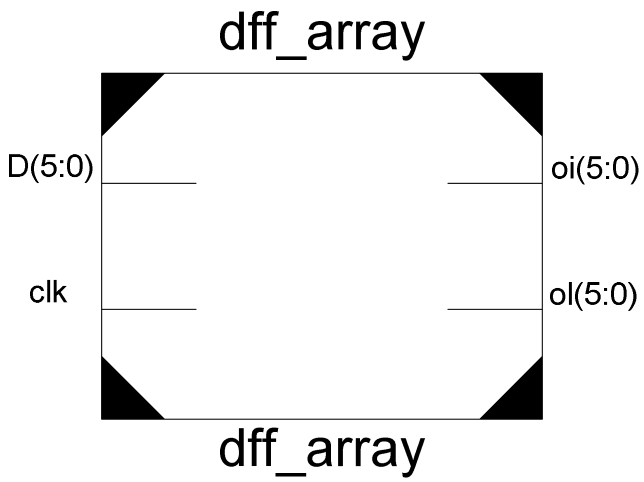

Fig. 6 D flip flop array

The output signals oi(5:0) are identical to the input signals D(5:0), while ol(5:0) are the value of the signals in the previous cycle.

In Figure 7 is shown the module that identify when a fault occurs. The last values of the signals are used to predict the signals values in the next cycle. Of course the values depend of the direction of the motion: left (L) or right (R).

These predicted values are compared with the incoming signals. When the predicted value is not the same with the incoming signal a fault is detected (f_detected).

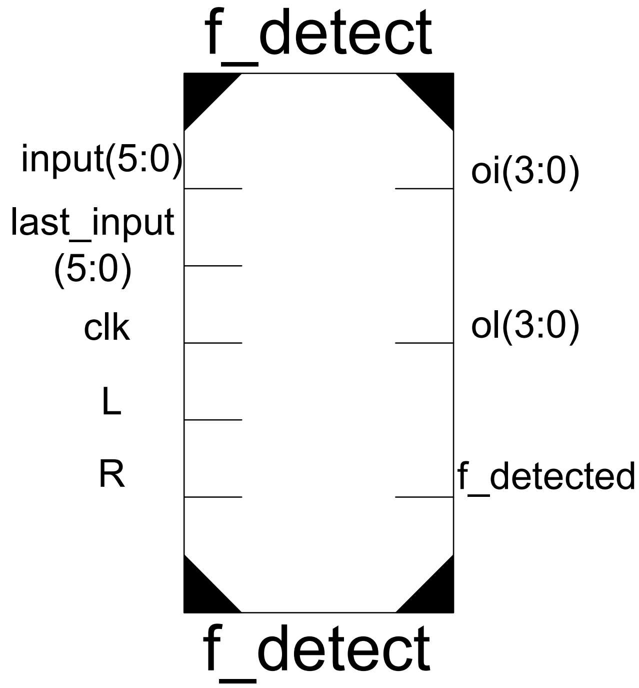

Fig. 7 Fault detection module

Notice that the output vectors of the module have a size of only four, not six. It was mentioned before that the extreme signals LL and RL have no use to identify the fault; it will be just an additional burden on calculations.

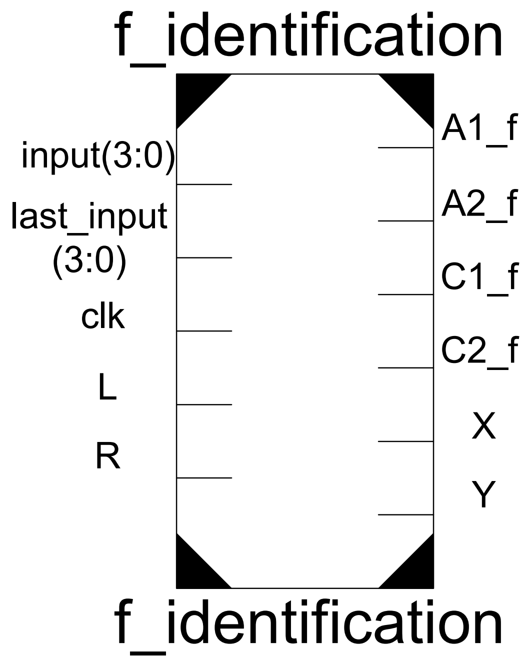

Fig. 8 Fault identification module

As shown in the Tables II, III, IV and V the positions of the light source can't be detected. The only way is to monitor the evolution in time of the four signals as described previously. A complete rotation of the mechanism from right to left or vice versa provide all the information required to identify the faulty sensor and also to dictate the appropriate control signals X, Y.

In Figure 8 the inputs are the last and the actual values of the four signals and the forced rotation of the mechanism: R or L. The outputs are faulty component and the appropriate signals X and Y.

Figure 9 shows how all the modules are incorporated in a top module. After the creation of constraints file and generating of bit file the Digilent FPGA board is programmed. The constraints file allocates six sliding switches for the inputs A1, A2, C1, C2, pause and reset. The onboard oscillator is used as a clock (clk). The outputs are simulated by allocating a light emitting diode (LED) for each output signal. When the fault A1 sensor is induced the LED associated with A1_f lights up.The process is repeated for A2, C1 and C2 faults. The LED associated with f_detected lights whenever one of the four faults is present. X and Y are the signals used by controller as explained previously.

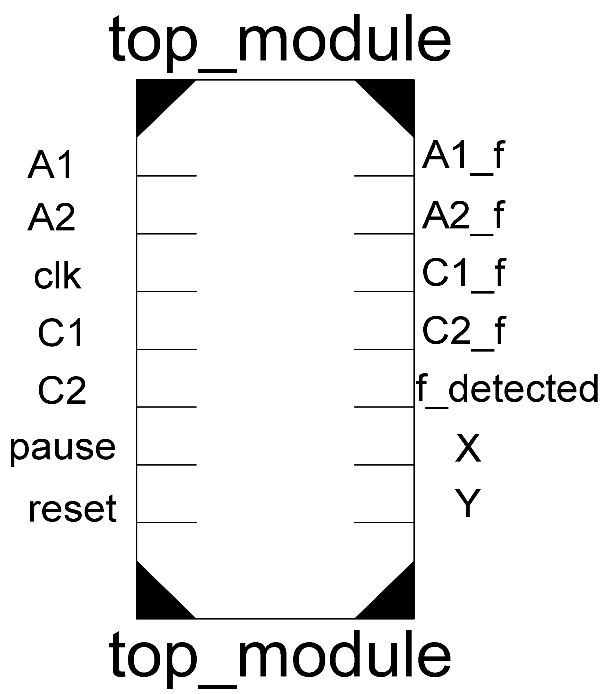

Fig. 9 Top module of VHDL simulation

IV. Matrix Method

The signals LL and RL are of no interest , therefore the sector S1 merges with S2 and S6 merges S7.

TABLE VIII
NEW SECTORS AND SIGNALS AFTER MERGER

	LH	H	L	RH
S12	1	1	1	1
S3	0	1	1	1
S4	0	0	1	1
S5	0	0	0	1
S67	0	0	0	0

The signals evolution in time could be considered vectors. In this case define a matrix M:

$$M = |LH \quad H \quad L \quad RH|$$

Similar the reading matrix R becomes:

$$R = |R1 \quad R2 \quad R3 \quad R4|$$

R1 is the reading vector for the signal LH when crosses all five sectors. Similar definitions for R2, R3 and R4.

Define a matrix F that can help identify the fault:

$$F = M^T * R$$

The F matrix is:

$$F = \begin{vmatrix} LH * R1 & LH * R2 & LH * R3 & LH * R4 \\ H * R1 & H * R2 & H * R3 & H * R4 \\ L * R1 & L * R2 & L * R3 & L * R4 \\ RH * R1 & RH * R2 & RH * R3 & RH * R4 \end{vmatrix}$$

The above interpretation shows clear that the columns of the F matrix dictate which would be the control signals. Two of the columns have the right values.

For no fault the values of the vectors are:

$$LH^T = |1 \quad 0 \quad 0 \quad 0 \quad 0|$$
$$H^T = |1 \quad 1 \quad 0 \quad 0 \quad 0|$$
$$L^T = |1 \quad 1 \quad 1 \quad 0 \quad 0|$$
$$RH^T = |1 \quad 1 \quad 1 \quad 1 \quad 0|$$

If is no fault R=M. In this case the matrix F is:

$$F = \begin{vmatrix} 1 & 1 & 1 & 1 \\ 1 & 2 & 2 & 2 \\ 1 & 2 & 3 & 3 \\ 1 & 2 & 3 & 4 \end{vmatrix}$$

Each column represents in order the evolution of the signals LH, H, L and RH. After the evaluation of the matrix F, only two columns are identical with the columns of the matrix F when no fault is detected.

The signals representing the two columns are selected to be the control signals. The first one is signal X and the second one is signal Y.

The matrix method offers the advantage of an automatic detection of the faulty sensor and allocation of the sensor signals to the control signals.

The apteryx suggests a scalar multiplication of two vectors.

V. Future Experiments

Solar panels can be automatically oriented to the sun for maximum efficiency.

If heat sensing detector are used the frame can track a target that radiate heat.

VI. Conclusions

The paper proposes a simple fault detection and identification (FDI) mechanism.

The simplicity of the mechanism makes it practical and easy to be implemented. The sensors are strategically placed to generate signals that can be easily monitored. When the target moves from one sector to another only one bit changes is value, similar to Gray code [6].

The sensor redundancy should provide a way of designing a FTC control system. In the proposed mechanism the reconfiguration is happened automatically.

An interesting future research is that in the case of redundant number of sensors to identify logical relations to identify the faulty component. It is similar of reverse engineering of Hamming code. A message is modified by adding extra bits that are calculated using the original message bits. At the destination the original message is recovered using some formulas to find out the location of the corrupted bit if exists.

In the case of redundant sensors we have more signals than needed to control the system. In addition two consecutive signals are related as shown in the tables. The redundant signals should be translated in the equivalent of encoded message, that can be decoded at the receiving end.

REFERENCES

[1] Minor M. Arturo, García P. Alejandro, " High–Precision Solar Tracking System", Proceedings of the World Congress on Engineering 2010 Vol II, WCE 2010, June 30 - July 2, 2010, London, U.K
[2] H. Mousazadeh, et al., "A review of principle and sun-tracking methods for maximizing solar systems output," Renewable andSustainable Energy Reviews, vol. 13, pp. 1800-1818, 2009.
[3] P. Roth, et al., "Design and construction of a system for suntracking," Renewable Energy, vol. 29, pp. 393-402, 2004.
[4] M. Blanke, M. Kinnaert, J. Lunze, M. Staroswiecki, "Diagnosis and Fault-Tolerant Control", ISBN 3-540-01056-4 Springer-Verlag Berlin Heidelberg New York
[5] M.Daigle, X. Koutsoukos, G. Biswas, "Fault Diagnosis of \Continuous Systems Using Discrete-Event Methods", Proceedings of the 46th IEEE Conference on Decision and Control, New Orleans, LA, USA, Dec. 12-14, 2007
[6] Tuvi; Moshe Schwartz (1999). "The Structure of Single-Track Gray Codes"). IEEE Transactions on Information Theory 45 (7): 2383–2396.