Autonomus Reconfiguration using FPAA for Bandwitdh Recovery in Satellite Subsystems

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Abstract: In recent years, satellite communication has gained increased prominence and driving factors are the reliability, new design techniques and reduced cost. The onboard control system components of the satellite are subjected to high temperature, shock and vibration both during initial transport and launch, and also during periodical orbital corrections. These effects can introduce faults in the control systems mounted on the space vehicle. Use of hybrid assembly technology for reducing size, weight and cost is recommended in satellite systems and hence, providing redundant hardware (a common method of recovering from faults) is not feasible since it increases both space and weight. In this context, an alternative approach of fault recovery is to perform reconfiguration of existing circuitry and Field Programmable Analog Array (FPAA) allows the creation of dynamically reconfigurable analogue circuits. This work focuses on reconfigurable hardware based bandwidth recovery for satellite subsystems using FPAA. The proposed FPAA assisted fault recovery system is generic and structure independent and aims at maintaining the system bandwidth in constrained situations of no access to internal circuit for repair or replacement of failed components.

Keywords: Satellite subsystem, Fault recovery, Autonomous reconfiguration, FPAA.

Nomenclature

u_1 = Radial thrust (small rocket engine)
u_2 = tangential thrust
r(t) = radial distance
θ(t) = angular distance
ω(t) = angular velocity = $\dot{\theta}(t)$
k = known constant
m = satellite mass

1. Introduction

FPAA allows fine tuning of a lot of adaptive circuits. The FPAA based circuit can be regarded as a universal analogue cell-array that can be configured with C macros or their translated bit series. The configurable analogue blocks of the FPAA can be reconfigured to operate better (more suitably) and automatically with a self-configuring algorithm. As reconfiguration is performed several times by the device, its actual version will own totally new features in comparison to the ones of its ancestors. This is particularly useful in the design of satellite subsystems where there are many inevitable sources of shock and vibration which can cause failure of one or more of the components of the control system mounted onboard. In spite of inherent damping schemes present, shock loads can cause sufficient vibrations of random amplitudes and if vibration inputs occur at resonance frequency or harmonics, vibration displacement will be maximized. As a result of one or more of the above effects, a fault can occur within a control system and fault recovery becomes essential, so as to continue service (atleast degraded service) and maintain system stability. For example, an increase or decrease in the value of a circuit element capacitor decreases or increases the system bandwidth respectively and either filters out useful signal (i.e. system response becomes too sluggish) or allows high frequency noise to enter the system. In worst case these changes can even cause the system to fail. In this context, in this work, a reconfigurable hardware based fault recovery at the system level using FPAA is proposed and implemented. In the event of a fault (manifested by a sudden change in the system bandwidth), the proposed reconfigurable hardware introduces compensating networks so as to meet the bandwidth requirements.

2. ORBITAL PERTURBATIONS

Satellite motion will deviate from the nominal orbit due to disturbances as shown in figure 1. The nonlinear differential equations governing the dynamics equations of motion for a communication satellite circulating the earth orbit is given as follows:

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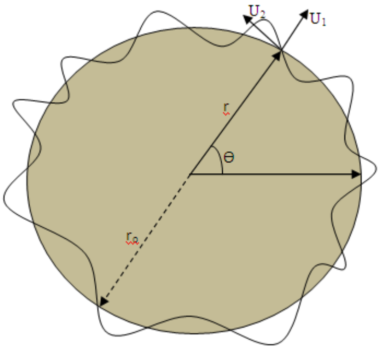

Figure 1 Satellite orbiting earth

$$\ddot{r}(t) = r(t)\dot{\theta}^2 - \frac{k}{r^2(t)} + \frac{u_1(t)}{m}$$

$$\ddot{\theta}(t) = -\frac{2\dot{\theta}(t)\dot{r}(t)}{r(t)} + \frac{1}{r(t)} + \frac{u_2(t)}{m}$$

If initial conditions are chosen such that $u_1^o = 0$, $u_2^o = 0$, $r(t) = r_o$, $\theta(t) = \omega_o t$ (reference trajectory), then from the equations of motion it follows that,

$$\omega_0^2 = \frac{k}{r_0^3}$$

The following state variables are chosen for the system

$$x_1 \triangleq r(t)$$
$$x_2 \triangleq \dot{r}(t)$$
$$x_3 \triangleq \theta(t)$$
$$x_4 \triangleq \dot{\theta}(t)$$

and the outputs are x_1 and x_3. In terms of state variables the equations of motion can be rewritten as,

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = x_1 x_4^2 - \frac{k}{x_1^2} + u_1$$
$$\dot{x}_3 = x_4$$
$$\dot{x}_4 = -2\frac{x_4 x_2}{x_1} + \frac{u_2}{u_1}$$

Linearizing the state equations with the help of Jacobian matrix about the reference trajectory, the orbital state equation matrix becomes

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 3\omega_0^2 & 0 & 0 & 2r_0\omega_0 \\ 0 & 0 & 0 & 1 \\ 0 & -2\frac{\omega_0}{r_0} & 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & \frac{1}{r_0} \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x$$

As can be observed from the above linearised model a variation in any of the parameters about its nominal value (an inevitable scenario) can cause significant vibration effects on the internal circuit components of the control system modules mounted onboard.

3. ANALOG CIRCUIT CREATION

A circuit creation typically involves three different but not independent policies namely, topology creating policy, part selection policy and parametric setting policy. It can be expressed as

S= f(T(C(P)) -----(1)
T= g(C(P)) and -----(2)
C= h(P) -----(3)

Where S: the circuit function, T: topology, C: component, P: parameter of components and f, g and h are functions and inner functions. The logical steps of the analog circuit creation are illustrated in steps 1 to 5 as follows:

```
Step 1: Create a circuit function
Step 2: Create a topology
Step 3: Create a component
Step 4: Create a parametric set of parts
Step 5: If Circuit fit
          {
           Retain analog circuit
           Return
          }
        Else
          {
           Perform reconfiguration of steps 4,3,2
          Go to step 5
          }
```

4. FIELD PROGRAMMABLE ANALOG ARRAYS (FPAA)

FPAAs help in the algorithmic implementation of the analogue circuit creation policies described in section 3. It provides a very convenient medium in which analog circuits and systems can be designed and implemented in a very short time frame [4]. The ultimate goal is to define a generic FPAA which would be capable of implementing almost any analog function. Instead, it is more pragmatic to categorize the analog circuits into different groups and define optimum circuit primitives for each, thus leading to a family of FPAAs. In that direction, switched current and switched capacitor based FPAAs may be utilized for the audio frequency range, whereas, OTA-C and current mode based FPAAs can be employed at higher frequencies.

4.1 FPAA ARCHITECTURE

Anadigm FPAA's are based on switched capacitor technology. The AN221E04 device consists of a 2x2 matrix of fully Configurable Analog Blocks (CABs), surrounded by a fabric of programmable interconnect resources. Configuration data is stored in an on-chip SRAM configuration memory and can also accommodate nonlinear functions. The FPAA features an advanced input/output structure that allows programming up to six outputs and has four configurable input/output cells and two dedicated output cells. The FPAA circuits can be programmed in many different ways such as with the help of a series E^2PROM or with a connected microcontroller through the i^2c line created as an inner structure.

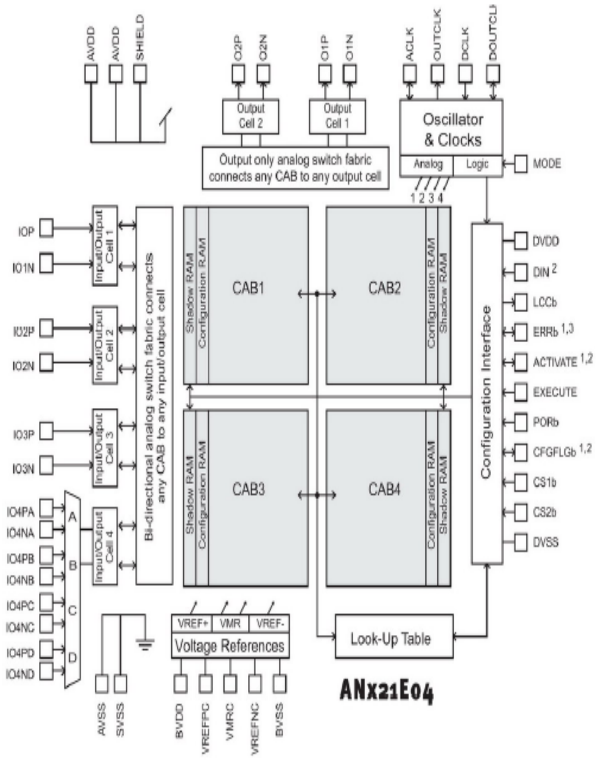

Figure 2 FPAA Architecture

5. FAULT TOLERANT MODELS

A generic FPAA based failure recovery model for a satellite subsystem, linearised as a 3^{rd} order system, but also applicable for nonlinear systems, is shown in figure 3. The model compares the actual system bandwidth with the specified bandwidth and accordingly gives a decision signal, using which, the FPAA either retains the existing configuration or perform reconfiguration of the compensator network.

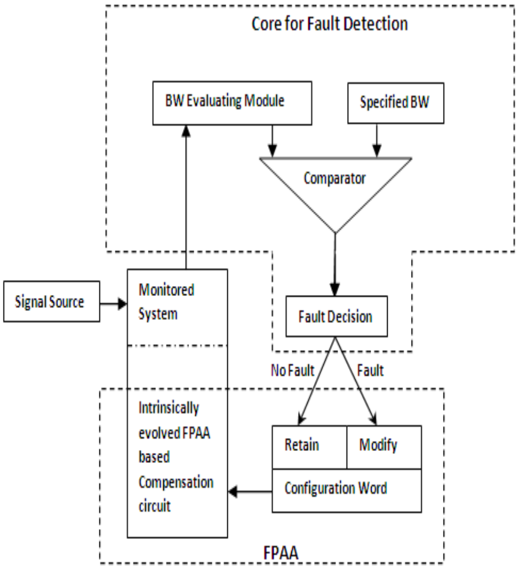

Figure 3 Proposed FPAA based autonomous reconfiguration model

6. IMPLEMENTATION RESULTS

The study was performed by varying the position of the poles of the monitored system above and below its nominal value. The effect of such pole variation is to alter the system bandwidth and impulse response [4]. The pole-zero plot, impulse response and frequency (magnitude and phase) response of the faultless system is shown in figure 4. The FPAA assisted compensated system response under different faulty scenarios are presented in case (i), (ii) and (iii). The respective system transfer function evolved for each case is given in appendix-I.

Case (i) Autonomous reconfiguration to compensate for decrease in bandwidth

The system response corresponding to a decrease in original system bandwidth due to an injected shift in the pole towards unity along negative real axis is shown in figure 5. The impulse and frequency response of the system with the FPAA evolved compensated network is shown in figure 6.

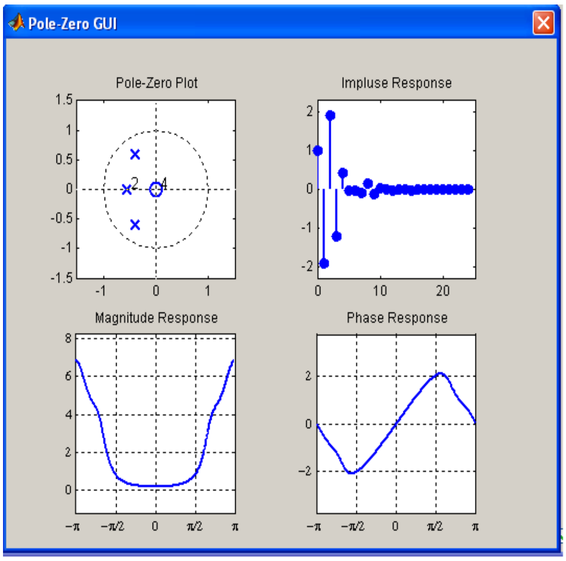

Figure 4 Response of faultless system

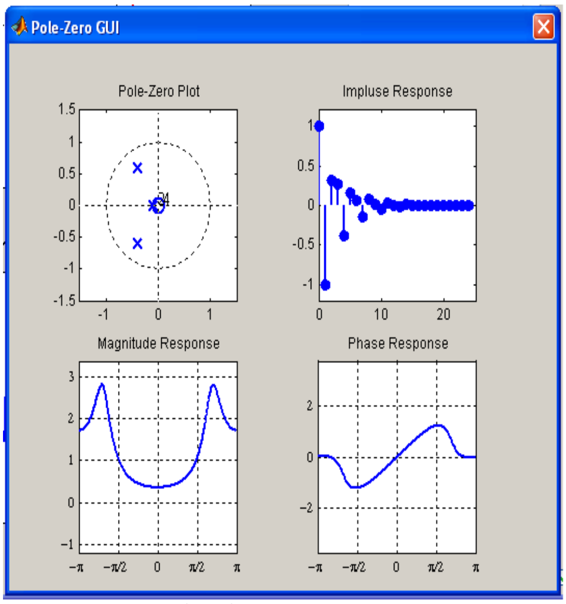

Figure 5 Response of the faulty system (resulting due to a decrease in bandwidth)

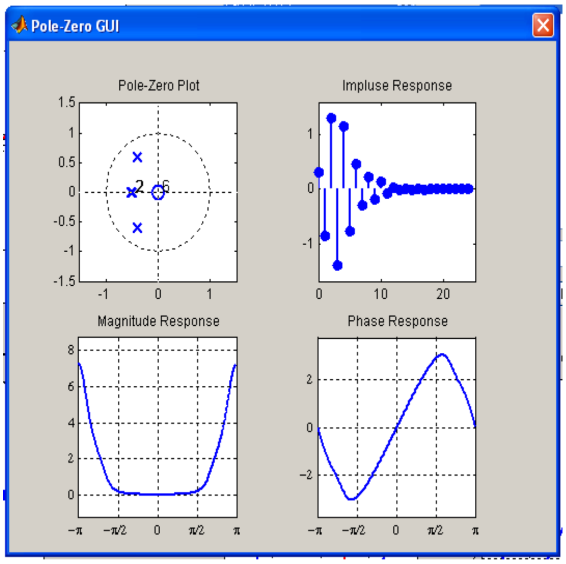

Figure 6 Response of the compensated system

Case (ii) Autonomous reconfiguration to compensate for increase in bandwidth

The study performed in this case is similar to that of case (i) except that the injected shift in pole position causes an increase in system bandwidth. The results obtained corresponding to this case is shown in figure 7 and 8.

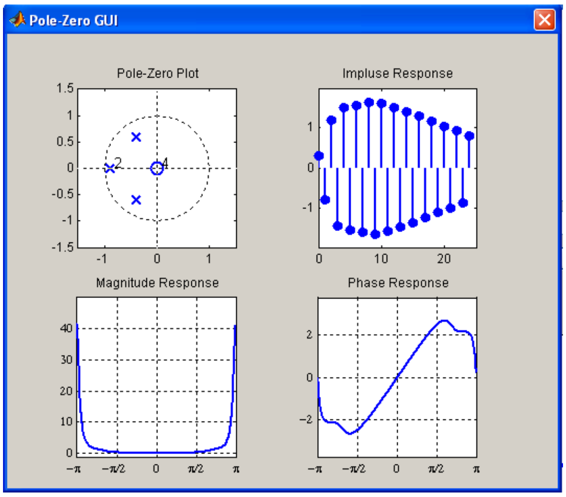

Figure 7 Response of the faulty system (resulting due to an increase in bandwidth)

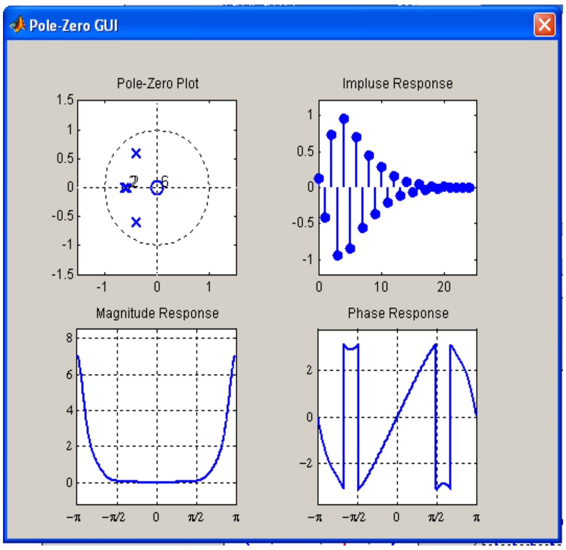

Figure 8 Response of the compensated system

Case (iii) Autonomous reconfiguration to compensate for instability

The worst case scenario of system becoming unstable due to variation in pole position (the cause being an internal failure of multiple components) and the system restored to stable state with the help of FPAA reconfigured compensator is presented in this case. The system response is given in figure 9 and 10 respectively.

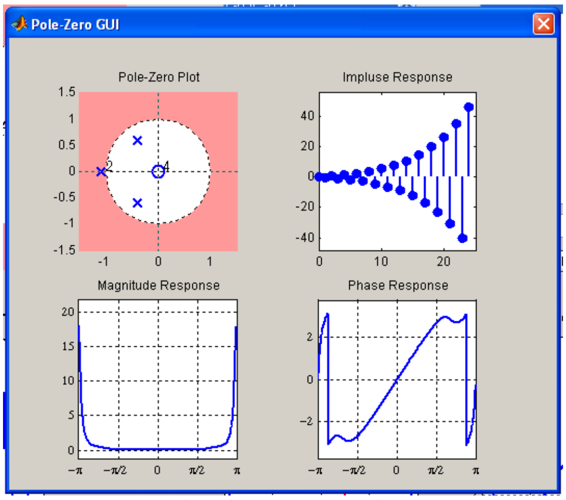

Figure 9 Response of the faulty system (reflecting an unstable system)

Proceedings of the 2005 NASA/DoD Conference of Evolution Hardware (EH'05).

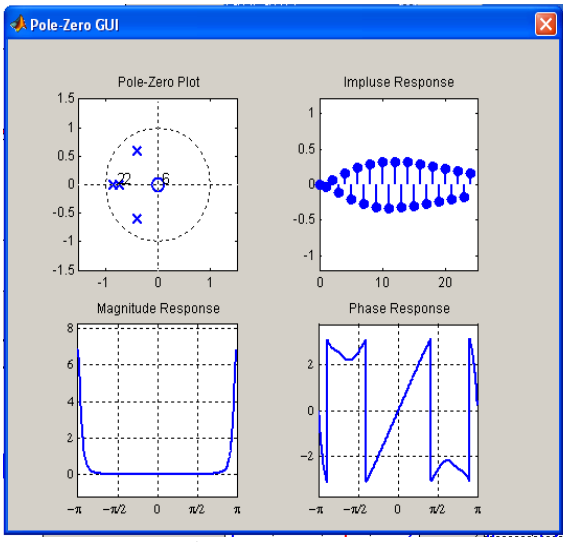

Figure 10 Response of the compensated system

7. CONCLUSION

A novel FPAA based autonomous reconfiguration assisted fault recovery model for a satellite subsystem modeled as a third order linear system is presented in this work. The suggested arrangement and algorithm assists in creating self organizing electronic circuit that is able to correct environmental changes within a certain range. An embedded core assists in deciding the reconfiguration activity. These cores and fault recovery units not only maintain the system stable and provide performance close to set limits but also eliminate the necessity for redundant circuits (traditionally installed to maintain reliability) and thereby optimize the area of the room required for spares.

8. REFERENCES

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9. BIOGRAPHIES

(1)Mrs. Fathima Jabeen is presently a research scholar in Vinayaka Mission University. Her areas of interest includes reconfigurable computing using embedded cores, FPAA programming, Satellite subsystem design and reliability engineering.

(2) Dr.M.Y.Sanavullah is presently Dean, Faculty of Electrical Engg., His areas of interest include control systems, signal processing and evolvable hardware.

APPENDIX – I

S.No	SYSTEM	H(Z)
i	FaultLess	$1/(1+1.9z^{-1}+1.702z^{-2}+.814z^{-3}+.1573z^{-4})$
ii	Faulty system (Decrease in Bandwidth)	$1/(1+z^{-1}+.69z^{-2}+.112z^{-3}+.0052z^{-4})$
iii	Compensated system for (ii)	$1/(1+2.84z^{-1}+3.7124z^{-2}+2.8395z^{-3}+1.3033z^{-4}+.32989z^{-5}+.035152z^{-6})$
iv	Faulty system (Increase in Bandwidth)	$1/(1+2.6z^{-1}+2.77z^{-2}+1.584z^{-3}+.4212z^{-4})$
v	Compensated system for (iv)	$1/(1+3.2z^{-1}+4.599z^{-2}+3.8384z^{-3}+1.9425z^{-4}+.55223z^{-5}+.067242z^{-6})$
vi	Faulty system (Unstable)	$1/(1+3z^{-1}+3.49z^{-2}+2.112z^{-3}+.6292z^{-4})$
vii	Compensated system for (vi)	$1/(1+3.98\ z^{-1}+6.8501\ z^{-2}+606827\ z^{-3}+3.9646\ z^{-4}+1.3566z^{-5}+.20573z^{-6})$