Hardware Evolution of Analog Speed Controllers for a DC Motor

David A. Gwaltney[1] and Michael I. Ferguson[2]

[1] NASA Marshall Space Flight Center,Huntsville, AL 35812, USA
David.A.Gwaltney@nasa.gov
[2] Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109, USA
Michael.I.Ferguson@jpl.nasa.gov

Abstract. Evolvable hardware provides the capability to evolve analog circuits to produce amplifier and filter functions. Conventional analog controller designs employ these same functions. Analog controllers for the control of the shaft speed of a DC motor are evolved on an evolvable hardware plaform utilizing a Field Programmable Transistor Array (FPTA). The performance of these evolved controllers is compared to that of a conventional proportional-integral (PI) controller. It is shown that hardware evolution is able to create a compact design that provides good performance, while using considerably less functional electronic components than the conventional design.

1 Introduction

Research on the application of hardware evolution to the design of analog circuits has been conducted extensively by many researchers. Many of these efforts utilize a SPICE simulation of the circuitry, which is acted on by the evolutionary algorithm chosen to evolve the desired functionality. An example of this is the work done by Lohn and Columbano at NASA Ames Research Center to develop a circuit representation technique that can be used to evolve analog circuitry in software simulation[1]. This was used to conduct experiments in evolving filter circuits and amplifiers. A smaller, but rapidly increasing number of researchers have pursued the use of physical circuitry to study evolution of analog circuit designs. The availability of reconfigurable analog devices via commercial or research-oriented sources is enabling this approach to be more widely studied. Custom Field Programmable Transistor Array (FPTA) chips have been used for the evolution of logic and analog circuits. Efforts at the Jet Propulsion Laboratory (JPL) using their FPTA2 chip are documented in [2,3,4]. Another FPTA development effort at Heidelberg University is described in [5]. Some researchers have conducted experiments using commercially available analog programmable devices to evolve amplifier designs, among other functions[6,7].

At the same time, efforts to use evolutionary algorithms to design controllers have also been widely reported. Most of the work is on the evolution of controller designs suitable only for implementation in software. Koza, et al., presented

E. Cantú-Paz et al. (Eds.): GECCO 2003, LNCS 2723, pp. 442–453, 2003.

automatic synthesis of control laws and tuning for a plant with time delay using Genetic programming. This was done in simulation [8]. However, Zebulum, et. al., have evolved analog controllers for a variety of industrially representative dynamic system models[10]. In this work, the evolution was also conducted in a simulated environment.

Hardware evolution can enable the deployment of a self-configurable controller in hardware. Such a controller will be able to adapt to environmental conditions that would otherwise degrade performance, such as temperature varying to extremes or ionizing radiation. Hardware evolution can provide fault-tolerance capability by re-routing internal connections around damaged components or by reuse of degraded components in novel designs. These features, along with the capability to accommodate unanticipated or changing mission requirements, make an evolvable controller attractive for use in a remotely located platform, such as a spacecraft. Hence, this effort focuses on the application of hardware evolution to the *in situ* design of a shaft speed controller for a DC motor. To this end, the Stand-Alone Board-Level Evolvable (SABLE) System[3], developed by researchers at the Jet Propulsion Laboratory, is used as the platform to evolve analog speed controllers for a DC motor.

Motor driven actuators are ubiquitous in the commercial, industrial, military and aerospace environments. A recent trend in aviation and aerospace is the use of power-by-wire technologies. This refers to the use of motor driven actuators, rather than hydraulic actuators for aero-control surfaces[11][12]. Motor driven actuators have been considered for upgrading the thrust vector control of the Space Shuttle main engines [13]. In spacecraft applications, servo-motors can be used for positioning sun-sensors, Attitude and Orbit Control Subsystems (AOCSs), antennas, as well as valves, linear actuators and other closed-loop controllers.

In this age of digital processor-based control, analog controllers are still frequently used at the actuator level in a variety of systems. In the harsh environment of space, electronic components must be rated to survive temperature extremes and exposure to radiation. Very few microcontrollers and digital signal processors are available that are rated for operation in a radiation environment. However, operational amplifiers and discrete components are readily available and are frequently applied. Reconfigurable analog devices provide a small form factor platform on which multiple analog controllers can be implemented. The FPTA2, as part of the SABLE System, is a perfect platform for implementation of multiple controllers, because its sixty-four cells can theoretically provide sixty-four operational amplifiers, or evolved variations of amplifier topologies. Further, its relatively small size and low power requirements provide savings in space and power consumption over the uses of individual operational amplifiers and discrete components[2].

The round-trip communication time between the Earth and a spacecraft at Mars ranges from 10 to 40 minutes. For spacecraft exploring the outer planets the time increases significantly. A spacecraft with self-configuring controllers could work out interim solutions to control system failures in the time it takes

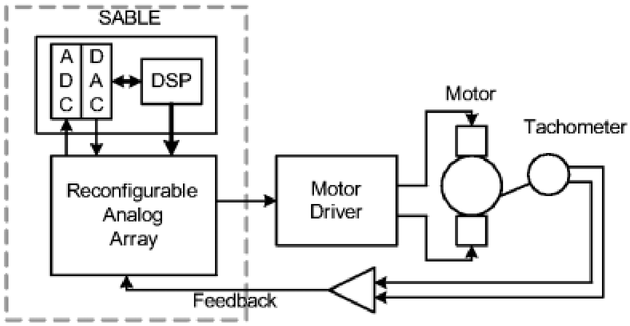

Fig. 1. Configuration of the SABLE System and motor to be controlled

for the spacecraft to alert its handlers on the Earth of a problem. The evolvable nature of the hardware allows a new controller to be created from compromised electronics, or the use of remaining undamaged resources to achieve required system performance. Because the capabilities of a self-configuring controller could greatly increase the probability of mission success in a remote spacecraft, and motor driven actuators are frequently used, the application of hardware evolution to motor controller design is considered a good starting point for the development of a general self-configuring controller architecture.

2 Approach

The JPL developed Stand-Alone Board Level Evolvable (SABLE) System[3] is used for evolving the analog control electronics. This system employs the JPL designed Second Generation, Field Programmable Transistor Array (FPTA2). The FPTA2 contains 64 programmable cells on which an electronic design can be implemented by closing internal switches. The schematic diagram of one cell is given in the Appendix. Each cell has inputs and outputs connected to external pins or the outputs of neighboring cells. More detail on the FPTA2 architecture is found in [2]. A diagram of the experimental setup is shown in Figure 1. The main components of the system are a TI-6701 Digital Signal Processor (DSP), a 100kSa/sec 16-channel DAC and ADC and the FPTA2. There is a 32-bit digital I/O interface connecting the DSP to the FPTA2. The genetic algorithm running on the DSP follows a simple algorithm of download, stimulate the circuit with a control signal, record the response, evaluate the response against the expected. This is repeated for each individual in the population and then crossover, and mutation operators are performed on all but the elite percentage of individuals.

The motor used is a DC servo-motor with a tachometer mounted to the shaft of the motor. The motor driver is configured to accept motor current commands and requires a 17.5 volt power supply with the capability to produce 6 amps of current. A negative 17.5 volt supply with considerably lower current requirements is needed for the circuitry that translates FPTA2 output signals to the proper range for input to the driver. The tachometer feedback range is roughly [-4, +4] volts which corresponds to a motor shaft speed range of [-1300, +1300] RPM. Therefore, the tachometer feedback is biased to create a unipolar signal, then reduced in magnitude to the [0, 1.8] volt range the FPTA2 can accept.

3 Conventional Analog Controller

3.1 Design

All closed-loop control systems require the calculation of an error measure, which is manipulated by the controller to produce a control input to the dynamic system being controlled, commonly referred to as the plant. The most widely used form of analog controller is a proportional-integral (PI) controller. This controller is frequently used to provide current control and speed control for a motor. The PI control law is given in Equation 1,

$$u(t) = K_P e(t) + \int \frac{1}{K_I} e(t) dt \ . \tag{1}$$

where $e(t)$ is the difference between the desired plant response and the actual plant response, K_P is called the proportional gain, and K_I is called the integral gain. In this control law, the proportional and integral terms are separate and added together to form the control input to the plant. The proportional gain is set to provide quick response to changes in the error, and the integral term is set to null out steady state error.

The FPTA2 is a unipolar device using voltages in the range of 0 to 1.8 volts. In order to directly compare a conventional analog controller design with evolved designs, the PI controller must be implemented as shown in Figure 2. This figure includes the circuitry needed to produce the error signal. Equation 2 gives the error voltage, V_e, given the desired response V_{SP}, or setpoint, and the measured motor speed V_{TACH}. The frequency domain transfer function for the voltage output,V_u, of the controller, given V_e, is shown in Equation 3,

$$V_e = \frac{V_{SP}}{2} - \frac{V_{TACH}}{2} + 0.9V \ . \tag{2}$$

$$V_u = (V_e - V_{bias2})(\frac{R_2}{R_1} + \frac{1}{sR_1C}) + V_e \ . \tag{3}$$

where s is complex frequency in rad/sec, $\frac{R_2}{R_1}$ corresponds to the proportional gain and $\frac{1}{R_1C}$ corresponds to the integral gain. This conventional design requires four op-amps. Two are used to isolate voltage references V_{bias1} and V_{bias2} from the rest of the circuitry, thereby maintaining a steady bias voltage in each case. V_{bias2} must be adjusted to provide a plant response without a constant error bias. The values for R_1, R_2, and C are chosen to obtain the desired motor speed response.

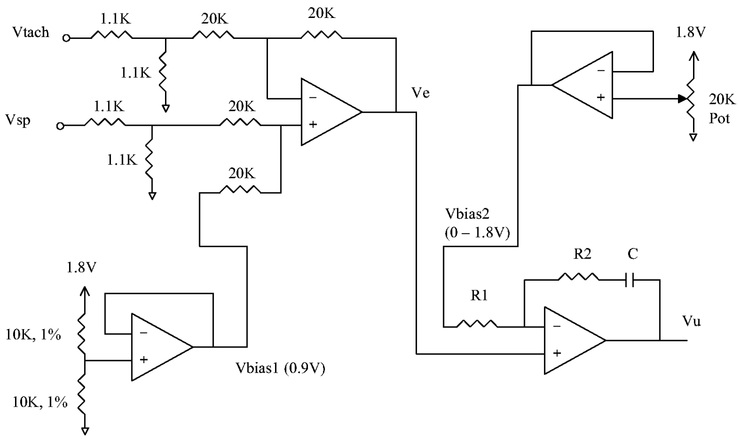

Fig. 2. Unipolar analog PI controller with associated error signal calculation and voltage biasing

3.2 Performance

The controller circuitry in Figure 2 is used to provide a baseline control response to compare with the responses obtained via evolution. The motor is run with no external torque load on the shaft. The controller is configured with $R_1 = 10K$ ohms, $R_2 = 200K$ ohms, and $C = 0.47u$F. V_{bias2} is set to 0.854 volts. Figure 3 illustrates the response obtained for V_{SP} consisting of a 2 Hz sinusoid with amplitude in the range of approximately 500 millivolts to 1.5 Volts, as well as for V_{SP} consisting of a 2 Hz square wave with the same magnitude. Statistical analysis of the error for sinusoidal V_{SP} is presented in Table 1 for comparison with the evolved controller responses. Table 2 gives the rise time and error statistics at steady state for the first full positive going transition in the square wave response. This is the equivalent of analyzing a step response. Note that in both cases V_{TACH} tracks V_{SP} very well. In the sinusoid case, there is no visible error between the two. For the square wave case, the only visible error is at the instant V_{SP} changes value. This is expected, because no practical servo-motor can follow instantaneous changes in speed. There is always some lag between the setpoint and response. After the transition, the PI controller does not overshoot the steady state setpoint value, and provides good regulation of motor shaft speed at the steady state values.

4 Evolved Controllers

Two cells within the FPTA2 are used in the evolution of the motor speed controllers. The first cell is provided with the motor speed setpoint, V_{SP} , and the motor shaft feedback , V_{TACH}, as inputs, and it produces the controller output, V_u. An adjacent cell is used to provide support electronics for the first cell. The evolution uses a fitness function based on the error between V_{SP} and V_{TACH}.

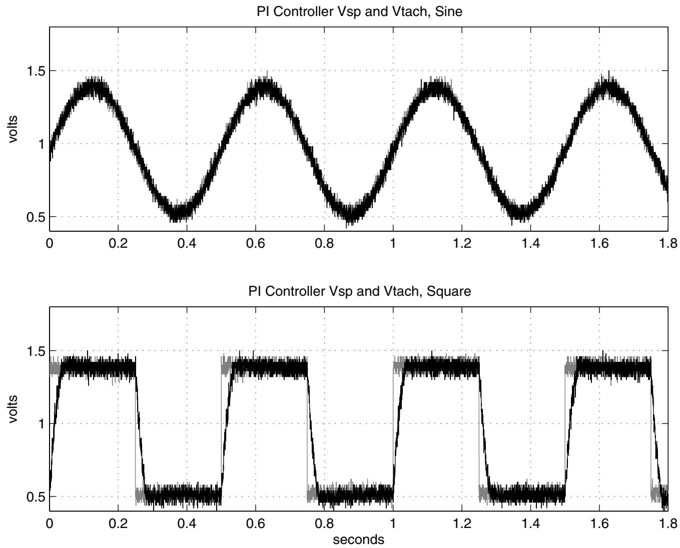

Fig. 3. Response obtained using PI controller. Vsp is gray, Vtach is black

Lower fitness is better, because the goal is to minimize the error. The population is randomly generated, and then modified to ensure that, initially, the switches are closed that connect V_{SP} and V_{TACH} to the internal reconfigurable circuitry. This is done because the evolution will, in many cases, attempt to control the motor speed by using the setpoint signal only, resulting in an undesirable "controller" with poor response characteristics. Many evolutions were run, and the frequency of the sinusoidal signal was varied, along with the population size and the fitness function. There were some experiments that failed to produce a desirable controller and some that produced very desirable responses, with the expected distribution of mediocre controllers in between . Two of the evolved controllers are presented along with the response data for comparison to the PI controller. The first is the best evolved controller obtained, so far, and the second provides a reasonable control response with an interesting circuit design. In each case, the data presented in the plots was obtained by loading the previously evolved design on the FPTA2, and then providing V_{SP} via a function generator. The system response was recorded using a digital storage oscilloscope.

4.1 Case 1

For this case the population size is 100 and a roughly 2 Hz sinusoidal signal was used for the setpoint. For a population of 100, the evaluation of each generation takes 45 seconds. The target fitness is 400,000 and the fitness function used is,

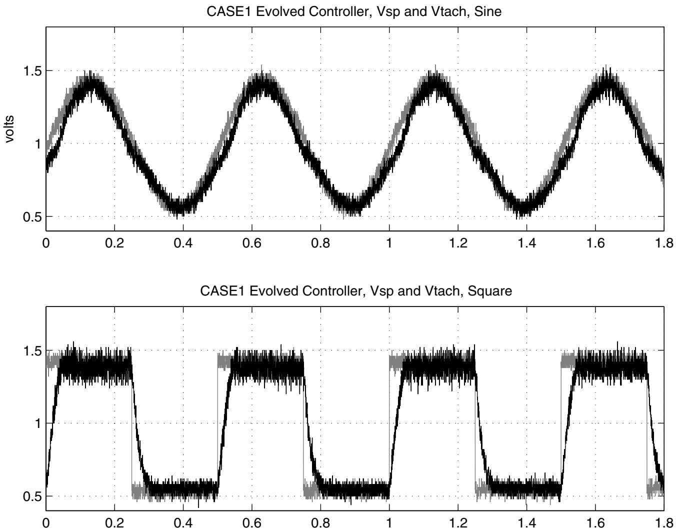

Fig. 4. Response obtained using CASE1 evolved controller. Vsp is gray, Vtach is black

$$F = 0.04 * \sum_{i=1}^{n} e_i^2 + \frac{100}{n} \sum_{i=1}^{n} |e_i| + 100000 * not(S_{57} \vee S_{53}) \ . \qquad (4)$$

where e_i is the error between V_{SP} and V_{TACH} at each voltage signal sample, n is the number of samples over one complete cycle of the sinusoidal input, and S_{57}, S_{53} represent the state of the switches connecting V_{SP} and V_{TACH} to the reconfigurable circuitry . This fitness function punishes individuals that do not have switches S_{57} and S_{53} closed. The location of these switches can be seen in the cell diagram in the Appendix. V_{SP} is connected to Cell_in6 and V_{TACH} is connected to Cell_in2. The evolution converged to a fitness of 356,518 at generation 97. The fitness values are large due to the small values of error that are always present in a physical system. Figure 4 illustrates the response obtained for V_{SP} consisting of a 2 Hz sinusoid with amplitude in the range of approximately 500 millivolts to 1.5 Volts, as well as for V_{SP} consisting of a 2 Hz square wave with the same magnitude. This is the same input used to obtain controlled motor speed responses for the PI controller.

In the sinusoidal case, the evolved controller is able to provide good peak to peak magnitude response, but is not able to track V_{SP} as it passes through 0.9. The evolved controller provides a response to the square wave V_{SP}, which has a slightly longer rise time but provides similar regulation of the speed at steady state. The statistical analysis of the CASE 1 evolved controller response to the sinusoidal V_{SP} is presented in Table 1. Note the increase in all the measures, with the mean error indicating a larger constant offset in the error response. Despite these increases, the controller response is reasonable and could

Table 1. Error metrics for sinusoidal response

Controller	Max Error	Mean Error	Std Dev Error	RMS Error
PI	0.16 V	0.0028 V	0.0430 V	0.0431 V
CASE1	0.28 V	0.0469 V	0.0661 V	0.0810 V

Table 2. Response and error metrics for square wave. First full positive transition only

Controller	Rise Time	Mean Error	Std Dev Error	RMS Error
PI	0.0358 sec	0.0626 V	0.1816 V	0.1920 V
CASE1	0.0394 sec	0.1217 V	0.2026 V	0.2362 V

be considered good enough. The rise time and steady state error analysis for the first full positive going transition in the square wave response is given in Table 2. While there is an increase in rise time and in the error measures at steady state, when compared to those of the PI controller, the evolved controller can be considered to perform very well. Note again that the increase in the mean error indicates a larger constant offset in the error response. In the PI controller, this error can be manually trimmed out via adjustment of V_{bias2}. The evolved controller has been given no such bias input, so some increase in steady state error should be expected. However, the evolved controller is trimming this error, because other designs have a more significant error offset. Experiments with the evolved controller show that the "support" cell is providing the error trimming circuitry.

It is notable that the evolved controller is providing a good response using a considerably different set of components than the PI controller. The evolved controller is using two adjacent cells in the FPTA to perform a similar function to four op-amps, a collection of 12 resistors and one capacitor. The FPTA switches have inherent resistance on the order of kilo-ohms, which can be exploited by evolution during the design. But the two cells can only be used to implement op-amp circuits similar to those in Figure 2 with the use of external resistors, capacitors and bias voltages. These external components are not provided. The analysis of the evolved circuit is complicated and will not be covered in more detail here.

4.2 Case 2

This evolved controller is included, not because it represents a better controller, but because it has an interesting characteristic. In this case, the population size is 200 and a roughly 3 Hz sinusoidal signal was used for the setpoint during evolution. For a population of 200, the evaluation of each generation takes 90 seconds. The fitness function is the same as used for Case 1, with one exception, as shown in Equation 5.

$$F = 0.04 * \sum_{i=1}^{n} e_i^2 + \frac{100}{n} \sum_{i=1}^{n} |e_i| \ . \tag{5}$$

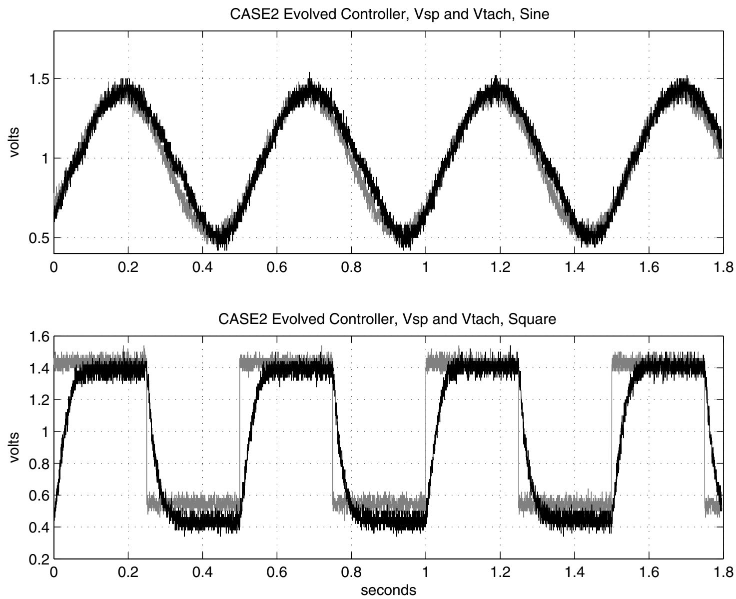

Fig. 5. Response obtained using CASE2 evolved controller. Vsp is gray, Vtach is black

In this case, the switches S_{57}, S_{53} are forced to be closed (refer to the cell diagram in the appendix), and so no penalty based on the state of these switches is included in the fitness function. The evolution converged to a fitness of approximately 1,000,000, and was stopped at generation 320. The interesting feature of this design is that switches S_{54}, S_{61}, S_{62}, S_{63} are all open. This indicates that the V_{TACH} signal is not directly connected to the internal circuitry of the cell. However, the controller is using the feedback, because opening S_{53} caused the controller to no longer work. The motor speed response obtained using this controller can be seen in Figure 5. The response to sinusoidal V_{SP} is good, but exhibits noticeable transport delay on the negative slope. The response to the square wave V_{SP} exhibits offset for the voltage that represents a "negative" speed. Overall the response is reasonably good. The analysis of this evolved controller is continuing in an effort to understand precisely how the controller is using the V_{TACH} signal internally.

5 Summary

The results presented show the FPTA2 can be used to evolve simple analog closed-loop controllers. The use of two cells to produce a controller that provides good response in comparison with a conventional controller shows that hardware evolution is able to create a compact design that still performs as required, while using less transistors than the conventional design, and no external components. Recall that one cell is can be used to implement an op-amp design on the FPTA2. While a programmable device has programming overhead that fixed discrete electronic and integrated circuit components do not, this overhead is typically neglected when comparing the design on the programmable device to a design using fixed components. The programming overhead is indirect, and is not a functional component of the design. As such, the cell diagram in the Appendix shows that each cell contains 15 transistors available for use as functional components in the design. Switches have a finite resistance, and therefore functionally appear as passive components in a cell. The *simplified* diagram in the data sheets for many op-amps indicate that 30, or more, transistors are utilized in their design, and op-amp circuit designs require multiple external passive components.

In order to produce self-configuring controllers that can rapidly converge to provide desired performance, more work is needed to speed up the evolution and guide it to the best response. The per generation evaluation time of 45 or more seconds is a bottleneck to achieving this goal. Further, the time constants of a real servo-motor may make it impossible to achieve more rapid evaluation times. Most servo-motor driven actuators cannot respond to inputs with frequency content of more than a few tens of Hertz, without attenuation in the response. Alternative methods of guiding the evolution or novel controller structures are required.

A key to improving upon this work and evolving more complex controllers is a good understanding of the circuits that have been evolved. Evolution has been shown to make use of parasitic effects and to use standard components in novel, and often difficult to understand, ways. Case 2 illustrates this notion. Gaining this understanding may prove to be useful in developing techniques for guiding the evolution towards rapid convergence.

Acknowledgements. The authors would like to thank Jim Steincamp and Adrian Stoica for establishing the initial contact between Marshall Space Flight Center and the Jet Propulsion Laboratory leading to the collaboration for this work. The Marshall team appreciates JPL making available their FPTA2 chips and SABLE system design for conducting the experiments. Jim Steincamps continued support and helpful insights into the application of genetic algorithms have been a significant contribution to this effort.

References

[1] Lohn, J. D. and Columbano, S. P., *A Circuit Representation Technique for Automated Circuit Design*, IEEE Transactions on Evolutionary Computation, Vol. 3, No. 3, September 1999.

[2] Stoica, A., Zebulum, R., Keymeulen, D., *Progress and Challenges in Building Evolvable Devices*, Evolvable Hardware, Proceedings of the third NASA/DoD Workshop on, July 2001, pp 33–35.

[3] Ferguson, M. I., Zebulum, R., Keymeulen, D. and Stoica, A., *An Evolvable Hardware Platform Based on DSP and FPTA*, Late Breaking Papers at the Genetic and Evolutionary Computation Conference (GECCO-2002), July 2002, pp. 145–152.

[4] Stoica, A., Zebulum, R., Ferguson, M. I., Keymeulen, D. and Duong V., *Evolving Circuits in Seconds: Experiments with a Stand-Alone Board Level Evolvable System*, 2002 NASA/DoD Conference on Evolvable Hardware, July 2002, pp. 67–74.

[5] Langeheine, J., Meier, K., Schemmel, J., *Intrinsic Evolution of Quasi DC solutions for Transistor Level Analog Electronic Circuits Using a CMOS FTPA Chip,* 2002 NASA/DoD Conference on Evolvable Hardware, July 2002, pp. 75–84.

[6] Flockton, S. J. and Sheehan, K., "Evolvable Hardware Systems Using Programmable Analogue Devices", Evolvable Hardware Systems (Digest No. 1998/233), IEE Half-day Colloquium on , 1998 ,Page(s): 5/1–5/6.

[7] Ozsvald, Ian, "Short-Circuit the Design Process: Evolutionary Algorithms for Circuit Design using Reconfigurable Analogue Hardware", Master's Thesis, University of Sussex, September, 1998.

[8] Koza,J. R., Keane, M. A., Yu, J., Mydlowec, W. and Bennet, F., *Automatic Synthesis of Both the Control Law and Parameters for a Controller for a Three-lag plant with Five-Second delay using Genetic Programming and Simulation Techniques*, American Control Conference, June 2000.

[9] Keane, M. A., Koza, J. R., and Streeter, M.J., *Automatic Synthesis Using Genetic Programming of an Improved General-Purpose Controller for Industrially Representative Plants*, 2002 NASA/DoD Conference on Evolvable Hardware, July 2002, pp. 67–74.

[10] Zebulum, R. S., Pacheco, M. A., Vellasco, M., Sinohara, H. T., *Evolvable Hardware: On the Automatic Synthesis of Analog Control Systems*, 2000 IEEE Aerospace Conference Proceedings, March 2000, pp 451–463.

[11] Raimondi, G. M., et. al., *Large Electromechanical Actuation Systems for Flight Control Surfaces*, IEE Colloquium on All Electronic Aircraft, 1998.

[12] Jensen, S.C., Jenney, G. D., Raymond, B., Dawson, D., *Flight Test Experience with an Electromechanicl Actuator on the F-18 Systems Research Aircraft,* Proceedings of the 19th Digital Avionics System Conference, Volume 1, 2000.

[13] Byrd, V. T., Parker, J. K, *Further Consideration of an Electromechanical Thrust Vector Control Actuator Experiencing Large Magnitude Collinear Transient Forces*, Proceedings of the 29th Southeastern Symposium on System Theory, March 1997, pp 338–342.

Appendix: FPTA2 Cell Diagram