Initial Experiments of Reconfigurable Sensor Adapted by Evolution.

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Abstract. Missions to planets with unknown environmental condition, have recently been approached with new ideas, such as use of biology-inspired mechanisms for hardware sensor adaptation. In this paper we describe the initial development of efficient mechanisms for smart sensing which will lead to higher quality data. The self-reconfigurable pre-processing analog electronics is based on evolvable hardware.

1 Introduction

Modern sensors provide high data rates with only a small fraction of the data carrying quality information. The current pre-processing electronics is not smart enough to eliminate useless/redundant data and the on-board real-time processing capabilities are limited. These restrictions impose large on-board storage memory and high communications bandwidth. If the electronics could adapt to incoming signals and the context of the measurement, more information could be obtained from the sensor and sent back to earth.

The concept of reconfigurable and adaptive electronics for signal conditioning has led to the design of a series of recent chips that allow programmable adjustment of amplifier gains, memory-based compensation of sensor non-linearity, etc [11]. However, the flexibility of these programmable devices is limited by the high level of reconfiguration granularity, and requires that all compensation data be predetermined through lab experiments and then stored in ROM; also no later changes in sensor characteristics or electronics itself could be considered once the sensor is in operation. A complementary technique, called evolvable hardware (EHW), allows the automatic determination of optimal electronic circuit configurations by evolutionary algorithms [1][2][3]. In particular, a chip designed for EHW experiments at the Jet Propulsion Laboratory (JPL) called a Field Programmable Transistor Array (FPTA) has high flexibility by reconfiguration at transistor level [4][5][14][16]. EHW has also been considered for various application hardware, from antennas to complete evolvable space systems that could adapt to changing experimental environments and, moreover, increase their performance during the mission [15].

In this paper we describe the initial development of efficient mechanisms for smart on-board sensing, adaptively controlling the reconfigurable pre-processing analog electronics using EHW, which will lead to higher quality data. The target is to demonstrate the mechanisms for the MARS'01 MECA (Mars Environmental Compatibility Assessment) Electrometer. We identify one application of the electrometer for which the reduction of the data can be considerable: discrimination task of materials with different triboelectric properties. The discrimination task requires a sophisticated signal conditioning able to analyze multiple responses in order to extract differences in signal and to adapt to ambient environmental conditions. The discrimination task is translated to fitness evaluation metric that is used by an evolutionary algorithm to determine the optimal configuration of the electronics. At this stage of the research, the search for an electronic circuit realization of a desired transfer characteristic is made in software as in *extrinsic* evolution using signals obtained from the electrometer [14]. In the near future we will use *intrinsic* evolution where the hardware actively participates in the circuit evolutionary process and is the support on which candidate solutions are evaluated.

This paper is organized as follows: Section 2 presents a description of the electrometer sensor array. Section 3 presents the adaptive sensor architecture. Section 4 presents the FPTA, the experiments and results obtained for the adaptive electrometer for a discrimination application in a changing environment. Section 5 provides conclusion.

2 Electrometer Sensor Array

The electrometer is a part of the MECA project that has its objective as a better understanding of the hazards related to the human exploration of Mars [10]. The MECA project also has a material patch experiment to determine the effects of dust adhesion, a wet chemistry laboratory to characterize the ionic content of the soil, and microscopy station to determine particle size and hardness. The electrometer was built into the heel of the Mars '01 robot arm scoop and has four sensor types (Fig. 1): (a) triboelectric field, (b) electric-field, (c) ion current, (d) temperature. The triboelectric field sensor array contains five insulating materials to determine material charging effects as the scoop is dragged through the Martian regolith and the insulating materials are rubbed against the Martian soil.

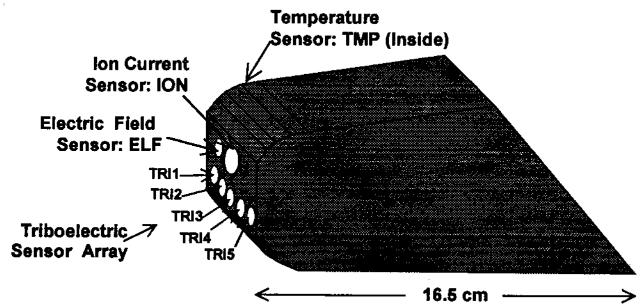

Figure 1: Electrometer sensor suite mounted in the heel of the Mars'01 scoop

In the rubbing sequence, depicted in Fig. 2, the scoop is first lowered against the Martian soil. During the start of the traverse, the electrometer is calibrated to zero by closing a switch. After reaching the end of its traverse, the scoop is abruptly removed from the soil at which time the triboelectric sensor response is measured. As seen on the left in Fig. 2, charge is generated triboelectrically across capacitor C3 as the insulator is rubbed on the Martian surface. Since the charges are in close proximity across C3, no charge appears across capacitors C1 or C2. As the insulator is removed from the surface, the charges redistribute themselves across C1 and C2 and provide the signal for the amplifier.

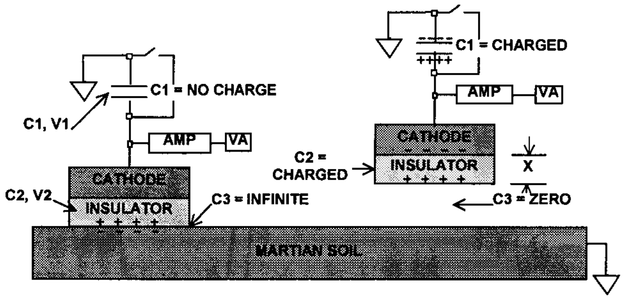

Figure 2: Operational scenario for the scoop and charge distribution in the electrometer during rubbing (left) and after removal from the surface (right).

This electrometer is an induction field meter [6] operated in a direct current mode, where the operational amplifier input current charges C1. The electrical schematic of the non-adaptive component of the triboelectric sensors is shown in Fig. 3. The design of the electric field sensor follows from the traditional electrometer [7]. The instrument is composed of a capacitive divider where C2 is the field sensing capacitor and C1 is the reference capacitor. The point between the capacitors is connected to the positive terminal of the first stage amplifier (terminal +5 of U3) operated in the follower mode. The sensing electrode is protected by a driven guard that is connected to the negative terminal of the first stage amplifier (terminal -6 of U3). A second operational amplifier (U4) is added to provide additional amplification. At the beginning of the measurements, C1 is discharged using the solid-state switch, S1 which has very low leakage. In the TRI sensor, C2 has an insulator dielectric which acquires charge during rubbing.

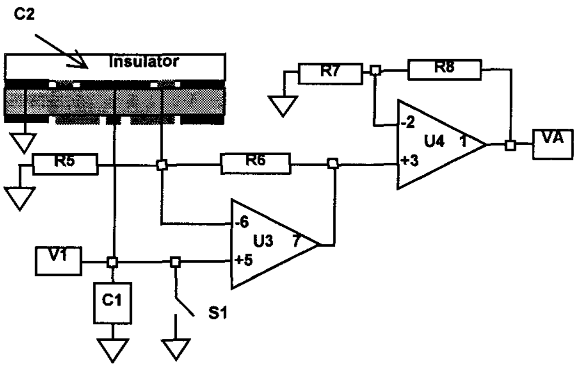

Figure 3: Schematic circuit representations for the non-adaptive component of the Triboelectric sensor (TRI) fully characterized before field use.

Four different insulating materials were loaded into the titanium triboelectric sensor head (Fig. 1). A typical laboratory experiment consists of manually rubbing a wool felt on the triboeletric head at room temperature. The results are shown in Figure 4. The falling period between 10 and 20 seconds represents the rubbing period. The large negative response is for the Rulon-J which is to be expected for Rulon-J rubbed on wool.

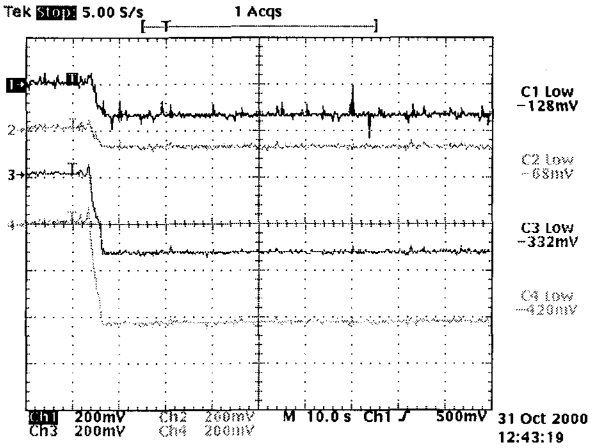

Figure 4: Response of triboelectric sensor array to white **wool felt** (For all figures: response C1 is ABS (TRI1), response C2 is **Polycarbonate** (TRI2), response C3 is **Teflon** (TRI3) and response C4 is **Rulon-J** (TRI4)).

3 Adaptive Sensor Architecture

The triboelectric sensor array is an example of a hybrid integrated array devices where the sensors are grouped on the same devices but where the signal processing is done on a separate device [8]. This sensor array employs similar sensors (in terms of the measurand) but sensors have subtle differences (i.e. partially correlated outputs) related to the triboelectric properties of materials, known as the triboelectric series

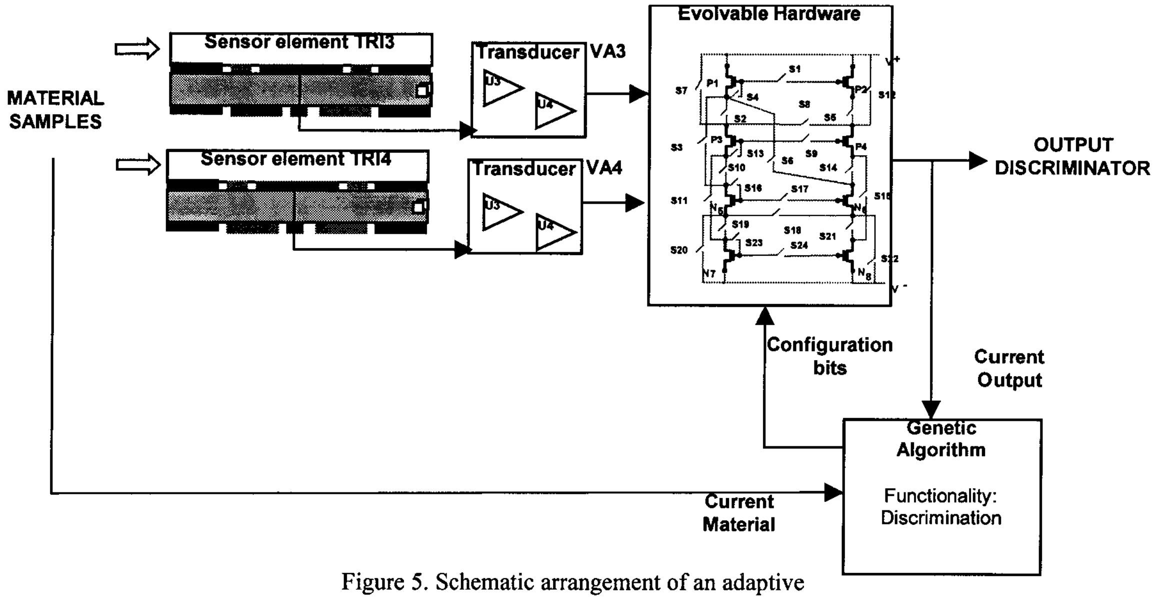

Figure 5. Schematic arrangement of an adaptive electrometer sensor array device

and respond to a very wide range of materials. (The triboelectric series orders the materials in a single list and indicates the direction and the amplitude of the charge transfer that occurs when two materials are rubbed). The signal processing must therefore carry out a sophisticated analysis of the responses to extract the subtle differences in signals. The approach we have chosen, as shown in Fig. 5, is to use an EHW discrimnator signal conditioner connected to the triboelectric sensor array and that will be able, after evolution, to discriminate the response of different materials with high precision.

Another important reason to use an adaptation mechanism is to be able to do *in-situ self-calibration* of the sensors and its electronics [9]. Indeed the sensors are very sensitive to ambient conditions, such as temperature, humidity, atmospheric and contact pressure, ambient gas, materials. They are also sensitive to the material and surface condition of the sensors. For example, the dust clinging on the insulator surface considerably affect the response of the triboelectric sensor arrays. Finally the sensor array has poor aging characteristic, that is the triboelectric sensing element is slowly corroded and thus changes its response characteristics with time. To remedy this high sensitivity to the ambient conditions and sensor conditions, we performed an *in-situ self-calibration*: calibrate the sensors right at the site with a set of reference materials with known triboelectric properties in the current environmental conditions.

Fig. 5 shows the basic arrangement of an adaptative electrometer sensor array system for discriminating different materials. The triboelectric property of the material is sensed by an array of sensors, each with its response, which is converted to an electrical signal via suitable transduction circuitry. The voltage signal VA_i is then injected to the evolvable hardware optimized for the current environment and a set of reference materials. The prediction of the triboelectric property of the material compared to the one of the reference materials is given in terms of output voltage. In the next section, we describe the EHW developed by JPL, called FPTA, and the experiments.

4 Adaptive Sensor Experiments

Our experiment was performed using the FPTA and an electrometer testbed. The idea of a FPTA was introduced first by Stoica [5]. The FPTA is a concept design for hardware reconfigurable at the transistor level. As both analog and digital CMOS circuits ultimately rely on functions implemented with transistors, the FPTA is a versatile platform for the synthesis of both analog and digital (and mixed-signal) circuits. Further, it is considered a more suitable platform for synthesis of analog circuitry than existing Field Programmable Gate Arrays (FPGAs) or Field Programmable Analog Arrays (FPAAs), extending the work on evolving simulated circuits to evolving analog circuits directly on the chip.

The FPTA module is an array of transistors interconnected by programmable switches (Fig. 9). The status of the switches (ON or OFF) determines a circuit topology and consequently a specific response. Thus, the topology can be considered as a function of switch states, and can be represented by a binary sequence, such as "1011...", where a 1 represents an ON switch and a 0 represents an OFF switch. The FPTA architecture allows the implementation of bigger circuits by cascading FPTA modules with external wires. To offer sufficient flexibility the module has all transistor terminals connected via switches to external terminals (except for power and ground) [10]. One FPTA module was fabricated through MOSIS, using 0.5-μm CMOS technology. We built a testbed to acquire the signals of the electrometer and extended it for future developments with a test board with four chips mounted on it and connected with the electrometer (Fig. 6).

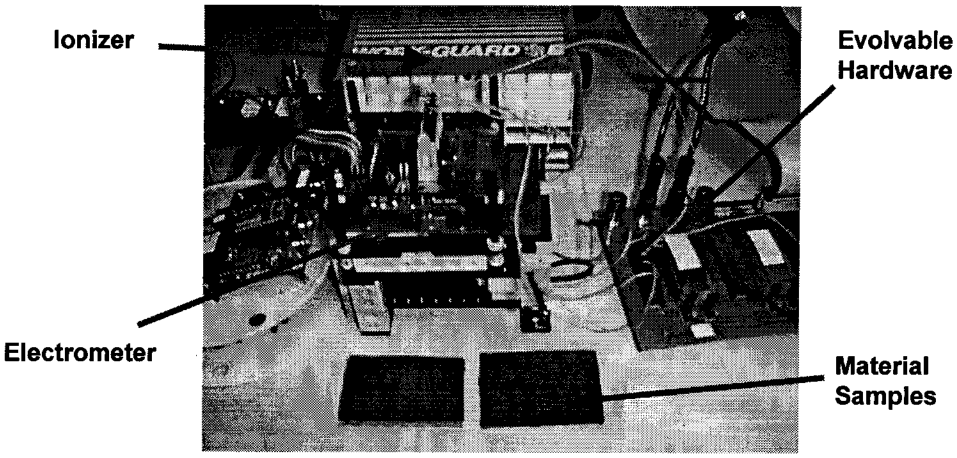

Figure 6. Module of the Field Programmable Transistor Array connected to the electrometer testbed.

The experiment shows that the EHW approach finds a FPTA circuit that is able to discriminate between the responses of the electrometer to three different materials chosen as reference. The experiments used three rubbing material samples (Polystyrene, wool felt and Teflon) and used only two insulating materials of the electrometer (Teflon and Rulon-J). The materials are ordered in the triboelectric series as follow with the first one becoming positively charged when rubbed on the other materials: Polystyrene, wool felt, Teflon and Rulon-J. The experiments start by an initialization procedure which puts the electrometer in a known state: the five electrometer insulators were cleaned by brushing followed by Am-241 alpha particle deionization. The deionization process was observed by running a trace and noting when the response no longer changed. After cleaning and deionization, the samples were placed in the apparatus as seen in Figure 6. The data acquisition was started and five points were acquired every second. The first fifty points were baseline points. During the next 200 points, the samples were rubbed by the apparatus from left to right as shown in Fig. 4, Fig. 7 and Fig.8. During the final data points, the rubbing was stopped and the rubbing material was no longer in contact with the electrometer insulating materials. At this stage of the research the circuit was obtained by *extrinsic evolution* using the SPICE simulator and the response of the electrometer.

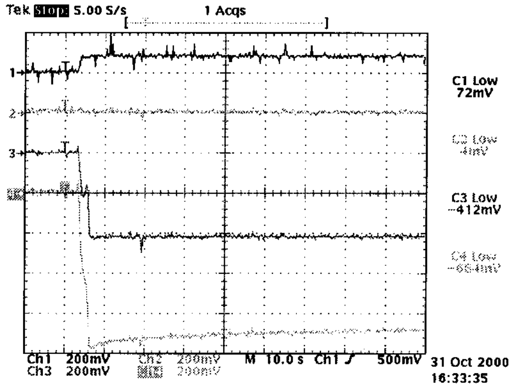

Figure 7. Response of triboelectric sensor array to **Polystyrene** (C1 is ABS, C2 is Polycarbonate, C3 is Teflon, C4 is Rulon-J).

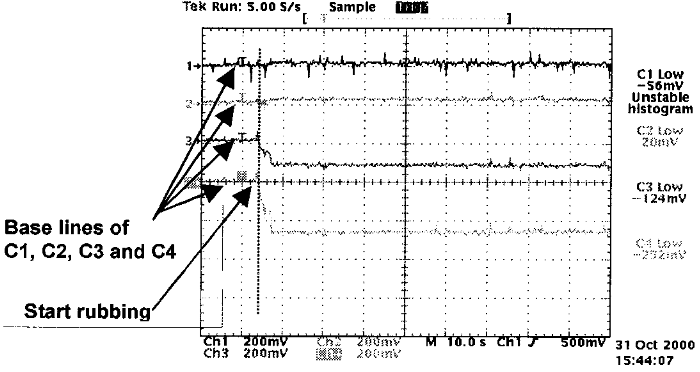

Figure 8. Response of triboelectric sensor array to **Teflon** (C1 is ABS, C2 is Polycarbonate, C3 is Teflon, C4 is Rulon-J).

The response of the electrometer was obtained in air at a pressure of 970mb, relative humidity of 33 percent and a temperature of 21°C. The evolvable hardware system used one FPTA cell. The circuit had two inputs and one output. At the two inputs, we injected the sensor responses of the insulating material TRI3 (Teflon, response C3) and TRI4 (Rulon-J, response C4) to the three rubbing materials in addition to the baseline as shown in Figs. 4, 7 and 8. The outputs were collected as a voltage signal (Vout on figure 9).

The following Genetic Algorithm parameters were used: Population: 40, Chromosome size: 24 bits for 1 FPTA, Mutation rate: 10%, Crossover rate: 90%, exponential selection, elite strategy: 20% population size. The fitness function seeks to maximize the voltage difference at the output when different materials are used for rubbing. It can be described by the following equation:

$$Fitness = \frac{1}{T} \int_t \sum_{i \neq j} \left| Vi(t) - Vj(t) \right|$$

where the indexes *i* and *j* sweep the four patterns of the three materials and the baseline and *T* is the period of time used to evaluate the fitness.

The main task of evolution is to synthesize a circuit able to discriminate among the three materials and the baseline. The solution circuit, shown in Figure 9, amplifies the voltage differences among the materials measured by the sensor such that the output voltages of the FPTA for each reference materials are distributed between Ground and 2.3 Volt.

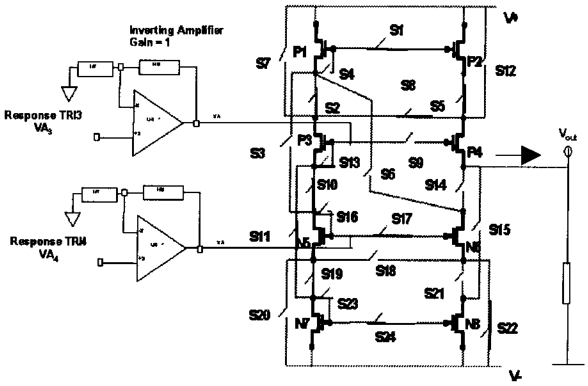

Figure 9. Evolved circuit able to discriminate among 3 reference materials and the baseline.

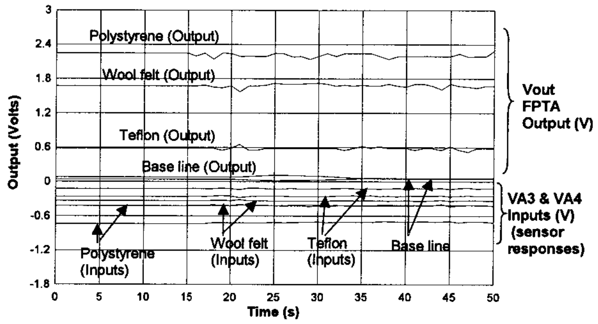

Figure 10. Response of the evolved circuit for 3 reference materials and the baseline. The time starts when the material sample is rubbed on the isolating materials of the electrometer

Figure 10 shows the response of the evolved circuit. In the bottom part of the graph are the responses (VA3 and VA4) of the electrometer to the 3 materials and the baselines. Before being applied to the FPTA, they pass through a unit gain inverter stage (Fig. 9). The circuit response for the four patterns is shown in the top part of the graph. In the circuit response, there is an average separation of 0.6V between the adjacent materials, except for the wool felt and teflon materials, for which the difference is 1.2V. The overall output range achieved a value around 2.3V, whereas the input range given by the responses of the sensor is around 0.7V (Table 1). The circuit allows for an unknown material rubbed on the electrometer to classify in-situ with high precision its triboelectric property compared to the reference materials and to send only to earth its classification.

Table 1: Inputs/Outputs of the Evolved Circuit

	Teflon	**Wool**	**Polystyrene**
- VA3 (TRI3)	0.124 V	0.332 V	0.412 V
- VA4 (TRI4)	0.252 V	0.420 V	0.684 V
Vout (output FPTA)	0.5 V	1.7 V	2.3 V

To assess the generalisation of the circuit solution we have tested the evolved circuit with sensor responses under slightly different environmental conditions which resulted in a decrease in the response of the sensors. As expected, the difference in response of the evolved circuit was smaller but it still captured the correct order of the patterns corresponding to the triboelectric series [12,13] (Figure 11).

Although the task in this experiment was easy due to the nearly uniform distribution of the input Voltages (Table 1), the next generation of FPTA, which integrates programmable resistors [20], will be able to tackle discrimination tasks with more sensor inputs and non-uniform distribution of the input Voltages. Moreover the programmable capacitors of the next generation of FPTA will also allow to work with time dependent input signals.

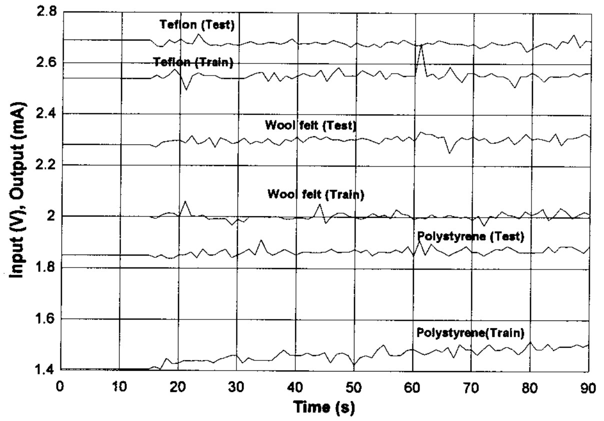

Figure 11. Response of the evolved circuit for 3 materials for slightly different environmental conditions than for experiment of Figure 10. The output measures the output current I_{out} at the drain of transistor P4.

6 Conclusion

These initial experiments, although illustrating the power of evolutionary algorithms to design analog circuit for sophisticated analysis of responses of sensor array and to maintain functionality by adapting to changing environments, only prepare the ground for further questions. The long term results of the proposed research would allow sensor electronics to adapt to incoming data and extract higher quality data, making available information otherwise not accessible. It will make sensor systems adaptive and intelligent. It will increase the amount of information available from sensors, while actually decreasing the amount of data needed for downlink in case of space missions.

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References

1 Higuchi, T., Niwa, T., Tanaka, T., Iba, H., de Garis, H., and Furuya, T. Evolving hardware with genetic learning: A first step towards building a Darwin machine. In Meyer, Jean Arcady, Roitblat, Herbert L. and Wilson, Stewart W. (editors).*From Animals to Animats 2: Proceedings of the Second International Conference on Simulation of Adaptive Behavior*. pp 417 - 424. 1993. Cambridge, MA: The MIT Press.

2 A. Thompson, "An evolved circuit, intrinsic in silicon, entwined in physics". In *International Conference on Evolvable Systems*. SpringerVerlag Lecture Notes in Computer Science, 1996, pp. 390405.

3 J. R. Koza, F. H. Bennett III,, D. Andre and M. A. Keane, Genetic Programming III–Darwinian Invention and Problem Solving, Morgan Kaufman, San Francisco, 1999

4 Stoica, A. Klimeck, G. Salazar-Lazaro, C. Keymeulen, D. and Thakoor, A. Evolutionary design of electronic devices and circuits,*Proceedings of the 1999 Congress on Evolutionary Computation,* Washington, DC, July 6-9. pp 1271-1278, 1999

5 Stoica, A. Toward evolvable hardware chips: experiments with a programmable transistor array. *Proceedings of 7th International Conference on Microelectronics for Neural, Fuzzy and Bio-Inspired Systems,* Granada, Spain, April 7-9, pp. 156-162. IEEE Comp Sci. Press, 1999.

6 J. A. Cross, *Electrostatics: Principles, Problems and Applications,* Adam Hilger (Bristol, UK).

7 *Electrometer Measurements*, Keithley Instuments (Cleveland OH), 1972

8 Julian W. Gardner, *Microsensors: Principles and Applications.* New York: John Wiley & Sons, 1994.

9 Gert van der Horn and Johan L. Huijsing, *Integrated Smart Sensors: Design and Calibration.* New York: Kluwer Academic Publishers, 1998.

10 M. Buehler et al., MECA Electrometer: Initial Calibration Experiments.In *Proceedings of the 10th Internaltional Conference (Electrostatics 1999).* Institute of physics Conference Series No 163, pp 189-196, Institute of Physics Publishing, Bristol, UK, 1999.

11 B. Schweber, Programmable analog ICs: designer's delight or dilemma ?. In *EDN.* April 2000. Cahners Publication.

12 O.J. McAteer, *Electrostatic Discharge Control.* McGraw-Hill, 1989.

13 N. Jonassen, *Electrostatics,* Chapman & Hall, 1998.

14 A. Stoica et al.. Reconfigurable VLSI Architectures for Evolvable Hardware: from Experimental Field Programmable Transistor Arrays to Evolution-Oriented Chips. In *IEEE Transactions on VLSI.* 9(1):227-232, April 2001. Piscataway, NJ: IEEE Press.

15 A. Stoica, J. Lohn and D. Keymeulen *Proceedings of the First and Second NASA/DoD Worshop on Evolvable Hardware,* IEEE Computer Society Press, 1999 and 2000.

16 Zebulum, R. Stoica, A. and Keymeulen, D., A flexible model of CMOS Field Programmable Transistor Array targeted to Evolvable Hardware, In *International Conference on Evolvable Systems*, pp. 274-283. Springer-Verlag Lecture Notes in Computer Science, 2000.