Journal of Engineering and Applied Sciences 9 (10-12): 389-395, 2014
ISSN: 1816-949X

The Remotely Reconfigurable Intelligence of the Space-Based Mobile Robot

[1]Valeriy Ivchenko, [1]Petr Krug, [1]Tatiana Morozova, [2]Andrey Ostroukh and [3]Sergey Pavelyev
[1]Institute of Moscow State Computer Science, Radio Engineering and Electronics, Moscow, Russia
[2]Department of Automation Control System, State Technical University MADI, Moscow, Russia
[3]Department of Moscow Power Engineering Institute, National Research University, Moscow, Russia

Abstract: The problems of design and implementation of remotely reconfigurable intelligence for space-based robotic systems and specifically mobile robots are highlighted. The classification of reconfiguration technologies, the specifications of remote reconfiguration, the functional structure of remotely reconfigurable intelligence are described. The space-based mobile robot-explorer Tourist is presented.

Key words: Remote modification, mobile robot, reconfigurable computing, field-programmable gate array, tourist

INTRODUCTION

Long duration of planetary exploration missions, taking months and years, imposes a specific set of requirements on the design of space-based robotic systems such as:

- High level of survivability, ability to continue to carry out the mission in case of partial malfunction of mechanical parts, hardware or software as well as in case of unpredictable changes of external environment parameters
- High level of adaptability (reserve), ability to continue to work in case of change of target (change of mission) or change of target acquisition way

Fulfillment of the earlier mentioned requirements is possible if the intelligence of the space-based robotic system has the ability to be reconfigured (modified) according to new emerging tasks on strategic or tactical level or the changing circumstances. This can be achieved by application of the reconfigurable computing technologies in the design of hardware on the basis of Field-Programmable Gate Arrays (FPGA). The modern level of technology in this field is represented by 20 nm scale FPGAs (16 nm scale under development), boasting up to 50% higher performance compared to previous generation analogues with up to two times lower power consumption. Radiation tolerant FPGAs suited for space-based missions possess total-dose tolerance from 300-1000 krad (Krug and Pavelyev, 2011).

Application of proposed technologies involves transmission of new or modified hardware configuration remotely (from Earth or planetary exploration orbital ship) to the digital intellectual control module of the space-based mobile robot which carries out the reconfiguration of FPGAs automatically.

CLASSIFICATION OF TECHNOLOGIES USED TO DESIGN RECONFIGURABLE INTELLIGENCE

The technologies used to design reconfigurable intelligence of autonomous control systems and mobile robots are presented on Fig. 1.

Element basis defines the scale of the minimal configuration block in the system. Systems on the basis of standard microprocessors contain blocks of the largest scale (separate microprocessors) while FPGAs allow the most flexible reconfiguration on the level of individual logic cells. Other types of element basis occupy intermediate position.

Specific requirements are imposed by the method of realization of the intelligence in a space-based robotic system. Reconfigurable intelligence on the basis of artificial neural networks can be designed more efficiently with the help of FPGAs which provide the most flexible changes to configuration. Hybrid architecture is better suited for adaptive fuzzy systems, processors on memory for expert systems, etc. In each case, the optimal choice for realization of reconfigurable intelligence requires detailed analysis of expected working conditions and internal specifications of the space-based robotic system.

For space-based robotic systems with reconfigurable intelligence and mobile robots in particular an important part plays the realization of control over system reconfiguration, since the decision to carry out reconfiguration may be taken automatically according to

Corresponding Author: Valeriy Ivchenko, Institute of Moscow State Computer Science, Radio Engineering and Electronics, Moscow, Russia

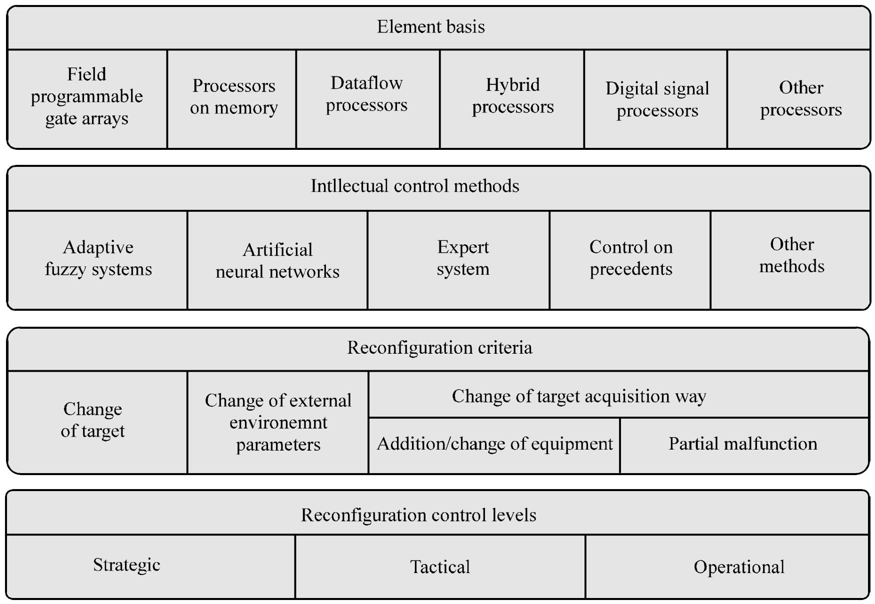

Fig. 1: Technologies used for realization of reconfigurable intelligence

a given set of criteria. Reconfiguration control in such case should be run by its own intellectual algorithm which may be different from the one used by the main intelligence of the space-based robotic system. The method of realization of intellectual control over system reconfiguration is selected according to expected working conditions, available computational resources and overall level of system automation.

Reconfiguration criteria for space-based robotic systems can be divided into such general groups as change of target, change of external environment parameters and change of target acquisition way which includes emergency malfunction of part of the equipment and scheduled change of hardware or software. Highest level of automation includes all of the earlier mentioned criteria but it is not always necessary.

Reconfiguration control can be carried out on strategic level, including definition of general targets during the system's operation and tactical level, including the choice of optimal way to solve current problems connected to the state of external environment. The higher the level of control, the larger can be the scale of the minimal configuration block. For different control levels individual methods of intellectual control over system reconfiguration may be applied (Ivchenko *et al*., 2012).

SPECIFICATIONS FOR REMOTE RECONFIGURATION

Reliability of hardware and software reconfiguration in real-time environment is one of the most important problems to be taken care of for successful design of remotely reconfigurable intelligence for space-based robotic systems.

Based on the analysis of common problems the following set of specifications for remotely reconfigurable intellectual control module of space-based robotic systems has been developed.

The set of specifications is divided into groups of functional specifications, reliability and security specifications, system specifications and user interface specifications.

Functional specifications:

- Reconfiguration of the intelligence in real time
- Reconfiguration of the intelligence in background mode without interfering with the main functions of the mobile robot
- Self-check and self-testing of the system after reconfiguration which ensures that new configuration starts running only after making sure the modified intelligence of the space-based robotic system functions correctly
- Continuous work of the mobile robot for the duration of the mission and after reaching the target with the purpose of switching to other missions with the use of new remotely modified intelligence

Reliability and security specifications:

- Standard means of authentication and integrity control for transmitted data (TCP/IP, UDP, UART etc.) with the purpose of reliable transfer of configuration data for remote reconfiguration

- Return to the previous configuration in case of negative self-check result without interrupting the functioning of the space-based robotic system
- Transfer, systematization and storage of reconfiguration log in the database of remote control center
- Software in the remote control center should provide the operator with data on technical condition of the space-based robotic system

System specifications:
- Data exchange with other space-based robotic systems working in a group
- Reconfiguration of the intelligence should take into account configurations of similar space-based robotic systems working in a group with the purpose of maintaining compatibility and common standards on data exchange (Gerkey and Mataric, 2004)
- Initiation of self-check by remote control center or locally
- Informing the remote control center on the completion of reconfiguration steps and system status
- Alerting the remote control center about emergency situations in remotely reconfigurable intellectual control module

User interface specifications:
- Software in the remote control center should provide the operator with a comfortable interface to receive and evaluate the data on technical condition of the space-based robotic system
- User interface should be sufficient, logical and free of excessive information
- Main interface window should display current status of the space-based robotic system, its remotely reconfigurable intellectual control module and reconfiguration controller which in general corresponds to three-step light indication normal, attention, danger
- In case of a malfunction detected by neural network classifier within reconfiguration controller the operator should be able to get fast access to the information about the malfunction source and the triggers which caused the alarm
- Information should be organized in multi-level structure allowing gradual access to specific data without unnecessary details

PROGRAMMABLE LOGIC DEVICES

Prospective element basis for remotely reconfigurable intelligence are Programmable Logic Devices (PLD) which represent a platform for creation of high-efficiency reconfigurable digital circuits and devices with low project time and costs (Donohoe *et al*., 2000, 2007; Vladimirova and Zheng, 2005; Walker *et al*., 2007; Chen *et al*., 2010). Inner structure of modern PLD can be modified in real time which allows creation of devices with fast reconfiguration of executable functions on their basis. Remote modification of the intelligence of space-based robotic systems implemented on the basis of reconfigurable computing technologies and PLD is estimated to increase their life cycle in certain applications by 15-20%.

PLD represent one of the fast developing directions in modern digital electronics. The technology attracts designers with the ability to create digital devices with arbitrary internal structure with relative ease. Compared to Application Specific Integral Circuits (ASIC), design on the basis of PLD requires significantly less time and cost lower thanks to implementing changes by reconfiguration of the same logic device. Modern PLD in most cases correspond to one of the following architectures:

- CPLD (Complex Programmable Logic Device), devices using non-volatile memory to store configuration data (Flash or EEPROM)
- FPGA (Field-Programmable Gate Array), devices using volatile memory to store configuration data which requires initialization after turning on the power supply

Modern high performance systems mostly use FPGAs which have significantly larger amount of logical cells and dedicated hardware resources for carrying out basic calculations.

HARDWARE RECONFIGURATION

The concept of remote reconfiguration of hardware designed on the basis of FPGA includes reliable loading of new configuration into active device (FPGA 0 or 1) (Fig. 2), running performance check of the loaded module and switching to usage of the new FPGA module without interrupting the current critical functions of the device. In the framework of the developed method, reliability of FPGA reconfiguration process is reached with the help of multi-domain architecture. The multi-domain FPGA architecture allows upgrade of software and hardware directly during device runtime. ACS constructed on the basis of the developed method can provide reliable loading of new FPGA modules in the active device, performance check of the

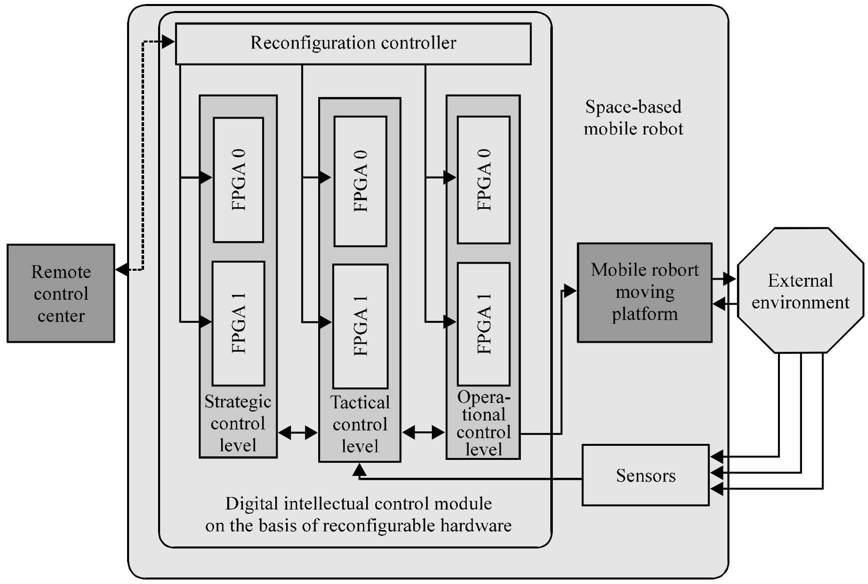

Fig. 2: Remote hardware reconfiguration diagram

loaded module and switch to usage of the new FPGA module without influencing performance of current critical functions of the device.

The method of reliable reconfigurationuses two standard functional modules: Reconfiguration server is located within the remote reconfiguration center which is connected to the space-based robotic system via network interface. Reconfiguration server remotely controls groups of space-based robotic systems and supervises reliable hardware reconfiguration.

Reconfiguration controller is a part of the digital intellectual control module within the space-based mobile robot. Reconfiguration controller may be a part of software or a separate processor and its task is controlling the process of hardware reconfiguration.

Proposed concept provides simple and automatic hardware reconfiguration. The concept includes:

- Automatic remote reconfiguration without operator participation
- Reconfiguration without physical exchange of hardware
- Simplifying the process of technological improvement of the device
- Running self-check and self-testing of digital intellectual control module
- Classification of emerging malfunctions with the help of artificial neural network

Fundamental basis for design of intellectual control systems for robots and other complex dynamic objects includes three key principles (Pryanichnikov *et al*., 2011; Gu and Hua, 2007; Lin *et al*., 2009; Makoto, 2009; Plunkett *et al*., 2010; Huang *et al*., 2004):

- Development of the principle of situational control when each class of possible system states corresponds to a given class of possible solutions
- The principle of hierarchical structure of the intellectual control system, including strategic behavior planning level, tactical action planning level, operational (actuator) level and sensors
- The principle of selecting modern intellectual technologies, suitable to solve problems on each level of control hierarch

The earlier mentioned principles of space-based robotic systems design allow to implement a wide range of intellectual features necessary to work in partially uncertain or fully uncertain conditions.

According to the principle of situational control, each class of system states which is considered possible in the process of research corresponds certain control solution (control signal, software or algorithmic control procedure, etc). Then each emerging situation observed and identified by sensors can be put into a certain class which already has the necessary control solution.

The principle of situational control on the basis of modern intellectual technologies demands a vast knowledge base on the principles of design and goals of the system, specific features of implementation of different algorithms, characteristics of operational mechanisms and the object of control. In this case, classification analysis of the stored knowledge in relation to current sensor data should provide parametric and structural setup of control algorithms, modification of target acquisition program and change of target if it becomes necessary.

The main architectural feature of such model of the intellectual control system compared to the standard one is addition of ways to store and process the knowledge with the purpose of determination of features required in uncertain conditions with random pattern of external influences. Such influences include unplanned change of targets, operational characteristics of the system or the object of control, parameters of external environment, etc.

If necessary, the system can be outfitted with the means of self-learning providing aggregation of experience and expanding the knowledge base. In general, the object of control may have complex structure including several functionally dependent subsystems.

The hierarchy of dependencies determines decomposition of initial targets and control tasks into recursive sequence of embedded components. Such distribution requires multi-level organization of the control system with intellectual capabilities for analysis and classification of current situation, creation of meaningful behavior strategy, planning of action sequence as well as generating operational laws according to given quality coefficients. The structure of intellectual control system of a complex dynamic object has to fit the principle of hierarchical structure and include strategic, tactical and operational (actuator) levels as well as a set of necessary sensors (Fig. 2).

Consistency of separate circuits of control hierarchy is determined by the set of functional elements which provide the necessary level of data support in the process of acquisition and aggregation of sensor data about current state and influences from external environment. The structure of each level of intellectual control requires the usage of unique combination of individual data representation models, data support, description of the object of control, etc.

SPACE-BASED MOBILE ROBOT-EXPLORER "TOURIST"

The space-based mobile robot-explorer Tourist (the name stands for remotely operated robotic explorer for land areas) was created in the framework of research program MARS-500 of the Institute of Biomedical Problems of the Russian Academy of Sciences and European Space Agency. Tourist was created to expand human capabilities in exploration of aggressive environments (such as other planets) with the help of remote control (Ivchenko *et al*., 2012). The robot-explorer (Fig. 3):

- Travels across the ground imitating the surface of Mars
- Is controlled remotely with visualization provided by cameras mounted on the robot
- Imitates the changes of temperature, pressure, humidity, atmospheric gas composition, etc. on the surface of Mars
- Exchanges information with landing module by radio channel
- Is equipped with remotely controlled robotic hand (manipulator) designed for recovery of soil samples, setting up research equipment on the Mars surface and bringing it back to landing module

Tourist is composed of the chassis, control devices, robotic hand placed on the moving module and the system of remote control located inside the planetary complex. Remote control system controls the moving module with the help of:

- Information about environment provided by a set of cameras mounted on the moving module
- Remote control of the main parameters of the moving module

Remote control system is also used for maintenance (charging the batteries of the moving module). Power supply is provided by a common AC source.

Remote control system includes computer (notebook) with power supply, tabletop manipulator USB-mouse, preset software and USB-COM adapter, USB adapter with four connecters, radio modem, video signal receiver, video acquisition device and battery charging device.

The moving module is powered by internal battery supporting continuous research for the duration of 2 h, after which it requires charging. Most of the details of the moving module are designed flat to support manufacturing with laser cutting which provides relatively low production cost with high precision and quality.

The moving module is composed of the chassis which house the robotic hand in front and control devices in the back. The construction of chassis includes boxlike hull made of aluminum sheets on the surface of which are mounted:

- The six leading wheels, three on each side of the chassis
- Frontal camera on the front side of the hull

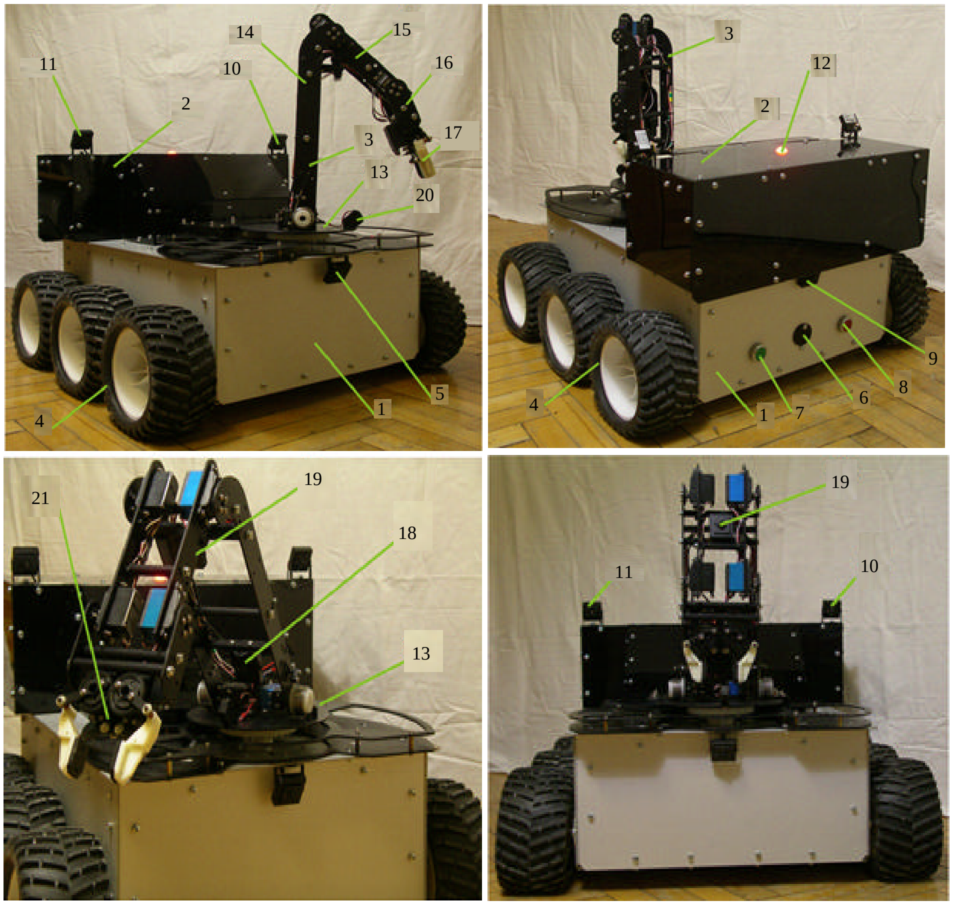

Fig. 3: External appearance of the space-based mobile robot-explorer tourist; 1 = Chassis; 2 = Control device; 3 = Manipulator hand; 4 = Wheels; 5 = Frontal camera; 6 = Charging connecter with cover; 7 = Green button ON; 8 = Red button OFF; 9 = Rear camera; 10 = Left camera; 11 = Right camera; 12 = Signal light ON; 13 = Foundation; 14 = Upper arm; 15 = Elbow; 16 = Hand; 17 = Fingers; 18 = Top camera; 19 = Observation camera; 20 = Laser range finder; 21 = Laser sight

- Charging connecter with cover, green button ON, red button OFF, rear camera on the back side of the hull

Inside the chassis are located six leading DC motors on the axis of which wheels are mounted, step motor moving the robotic hand, battery, digital circuits of motor drivers.

The wheels have one degree of freedom-rotating around the axis. The moving module takes turns by rotating left or right wheels separately. Diameter of wheels is 200 mm. The number of wheels (6) was determined according to the maximum load on each wheel. The implemented turning method was chosen because of its simplicity.

The robotic hand is designed for recovering samples from the surface of Mars, setting up sensors on the surface and eventual recovery of the sensors for return to the planetary complex. The structure of the robotic hand comprises the manipulator with fivedegrees of freedom remotely controlled by operator and capable of picking up small load from the ground (up to 200 g) and putting it into special case at the foundation of the robotic hand. It is also capable of taking an object out of the case and putting it on the surface.

CONCLUSION

Until recently the robot-explorer Tourist as well as other space-based mobile robots had the disadvantage of requiring manual remote control. Inability of the mobile robot to independently carry out interpretation of events, control operations necessary to reach mission target was caused by the lack of universal intelligence and corresponding software capable of taking into account all possible missions in advance and all possible situations emerging in the course of planetary missions.

IMPLEMENTATIONS

Implementation of the proposed technologies of remote modification of the intelligence would improve survivability and allow the mobile robot-explorer tourist and other similar space-based robotic systems to continue their work in case of change of their missions.

ACKNOWLEDGEMENT

The research was carried out with financial support of the Ministry of Education and Science of the Russian Federation in the framework of the Agreement No. 14.574.21.0102, 31.07.2014.

REFERENCES

Chen, F., G. Dai, Z. Gao, G. Xue and J. Zhang, 2010. Dynamic local reconfigurable system for real-time fault tolerance of hardware. CN 101788931 China, G06F11/00, January 29, 2010.

Donohoe, G.W., D.M. Buehler, K.J. Hass, W. Walker and P.S. Yeh, 2007. Field programmable processor array: Reconfigurable computing for space. Proceedings of the IEEE Aerospace Conference, March 3-10, 2007, Big Sky, MT., pp: 1-6.

Donohoe, G.W., K.J. Hass, S. Bruder and P.S. Yeh, 2000. A reconfigurable data path processor for space applications. Proceedings of the Military and Aerospace Programmable Logic Devices, September 24-28, 2000, Laurel, MD., pp: 24-28.

Gerkey, B.P. and M.J. Mataric, 2004. A formal analysis and taxonomy of task allocation in multi-robot systems. Int. J. Rob. Res., 23: 939-954.

Gu, S. and X. Hua, 2007. Dynamic reconfigurable instruction computer processor and implementing method. International Classification, G06F15/78, G06F15/76, August 8, 2007.

Huang, Z., S. Malik, N. Moreano and G. Araujo, 2004. The design of dynamically reconfigurable datapath coprocessors. J. ACM Trans. Embedded Comput. Syst., 3: 361-384.

Ivchenko, V.D., P.G. Krug, E.N. Matyukhina and S.A. Pavelev, 2012. The use of technology of reconfigurable intellect in autonomous control systems and mobile robots. Ind. Automat. Control Syst. Controllers, 11: 33-38.

Krug, P.G. and S.A. Pavelyev, 2011. The reconfigurable intelligence on the basis of the field programmable gate àrrays. Ind. Automat. Control Syst. Controllers, 5: 43-49.

Lin, Z., H. Ren, Z. Bingchun, Z. Zhongmin and Z. Zhangchun, 2009. Reconfigurable data processing platform. International Classification, G06F17/50, G06F15/78, January 21, 2009.

Makoto, H., 2009. Reconfigurable computing device and method for inspecting configuration data. US 2010036972 USA, G06F3/00, September 17, 2009.

Plunkett, R.T., G. Heidari and P.L. Master, 2010. Method and system for managing hardware resources to implement system functions using an adaptive computing architecture. U.S. Patent No. 7,752,419, U.S. Patent and Trademark Office, Washington, DC.

Pryanichnikov, V.E., V.P. Andreev, V. Ivchenko, S. Kuvshinov, E.A. Prysev, 2011. Adaptive environment for developing and programming of mobile robots. Proceedings of the 22th International DAAAM Symposium Intelligent Manufacturing and Automation: Theory, Practice and Education, November 23-26, 2011, Vienna.

Vladimirova, T. and D. Zheng, 2005. Reconfigurable system-on-a-chip based platform for satellite on-board computing. Proceedings of the 1st Annual ESA Workshop on Spacecraft Data Systems and Software, October 17-20, 2005, Noordwijk, The Netherlands, pp: 111-117.

Walker, W., G.W. Donohoe, D. Buehler, K.J. Hass, C. Canine and P.S. Yeh, 2007. The field programmable processor array: Design and testing. Proceedings of the 13th NASA Symposium on VLSI Design, June 5-6, 2007, Post Falls, Idaho.