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## CONTENTS

CFI: Control Flow Integrity or Control Flow Interruption?  
**Nicolo Maunero, Paolo Prinetto, Gianluca Roascio**  
1

From Abstract Modeling of ADAS Applications to an Accelerator-based Hardware Realization  
**Samira Ahmadi Farsani, Katayoon Basharkhah, Amin Mohaghegh, Zainalabedin Navabi**  
7

Unified STIL Flow: A Test Pattern Validation Approach for Compressed Scan Designs  
**Slimane Boutobza, Andrea Costa, Sorin Popa**  
13

An Accelerator-based Architecture Utilizing an Efficient Memory Link for Modern Computational Requirements  
**Saba Yousefzadeh, Katayoon Basharkhah, Nooshin Nosrati, Rezgar Sadeghi, Jaan Raik, Maksim Jenihhin, Zainalabedin Navabi**  
23

Antenna Array Calibration Algorithm Based on Phase Perturbation  
**Victor Djigan, Vladislav Kurganov**  
29

Power Supply Noise Rejection Improvement Method in Modern VLSI Design  
**Vazgen Melikyan, Artur Mkhitaryan, Hakob Kostanyan, Hayk Grigoryan, Harutyun Kostanyan, Mushegh Grigoryan, Ruben Musayelyan, Hayk Margaryan**  
34

Making System Level Test Possible by a Mixed-mode, Multi-level, Integrated Modeling Environment  
**Nooshin Nosrati, Katayoon Basharkhah, Rezgar Sadeghi, Carna Zivkovic, Christoph Grimm, Zainalabedin Navabi**  
38

Fast and Efficient Implementation of Lightweight Crypto Algorithm PRESENT on FPGA through Processor Instruction Set Extension  
**Abdullah Varici, Gurul Saglam, Seckin Ipek, Abdullah Yildiz, Sezer Gören, Aydin Aysu, Deniz Iskender, T. Baris Aktemur, H. Fatih Ugurdag**  
43

Qubit Test Synthesis Processor for SoC Logic  
**Wajeb Gharibi, David Devadze, Vladimir Hahanov, Eugenia Litvinova, Ivan Hahanov**  
48

Increasing the Effective Volume of Digital Watermark Used in Monitoring the Program Code Integrity of FPGA-Based Systems  
**Kostiantyn Zashcholkin, Oleksandr Drozd, Ruslan Shaporin, Olena Ivanova, Yulian Sulima**  
53

Unit Regression Test Selection According To Different Hashing Algorithms  
**Hakobyan Hovhannes H., Vardumyan Arman V., Kostanyan Harutyun T.**  
59

SCOAP-based Directed Random Test Generation for Combinational Circuits  
**Seyyede Maryam Ghasemy, Maryam Rajabalipanah, Saeideh Sarmadi, Zainalabedin Navabi**  
63
OR2-NOC: Offline Robust Routing Algorithm For 2-D Mesh Nocs Architectures
Arezoo Beheshti Soofian, Mina Zoffy Lighvan, Zahra Eghbali

Simulation of Nodes and Blocks of Matching Processor of the Parallel Dataflow Computing System "Buran"
Nikolay Levchenko, Anatoly Okunev, Dmitry Zmejev

Optimized Time-Delayed Feedback Control of Fractional Chaotic Oscillator with Application to Secure Communications
Amir Rikhtegar Ghiasi, Mona Saber Gharamaleki, Elaheh Mohammadi asl Khasraghi, Zahra Sattarzadeh Kalajahi

Implementation Variants of the Global Distributed Associative Computing Environment for the Parallel Dataflow Computing System “Buran”
Nikolay Levchenko, Anatoly Okunev, Dmitry Zmejev

Researching Resilience a Holistic Approach
Zoya Dyka, Ievgen Kabin and Peter Langendörfer

Modeling and Debugging Tools Development for Recurrent Architecture
Dmitry Khilko, Yury Stepchenkov, Yury Shikunov, George Orlov

Caution: GALS-ification as a Means against SCA Attacks
Zoya Dyka, Ievgen Kabin, Dan Klann, Frank Vater and Peter Langendoerfer

Unit Regression Test Selection Mechanism Based on Hashing Algorithm
Melikyan Vazgen Sh., Hakobyan Hovhannes H., Kaplanyan Taron K., Momjyan Arsen M.

Qubit Fault Detection in SoC Logic
Mikhail Karavay, Vladimir Hahanov, Eugenia Litvinova, Hanna Khakhanova, Irina Hahanova

The Fault Tolerant CMOS Logical C-Element for Digital Devices Resistant to Single Nuclear Particles
Yuri V. Katunin, Vladimir Ya. Stenin

Development of a Simulation Tool to Estimate Final Electricity Consumption and Determine the Optimum Cooling System for Data Centers
Beyzanur Toprak, Beyzanur Bora and Gül Nihal Güğül

Terms of Arrangement Reckoning Self-Checking Embedded Check Circuits Based on Boolean Complement up to Constant-Weight Code ‘1-out-of-3’
Dmitry Efano, Valery Sapoznikov, Vladimir Sapoznikov, German Osadchy, Dmitry Pivoarov

Use of Natural Information Redundancy in On-Line Testing of Computer Systems and their Components
Oleksandr Drozd, Anatoly Sachenko, Svetlana Antoshchuk, Julia Drozd, Mykola Kuznietsov
Self-Dual Complement Method up to Constant-Weight Codes for Arrangement of Combinational Logical Circuits Concurrent Error-Detection Systems
Dmitry Efanov, Valery Sapozhnikov, Vladimir Sapozhnikov, German Osadchy, Dmitry Pivovarov

Decision Making in VLSI Components Placement Problem Based on Grey Wolf Optimization
Elmar V. Kuliev, Vladimir Vl. Kureichik, Ilona O. Kursitys

Intelligent Flow Meter on Acoustic Multivibrator
Zh. A. Sukhinetes, Gulin A. I., Bureneva O.I., Prokopenko N.N., Valiamova O.O.

Technique to Simulate Oscillator Circuits with the Degradation Models
Mark M. Gourary, Sergey G. Rusakov, Sergey L. Ulyanov, Michael M. Zharov

Polynomial Code with Detecting the Symmetric and Asymmetric Errors in the Data Vectors
Ruslan B. Abdullaev, Dmitrii V. Efanov, Valerii V. Sapozhnikov, Vladimir V. Sapozhnikov

Diagnostics of Audio-Frequency Track Circuits in Continuous Monitoring Systems for Remote Control Devices: Some Aspects
Dmitrii V. Efanov, German V. Osadchy, Valerii V. Khóroshev, Dmitrii A. Shestovitskiy

Length Limiting of Quantum Key Distribution at Two-Stage Synchronization
Rumyantsev K.E., Shakir H.H.Sh.

Technological Foundations of Traffic Controller Data Support Automation
Joseph M. Kokurin, Dmitrii V. Efanov

Sum Codes of Weighted Data Bits for Objectives of Automation Logical Devices Technical Diagnostics
Dmitry Efanov, Valery Sapozhnikov, Vladimir Sapozhnikov, German Osadchy, Teng Teng

Algorithm for Extraction of the Iris Region in an Eye Image
Sh.Kh. Fazilov, O.R. Yusupov

Processing An Effective Method For Clock Tree Synthesis
Narek Avdalyan, Kamo Petrosyan

Development of Automation Systems at Transport Objects of MegaCity
Andrei Belyi, Dmitrii Shestovitskii, Valerii Myachin, Dmitrii Sedykh

Advanced Indication of the Self-Timed Circuits
Yury Stepchenkov, Yury Shikunov, Yury Diachenko, Denis Diachenko, Yury Rogdestvenski

X

2019 IEEE EWDTS
Main Solutions of Structural Health Monitoring in Managing the Technical Condition of Transport Objects
Andrei Belyi, Dmitrii Shestovitskii, Eduard Karapetov, Dmitrii Sedykh, Vladimir Linkov

A Technique for Semiconductor Devices Modeling Using Physical Templates
Alexandr M. Pilipenko, Vadim N. Biryukov, Alexander I. Serebryakov

Statistical Analysis of Discriminators under the Influence of Additive Correlated non-Gaussian Noise Described by Markov Processes
Artyushenko V.M., Volovac V.I.

Accurate Soft Error Rate Reduction using Modified Resolution Method
Alexander Stempkovskiy, Dmitry Telpukhov, Vladislav Nadolenko

Neural Net as Pseudo-Inverse Filter in Speech Coding Problem
Rustam Latypov, Evgeni Stolov

Protograph Sieving Method for Construction Moderate Length Multi-Edge Type QC-LDPC Codes
Svistunov German, Usatyuk Vasiily, Egorov Sergey

Calculating the Parameters of the Short-Range Microwave Information Channel Resistant to Signal Fading
Artyushenko V. M., Volovac V. I.

The Implementation of the Genetic Algorithm Using Cloud-Based Computing on the Internet
Kureichik V. M., Logunova J.A.

A Template Model of Junction Field-Effect Transistors for a Wide Temperature Range
Alexandr M. Pilipenko, Vadim N. Biryukov, Nikolay N. Prokopenko

Synthesis of Signal Quadrature Processing Algorithms under the Influence of Band-limited non-Gaussian Noise
Artyushenko V.M., Volovac V.I.

Planar Butler Matrix Based on Compact Taps
Denis A. Letavin

All-Pass Second-Order Active RC-Filter with Pole Q-Factor's Independent Adjustment on Differential Difference Amplifiers
Darya Yu. Denisenko, Nikolay N. Prokopenko, Nikolay V. Butyrlagin

Planar Compact Directional Coupler on Artificial Transmission Lines
Denis A. Letavin

Silicon Photomultipliers' Analog Interface with Wide Dynamic Range
Oleg V. Dvornikov, Yaroslav D. Galkin, Nikolay N. Prokopenko, Alexey E. Titov, Vladimir A. Tchekhovski, Anna V. Bugakova

2019 IEEE EWDT S
A Novel Technique For Atomic Instructions Functional Verification
Using Lock Contention Analysis
Chibisov Peter, Grevtsev Nikita 274

Calculation of Phase Center of Arbitrary Electromagnetic Radiation Sources
in Near Field Zone
Nikolay Anyutin, Ivan Malay, Alexey Malyshev 281

Method of Calculating the Spare Parts System Availability for Electronic Means
Pankovsky B. E., Polesskly S. N. 285

Ternary Questionnaires
Dmitrii V. Efanov, Valerii V. Khóroshev 289

Harmonic Distortions in Analog Interfaces Based on Differential Difference Amplifiers
Nikolay V. Butyrlagin, Anna V. Bugakova, Nikolay N. Prokopenko,
Mikhail F. Mitsik, Alexey E. Titov 301

Intelligent Sensor Measurement of GTE Gas Temperature with Thermistors
Zh. A. Sukhinetas, A. I. Gulin, N. M. Safyannikov, N. N. Prokopenko,
O. O. Valiamova, O.I. Bureneva 305

Application of Modern Microelectronic Technology in Marshalling Process
of Railway Stations
Michael A. Gordon, Alexey N. Kovkin, Dmitry V. Sedykh, Anton A. Movshin,
Oleg A. Abramov 309

Ternary Parity Codes: Features
Dmitrii V. Efanov 315

Fast and Secure Unified Field Multiplier for ECC Based
on the 4-Segment Karatsuba Multiplication
Ievgen Kabin, Zoya Dyka, Dan Klann and Peter Langendoerfer 320

Construction of Length and Rate Adaptive MET QC-LDPC Codes
by Cyclic Group Decomposition
Usatyuk Vasilyl, Egorov Sergey, German Svistunov 326

A Technique for the Accounting of Surrounding Circuitry During Generation
of the Simplified Models
Mark M. Gourary, Sergey G. Rusakov, Sergey L. Ulyanov, Michael M. Zharov 331

A Signal Processing Approach for the Failure Analysis of Rolling-Element Bearing
of Vehicle Brake Tester Used at a Vehicle Inspection Station
Selman Kulac 337

Modified Modular Unit Bits Sum Codes with Arbitrary Account Modules
Dmitrii V. Efanov, Anna O. Filippochnkina, Mariia V. Ivanova 343
Systems for Reflectometry Analysis of Defects in Metal Structures of Transport Mobile Objects
Julia V. Alevedinova 350

Parametric Optimization Subsystem in LTspice Environment of Analog Microcircuits for Operation at Low Temperatures
Maxim V. Liashov, Nikolay N. Prokopenko, Andrei A. Ignashin, Oleg V. Dvornikov, Alexey A. Zhuk 356

Boosting Model of Bioinspired Algorithms for Solving the Classification and Clustering Problems
Ilona Kursitys, Alexander Natskevich, Elvira Tsyrulnikova 360

Modeling Technique of Large Signal Dynamics for Electromagnetic Levitation Melting System
Idan Sassonker, Moria Elkayam, Alon Kuperman 366

On a Method for Segmentation of Memory Instances with Row Redundancies
Karen Amirkhanyan, Valery Vardanian 371

Elaboration of the Functioning Algorithm of Three-Dimensional Model of Computer System Safety
Victor V. Zhihin, Larissa V. Cherckesova, Irina I. Drozdova, Vitaliy M. Porksheyan, Ivan A. Sakharov, Olga A. Safaryan, Andrey G. Lobodenko, Sergey A. Morozov 376

Interface and Software for the System of Automatic Seeding of Grain Crops
Maksim A. Litvinov, Maksim N. Moskovskiy, Ilya V. Pakhomov, Igor G. Smirnov 380

Cross-Platforming Web-Application of Electronic On-line Voting System on the Elections of Any Level
Evgeniy V. Palekha, Olga A. Safaryan, Irina S. Trubchik, Vitaliy M. Porksheyan, Olga N. Manaenkova, Sergey A. Morozov, Larissa V. Cherckesova, Boris A. Akishin 384

Theoretical Bases of the Course Motion Two Axles Agriculture Transports Vehicle According Wheels Slipping
Maksim A. Litvinov, Maksim N. Moskovskiy, Ilya V. Pakhomov, Anatoly A. Gulyaev 388

Modification and Optimization of Solovey-Strassen’s Fast Exponentiation Probabilistic Test Binary Algorithm

Reliability Issues in the Parallel Dataflow Computing System
Nikolay Levchenko, Anatoly Okunev, Dmitry Zmejev 395

Modification and Optimization of Pollards’s Factorization $\rho$-Method by Means of Recursive Algorithm of Number Calculation Factorization
Ivan A. Smirnov, Larissa V. Cherckesova, Pavel V. Razumov, Yelena A. Revyakina, Nickolay V. Boldyrikhin, Vitaliy M. Porksheyan, Olga A. Safaryan, Andrey G. Lobodenko 400
Deriving Low Power Test Sequences Detecting Robust Testable PDFs
A. Matrosova, V. Andreeva, V. Tychinskiy

Development of Modified Block Cipher Algorithm TEA, Free from Vulnerability of “Connected Keys Attack”

Masking Internal Node Faults and Trojan Circuits in Logical Circuits
A. Matrosova, V. Provvkin, E. Nikolaeva

Masking Robust Testable PDFs
Anzhela Matrosova, Sergei Ostanin, Semen Chernyshov

Associative Processors: Application, Operation, Implementation Problems
Egor Kuzmin, Nikolay Levchenko, Anatoly Okunev

SWIELD: An In Situ Approach for Adaptive Low Power and Error-Resilient Operation
Mitko Veleski, Rolf Kraemer, Milos Krstic

Automating of Human Resources Management using Genetic Algorithms
Agata V. Markevich, Valentina G. Sidorensko

Evaluating the Length of Distinguishing Sequences for Non-Deterministic Input/Output Automata
Igor Burdonov, Alexandr Kossachev, Nina Yevtushenko, Alexey Demakov

Voltage Regulation Analysis in Energy Transmission Systems Using STATCOM
Hamza Feza Carlak, Ergin Kayar

Research of the Effect of Discrete Light Sources on Seeds of Vegetable and Green Cultures and the Possibility of their Approximation to Modified Sunlight
Danila Yu. Donskoy, Alexander D. Lukyanov, Marko Petković, Eugenia P. Kluchka

Deriving Adaptive Homing Sequences for Weakly Initialized Nondeterministic FSMs
Evgenii Vinarstii, Aleksandr Tvardovskii, Larisa Evtushenko, Nina Yevtushenko

Non-Canonical Topography of the z-Plane Discretized due to Quantization of the IIR Digital Filter Coefficients
Vladislav Lesnikov, Tatiana Naumovich, Alexander Chastikov

Modification of the U-Net Neural Network in the Task of Multichannel Satellite Images Segmentation
Vladimir Khrystovchew, Roman Larionov, Anna Ostrovskaya, Alexander Semenov

Complementary JFETs Integrated into the Microwave Complementary Bipolar Double Self-Aligned Technology
Dmitry G. Drozdov, Nikolay N. Prokopenko, Evgeny M. Savchenko, Andrey I. Grushin, Pavel A. Dukanov

XIV
The Discrete Structure of the Zeros and Poles Location in the z-Plane of the Arbitrary Order IIR Digital Filters with a Finite Word Length
Vladislav Lesnikov, Tatiana Naumovich, Alexander Chastikov, Alexander Metelyov

Permanent Monitoring Systems of the Contact-Wire of Railroad Catenary: the Main Tasks of Implementation
Dmitrii V. Efanov, German V. Osadchy, Dmitrii V. Barch, Andrei A. Belyi

Design of Real-Time System Logic Control on FPGA
Maryna Miroshnyk, Dariia Rakhlis, Inna Filippenko, Elvira Kulak, Maksym Hoha, Mykyta Malakhov, Vladyslav Sergienko

Emerging Culture of Social Computing
Anastasia Hahanova, Svetlana Chumachenko, Vladimir Hahanov, Abdullayev Vugar Hacimahmud, Ka Lok Man, Alexander Mishchenko

Forest Areas Segmentation on Aerial Images by Deep Learning
Vladimir Khryashchev, Anna Ostrovskaya, Vladimir Pavlov, Roman Larionov

An Analysis of LockerGoga Ransomware
Alexander Adamov, Anders Carlsson, Tomasz Surmacz


The Software Platform for Evaluation of Effectiveness of Network Systems Analysis Technologies
Olha Ponomarenko, Valeriy Gorbachov, Abdulrahman Kataeba Batiaa, Oksana Kotkova

Multidimensional Hierarchical Model of Behavioral Check of Distributed Information Systems
 Oleksandr Martynyuk, Oleksandr Drozd, Hanna Stepova, Dmitry Martynyuk and Lyudmila Sugak

Development of Method For Automation of SPICE Models Generation
Melikyan Vazgen Sh., Martirosyan Meruzhan K.

Comparison of Grapheme-to-Phoneme Conversions For Spoken Document Retrieval
Dmitriy Prozorov, Alexandra Tatarinova

Formalized Methods of Analysis and Synthesis of Electronic Document Management of Technical Documentation
Dilshod Baratov, Aripov Nazirjon and Ruziev Davron

Non-Invasive System for Determining the Level of Iron in the Blood
Andrey Azarov, Elena Shirokova, Igor Shirokov

2019 IEEE EWDTS
The Using of Electronic Document Management Tools of Technical Documentation for the Assessment of the Life of the Train Traffic Control Devices
Dmitry V. Sedykh, Michael N. Vasilenko, Andrei Belyi, Denis V. Zuyev, Michael A. Gordon 544

Automation of Layout Design of Spiral Conical Scans
Marina Byrdina, Lema Bekmurzaev, Mikhail Mitsik, Dmitry Kelekhsaev and Anatoly Kondratenko 548

Secure Communication Using the Synchronization of Time-Varying Complex Networks by Fuzzy Impulsive Method
Reza Behinfaraz, Sehraneh Ghaemi, Sohrab Khanmohammadi, Mohammadali Badamchizade 552

Description of the Spatial Shape Surface of an Air Supported Dynamic Figure
Mikhail Mitsik, Lema Bekmurzaev, Marina Byrdina, Olga Aleynikova, Victor Kokhanenko 556

Solution of the Dynamic Problem of Optimal Design of Electronic Devices Based On the Gravity Center Method
Mikheil Donadze and Zuraq Meskhidze 560

Intelligent Transport Systems as a Way to Improve the Quality of the Rail-Train Multimodal Freight Transportation
Natalia Goncharova 565

Remote Administration of Information Systems Via E-mail
Zaza Davitadze, Gregory Kakhiani and George Beria 572

Method of Indirect Steganographic Embedding Based on Functionality for Adaptive Position Number
Vladimir Barannik, Dmitry Barannik, Nataliy Barannik 577

Surface visualization of flexible elastic shells
Marina V. Byrdina, Lema A. Bekmurzaev, Mikhail F. Mitsik, Svetlana V. Rubtsova 582

AUTHORS INDEX 586
Design of real-time system logic control on FPGA

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Abstract—Problems of real-time hardware logic control systems design on the FPGA are considered. The control algorithm is implemented based on a timed FSM model, represented by a temporal state diagram. The design of the control device model using hardware description language VHDL in the form of the three-process pattern is made. The functional verification of the model was carried out using Active-HDL tools, the synthesis of the circuit was carried out on the Spartan 3E FPGA technology platform using Xilinx ISE CAD tools. The hardware costs for the circuit implementation of the control device were analyzed.

Keywords—timed FSM, temporal state diagram, VHDL, functional verification, pattern, FPGA.

I. INTRODUCTION

Among the entire set of control systems, the significant part are logical control systems, in which control signals take values of the logical zero or one, depending on boundary values of physical quantities that define these parameters. For the technical implementation of these systems, the Finite State Machine (FSM) is the most suitable, and the visual representation of functioning algorithm is a state diagram. The distinctive feature of the FSM for logic control is that among input values there are not only announcing signals of the operational state machine, but also external, towards to the controlled system, events of external world, which are playing role of interrupts for the control algorithm.

A control FSM functions in machine time, is determined by the operation time of machine. But the most of real logical control systems cooperate with external world in the metric time, i.e. they are real-time systems.

The real-time control system is a system in which the resultant action (activity) depends not only on logical values of simple control actions, but also on time during which these actions are performed. The main difference between tasks in real time and tasks that are not dependent on time is that tasks in real-time systems must be completed within a specified period of time, that allow to complete processing of data correctly. For their implementation, it is customary to use a timed FSM model, which allows taking into account the effect of metric time on transitions between technical states of control system.

Any local digital device that implements an information processing or control algorithm can be implemented in two ways: hardware or software-hardware. With hardware implementation method, a given algorithm is described in hardware description language (HDL) and is synthesized by instrumental tools of computer-aided design (CAD) in FPGA (Field-Programmable Gate Array circuit). The advantage of this approach is hardware flexibility (ability to implement any algorithm) and a sufficiently large speed.

During describing the functioning algorithm for digital logical control devices in CAD systems, one of code styles is the style of automata-based programming. In automata-based programming, a concept of “state” is used as the base one [1]. A state is a mathematical abstraction that is uniquely associated to each of physical states of a control object, since usually an operation of technical systems is shown through a change of their states. At the same time, each state in a control algorithm maintains a control object in a proper state, and the transition to a new state in an algorithm leads to the transition of an object to a new corresponding state, which ensures the process of object’ logical control. A state is a set of parameters of a technical system at a given moment of time. A current state carries all information about the history of a system, which is necessary to determine its response to any input action that is formed at a given time.

Thus, the task of developing an unified pattern in the hardware description language for the design of real-time logic control devices, which based on FSM in the style of automata-based programming, becomes urgent. The goal of this work is to develop a pattern for describing finite state
machine in the hardware description language VHDL, and automated synthesis of the received model with.

II. THE MODEL OF STRUCTURAL FSM IN REAL-TIME SYSTEMS

When describing a behavior of real-time control systems, it is necessary to take into account timing aspects of their behavior. For this, a state machine model is expanded by introducing a timed variable, and the concept of a timed FSM [2, 3] is introduced. A timed variable constantly increases its value and "resets" to 0 upon the arrival of an input signal and a FSM transitions to a new state. Time variables are measured in automata cycles.

As a rule, three parameters are used to describe timing aspects in the automata-based model: timing constraints \( t_i \) (input) timeouts \( t_o \) and output delays \( t_e \), which sometimes are called as output timeouts. An input timeout determines the maximum waiting time for input effects (events) for each state of a FSM. If an input symbol was not filed before the end of a timeout, a state machine starts polling input variables and can switch to another state. Time constraints are intervals on transitions that limit the time during which the transition can be performed. Output delays (output timeouts) shows the time that a state machine spends on executing of a transition, i.e. an output signal will appear at an output after a time interval, which is determined by the output delay.

In logical control systems, a concept of "input values" is divided into input actions and events. Input actions are implemented automatically by polling in accordance with an algorithm of its operation in a control loop, and events are implemented instantaneously and lead to a change in a state of the state machine.

Event processing in real-time systems, as a rule, are determined on a basis of dynamic characteristics of control processes and related events. An event is an abstract concept, implying such a change in environmental conditions, which generates a certain reaction of a system [4]. Events can be generated both by an external environment and within a control system by its components.

There are three main options for an interaction of a control FSM with an external environment.

1. Events are used for an interaction of a control and operating FSM within an automatic control system. In this case, if events are exceptional (two events cannot occur simultaneously), events' processing doesn't differ from processing of input variables values of a FSM.

2. Events along with input variables provide an interaction of a FSM with an external environment. This design solution should reflect the difference between events and input variables: a FSM processes events at the moment of its occurrence, while values of input variables are polled by a FSM on its own initiative.

3. An each event is associated with a separate state (transition) of a FSM. This solution is only suitable for implementing of an exceptional event model. In addition, it reflects an active role of events, and the fact that the occurrence of events, by itself, initiates an operation of a FSM. This solution is the best coordinated with traditional event systems, where any output function is related to the content of events.

Depending on a purpose and features of using models of a timed FSM, there are many modifications of such models, which differently take into account both, the method of events’ processing and the way of delays’ accounting in states of a FSM [5, 6].

Based on functioning features of logic control systems, a full model of a structural timed FSM can be represented by a nine \( W = (X, Y, Z, f, g, z_0, T, T_o, T_e) \), where:

- \( X = \{X_c, X_e\} \) - a set of input variables, \( X_c \) - a set of announcing signals from a control object, \( X_e \) - a set of external events,
- \( Y = \{Y_c, Y_e\} \) - a set of output variables, \( Y_c \) - a set of reactions (control signals), \( Y_e \) - a set of activities (output functions);
- \( Z \) - a set of internal variables that determine coding states of a FSM;
- \( f \) - a transition function,
- \( g \) - an output function;
- \( z_0 \) - a code of the initial state of a FSM;
- \( T_e = \{t_1, t_2, \ldots, t_g\} \) - a set of timed variables for timing restrictions on each arc of a state diagram, where \( p \) - is a number of arcs in a state diagram, \( k = \{1, k\}, k \) - a maximum number of clocks’ restrictions on transitions to the \( i \)-th node of a state diagram in polling mode, \( k = \{1, \infty\}, \infty \) - responds exclusively by an effective transition function, \( T_o = \{t_{o1}, t_{o2}, \ldots, t_{on}\} \) - a set of timed variables for timeouts (expected) of each state of a FSM, \( T_o = \{1, n\} \) - timeout for each state, \( n \) - a number of states of a FSM;
- \( T_e = \{t_{e1}, t_{e2}, \ldots, t_{en}\} \) - is a set of delays for the realization of the corresponding output signal, where \( m \) - is a number of output variables, \( t_{o1} = \{1, l\} \), where \( l \) - is a maximum number of clock cycles for the realization of output functions in the specified state of a FSM.

In general, a timed FSM can contain all three time parameters, but for a specific task timed FSM with one or two of specified parameters can be used.

A classical model of timed FSM, which consist of three timing parameters \( < t_o, t_i, t_e > \) can’t be directly attributed to the traditional Moore model. The output function is similar to Moore FSM, but the output signal is formed after delay, and not when the FSM transits to a new state. A time of appearance (change) of output signals is connected to a working edge of the synchronization signal. In the proposed model of the timed FSM, the logic of its operation is as follows.

During FSM transitions to the current state \( a_i \), the main time parameter \( t_o(a_i) \) (timeout) is determined for it, that is, a time during which a FSM should be in the current state if an external event will not transfer the FSM into another state ahead of time. Value of \( t_o \) is defined in FSM cycles. After the time \( t_o \) is expired, a FSM responds to input signals (polls them) and transfers to a next state. Output signals of a FSM in the current state \( a_i \) appear at outputs of the FSM at the time determined by \( t_o(a_i) \) (output delays), that is, output delays for signals \( y_i \) in the state \( a_i \). For each of output signals \( y_j \), the initial delay is determined in FSM cycles and can be different. When \( y_j = 0 \), timed FSM approaches the classical Moore model.

A processing of external events is as follows. For each state \( a_i \), the time constraints \( t_i (a_i) \) (input constraints) are set,
that is, a time interval during which a FSM, staying in the state $a_i$, can process initial events. Timing constraints are determined in FSM clock cycles and calculated as $t_c = (t_1 - t_0)$, where $t_0$ is the beginning of timing constraints’ “window”, $t_1$ is the end of timing constraints’ “window”. When $t_1 = \infty$, a timed FSM without input timing constraints is considered. If an external event occurs outside of the "window" of timing constraints, a state machine does not respond to it.

Logic control devices, based on FSM, function in a FSM time, which is measured in FSM clock cycles, i.e. discrete time intervals during which a FSM transfer from one state to another. The duration of a FSM cycle in real devices is usually determined by the frequency of the clock signal $Clk$.

A temporal state diagram is used to describe a timed FSM. All timing parameters of a temporal state diagram are implemented through loops. Conditions for those loops are counting of the number of clock cycles $Clk$, which is implemented by the counter ($counter$) in the FPGA [7]. The fragment of the temporal state diagram for three states is shown in fig. 1.

Figure 2 shows the fragment of the temporal state diagram of Moore FSM functioning.

In the considered state diagram, the signal $Btn$ – is an event that is, essentially, the input signal with the highest priority. In this regard, in the pattern during description of transitions from considered state it is checked firstly in the IF branch. In all other transitions from this state (elsif ... else branch) this signal is equal $Btn$ and is not explicitly written. Therefore, for greater clarity, the arc with $Btn$ is highlighted by a dotted line on the state diagram, and $Btn$ is not present in the expressions of the transition conditions, that is, the orthogonalization of transition conditions is not violated here.

Figure 4 presents fragments of the VHDL model corresponding to the temporal state diagram in Figure 3. Here state synchronization – is the process of new state assigning, timer synchronization – is the process of the FSM clock’ counter implementation, transition function – is the combinational process of the transition function implementation, output function – is the conditional assignment statement for output signals.

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III. AN EXAMPLE OF AN AUTOMATED DESIGN OF TIMED FSM ON FPGA

When designing an operation algorithm of a digital device in HDL, it is important that the developed HDL code doesn’t go beyond limits of the synthesized subset of the particular HDL. Single-process and two-process patterns for design of HDL-models of Moore timed FSM with delays in states are considered in [7, 8].

On the one hand, a single-process pattern is correctly synthesized for Moore FSM, but it generates hardware redundancy for Mealy FSM (register for output signals is synthesized). On the other hand, a two-process pattern, taking into account the counter signal that implements the delay, is not synthesized correctly. Therefore, for the implementation of a VHDL model of a timed FSM, it was proposed to use a three-process pattern: a synchronous process of new state assigning, a synchronous process of implementing FSM clock’ counter and a combinational process of transition function implementing. Outputs function of Moore timed FSM is implemented through the conditional signal assignment statement out of processes.

As an example of the implementation of proposed structure of a timed FSM’ HDL-model, let’s consider the temporal state diagram of the modified Moore FSM, which is represented in fig. 3. In this state diagram, $x_i$ and $x_f$ are considered as input actions, and $Btn$ is considered as an event.

Timing parameters for the temporal state diagram, which is preset in FSM cycles, are as follows:
- input constraints for $Btn$: [3; 3] for $a_1$, [4; 5] for $a_2$;
- timeouts for states: $T_1 = 6$, $T_2 = 7$, $T_3 = 9$, $T_4 = 5$;
- output delays for signals: $y_1(d_1) = 1$, $y_2(d_2) = 2$.

---

process (Clk, Reset) begin
if $Reset = '1'$ then state <= $a_1$;
elseif rising_edge(Clk) then state <= next_state;
end if;
end process;
-- clk synchronization
process (Clk, Reset)
begin
  if Reset = '1' then count <= (others => '0');
  elsif rising_edge(Clk) then
    if State /= next_state then count <= (others => '0');
    else count <= count + 1;
    end if;
  end if;
end process;

-- transition function
process (state, x, Btn, count)
begin
  case State is
    when 2 =>
      if Btn = '1' and count >= constraint_a2_L - 1 and
         count < constraint_a2_H then next_state <= a4;
      elsif count < T2 - 1 then next_state <= state;
      elsif x(1) = '1' then next_state <= a4;
      elsif x(2) = '1' then next_state <= a1;
      else next_state <= a3;
    end if;
  -- output function
  y(1) <= '1' when ( (state = a1) or (state = a2) or (state = a4) )
  and count = output_delay_Y1 else '0';
end process;

Fig. 4. Fragment of the VHDL model of timed Moore FSM

Figure 5 shows the timing diagram (waveform) of the simulation results of the considered control device of the ALDEC Active-HDL system.

The processing of the Bln event at time 2550 ns is of particular interest. This event falls into the interval Input Constraint for Bln {4, 5} for the state a2 and realizes the transition to the state a3 (highlighted arc Bln in fig. 3).

The synthesis report in figure 6 shows the results of the synthesis of the control device in the XILINX ISE system for FPGA: Spartan 3E, XC3S500E chip, Package FG 320 (xc3s500e-4fg320).

The structure, consisting of two blocks, is synthesized: control FSM (2 D flip-flops for states coding, combinational circuits implementing transition and output functions) and counter based on 4 D flip-flops for counting 9 cycles of the maximum timeout. To confirm the complete correctness of timing parameters of the proposed model, it was necessary to perform timing simulation, but this is the subject of further research.

CONCLUSION

As a result of the conducted research, it was shown that during automated design of real-time logic control systems it is advisable to use models of the timed control FSM. Problems of constructing timed FSM that take into account timing constraints, input timeouts and output delays were considered. To describe these models in hardware description language VHDL during automated design, a three-process pattern in the style of automata-based programming for Moore FSM was developed, which contains the combinational process for describing transition functions, the synchronous process for new state assigning, and the synchronous process for accounting of FSM cycles. The simulation of developed VHDL model in the Active-HDL system and the circuit synthesis using the XILINX ISE CAD tools in the FPGA on the Spartan 3E board showed the efficiency of the proposed model. At the same time, hardware costs don’t go beyond the standard rate for FSM states’ encoding and formation discharges of FSM cycles’ counter.

A practical value of obtained results is that authors proposed the pattern, describing algorithms for the functioning of the timed FSM in real-time logic control systems in the VHDL language, which can be used by beginner designers of digital logic control systems, as well as students of the specialty “Computer Engineering”.

A direction of further research may be the use of the Mealy model for the implementation of timed control FSM.

REFERENCES