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FPGA to study the behavior of a manipulator using sliding innovation filter

Mohammad AlShabi [a*], Talal Bonny [b], S. Andrew Gadsden [c]
[a] Department of Mechanical & Nuclear Engineering, College of Engineering, University of Sharjah, UAE; [b] Department of Computer Engineering, College of Computing and Informatics, University of Sharjah, UAE; [b] Department of Mechanical Engineering, McMAster University, Canada

ABSTRACT

Field programmable gate arrays (FPGAs) are increasingly popular due to their customizability, which enables them to be tailored to specific applications, resulting in minimal resource usage that saves energy and space. In this work, we used an FPGA with a Z-board from Xilinx to simulate the application of the sliding innovation filter (SIF) to a robotic arm. SIF is a predictor-corrector filter used for both linear and nonlinear systems to estimate states and/or parameters. It shares similar principles with sliding mode observer and smooth variable structure filter (SVSF) and uses a correction gain derived to satisfy Lyapunov stability, keeping the estimates near the measurements. We tested SIF on a manipulator with two joints (rotational and prismatic), using FPGA to run the simulation while tracking resource utilization. We compared the results with those of SVSF.

Keywords: SIF, SVSF, Mathematical Modeling, FPGA, maneuvering.

1. INTRODUCTION

The Sliding Innovation Filter (SIF) [1-5] is a model-based filter [6-23] that can be used in signal processing, fault detection, and diagnosis applications [24-29]. This type of filter utilizes a predefined model that replicates the system under investigation, and apply the input signal to stimulate that model. The outcome is subsequently refined to minimize the effect of disturbances and uncertainties. Moreover, the extensive research on sigma-point Kalman filters, smooth variable structure filters, and optimization techniques has been conducted, showcasing their wide-ranging applications in signal processing, sensor fusion, control systems, robotic arms, quadrotor controllers, photovoltaic models, and fault detection in electromechanical systems [29-35].

The SIF share similar principles to the Smooth Variable Structure Filter (SVSF), which was introduced in 2007. The filter employs the actual trajectory as hyperplanes to constrain the estimate within its vicinity. This is accomplished using a correction gain derived from the Lyapunov stability theorem. Both filters have been demonstrated to be robust and stable in the literature [35-39]. To smooth out the noise, the filter employs a smoothing boundary layer. Nonetheless, it was discovered that its noise and disturbance filtering capabilities are enhanced when it is combined with other filters [40-44].

This study focuses on implementing the SIF using a field-programmable gate array (FPGA). The SIF is applied to a target tracking problem involving a moving vehicle on a 2D plane. Section 2 summarizes the SIF and the system, while section 3 focuses on the FPGA. The findings are analyzed in section 4, followed by a conclusion in section 5.

* malshabi@sharjah.ac.ae, University of Sharjah, PO Box: 27272.

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2. SYSTEM AND FILTER MODELING

2.1. System under study

To test the SIF, a moving vehicle model is implemented using FPGA system. The system has five states including the positions in x- and y- axes, the velocities in x- and y- axes, and the maneuvering angle. They are referred to as x_1, x_2, x_3, x_4 and x_5. The system's positions are assumed to measured. The vehicle follows a "L-Shape" path.

The system and measurement models are summarized as [45]:

$$\begin{bmatrix} x_{1,k+1} \\ x_{2,k+1} \\ x_{3,k+1} \\ x_{4,k+1} \\ x_{5,k+1} \end{bmatrix} = \begin{bmatrix} x_{1,k} + \frac{x_{3,k}\sin(x_{5,k})}{x_{5,k}} + \frac{x_{4,k}(1-\cos(x_{5,k}))}{x_{5,k}} \\ x_{2,k} + \frac{x_{3,k}(1-\cos(x_{5,k}))}{x_{5,k}} + \frac{x_{4,k}\sin(x_{5,k})}{x_{5,k}} \\ \cos(x_{5,k})\ x_{3,k} - \sin(x_{5,k})\ x_{4,k} \\ \sin(x_{5,k})\ x_{3,k} + \cos(x_{5,k})\ x_{4,k} \\ x_{5,k} \end{bmatrix} + \begin{bmatrix} w_{1,k} \\ w_{2,k} \\ w_{3,k} \\ w_{4,k} \\ w_{5,k} \end{bmatrix} \to \mathbf{x}_{k+1} = f(\mathbf{x}_k) + \mathbf{w}_k \quad (1)$$

$$\begin{bmatrix} z_{1,k+1} \\ z_{2,k+1} \end{bmatrix} = \begin{bmatrix} x_{1,k+1} \\ x_{2,k+1} \end{bmatrix} + \begin{bmatrix} v_{1,k+1} \\ v_{2,k+1} \end{bmatrix} \to \mathbf{z}_{k+1} = \mathbf{H}\mathbf{x}_{k+1} + \mathbf{v}_{k+1}, \mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \quad (2)$$

Where $\mathbf{x}_{k+1}$ and $\mathbf{z}_{k+1}$ are the states and measurement vectors, respectively, and $\mathbf{w}_k$ and $\mathbf{v}_{k+1}$ are the systems and measurement noise vectors, respectively. $\mathbf{H}$ is the measurement matrix.

2.2. Sliding Innovation Filter

The SIF shares the same principles of the SVSF in [45], the algorithm's equations can be summarized as:

1- **Prediction Stage**, The a priori estimate ($\hat{x}_{k+1|k}$) and its measurement ($\hat{z}_{k+1|k}$), are calculated as:

$$\begin{bmatrix} \hat{x}_{1,k+1|k} \\ \hat{x}_{2,k+1|k} \\ \hat{x}_{3,k+1|k} \\ \hat{x}_{4,k+1|k} \\ \hat{x}_{5,k+1|k} \end{bmatrix} = \begin{bmatrix} \hat{x}_{1,k|k} + \frac{\hat{x}_{3,k|k}\sin(\hat{x}_{5,k|k})}{\hat{x}_{5,k|k}} + \frac{\hat{x}_{4,k|k}(1-\cos(\hat{x}_{5,k|k}))}{\hat{x}_{5,k|k}} \\ \hat{x}_{2,k|k} + \frac{\hat{x}_{3,k|k}(1-\cos(\hat{x}_{5,k|k}))}{\hat{x}_{5,k|k}} + \frac{\hat{x}_{4,k|k}\sin(\hat{x}_{5,k|k})}{\hat{x}_{5,k|k}} \\ \cos(\hat{x}_{5,k|k})\ \hat{x}_{3,k|k} - \sin(\hat{x}_{5,k|k})\ \hat{x}_{4,k|k} \\ \sin(\hat{x}_{5,k|k})\ \hat{x}_{3,k|k} + \cos(\hat{x}_{5,k|k})\ \hat{x}_{4,k|k} \\ \hat{x}_{5,k|k} \end{bmatrix} \to \hat{\mathbf{x}}_{k+1|k} = f(\hat{\mathbf{x}}_{k|k}) \quad (3)$$

$$\begin{bmatrix} \hat{z}_{1,k+1|k} \\ \hat{z}_{2,k+1|k} \end{bmatrix} = \begin{bmatrix} \hat{x}_{1,k+1|k} \\ \hat{x}_{2,k+1|k} \end{bmatrix} \to \hat{\mathbf{z}}_{k+1|k} = \mathbf{H}\hat{\mathbf{x}}_{k+1|k} \quad (4)$$

2- **Update/Correction Stage**, The a posteriori estimate ($\hat{x}_{k+1|k+1}$) and its measurement ($\hat{z}_{k+1|k+1}$), are calculated as

$$\begin{bmatrix} x_{1,k+1|k+1} \\ x_{2,k+1|k+1} \end{bmatrix} = \begin{bmatrix} x_{1,k+1|k} \\ x_{2,k+1|k} \end{bmatrix} + \begin{bmatrix} \frac{(z_{1,k+1} - \hat{z}_{1,k+1|k})}{\psi_1} \\ \frac{(z_{2,k+1} - \hat{z}_{2,k+1|k})}{\psi_2} \end{bmatrix} \to \hat{\mathbf{x}}_{k+1|k+1} = \hat{\mathbf{x}}_{k+1|k} + \mathbf{K}_{k+1} \quad (5)$$

3. FPGA IMPLEMENTATION

A FPGA is a type of integrated circuit that contains programmable logic gates, memory, and other elements on a chip. FPGAs are used in a wide range of applications, including security [46, 47], image processing [48, 49], face and object recognition [50-64], quantum computing [65-77], and artificial intelligence [64, 78-86]. To demonstrate the performance of the system and filter, we used a Zynq-7000 FPGA [78, 79, 87]. The FPGA board features a 1GHz dual-core Cortex-A9 MPCore ARM, Xilinx© 28 nm Programmable Logic, 512 MB DDR3 memory, and eXtensible Interface (AXI) interconnects [88]. To simplify implementation of the model into hardware description language such as VHDL, we used the Simulink toolbox of MATLAB. Fig. 1 through Fig. 5 show the Simulink blocks of the system and filter, including the top-level of x_1, x_2, x_3, x_4, and x_5, respectively. The system and SIF are modeled and simulated using the Xilinx© Vivado design suite [89].

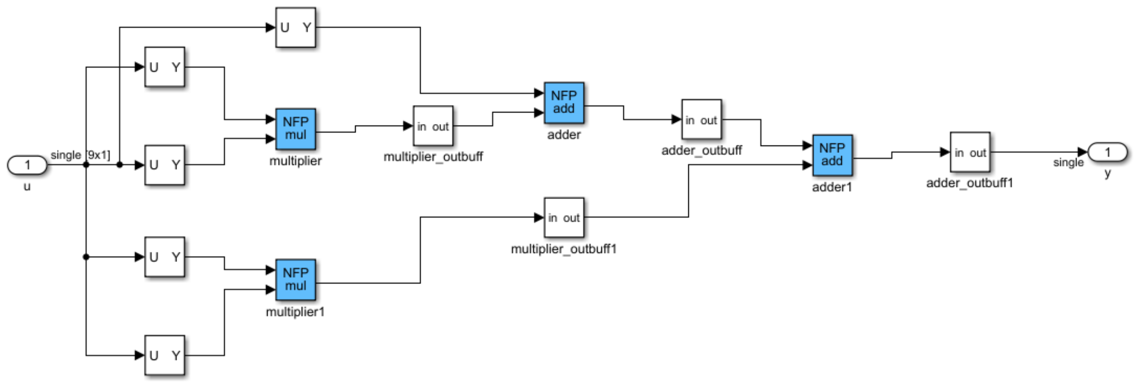

Figure 1. Simulink blocks of x_1

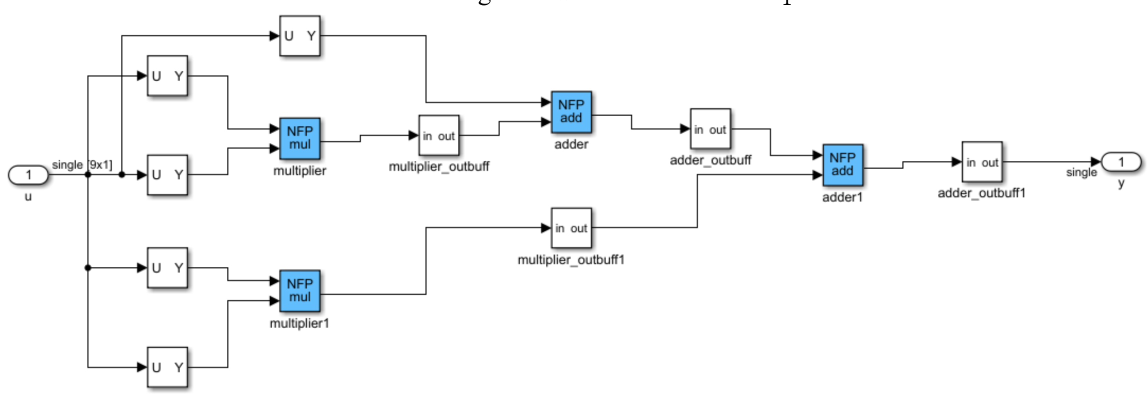

Figure 2. Simulink blocks of x_2

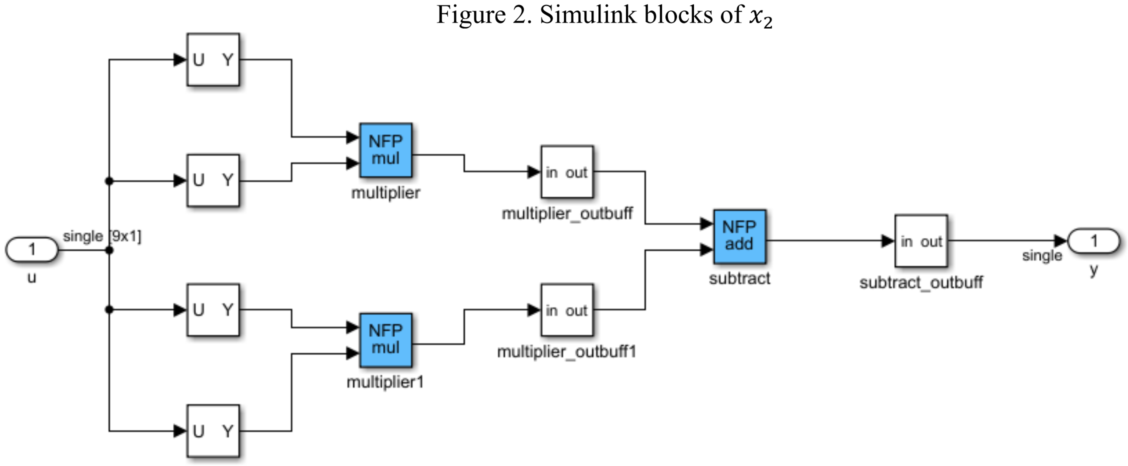

Figure 3. Simulink blocks of x_3

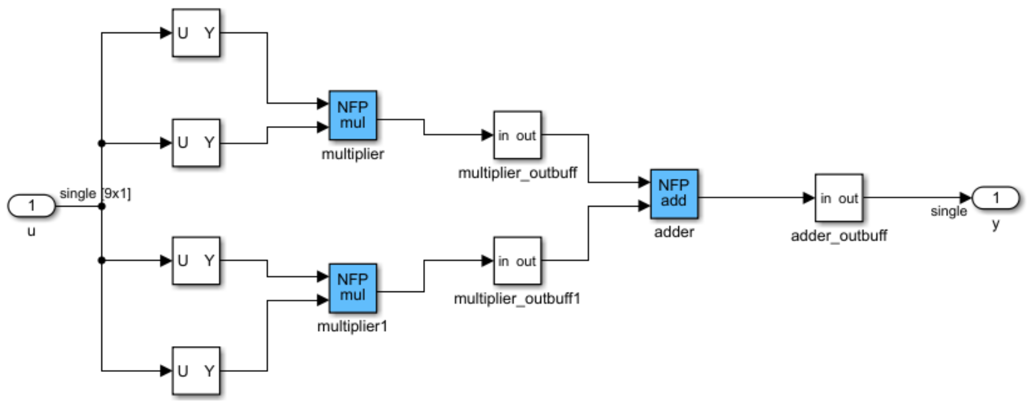

Figure 4. Simulink blocks of x_4

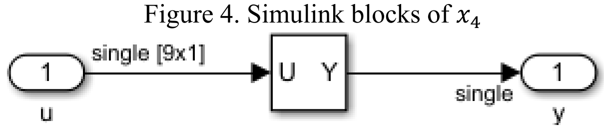

Figure 5. Simulink blocks of x_5

4. RESULTS AND DISCUSSION

We tested the models that were described in Section 3. Fig. 6 shows the resultant trajectory of the SIF in the $x_1 - x_2$ plane. The results verify the SIF's behavior, which follows the planned trajectory. Figure 7 shows the trajectories in x- and y- axes. These results confirm the efficiency of the SIF method, which matches the efficiency obtained by the SVSF in [45].

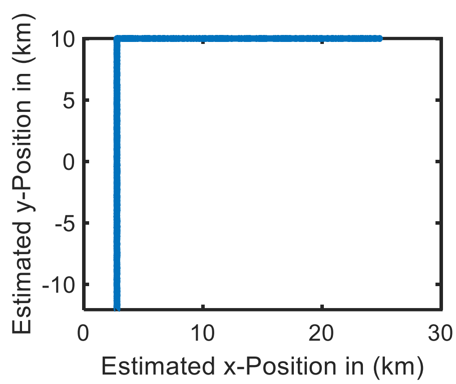

Figure 6. Simulated trajectories of $x_1 - x_2$

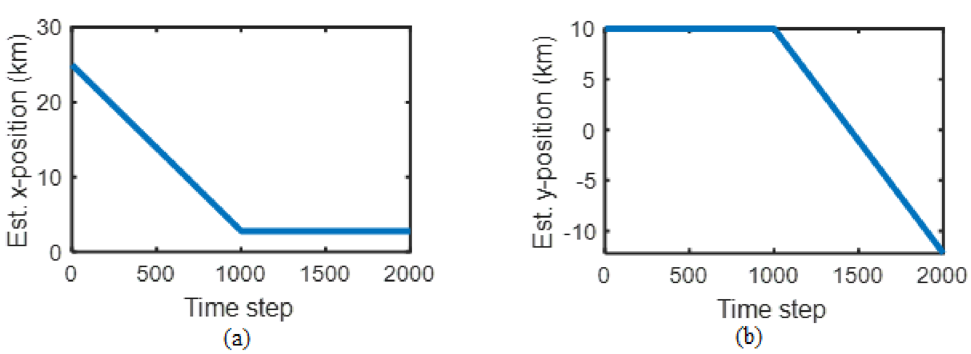

Figure 7: The estimated positions in (a) x and (b) y planes.

To implement the system on FPGAs, the basic hardware blocks required are adders, subtractors, multipliers, Sine and Cosine functions. The FPGA resources necessary for implementing the system and filter are relatively small. Specifically, less than 1% of Flip-Flops, 25% of Look-up Tables, and 8% of DSPs are required. This utilization is significantly less than what is required by the SVSF reported in [45], where 35% of Look-up Tables and 12% of DSPs were used. These are equivalent to 28.5% and 33% less usage in these resources.

5. CONCLUSION AND FUTURE WORK

Recent advancements in robotics have been made possible by improvements in control and estimation methods. One such advancement is the integration of advanced filtering methods like the unscented smooth variable structure filter and the sigma-point smooth variable structure filter into robotic arms. The smooth variable structure filter has also been extensively reviewed for its potential in nonlinear control and estimation in robotics.

In this paper, we used FPGA to program the SIF for a two-dimensional vehicle's path estimation. The results demonstrate that SIF required a smaller portion of resources compared to the SVSF, where it requires 1% Flip-Flops, 25% Look-up Tables (compared to 35% for SVSF), and 8% DSPs (compared to 12% for SVSF) for calculations in five-dimensional space. This amount is significantly less than its peers SVSF. In future work, we plan to conduct a comprehensive comparison of different filter algorithms using FPGA to measure resource utilization.

REFERENCES

[1] S. A. Gadsden and M. Al-Shabi, "The Sliding Innovation Filter," IEEE Access, vol. 8, pp. 96129-96138, 2020, doi: 10.1109/access.2020.2995345.

[2] M. AlShabi and S. A. Gadsden, "Formulation of the Alpha Sliding Innovation Filter: A Robust Linear Estimation Strategy," Sensors, vol. 22, no. 22, p. 8927, 2022.

[3] M. Al-Shabi and S. A. Gadsden, "A multiple model-based sliding innovation filter and its application on aerospace actuator," in Signal Processing, Sensor/Information Fusion, and Target Recognition XXXI, vol. 12122: SPIE, pp. 351-360.

[4] M. A. AlShabi et al., "Application of the sliding innovation filter for fault detection and diagnosis of an electromechanical system," in Signal Processing, Sensor/Information Fusion, and Target Recognition XXX, 2021, vol. 11756: SPIE, pp. 47-53.

[5] M. A. AlShabi et al., "The two-pass sliding innovation smoother," in Signal Processing, Sensor/Information Fusion, and Target Recognition XXX, vol. 11756: SPIE, pp. 63-71.

[6] L.-H. Zhao et al., "Sliding mode observer for vehicle velocity estimation with road grade and bank angles adaptation," in 2009 IEEE Intelligent Vehicles Symposium: IEEE, pp. 701-706.

[7] N. Sadati and A. Ghaffarkhah, "POLYFILTER: A new state estimation filter for nonlinear systems," in 2007 International Conference on Control, Automation and Systems: IEEE, pp. 2643-2647.

[8] T. Kailath, "A view of three decades of linear filtering theory," IEEE Transactions on information theory, vol. 20, no. 2, pp. 146-181, 1974.

[9] V. Jilkov and X. R. Li, "On the Generalized Input Estimation," INFORMATION AND SECURITY, vol. 9, pp. 107-113, 2002.

[10] Y. Feng et al., "Hybrid terminal sliding-mode observer design method for a permanent-magnet synchronous motor control system," IEEE Transactions on Industrial Electronics, vol. 56, no. 9, pp. 3424-3431, 2009.

[11] S. E. Saddow and A. K. Agarwal, Advances in silicon carbide processing and applications. Artech House, 2004.

[12] A. Daryabor and H. R. Momeni, "A sliding mode observer approach to chaos synchronization," in 2008 International Conference on Control, Automation and Systems: IEEE, pp. 1626-1629.

[13] S. Chen and J. Moskwa, "Application of nonlinear sliding-mode observers for cylinder pressure reconstruction," Control Engineering Practice, vol. 5, no. 8, pp. 1115-1121, 1997.

[14] P. C.-P. Chao and C.-Y. Shen, "Sensorless tilt compensation for a three-axis optical pickup using a sliding-mode controller equipped with a sliding-mode observer," IEEE transactions on control systems technology, vol. 17, no. 2, pp. 267-282, 2008.

[15] H. Chaal et al., "Sliding mode observer based direct torque control of a brushless doubly-fed reluctance machine," in 2009 IEEE Symposium on Industrial Electronics & Applications, vol. 2: IEEE, pp. 866-871.

[16] G. Bartolini et al., "Robust speed and torque estimation in electrical drives by second-order sliding modes," IEEE Transactions on Control Systems Technology, vol. 11, no. 1, pp. 84-90, 2003/01 2003.

[17] G. Bartolini, "Adaptive and Sliding Mode Control," in Automation and Control Engineering, ed: CRC Press, 2002.

[18] J.-P. Barbot et al., "Sliding mode observer for triangular input form," in Proceedings of 35th IEEE conference on decision and control, vol. 2: IEEE, pp. 1489-1490.
[19] Y. Bar-Shalom and X.-R. Li, "Estimation and tracking- Principles, techniques, and software," Norwood, MA: Artech House, Inc, 1993., 1993.
[20] Y. Bar-Shalom et al., Estimation with applications to tracking and navigation: theory algorithms and software. John Wiley & Sons, 2001.
[21] B. Bandyopadhyay et al., "Sliding mode observer based sliding mode controller for slosh-free motion through PID scheme," IEEE Transactions on Industrial Electronics, vol. 56, no. 9, pp. 3432-3442, 2009.
[22] C. Aurora et al., "Speed regulation of induction motors: A sliding mode observer-differentiator based control scheme," in Proceedings of the 40th IEEE Conference on Decision and Control (Cat. No. 01CH37228), vol. 3: IEEE, pp. 2651-2656.
[23] C. Aurora and A. Ferrara, "A sliding mode observer for sensorless induction motor speed regulation," International Journal of Systems Science, vol. 38, no. 11, pp. 913-929, 2007.
[24] A. Jarndal et al., "Enhancement of Sensitivity in AlGaN/GaN HEMT Based Sensor Using Back-Barrier Technique," IEEE Sensors Journal, vol. 22, no. 16, pp. 15742-15749, 2022.
[25] M. Al-Shabi et al., "Modified asymmetric time-varying coefficient of particle swarm optimization," in 2020 Advances in Science and Engineering Technology International Conferences (ASET): IEEE, pp. 1-7.
[26] M. Al-Shabi et al., "Estimating PV models using multi-group salp swarm algorithm," IAES International Journal of Artificial Intelligence, vol. 10, no. 2, p. 398, 2021.
[27] M. AlShabi et al., "Estimating one-diode-PV model using autonomous groups particle swarm optimization," IAES International Journal of Artificial Intelligence, vol. 10, no. 1, p. 166, 2021.
[28] M. AlShabi et al., "Multi-group grey wolf optimizer (MG-GWO) for estimating photovoltaic solar cell model," Journal of Thermal Analysis and Calorimetry, vol. 144, pp. 1655-1670, 2021.
[29] M. Al-Shabi et al., "Improved Asymmetric Time-varying Coefficients of Particle Swarm Optimization," in 2020 IEEE Canadian conference on electrical and computer engineering (CCECE): IEEE, pp. 1-4.
[30] M. Al Shabi et al., "A comprehensive comparison of sigma-point Kalman filters applied on a complex maneuvering road," in Signal Processing, Sensor/Information Fusion, and Target Recognition XXV, vol. 9842: SPIE, pp. 523-533.
[31] M. Al-Shabi et al., "Robustnonlinear control and estimation of a PRRR robot system," International Journal of Robotics and Automation, vol. 34, no. 6, pp. 632-644, 2019.
[32] M. Al-Shabi et al., "Smooth Variable Structure Filter for pneumatic system identification," in 2011 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT): IEEE, pp. 1-6.
[33] M. AlShabi et al., "Application of the sliding innovation filter to unmanned aerial systems," in Unmanned Systems Technology XXIII, vol. 11758: SPIE, pp. 241-248.
[34] M. A. AlShabi et al., "A comparison of sigma-point Kalman filters on an aerospace actuator," in Sensors and Systems for Space Applications XIV, vol. 11755: SPIE, pp. 150-159.
[35] M. Avzayesh et al., "The smooth variable structure filter: A comprehensive review," Digital Signal Processing, vol. 110, p. 102912, 2021.
[36] S. Gadsden et al., "Two-pass smoother based on the SVSF estimation strategy," in Signal Processing, Sensor/Information Fusion, and Target Recognition XXIV, vol. 9474: SPIE, pp. 66-76.
[37] S. Gadsden et al., "Square-root formulation of the SVSF with applications to nonlinear target tracking problems," in Signal Processing, Sensor/Information Fusion, and Target Recognition XXIV, 2015, vol. 9474: SPIE, pp. 54-65.
[38] M. Avzayesh et al., "A Hybrid Estimation-Based Technique for Partial Discharge Localization," IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 11, pp. 8744-8753, 2020/11 2020.
[39] S. A. Gadsden and M. Al-Shabi, "A study of variable structure and sliding mode filters for robust estimation of mechatronic systems," in 2020 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), 2020: IEEE, pp. 1-6.
[40] M. Al-Shabi and K. S. Hatamleh, "The unscented smooth variable structure filter application into a robotic arm," in ASME International Mechanical Engineering Congress and Exposition, vol. 46483: American Society of Mechanical Engineers, p. V04BT04A037.
[41] M. Al-Shabi et al., "The cubature smooth variable structure filter estimation strategy applied to a quadrotor controller," in Signal Processing, Sensor/Information Fusion, and Target Recognition XXIV, 2015, vol. 9474: SPIE, pp. 464-475.
[42] M. Al-Shabi et al., "Kalman filtering strategies utilizing the chattering effects of the smooth variable structure filter," Signal Processing, vol. 93, no. 2, pp. 420-431, 2013.
[43] M. Al-Shabi et al., "The sigma-point central difference smooth variable structure filter application into a robotic arm," in 2015 IEEE 12th International Multi-Conference on Systems, Signals & Devices (SSD15), 2015: IEEE, pp. 1-6.
[44] M. Al-Shabi, "Sigma-point Smooth Variable Structure Filters applications into robotic arm," in 2017 7th International Conference on Modeling, Simulation, and Applied Optimization (ICMSAO), 2017: IEEE, pp. 1-6.
[45] M. Al Shabi and T. Bonny, "The application of the SVSF into maneuvering system using FPGA," in Unmanned Systems Technology XXIV, 2022, vol. 12124: SPIE.

[46] T. Bonny and Q. Nasir, "Clock glitch fault injection attack on an FPGA-based non-autonomous chaotic oscillator," Nonlinear Dynamics, vol. 96, pp. 2087-2101, 2019.
[47] T. Bonny, "Chaotic or hyper-chaotic oscillator? Numerical solution, circuit design, MATLAB HDL-coder implementation, VHDL code, security analysis, and FPGA realization," Circuits, Systems, and Signal Processing, vol. 40, no. 3, pp. 1061-1088, 2021.
[48] T. Bonny and S. Henno, "Image edge detectors under different noise levels with FPGA implementations," Journal of Circuits, Systems and Computers, vol. 27, no. 13, p. 1850209, 2018.
[49] F. AlMutairi and T. Bonny, "Image Encryption Based on Chua Chaotic Oscillator," presented at the 2020 3rd International Conference on Signal Processing and Information Security (ICSPIS), 2020/11/25, 2020.
[50] T. Bonny et al., "Multiple histogram-based face recognition with high speed FPGA implementation," Multimedia Tools and Applications, vol. 77, no. 18, pp. 24269-24288, 2018/02/12 2018.
[51] T. Bonny et al., "SHORT: Segmented histogram technique for robust real-time object recognition," Multimedia Tools and Applications, vol. 78, no. 18, pp. 25781-25806, 2019/06/03 2019.
[52] M. Alhammadi et al., "Cursor Control Using electroencephalogram (EEG) Technology," in 2022 International Conference on Electrical and Computing Technologies and Applications (ICECTA): IEEE, pp. 415-419.
[53] W. Al Nassan et al., "AN LSTM model-based Prediction of Chaotic System: Analyzing the Impact of Training Dataset Precision on the Performance," in 2022 International Conference on Electrical and Computing Technologies and Applications (ICECTA): IEEE, pp. 337-342.
[54] W. Al Nassan et al., "A Customized Convolutional Neural Network for Dental Bitewing Images Segmentation," in 2022 International Conference on Electrical and Computing Technologies and Applications (ICECTA): IEEE, pp. 347-351.
[55] I. Ahmad et al., "An FPGA based approach for people counting using image processing techniques," in 2019 11th International Conference on Knowledge and Smart Technology (KST): IEEE, pp. 148-152.
[56] D. Younis and B. M. Younis, "Low cost histogram implementation for image processing using FPGA," in IOP Conference Series: Materials Science and Engineering, vol. 745, no. 1: IOP Publishing, p. 012044.
[57] M. Manuel et al., "Model-based design space exploration for approximate image processing on FPGA," in 2020 IEEE Nordic Circuits and Systems Conference (NorCAS): IEEE, pp. 1-7.
[58] L. Kalms et al., "Hiflipvx: An open source high-level synthesis fpga library for image processing," in Applied Reconfigurable Computing: 15th International Symposium, ARC 2019, Darmstadt, Germany, April 9–11, 2019, Proceedings 15: Springer, pp. 149-164.
[59] T. Imsaengsuk and S. Pumrin, "Feature Detection and Description based on ORB Algorithm for FPGA-based Image Processing," in 2021 9th International Electrical Engineering Congress (iEECON): IEEE, pp. 420-423.
[60] A. Dehghani et al., "A new approach for design of an efficient FPGA-based reconfigurable convolver for image processing," The Journal of Supercomputing, pp. 1-19, 2022.
[61] D. Bekker et al., "Guiding DART to Impact—the FPGA SoC Design of the DRACO Image Processing Pipeline," in 2021 IEEE Space Computing Conference (SCC): IEEE, pp. 122-133.
[62] F. Siddiqui et al., "Fpga-based processor acceleration for image processing applications," Journal of Imaging, vol. 5, no. 1, p. 16, 2019.
[63] P. Garcia et al., "Optimized memory allocation and power minimization for FPGA-based image processing," Journal of Imaging, vol. 5, no. 1, p. 7, 2019.
[64] P. Yan and Z. Xiang, "Acceleration and optimization of artificial intelligence CNN image recognition based on FPGA," in 2022 IEEE 6th Information Technology and Mechatronics Engineering Conference (ITOEC), vol. 6: IEEE, pp. 1946-1950.
[65] T. Bonny and A. Haq, "Emulation of high-performance correlation-based quantum clustering algorithm for two-dimensional data on FPGA," Quantum Information Processing, vol. 19, no. 6, 2020/05/02 2020.
[66] H. Abrar Ul and T. Bonny, "Cancer Transcriptome Analysis with RNA-Seq Using Quantum K-means Clustering Algorithm," presented at the 2020 Advances in Science and Engineering Technology International Conferences (ASET), 2020/02, 2020.
[67] Y. Xu et al., "QubiC: An open-source FPGA-based control and measurement system for superconducting quantum information processors," IEEE Transactions on Quantum Engineering, vol. 2, pp. 1-11, 2021.
[68] J. Pilch and J. Długopolski, "An FPGA-based real quantum computer emulator," Journal of Computational Electronics, vol. 18, pp. 329-342, 2019.
[69] Y. H. Lee et al., "An FPGA-based quantum computing emulation framework based on serial-parallel architecture," International Journal of Reconfigurable Computing, vol. 2016, 2016.
[70] M. Khalid et al., "An FPGA-based hardware abstraction of quantum computing systems," Journal of Computational Electronics, vol. 20, pp. 2001-2018, 2021.
[71] A. U. Khalid et al., "FPGA emulation of quantum circuits," in IEEE International Conference on Computer Design: VLSI in Computers and Processors, 2004. ICCD 2004. Proceedings.: IEEE, pp. 310-315.
[72] T. Suzuki et al., "Quantum AI simulator using a hybrid CPU–FPGA approach," Scientific Reports, vol. 13, no. 1, p. 7735, 2023.

[73] X. Qin et al., "An FPGA-based hardware platform for the control of spin-based quantum systems," IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 4, pp. 1127-1139, 2019.
[74] A. G. Mazăre et al., "New FPGA design solution using quantum computation concepts," in 2021 IEEE 27th International Symposium for Design and Technology in Electronic Packaging (SIITME): IEEE, pp. 388-391.
[75] H. Li and Y. Pang, "FPGA-accelerated quantum computing emulation and quantum key distillation," IEEE Micro, vol. 41, no. 4, pp. 49-57, 2021.
[76] K. S. Hatamleh et al., "Unmanned aerial vehicles parameter estimation using artificial neural networks and iterative bi-section shooting method," Applied Soft Computing, vol. 36, pp. 457-467, 2015.
[77] S. Gadsden et al., "Estimation strategies for the condition monitoring of a battery system in a hybrid electric vehicle," International Scholarly Research Notices, vol. 2011, 2011.
[78] M. AlFarah and T. Bonny, "Chaotic Oscillator Prediction Based on Artificial Neural Network and its Realization on FPGA," presented at the 2022 Advances in Science and Engineering Technology International Conferences (ASET), 2022/02/21, 2022.
[79] M. Al-Mheiri et al., "Car Plate Recognition Using Machine Learning," presented at the 2022 Advances in Science and Engineering Technology International Conferences (ASET), 2022/02/21, 2022.
[80] X. Xu and J. Zhang, "Rethinking FPGA security in the new era of artificial intelligence," in 2020 21st International Symposium on Quality Electronic Design (ISQED): IEEE, pp. 46-51.
[81] K. P. Seng et al., "Embedded intelligence on FPGA: Survey, applications and challenges," Electronics, vol. 10, no. 8, p. 895, 2021.
[82] L. Qi and K. Yao, "Artificial intelligence enterprise human resource management system based on FPGA high performance computer hardware," Microprocessors and Microsystems, vol. 82, p. 103876, 2021.
[83] S. Saravanan, "Smart Automotive Systems Supported by Configurable FPGA, IoT, and Artificial Intelligence Techniques," in FPGA Algorithms and Applications for the Internet of Things: IGI Global, 2020, pp. 108-132.
[84] E. RAPUANO, "FPG-AI: HW/SW co-design techniques for the automation of Artificial Intelligence deployment on FPGA platforms," 2023.
[85] Y. Y. Lee et al., "Reinventing FPGA Optimised Stochastic Computing Convolutional Neural Network Architecture for Highly Efficient Artificial Intelligence Workload," Available at SSRN 4385482.
[86] M. Abernot et al., "FPGA implementation of Oscillatory Neural Networks for Artificial Intelligence edge computing," in ACM Europe Summer school on HPC Computer Architectures for AI and Dedicated Applications,
[87] I. Digilent, (2016),. www.zedboard.org (accessed. Januray 2023).
[88] Xilinx, ""Xinlinx: 7 Series FPGAs Overview, vol. 1.,"" 2019.
[89] "Xilinx: Vivado design suite - hlx editions." www.xilinx.com/products/designtools (accessed Januray 2023).