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A Novel Bio-Inspired Approach for High-Performance Management in Service-Oriented Networks

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***Abstract*—Service-continuity in distributed computing can be enhanced by designing self-organized systems, with a non-fixed structure, able to change their structure and organization, as well as adaptively react to internal and external environment changes. In this paper, an architecture exploiting a bio-inspired management approach, i.e., the functioning of cell metabolism, for specialized computing environments in Service-Oriented Networks (SONs) is proposed. Similar to the processes acting in metabolic networks, the nodes communicate to each other by means of stimulation or suppression chains giving rise to emergent behaviors to defend against foreign invaders, attacks, and malfunctioning. The main contribution of this work is a novel bio-inspired methodology for SON analysis to improve the network reliability and robustness for maintaining service-continuity. To show the effectiveness of the proposed computational framework, an embedded Field-Programmable Gate Array (FPGA) prototyped SON for a relevant healthcare imaging application is also outlined. In particular, our case study extracts and analyzes the Cerebral Vascular Tree from Magnetic Resonance Angiography series *via* a Maximum Intensity Projection algorithm; the proposed solution addresses and implements some basic issues of an interesting diagnosis tool for cerebral aneurysm detection. The prototyped system was tested and evaluated in terms of execution time and used resource analysis, by achieving a 4× speed-up factor compared to the software counterpart.**

***Index Terms*—service-oriented networks, bio-inspired networks, high-performance management, FPGA technology, biomedical imaging, cerebral vascular tree reconstruction, maximum intensity projection, magnetic resonance angiography**

I. Introduction

THE increasing complexity of heterogeneous distributed computing environments poses a major challenge to all the staff managing large-scale networks: currently, each separate management system retains control of its own resources. To provide new services, the management systems need to yield effective means for its usage to other systems. Meanwhile, the mechanisms must be transparent to the end-users. In other words, the value of the network is based on the services provided to the end-users rather than the communication capability. The efficient management of the various services is becoming increasingly important for both providers and end-users [1].

Current Internet-based services are mostly provided by a client-server paradigm, with specific Personal Computers (PCs) or Personal Digital Assistants (PDAs), serving as clients, which access the servers of either specific companies/institutions or individuals. A ubiquitous environment could lead to a society where all entities can freely connect and collaborate with each other [2].

Bio-inspired hardware architectures, which are analyzed and investigated in [3], link several disciplines including Artificial and Computational Intelligence, Evolutionary Computation, bio-robotics, agent-based systems, and digital ecosystems [4]. Inspired by the characteristics of biological systems and following the guidelines described in [3], a novel e-service emergent method based on a bio-network service platform is proposed. The nodes communicate to each other by means of stimulation or suppression chains giving rise to emergent behaviors to defend against foreign invaders, attacks, and malfunctioning [5][6]. The system is self-organized, with a non-fixed structure that should adaptively vary according to the dynamic changes of both network and environment.

Since Service-Oriented Networks (SONs) typically manage large amounts of calculations dealing with both computational cost and resource constraints, this paper presents an embedded SON implemented using the Field-Programmable Gate Array (FPGA) technology. In order to enhance the network performance and service management, the paradigm of biological networks is exploited. Starting from some selected mechanisms in biological networks, the techniques to investigate biological networks were adapted and optimized to handle the proposed bio-inspired SON framework. Fig. 1 shows the workflow of our bio-inspired SON architecture. The FPGA boards, implementing monitor and service nodes, are connected to the SON: this makes the proposed architecture a flexible solution in networked environments, wherein a shared use is generally required. This architecture can provide specialized e-services in a distributed environment, able to take advantage of FPGA hardware acceleration for computationally expensive algorithms.

In this paper, we aim to investigate the Metabolic Network (MN) techniques as a bio-inspired solution in the SON management. The proposed bio-SON consists of two main node types: (*i*) the monitor node, and (*ii*) the functionality node. Starting from the MN analysis, the SON robustness can be investigated by using three interacting techniques [7], namely: (*i*) Topological Analysis (TA) [8], (*ii*) Flux Balance Analysis (FBA) [9], and (*iii*) Extreme Pathway Analysis (ExPA) [10]. The main contribution of this work is a novel bio-inspired methodology for SON analysis to improve the network reliability and robustness for maintaining service-continuity. Different from a passive analysis, our approach has the objective of identifying an alternative path, when allowed by the redundancy in the network, to continue providing the requested service. In our case, increasing the robustness is considered as service-continuity (where a service denotes the execution of a sequence of basic functionalities) and the resulting SON shows a higher robustness. To show the effectiveness and feasibility of our bio-inspired framework, we present a proof-of-concept for biomedical imaging environments. More specifically, the developed embedded SON combines a monitor node that exploits bio-inspired techniques for network management and a sequence of functionality nodes providing, as in the case of a Cerebral Vascular Tree (CVT) reconstruction service based on Maximum Intensity Projection (MIP) from Magnetic Resonance Angiography (MRA) series, an interesting diagnosis tool useful for cerebral aneurysm detection. Our bio-inspired SON implementation was deployed onto the Celoxica RC203E board (Celoxica Ltd., London, UK) and was evaluated in terms of execution time and required resources.

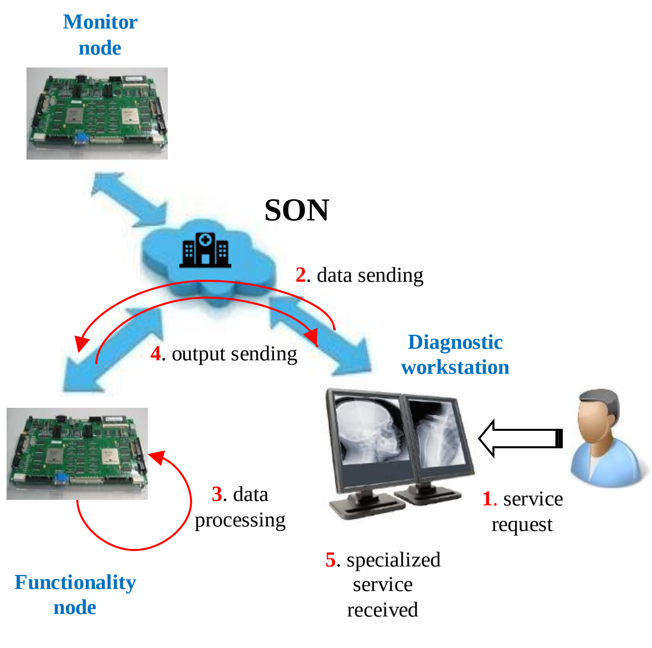

Fig. 1. Workflow of the proposed bio-inspired SON architecture.

The manuscript is structured as follows. Section II outlines the background and introduces the basic concepts of SONs. Section III discusses the biological approach applied to network-based environments. Section IV describes the proposed bio-inspired SON. Section V illustrates and discusses the implemented healthcare imaging case study. Finally, Section VI provides conclusions and future research avenues.

II. Background

An SON is a set of networked devices that collaborate to supply different services. In this context, a service is defined as a combination of distinct software components existing as a single instance and interacting with applications and other services through a loosely coupled, message-based communication model [11]. SON devices work at the application layer to provide functions, such as service-based routing, content transformation, and integration protocols to consumers and providers. SONs provide many benefits regarding performance and efficiency, and enable the integration of heterogeneous environments [12].

An SON is focused on the services provided across a network rather than the technologies or their related components. The used technologies and components are hidden to the end-users and third-parties, so they only consider how to get and use the services. Nevertheless, the quality of a service strongly depends on the communication links and the inherent quality of the devices. Services can be implemented in different languages and deployed onto several platforms, but due to their complexity, they are mainly implemented on PC-oriented platforms. However, the number of services implemented on architectures based on the FPGA technology, which takes advantage of the special features that these devices offer, is growing.

Due to the increasing demand for more efficient network management systems, the concept of Service-Oriented Architecture (SOA) has attracted networking professionals' attention. An SOA provides patterns for architecture, design, implementation of loosely coupled, distributed services regardless of an underlying platform or implementation; thus, it represents a well-suited solution for building a more efficient network management system [13].

The work in [14] proposed a multimedia platform based on an SOA for indoor teaching of musical instruments. With the goal of delivering better teaching, a multimedia teaching platform based on an SOA was designed. Firstly, the characteristics and requirements of multimedia were analyzed from the specific requirements, and the corresponding functionalities were designed and implemented for each operator. Secondly, this SOA architecture allowed for realizing a centralized management and distributed deployment, along with a flexible expansion and convenient maintenance of the system. Finally, a small-scale multimedia teaching platform was constructed, while the effectiveness of the developed teaching platform was verified by the actual test. Telecommunication providers may also use SOAs to provide its users with more and more services and features. In fact, many operators have to launch various digital services (over text messaging and voice calls) to transform their networks from naïve pipes to smart ones. By using Software-Defined Networking (SDN), it is possible to boost the network transformation more easily and also foster the innovation of novel telecommunication services, such as Software-Defined Wide-Area Networks (SD-WANs). To provide a dynamic network control, in [15] a new SON-based provisioning system to support on-demand self-service network services was proposed. Wireless Sensor Networks (WSNs) represent an evolution with respect to traditional communication nodes. WSNs have become essential components for their flexibility capable of supporting a wide variety of services (e.g., environmental, surveillance, traffic control, healthcare) [16]. These applications must deal with critical challenges, such as communication, security, power consumption, data aggregation, heterogeneity of sensor hardware, and Quality of Service (QoS) issues. An SOA might be effectively integrated with WSN applications to address those challenges.

The authors of [17] proposed an embedded Web Service for the integration of applications running on heterogeneous architectures. This solution was obtained through the provision of a support for the development and deployment of Web Services onto embedded platforms supported by an embedded operating system. The authors relied on the SHIP board as platform and the gSOAP as Web Service development toolkit. However, their architecture showed some disadvantages:

- gSOAP simplifies the realization of applications, but invariably increases the need for hardware resources and computational power;
- although the SHIP board is a low-cost solution, it presents clear drawbacks in terms of performance and liability because of the software complexity;
- it is necessary to modify the gSOAP source code in order to make it compatible with the SHIP operating system.

The authors of [18] proposed the Service Oriented Automatic Switched Transport Network (SO-ASTN) as an enabling technology to support Global Grid Computing. The SO-ASTN architecture was conceived in terms of functional blocks and interfaces and was open to various hardware and software implementations in order to optimize performance by potential manufacturers. The improvement with respect to the classic ASTN architecture was mainly due to the integration of an extra functional layer, namely the Service Plane, which contains the intelligence for service provisioning. After verifying the user identity, it arranges any activity needed for the actual service provisioning, management and real-time monitoring of service performance. Moreover, it is able to hide and mask the transport network details to the user.

In this work, we propose a bio-inspired method for the analysis and management of formerly designed or pre-existing SONs. In fact, it must be considered that often the networks already exist, with a pre-existing infrastructure, such as in healthcare computing environments where the proposed solution must fit with well-established computer-assisted work practices [19]. Therefore, when the network design has been already accomplished, intervening at the level of service monitoring and resource allocation/use is the only solution, as in the Software Defined Communication Systems (SDCSs) [20]. We have implemented a methodology that aims to increase the robustness and reliability of a SON, with particular focus on the service-continuity, by leveraging the MN formalism along with bio-inspired techniques. In order to demonstrate the effectiveness of our approach, the medical field was chosen as a case study for its critical characteristics, such as the need for always providing a reliable result to support the subsequent diagnosis and intervention [21][22]. In the context of neuroradiology, CVT-based analyses [23][24] and aneurysm detection [25][26][27][28][29] are hot topics. In these critical scenarios, SONs can enable remote collaboration and decision support for acute stroke care [30]. All the details of our approach and the proposed case of study are fully explained in what follows.

III. The Biologically-Inspired Approach in Networked Environments

The increased complexity of communication technologies has led to new challenges in network management and, more specifically, in efficient mechanisms for bandwidth and resource management. Future data communication networks reveal three emerging trends: (*i*) increasing network size, (*ii*) increasing traffic volumes, and (*iii*) dynamic network topologies. Efficient network management solutions are required to be scalable – coping with large and increasing traffic volumes – as well as to provide decentralized and adaptive routing strategies according to the dynamics of the network topology. Since biological systems exhibit properties that meet the requirements of self-governance, this work proposes a bio-inspired approach to efficiently leverage these mechanisms [31][32][33]. With more details, the authors of [31] and [32] developed a solution that meets the requirements of self-governance. Their work proposed a bio-inspired technique to efficiently manage resources in Internet Protocol (IP)-based core networks. This approach, called Bio-Inspired Resource Self-Management, aimed at providing a holistic solution for Internet Service Providers (ISPs) to manage their resources at different time-scales, as well as automating the interactions with underlying carrier network operators for dynamic resource provisioning. Their solution was based on the adaptation and integration of various biological principles, such as blood glucose homeostasis, chemotaxis, reaction-diffusion, and hormone signaling. Generally, the bio-inspired principles support a high degree of robustness, which is a key feature towards adapting in fluctuating network environments. In [33], the authors introduced preliminary studies for FUNNet, a new routing algorithm inspired by the kingdom of fungi. Fungi form robust, resilient and responsive networks that can modify their own topology as a consequence of changes in local conditions. Fungi are capable of expanding in size as they self-regulate and optimize the balance between exploration and exploitation according to the transport of the internal resource, i.e., 'traffic', within the network. FUNNet was based on the biological processes that are responsible for simulating fungal networks in a bio-inspired routing protocol.

However, among biological systems, MNs play a central role. The biologically-inspired models available in the literature, MNs have been considered for their natural description *via* a connectionist structure and their redundancy capacity [34][35][36], since they are organized as highly connected functional modules [37][38]. These biological networks can compensate for internal malfunctions, continuing to produce certain substances for cell survival, by the identification of alternative paths between source and destination nodes [39]. The equivalence between SONs and MNs (for instance, denoting the *Escherichia coli* central metabolism network [35]) can be summarized as follows:

- both types of networks are characterized by a scale-free structure [40];
- both types of networks can be formalized as a graph [36];
- the MNs and SONs are composed of functional modules [37] and clusters of nodes [38], respectively;
- the MNs have (few) hub and (many) non-hub nodes [35][36], while the SONs have monitor (few) nodes and (many) basic functionality nodes. To some extent, SONs can be similarly represented, with central node hubs (with many connections) and peripheral nodes (with few connections) that perform simple or composite functions divided into modules/clusters that provide a set of services. Central hub nodes are implemented by monitor nodes and clusters represent the functional modules of the MNs;
- in the MNs a path between an input node and an output node represents a series of chemical reactions in order to produce a substance for cell survival [37], while in the SONs a similar path represents the sequential execution of a list of basic functionalities to provide the requested service (that is the principal aim of this work).

In this work, we aim at investigating the MN-based analysis techniques as a bio-inspired solution for effective SON management. These networks comprise the chemical reactions of metabolism, as well as the regulatory interactions that guide these reactions. An MN can be represented by a graph, where the nodes are chemical compounds involved in cellular reactions (i.e., metabolites) and the arcs (i.e., links) represent biochemical reactions, catalyzed by a specific enzyme. MNs represent a powerful tool for studying, understanding, and modeling metabolism; furthermore, they have some important properties related to the conservation of thermodynamic constraints, such as mass and energy [40]. From a functional perspective, MNs are composed of the interconnection of several functional modules. Generally, each functional module is composed of a high number of nodes. In other words, complex cellular networks are composed of several functional modules, reproducing metabolic pathways and describing the entire cellular metabolism of an organism. Each functional module produces a particular substance for cell survival.

MNs are considered as highly dynamic environments, where there is no central point of control, while the robustness is closely related to their inherent redundancy. Usually, every network has a real variety of different paths connecting each pair of nodes, so that its topological structure determines how it can respond to faults and failures [34]. However, the MNs' global behavior depends on the basic knowledge of their functional modules.

Interestingly, MN robustness can be investigated by using three interacting techniques [7]:

- TA [8], which conveys information on network structural aspects;
- FBA [9], which identifies the optimal conditions for cell growth, providing – under particular chemical and physical constraints – the flux combinations yielding the maximum rate of cell biomass production;
- ExPA [10], identifying metabolic pathways required for cell survival.

To summarize, SONs can be considered as fully distributed schemes, implementing peer-to-peer interactions [41][42]. When the architecture presents few highly connected nodes (i.e., hubs) and many low connected nodes, the corresponding SON has a scale-free architecture [43]. In scale-free networks, the nodes' degree distributions of many different complex networks can be better described by a power-law of the form $P \sim k^{\gamma}$ rather than the conventional Poisson distribution. The power-law degree distribution implies that a few nodes have a massive amount of links, while a large number of small degree nodes are present. Assuming that high degree nodes play a more important role than lower degree nodes, the scale-free networks are considered error tolerant (i.e., high probability than a randomly chosen node has a low degree) and attack vulnerable (i.e., a high degree node might be intentionally attacked) [38][40].

A. Biologically-Inspired Network Management Tools

This section describes the main features of the Bio-Inspired Analysis Methodology (BIAM) framework for biologically-inspired network management [44]. BIAM allows for analyzing the main structural and functional characteristics of metabolic networks, through the use of several interacting investigation techniques based on TA [8], FBA [9], and ExPA [10]. Classic techniques for network analysis passively monitor the network status and functionalities, under normal and perturbed conditions. Differently, our approach can effectively monitor the network status under normal conditions and yield an alternative solution found by exploiting the redundancies in the network. This characteristic allows the network to continue providing the requested service: a higher SON robustness leads to service-continuity. The proposed biologically-inspired SON is the implementation of a network consisting of two main node types: (*i*) the monitor node, and (*ii*) the service node (Fig. 2).

The network behavior can be investigated in both normal working conditions and in perturbed ones, after a targeted attack against a network arc (i.e., reaction) or node (i.e., metabolite). Thus, an attack to a network arc corresponds to the deactivation of the flows corresponding to the reactions associated with it, while the damage of a node is the deactivation of the corresponding incoming and outcoming flows [45][46]. In what follows, the three implemented investigation techniques are briefly described.

1) Topological Analysis

The TA conveys information regarding the network structural aspects, such as the network size (for example, the definition of its diameter) and significance of each node within the network. In addition, it provides a list of inbound and outbound hub nodes. With more details, the topological analysis yields the following parameters and coefficients: metabolites' number; reactions' number; network diameter; input average degree (related to the input link number of a node); output average degree (related to the output link number of a node); within-module degree; participation coefficient.

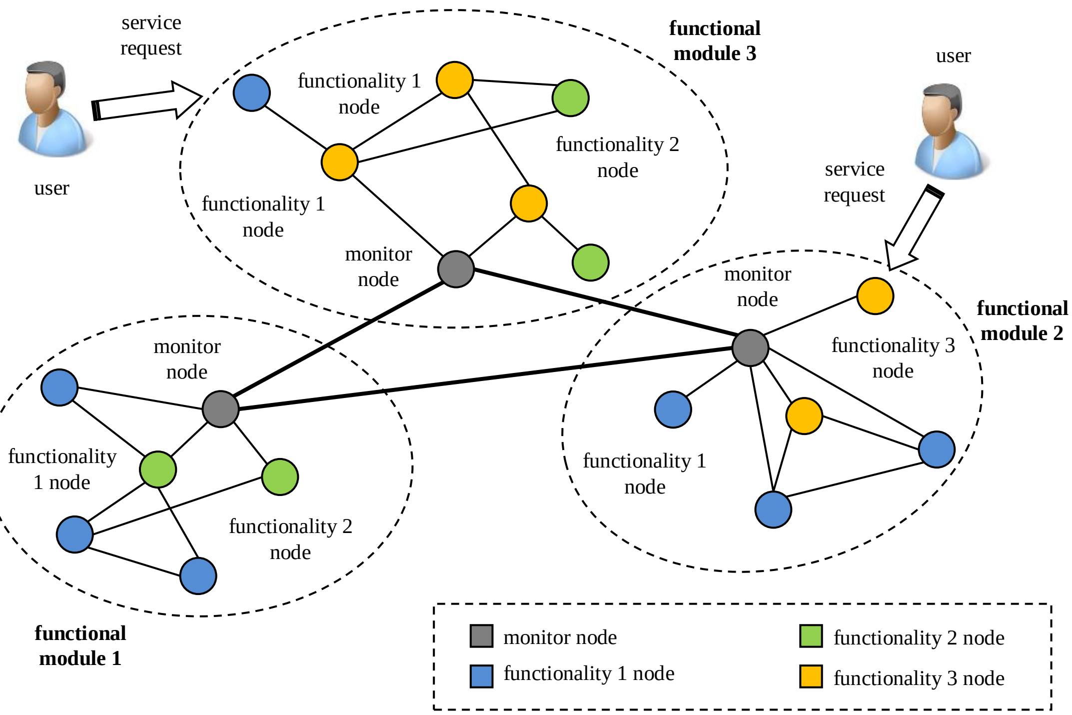

Fig. 2. General scheme of an SON providing specialized computing services.

Among all the biological information obtained from the TA, those of great relevance for the network management are: (a) the metabolites' number, (b) the reactions' number, (c) the diameter and (d) the node significance. These parameters correspond to the number of nodes in the network, the existing links between nodes and to their type (unidirectional/bidirectional), the highest distance between two network nodes and to the functionality type provided by the node, respectively. Fig. 3 shows an example where the information conveyed by the TA (according to the number of nodes present in the network, the links available between each node pair, and the network diameter) allows us to infer the network topology and correctly provide the requested service.

2) *Flux Balance Analysis*

The FBA identifies the optimal conditions for cell growth and provides, under particular chemical and physical constraints, the flux combinations yielding the maximum rate of cell biomass production. Thus, it provides important information regarding the ideal speed of nutrients' administration, called nutrient-uptake. The FBA is valuable in cancer heterogeneity modeling [47], and also for spatio-temporal dynamics when combined with other bio-inspired techniques, such as Cellular Automata [48][49].

The FBA implemented in BIAM performs several operations:

- *network displaying*: reactions, metabolites (nutrients and products), maximum and minimum capacity of each reaction (capacities represent the typical saturation velocity of a given enzyme) are displayed;
- *genetic manipulations*: the network maximum and minimum capacities can be modified (the user can also choose to remove one or more nodes or reactions);
- *results*: the optimal biomass value of a network, under particular environmental conditions; the reactions involved in the biomass production; the minimum set of reactions needed to guarantee the metabolism survival.

The use of the FBA inside a networking scenario conveys information about single link capacities and about the overall data exchange throughput (network biomass): the reduction of biomass means that a problem (e.g., congestion, link down) is occurring somewhere in the network. In other words, the FBA allows for identifying which of all possible paths, between source and destination data, it is the most suitable (for instance, in terms of speed, throughput, and shortest path) to obtain the desired final results (Fig. 4).

3) *Extreme Pathway Analysis*

The ExPA computes the network extreme pathways within the metabolic network. This technique selects the metabolic pathways required for cell survival. BIAM detects the network extreme pathways in three steps:

- *user interactions*: the user must select the directions of fluxes (incoming, outcoming or bidirectional);
- *processing*: the framework implements the ExPA algorithm for detecting the extreme rays and generating the vectors of convex polyhedral cones;

- *results*: the framework returns the list of extreme pathways as a function of linear combinations of internal and external fluxes. Moreover, it shows the maximum length for each extreme pathway, and the Participation Coefficient of each internal or external flux. The participation coefficient represents the degree value of each flow participating in the extreme pathway composition.

The monitor node uses the ExPA to determine whether a link is no longer available on the functional module. If the functionality/node is not available, it sends a request to all network monitor nodes in order to determine if an alternative path can reach the functionality/node inside another functional module. This property is useful to allow for continuously providing the service (Fig. 5). Similar to MNs, where extreme pathways are all the paths that connect an input node to an output node in order to produce organic material – such as a biomass – in SONs, these paths represent all the paths that can provide the requested service.

The proposed analysis strategy for information flow and fault/error tolerance detection requires several steps. The first step is represented by topological property detection in the analyzed SON. It is possible that most network nodes belong to a single pathway. Successively, the role of each node should be identified and the ExPA and FBA methods are performed. This integrated approach produces an in-depth knowledge on SONs and interacting processes.

The three interacting techniques (i.e., TA, FBA and ExPA) yield SON architectural information under normal or perturbed conditions. The retrieved information can be used to define the status and suggest feasible solutions to restore and preserve SON architecture and functionalities.

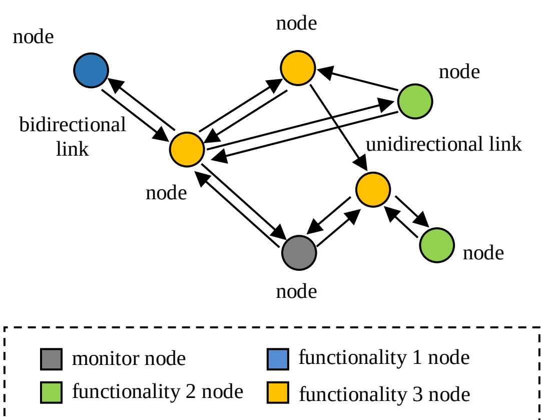

Fig. 3. Information provided by the TA (depending on the number of nodes present in the network, on the links available between each node pair and on the network diameter) used to infer the network topology, necessary to correctly provide the requested service.

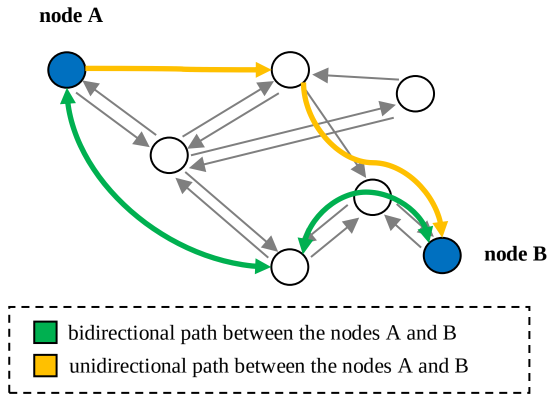

Fig. 4. Two possible paths detected between the source (node A) and destination (node B): the bidirectional and unidirectional paths are represented in green and yellow, respectively. The information provided by the FBA is used to determine which route will take the packets depending on the requested service.

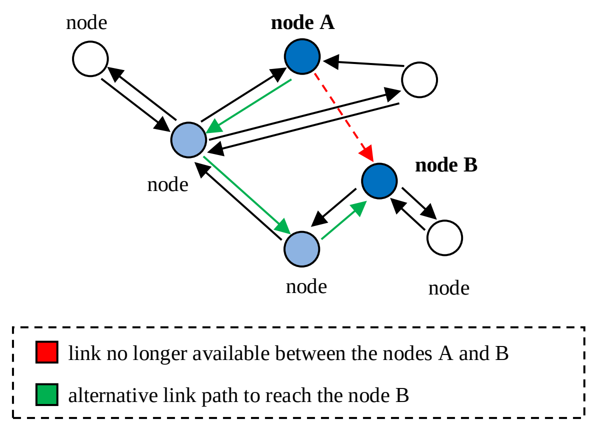

Fig. 5. The ExPA can determine if a link (in red) between two nodes is no longer available and if an alternative path (in green) exists.

IV. THE PROPOSED BIOLOGICALLY-INSPIRED SON

The proposed bio-SON is the implementation of a network consisting of two main node types: (*i*) the monitor node, and (*ii*) the service node (Fig. 2).

Monitor nodes, connected to each other, are used to perform the analysis for the management of the whole network. Each node manages its own functional module, constructing the routing tables on the node service, identifying all possible paths to provide any available service, and periodically updating the topological structure of the network. The service node is an *ad hoc* hardware realization for the optimization of the execution time and computing resources needed to provide the service.

Despite of existing work, an FPGA-based technology for embedded architecture implementation was chosen and realized. The proposed solution offers the following advantages with respect to traditional PC-based architectures:

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- lower costs of design, development and maintenance:
  - a lower amount of hardware resources entails a lower cost device;
  - the possibility of realizing the whole service in just one device implies a lower cost for the SONs;
  - FPGAs are plug-and-play devices that denote simple installation;
- efficient power consumption management, thanks to the possibility of executing several cores at different clock rates;
- high-performance, due to a fully hardware implementation of the service [50][51];
- reliability and robustness, since it is hard to keep control of the system under Denial-of-Service style attacks. In addition, because of the absence of an Operating System, the services are less vulnerable to other types of attack;
- dedicated hardware with low power consumption allows us to integrate services into embedded applications.

A. Network Setup

Aiming at guaranteeing the services offered by the network, it is essential to ensure its correct setup (in the initial configuration phase) and, if any problem occurs (e.g., external attacks or malfunctions affecting one or more nodes) or when necessary, perform a new network setup to guarantee the availability of the services. In the initial phase, the goal is to set-up the network with redundant logical paths providing all the requested services. The following parameters are defined:

- N is the network nodes' number;
- M is the functionalities' number available in the network;
- $\{f_1, f_2, \dots, f_M\}$ denotes the set of M functionalities available at a low-level;
- **FI** (Functionality Importance) is an $M \times 1$ vector where the i-th element ($i \in \{1,2,\dots,M\}$) quantifies the importance of the functionality i, used in the network setup phase in order to have multiple (redundant) nodes with the same functionality;
- **CM** (Connectivity Matrix) is an $N \times N$ matrix where each element (i,j) defines the existence or not of a link connecting the node i to the node j.

The TA discovers information regarding the network structural aspects, making it possible, for instance to detect non-hub and hub nodes. Given a network with N processing nodes, and a number of connections between nodes (as defined in the **CM** matrix), the network setup procedure is performed as follows:

i. Q monitor nodes are selected among candidates (hub nodes) obtained after the TA execution;

ii. X_q nodes are assigned to each monitor node ($\forall q = 1,\dots,Q$ and with $\sum_{q=1}^{Q} X_q = N$) in order to have Q functional modules;

iii. M functionalities (with $M < N$) are assigned to the first M nodes;

iv. functionalities with higher importance (as defined in the **FI** matrix) are assigned to remaining $M - N$ nodes, in order to guarantee a minimum redundancy;

v. each node stores the information in the **C** matrix, providing the functionalities provided by each node belonging to its own functional module (Fig. 6);

Thus, the result of the network setup phase is a matrix **C**, as schematized in Fig. 6, where the characteristics of each node are defined in terms of (i) provided functionality and (ii) list of functionalities provided by all the network nodes.

Each node receives a packet with the data to be processed and the sequence of functionalities to be performed for obtaining the requested service. The first node applies its own functionality and sends the obtained result to the node capable of providing the next functionality in the sequence. The node executing the last functionality of the sequence sends the result back to the requesting node. If the i-th node of the functional module (according to its local information) is not aware about which node performs a needed functionality, it sends a request to its monitor node (belonging to the same functional module). Each monitor node contains, for all the nodes present in the network, the information illustrated in Fig. 6.

The setup network is performed in the first startup phase and must be repeated whenever the network topology changes (e.g., fallen node, inability to reach a destination, connectivity problems). Each node, with an exact time interval, broadcasts a 'heart-beat' to communicate that everything is properly working. When any node falls down, it will not send its heart-beat and one of its neighbors will detect the event (a similar situation occurs when a link is disrupted). The first neighbor detecting the problem will start a new network setup procedure to restore the functionality that is no longer available, as well as to guarantee service-continuity.

B. Service Management

The bio-inspired techniques – ExPA and FBA – after functionality assignments, yield architectural information about the SON.

For service management, the following parameters are defined and used:

- ***AP*** (All-Paths) is a matrix where each row represents the list of low-level functionalities between a pair of input-output nodes, obtained after the ExPA execution;
- ***SP*** (Service Path) is a $P \times M$ matrix in which the j-th service is defined in the row j as a sequence of the M functionalities of the single nodes of the network;
- ***SLB*** (Single Link Bandwidth) is an $N \times N$ matrix where each element (i,j) quantifies the bandwidth of the link joining the node i to the node j;
- ***APB*** (All-Path Bandwidth) is a matrix, where each row represents the bandwidth of each of path between a pair of input-output nodes, obtained after the ExPA execution considering ***SLB*** matrix.

The ExPA computes the network extreme pathways within the network; in particular, it allows for identifying all the paths, rows of the **AP** matrix, as sequences of functionalities that the SON is able to provide.

Node ID	Node Functionality	$f_{1,q}$				$f_{2,q}$		$f_{3,q}$	…	
1	f_1	1	3	…	6	2	4	7	…	…

Fig. 6. Example of network information stored in each node belonging to the q-th functional module: for each functionality, the i-th node is aware about the nodes list providing it.

Depending on the specific application domain, services are defined as a sequence of functionalities (see Figs. 6 and 8). A domain expert collects this information defining the **SP** matrix as shown in Table I. With more details, the **SP** matrix $\{s_1, s, \ldots, s_P\}$, defining the set of P services that can be requested to the network (as a composition of low-level functionalities), is loaded in all network nodes during the setup phase. When a service s_i $(\forall i = 1, \ldots, P)$ is requested to the network, a check is performed to find in the **AP** the same sequence.

The FBA conveys information about single link capacities and about the overall data exchange throughput. If during the previous check the many sequences are found in the **AP** matrix, to realize the requested service, the FBA execution, considering **APB** matrix, allows for choosing the sequence to optimize bandwidth of the path.

TABLE I
EXAMPLE OF AN SP MATRIX, DEFINING P SERVICES IN TERMS OF A SEQUENCE OF LOW-LEVEL FUNCTIONALITIES

Service	Service Definition (in terms of functionalities' sequence)
s_1	f_1, f_3, f_4
s_2	f_2, f_3
s_3	f_4, f_1
…	…
s_P	f_2, f_3, f_4

V. Case Study: Early Implementation of an Embedded Bio-SON for Cerebral Vascular Tree Reconstruction

This section describes an embedded bio-SON composed of a monitor node and a service node deployed onto two interacting FPGA boards. The first node is implemented by means of the previously described bio-inspired tools for network management. The second node provides the CVT reconstruction service.

The provided service was divided into a sequence of low-level functionalities applied to the input MRA image series. Figs. 7 and 8 show a high-level representation and the scenario of the of the CVT reconstruction request composed of three functionalities: 1) sharpening filter; 2) MIP reconstruction; 3) dataset rotation.

When the user selects the high-level service (i.e., CVT reconstruction), the following steps are performed:

- the requested service is subdivided, according to the **SP** matrix, into P services in terms of a sequence of low-level functionalities (such as in the example shown in Table I);
- the data are sent to each functionality node of the processing chain;
  - if all the nodes are within the same functional module, no monitor node is queried to route the data;
  - otherwise, the monitor node is queried to properly route the data to the other functional modules providing the desired functionality;
- the final output data are sent back to the requesting user.

The proposed experimental validation represents just an early implementation of our computational framework. The aim of the implementation is to show potentialities in a case study, such as medical imaging, where reliability and flexibility are fundamental. However, this proof-of-concept is functional for verifying the effectiveness of the proposed methodology. The scenario in Figure 8 was modeled to show the system working under perturbed conditions. We implemented the portion of the whole scenario that is the best-suited to the limited hardware resource availability (i.e., two RC203 boards in our laboratory).

Tables IV and V show the resources needed for realizing the basic functionalities and the monitor node, respectively; it is possible to observe that the first board is necessary for the implementation of the monitor node, while the second one is needed for realizing the three functionalities described.

Accordingly, it was not possible to show the monitor node in working mode since it only intervenes in the initial setup phase of the network (by means of TA, FBA, and ExPA) and then remains in a waiting state until a new request is performed.

A. The Monitor Node Implementation

The monitor node, necessary for the SON management, is based on the approach used to realize the metabolic processor in [52]. Fig. 9 outlines the overall block scheme of thee monitor node, along with the main components. The following guidelines and design choices were adopted.

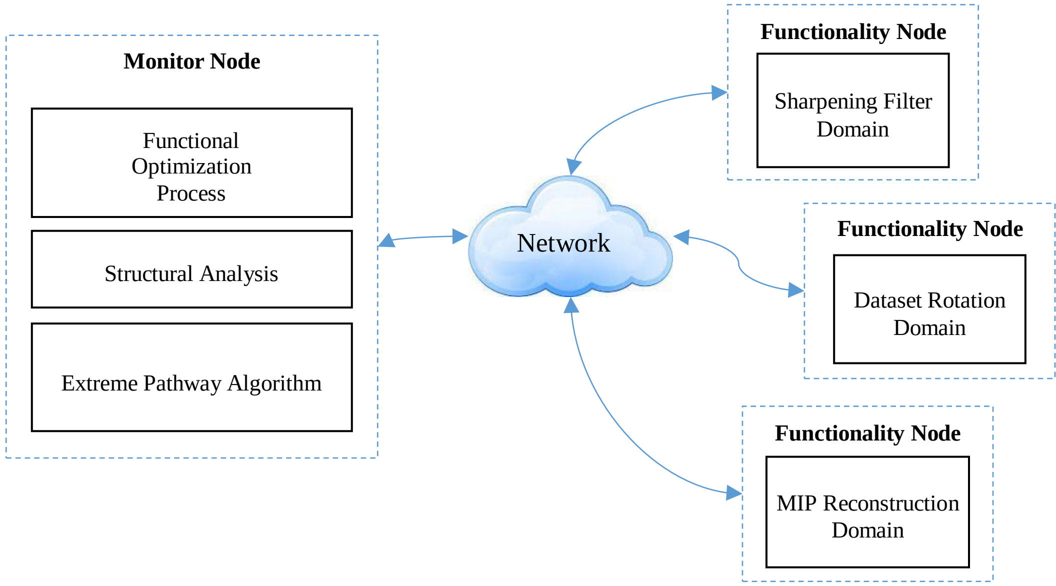

Fig. 7. High-level representation of the overall architecture of the CVT reconstruction service.

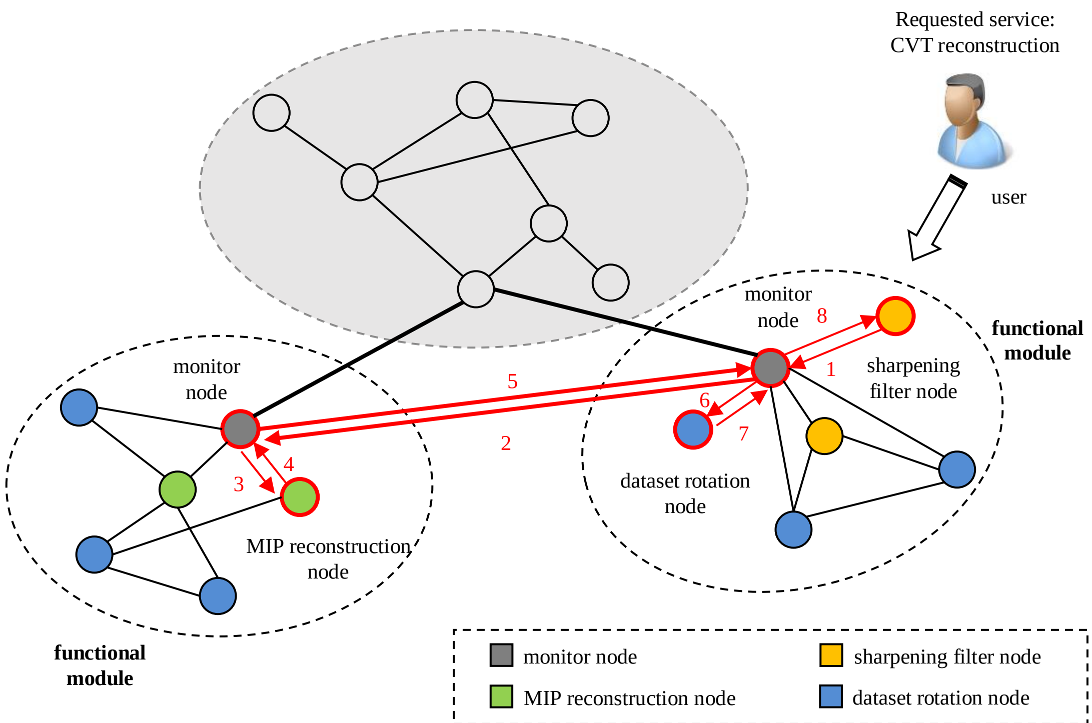

Fig. 8. Scenario of service provision in a bio-inspired SON. In this case, the service (CVT reconstruction) is requested, which includes functionalities belonging to different functional modules. Starting from the first processing operation (i.e., sharpening filter), the data are sequentially processed until the last functionality is performed (i.e., dataset rotation). The last node sends the result packet back to the requesting user.

1. *Input Block*. Inputs of the monitor node consist of a network structure representation: metabolites, link capacity and stoichiometric coefficients, based on static environmental parameters (i.e., temperature, humidity, and pressure).
2. *Embedded Metabolic Processor Block*. The embedded metabolic network is the core of the monitor node and is composed of three functional modules: functional optimization process, structural analysis, and the ExPA algorithm. These blocks receive the network structure representation and yield the related optimized outputs. With more details:

- Functional Optimization Process. This functional block implements the simplex algorithm [53], used in the Operational Research, to calculate the best solution in the FBA.

- Structural Analysis. This analysis is used to calculate the network node type. The nodes of a complex (metabolic) network can be classified into distinct groups according to the evaluation of two parameters: the connectivity degree and the Participation Coefficient. With these two parameters and their characteristics, seven different node types can be defined and how each node is positioned within the network. The metabolic network nodes are defined as non-hub and hub nodes.
- ExPA. This analysis determines if a link is no longer available on the functional module. Besides, in this first implementation, this algorithm is used to calculate the network diameter, in order to optimize the resource consumption.

3. *Output Block*. The output results provided by the monitor node consist of the identified hub/non-hub nodes, the final biomass, the flow rates based on the optimal flows value, and possible extreme pathways.

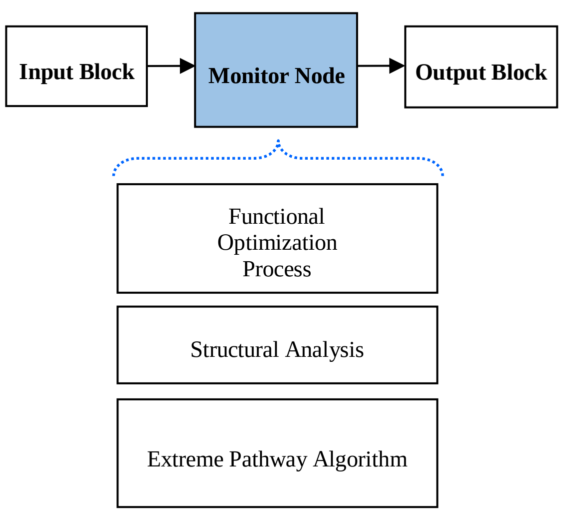

Fig. 9. Overall block scheme of the monitor node used in the SON optimization.

B. *The Service: Cerebral Vascular Tree Reconstruction*

In medical imaging, MRA can allow for the computer-assisted detection of cerebral aneurysms [25], especially by exploiting Convolutional Neural Networks (CNNs) [27]. In addition, the combination of CNN-based classification and the MIP algorithm represented an effective solution in [29]. After the CVT segmentation, Zhou *et al.* [28] devised 3D cerebrovascular mesh models from the medical images for intracranial aneurysm detection by an ensemble deep model. Along with aneurysm detection [26], CVT-based applications in the clinical practice pertain to neurovascular abnormality grading for rapid surgical repair, as well as to risk prediction of adverse events *via* graph-based models [23][24]. In these critical scenarios, SONs can enable remote collaboration and decision support for acute stroke care [30].

As a service provided by the SON, this case study presents a networked node for reconstruction of the cerebral vessels starting from 2D Phase-Contrast (PC)-MRA sequences. Indeed, networked and cloud services in healthcare have been gaining importance: FPGAs can enable real-time analyses for clinical diagnosis [54][55], as well as performing specialized tasks, such as image enhancement [56] and reconstruction [57]. Moreover, an FPGA-powered fault-tolerant [58] medical imaging system was proposed in [59], by increasing the reliability *via* hardware redundancy.

The node allows us to reconstruct projections of the CVT starting from a PC-MRA dataset using an MIP algorithm [60][61]. The prototyped system, implemented using a Celoxica RC203E board, is connected through an Ethernet port, realizing a specialized networked node for MIP reconstructions. Moreover, the choice of the MIP algorithm is not restrictive, since it involves image processing with a sufficient degree of complexity. However, the FPGA can be considered as a general-purpose service provider, thanks to its ability to perform and offer different specialized processing algorithms.

The proposed processing node can be viewed as a shared resource supporting medical decision-making tasks [62]. In a clinical scenario, the node connected to the hospital network may represent a specialized processing system for MIP reconstruction, available for shared use in various medical departments and hospital wards. The board, used for the realization of the proposed MIP reconstruction node, is connected to the workstation through an Ethernet interface. This makes the management of the final node very straightforward, particularly in distributed environments where the system could be used by multiple users.

Following the paradigm illustrated in Fig. 7, in our early implementation we decided to deploy the basic functionalities realizing the CTV reconstruction within the same FPGA. This was possible by defining different domains – one for each functionality – within the FPGA board, and implemented the communication between domains *via* channels. Moreover, it is interesting to note that, among FPGAs currently available in our laboratory, the Celoxica RC203E is the only one with a touch-screen, making it possible to use the FPGA as a processing node, as well as a service point, allowing for a direct interaction between the user. In our implementation, we realized the following three domains (Fig. 10):

- Sharpening filter domain: implementing a high-pass filter to enhance blood vessel contrast with respect to the background;
- MIP reconstruction domain: after the previous pre-processing phase performed on the input PC-MRA images, the MIP algorithm is applied, where the maximum voxel value, along a specific projection line, is determined. The projection line refers to the chosen point-of-view;
- Dataset rotation domain: when the user decides to change the point-of-view, it is necessary to rotate the input PC-MRA series and recalculate the MIP accordingly.

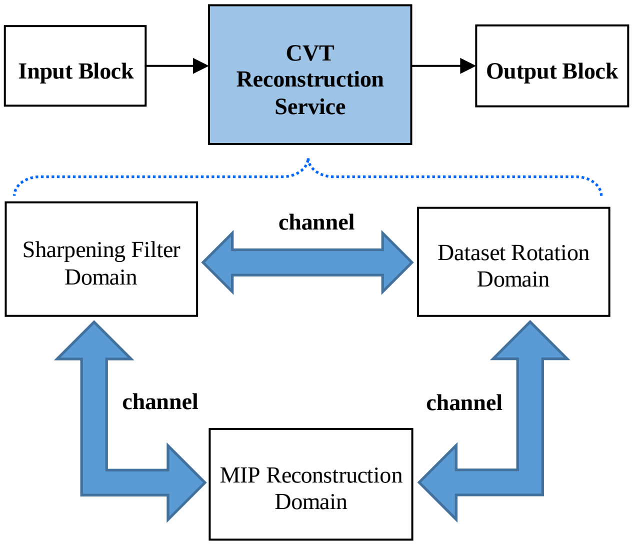

Fig. 10. Overall block scheme of the CVT service. The service was divided into three functionalities, where each of which was implemented within a specific domain on the FPGA board. The communication across different domains is guaranteed by using channels.

Fig.11a shows the RC203E board connected with an PC-MRA during the input phase. Moreover, using the touch-screen available on the Celoxica RC203E FPGA board is possible to perform rotations, obtaining an MIP reconstruction with different points-of-view. In particular, eight sensitive areas, depicted in Fig. 11b, are available to obtain different views (with rotation steps of 15°) of the CVT reconstruction. In a networked environment, the rotation of the reconstruction can be performed from the user interface available on the diagnostic workstation. After the CVT reconstruction, the projection image is transferred to the user that requested the service.

C. Embedded Solution Characteristics and Results

This section summarizes the embedded implementation of the proposed bio-SON in terms of execution time, as well as used resources. To have a first qualitative evaluation of the CVT reconstruction, the result achieved by the hardware infrastructure deployed onto the RC203E was compared against the result obtained by the corresponding software implementation, by means of visual inspection from an experienced radiologist, who considered the two results clinically equivalent.

1) PC-MRA Dataset Description

In our experiments, we used healthy volunteer acquisitions to perform CVT reconstructions on the FPGA service node. PC-MRA imaging optimizes the acquisition of blood flow data. Table II shows the MR acquisition parameters, as well as the dataset characteristics.

2) Execution Time Analysis

To evaluate the effectiveness of the proposed embedded implementation, it is interesting to consider a comparison with the corresponding software implementation of the service. Considering a platform with an Intel Core i5 CPU (Intel Corp., Santa Clara, CA, USA) running at 2.4 GHz, the cycles' number needed for the software processing is 3600×106, whereas the hardware implementation requires 957×106 cycles (Table III), obtaining approximately a 4× speed-up factor.

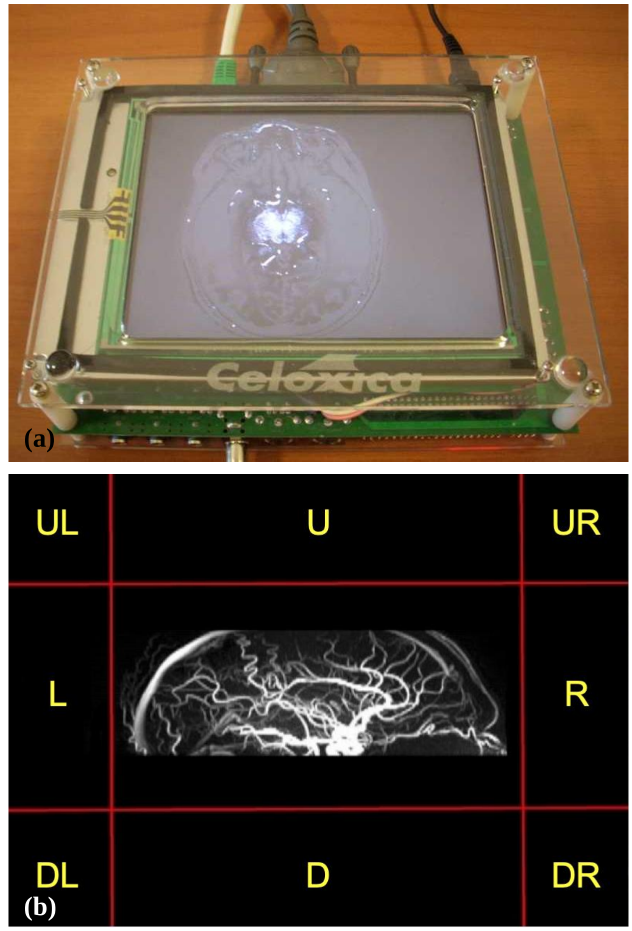

Fig. 11. (a) Celoxica RC203E FPGA board displaying an PC-MRA image; (b) Sensitive areas displayed on the touch-screen of the board, allowing for possible rotations on the CVT reconstruction (U: Up, D: Down, L: Left, R: Right). This interactive solution allows the user to perform incremental rotations *via* the eight direction controls. An example of a CVT reconstruction from a lateral view (90° rotation along *y*-axis) is shown.

3) Used Resources Analysis

Table IV shows the relevant information about the FPGA resources used for the implementation of the monitor node. Interestingly, Table V provides the technical details concerning the hardware resources used for CVT reconstruction service. The monitor node requires a higher amount of hardware resources with respect to the CVT reconstruction service node, especially when considering Look-Up Tables (LUTs). This evidence is due to the circuital complexity introduced by the bio-inspired techniques exploited for network management, as shown also by the number of used Arithmetic Logic Unit (ALU) components. Interestingly, the CVT reconstruction service node is a resource-efficient implementation and the sharpening filter represents the most demanding domain in terms of LUTs and flip flops.

TABLE II
MR PARAMETERS OF THE PC-MRA ACQUISITIONS AND DATASET CHARACTERISTICS.

Parameters / Characteristics	Value
Repetition Time (TR)	6.90 ms
Echo Time (TE)	3.48 ms
Flip angle	10°
Slice thickness	1.5 mm
MR protocol	2D Phase-Contrast
Image size	400 × 400 pixels
Slices' number	60

TABLE III
SPEED-UP FACTOR COMPARISON BETWEEN THE SOFTWARE AND HARDWARE IMPLEMENTATIONS.

Implementation	Working Frequency	Clock Cycles
Software	2,400 MHz	3.600×10^6
Hardware	25.175 MHz	957×10^6

TABLE IV
FPGA HARDWARE RESOURCES USED TO IMPLEMENT THE NETWORK MONITOR NODE. THE USED PERCENTAGE OF RESOURCES IS ALSO SHOWN.

FPGA Resource	Available	Monitor Node
LUT	28,672	26,283 (91.7%)
Flip Flop	28,672	10,923 (38.1%)
Block RAMs	96	4 (4.2%)
ALU	96	50 (52.1%)

TABLE V
FPGA HARDWARE RESOURCES USED TO IMPLEMENT THE CVT RECONSTRUCTION SERVICE. THE USED PERCENTAGE OF RESOURCES IS ALSO SHOWN.

FPGA Resource	Available	Sharpening Filter Domain	MIP Reconstruction Domain	Dataset Rotation Domain
LUT	28,672	3,375 (11.8%)	606 (2.1%)	2,625 (9.2%)
Flip Flop	28,672	1,871 (6.5%)	355 (1.2%)	1,129 (3.9%)
Block RAMs	96	1 (1.0%)	1 (1.0%)	1 (1.0%)
ALU	96	2 (2.1%)	1 (1.0%)	2 (2.1%)

VI. CONCLUSIONS AND FUTURE WORK

In this paper, a bio-inspired management approach for specialized computing environments exploiting SONs was proposed. Similar to biological environments, the nodes are able to communicate through stimulation or suppression chains for defending against foreign invaders, attacks, and malfunctioning. Even though this work focused on a bio-inspired method for the analysis and management of formerly designed or pre-existing SONs. The devised analysis can convey important information during the design phase and it might be seamlessly integrated into a design process for robust and reliable SONs. According to the current experience (i.e., analysis and management), our next step will undoubtedly aim to introduce our methodology in the design phase, where and if possible.

Considering the current embedded computing solutions, an FPGA-based technology for an early implementation of an embedded architecture was chosen. The case study is a bio-SON consisting of a monitor node implemented *via* bio-inspired tools for network management and a service in healthcare imaging environments (namely, CVT reconstruction) provided as a sequence of nodes with low-level functionalities (namely, sharpening filter, MIP reconstruction, and dataset rotation). In particular, the embedded implementation achieved a 4× speed-up factor compared to the software counterpart.

Concerning the medical imaging case study presented here, the combination of the specialized service for CVT reconstruction with CNN-based solutions could be interesting for medical diagnosis, with particular interest to cerebral aneurysm detection [27][29]. By so doing, fully FPGA-powered solutions can be feasible, by leveraging the latest trend of this technology [63][64]; such a comprehensive clinical decision support system might be integrated into an SON leveraging the proposed bio-inspired framework for efficient high-performance computing in healthcare.

Finally, in the near future, by using dynamic reconfigurable techniques [65], the monitor nodes may be replaced during the normal network activity by means of an election algorithm. This characteristic will increase the network robustness and reliability when a monitor node is disrupted. Moreover, the partial reconfiguration technique can optimize the ability to provide either new services or an existing service from by busy/out-of-service nodes. Our aim was also to propose the implementation on hardware devices to open an interesting research line on a fault-tolerance computation method that can yield acceptable results even in the presence of partial faults to the available hardware structures.

REFERENCES

[1] C. Qian, F. Bin, S. Junde, "Service-oriented network management", in *Proc. IEEE International Conferences on Info-Tech and Info-Net*, 2001, vol. 5, pp. 170–174. doi: 10.1109/ICII.2001.983513.

[2] M. Takemoto, H. Sunaga, K. Tanaka, H. Matsumura, E. Shinohara, "The ubiquitous service-oriented network (USON)–an approach for a ubiquitous world based on P2P technology", in *Proc. 2nd IEEE International Conference on Peer-to-Peer Computing (P2P)*, 2002, pp. 17–21. doi: 10.1109/PTP.2002.1046307.

[3] S. Vitabile, "Biologically inspired hardware: status and perspectives", in *Proc. 15th IEEE International Conference on Network-Based Information Systems (NBiS)*, 2012, pp. 811–814. doi: 10.1109/NBiS.2012.155.

[4] L. Rundo, C. Militello, S. Vitabile, G. Russo, E. Sala, M.C. Gilardi, "A survey on nature-inspired medical image analysis: a step further in biomedical data integration", *Fundam. Inform*, vol. 171(1-4), pp. 345–365, 2020 (In press). doi: 10.3233/FI-2020-1887.85030.

[5] R. Albert, H. Jeong, A.L. Barabasi, "Error and attack tolerance of complex networks", *Nature*, vol. 406, pp. 378–382 2000. doi: 10.1038/35019019.

[6] P. Crucitti, V. Latora, M. Marchiori, A. Rapisarda, "Error and attack tolerance of complex networks", *Physica A,* vol. 340, pp. 388–394, 2004. doi: 10.1016/j.physa.2004.04.031.

[7] S. Vitabile, V. Conti, B. Lanza, D. Cusumano, F. Sorbello, "Metabolic networks robustness: theory, simulations and results", *J. Interconnect. Netw.,* vol. 12, no. 3, pp. 221–240, 2011. doi: 10.1142/S0219265911002964.

[8] V. Lacroix, L. Cottret, P. Thébault, M.F. Sagot, "An introduction to metabolic networks and their structural analysis", *IEEE/ACM Trans. Comput. Biol. Bioinform.*, vol. 5, no. 4, pp. 594–617, 2008. doi: 10.1109/TCBB.2008.79.

[9] K.J. Kauffman, P. Prakash, J.S. Edwards, "Advances in flux balance analysis", *Curr. Opin. Biotechnol.*, 2003, vol. 14, no. 5, pp. 491–496, 2003. doi: 10.1016/j.copbio.2003.08.001.

[10] C.H. Schilling, D. Letscher, B. Palsson, "Theory for the systemic definition of metabolic pathways and their use in interpreting metabolic function from a pathway-oriented perspective", *J. Theor. Biol.*, vol. 203, no. 3, pp. 229–248, 2000. doi: 10.1006/jtbi.2000.1073.

[11] M. Endrei, J. Ang, A. Arsanjani, S. Chua, P. Comte, P. Krogdahl, M. Luo, T. Newling, "*Patterns: Service-Oriented Architecture and Web Services*", Ed. IBM Redbooks: Armonk, NY, USA, 2004. ISBN: 073845317X.

[12] R.D. Callaway, M. Devetsikiotis, Y. Viniotis, A. Rodriguez, "An autonomic service delivery platform for service-oriented network environments", *IEEE Trans. Serv. Comput.*, vol. 3, no. 2, pp. 104–115, 2010. doi: 10.1109/TSC.2010.10.

[13] D.K. Chen, "Systematic review of applying service oriented architecture in networking", in Proc. *6th IEEE International Conference on Intelligent Information Hiding and Multimedia Signal Processing (IIHMSP)*, 2010, pp. 167–170. doi: 10.1109/IIHMSP.2010.49.

[14] Y. Liu, "Design and implementation of multimedia teaching platform based on SOA architecture", Multimed. Tools and Appl., vol. 79, pp. 10899–10914, 2020. doi: 10.1007/s11042-020-08735-7.

[15] T. Wang, Y. Chen, C. Hsu, K. Hsu, H. Young, "Design and implementation of a service-oriented network provisioning system for network as a service", in Proc. *19th IEEE Asia-Pacific Network Operations and Management Symposium (APNOMS)*, 2017, pp. 280–283. doi: 10.1109/APNOMS.2017.8094128.

[16] R. Alshinina, K. Elleithy, "Performance and challenges of service-oriented architecture for wireless sensor networks", *Sensors*, vol. 17, no. 3, art. no. 536, 2017. doi: 10.3390/s17030536.

[17] G. Bertoni Machado, F. Siqueira, R. Mittmann, and C.A. Vieira e Vieira, "Embedded systems integration using web services", in *Proc. of IEEE International Conference on Networking, International Conference on Systems and International Conference on Mobile Communications and Learning Technologies (ICNICONSMCL)*, 2006, pp. 1–6. doi: 10.1109/ICNICONSMCL.2006.89.

[18] F. Boroncelli, B. Martini, P. Castoldi, A. Aprigliano, "Experimental validation of a service oriented network architecture applied to global grid computing", in *Proc. 1st IEEE International Conference on Automated Production of Cross Media Content for Multi-Channel Distribution (AXMEDIS)*, 2005, pp. 1–8. doi: 10.1109/AXMEDIS.2005.20.

[19] P. Bonetto, G. Oliva, A.R. Formiconi, "MedIGrid: a medical imaging environment based on a grid computing infrastructure", in Proc. *25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (IEEE-EMBS)*, vol. 2, pp. 1338–1341, 2003. doi: 10.1109/IEMBS.2003.1279543.

[20] B. Mao, F. Tang, Z.M. Fadlullah, N. Kato, "An intelligent route computation approach based on real-time deep learning strategy for software defined communication systems", *IEEE Trans. Emerg. Topics Comput.*, 2019, in press. doi: 10.1109/TETC.2019.2899407.

[21] A.H. Sodhro, A.S. Malokani, G.H. Sodhro, M. Muzammal, L. Zongwei, "An adaptive QoS computation for medical data processing in intelligent healthcare applications", *Neural Comput. Appl.*, vol. 32, no. 3, pp. 723–734, 2020. doi: 10.1007/s00521-018-3931-1.

[22] E.J. Topol, High-performance medicine: the convergence of human and artificial intelligence. *Nat. Med.*, vol. 25, no. 1, pp. 44–56, 2019. doi: 10.1038/s41591-018-0300-7.

[23] S. Moriconi, M.A. Zuluaga, H.R. Jäger, P. Nachev, S. Ourselin, M.J. Cardoso, "Inference of cerebrovascular topology with geodesic minimum spanning trees", *IEEE Trans. Med. Imaging*, vol. 38, no. 1, pp. 225–239, 2019. doi: 10.1109/TMI.2018.2860239.

[24] R. Kwitt, D. Pace, M. Niethammer, S. Aylward, "Studying cerebral vasculature using structure proximity and graph kernels", in Proc. *International Conference on Medical Image Computing and Computer-Assisted Intervention (MICCAI)*, LNCS, Springer, Berlin-Heidelberg, Germany, vol. 8150, pp. 534–541, 2013. doi: 10.1007/978-3-642-40763-5_66.

[25] X. Yang, D.J. Blezek, L.T. Cheng, W.J. Ryan, D.F. Kallmes, B.J. Erickson, "Computer-aided detection of intracranial aneurysms in MR angiography", *J. Digit. Imaging*, vol. 24, no. 1, pp. 86-95, 2011. doi: 10.1007/s10278-009-9254-0.

[26] S. Miki, N. Hayashi, Y. Masutani, Y. Nomura, T. Yoshikawa, S. Hanaoka, *et al.* "Computer-assisted detection of cerebral aneurysms in MR angiography in a routine image-reading environment: effects on diagnosis by radiologists", *Am. J. Neuroradiol.*, vol. 37, no. 6, pp. 1038-1043, 2016. doi: 10.3174/ajnr.A4671.

[27] D. Ueda, A. Yamamoto, M. Nishimori, T. Shimono, S. Doishita, A. Shimazaki, *et al.*, "Deep learning for MR angiography: automated detection of cerebral aneurysms", Radiology, vol. 290, no. 1, pp. 187–194, 2018. doi: 10.1148/radiol.2018180901

[28] M. Zhou, X. Wang, Z. Wu, J.M. Pozo, A.F. Frangi, "Intracranial aneurysm detection from 3D vascular mesh models with ensemble deep learning", in *Proc. International Conference on Medical Image Computing and Computer-Assisted Intervention (MICCAI)*, LNCS, Springer, Cham, Switzerland, vol. 11767, pp. 243-252, 2019. doi: 10.1007/978-3-030-32251-9_27.

[29] T. Nakao, S. Hanaoka, Y. Nomura, I. Sato, M. Nemoto, S. Miki, *et al.*, "Deep neural network-based computer-assisted detection of cerebral aneurysms in MR angiography", *J. Magn. Reson. Imaging*, vol. 47, no. 4, pp. 948–953, 2018. doi: 10.1002/jmri.25842.

[30] R.D. Barros, J. Borst, S. Kleynenberg, C. Badr, R.R. Ganji, H. de Bliek, *et al.*, "Remote collaboration, decision support, and on-demand medical image analysis for acute stroke care", in *Proc. European Conference on Service-Oriented and Cloud Computing (ESOCC)*, LNCS, Springer, Cham, Switzerland, vol. 9306, pp. 214-225, 2015. doi: 10.1007/978-3-319-24072-5_15

[31] S. Balasubramaniam, D. Botvich, J. Mineraud, W. Donnelly, "BiRSM: bio-inspired resource self-management for all IP-networks", *IEEE Network*, vol. 24, no. 3, pp. 20–25, 2010. doi: 10.1109/MNET.2010.5464223.

[32] S. Balasubramaniam, D. Botvich, W. Donnelly, J. Strassner, "A biologically inspired policy based management system for survivability in autonomic networks", in *Proc. 4th IEEE International Conference on Broadband Communications, Networks and Systems (BROADNETS)*, 2007, pp. 160–168. doi: 10.1109/BROADNETS.2007.4550420.

[33] X. Hao, R. Falconer, D. Bradley, J. Crawford, "FUNNet – a novel biologically-inspired routing algorithm based on fungi", in *Proc. 2nd IEEE International Conference on Communication Theory, Reliability, and Quality of Service*, 2009, pp. 97–102. doi: 10.1109/CTRQ.2009.23.

[34] V. Conti, B. Lanza, S. Vitabile, F. Sorbello, "Neural networks and metabolic networks: fault tolerance and robustness features", *Front. Artif. Intell. Appl.*, vol. 204, pp. 39–48, 2009. doi: 10.3233/978-1-60750-072-8-39

[35] E. Ravasz, A.L. Somera, D.A. Mongru, Z.N. Oltvai, A.L. Barabási, "Hierarchical organization of modularity in metabolic networks", *Science*, vol. 297, no. 5586, pp. 1551–1555, 2002. doi: 10.1126/science.1073374

[36] P. Holme, "Metabolic robustness and network modularity: a model study", *PLoS One*, vol. 6, no. 2, 2011. doi: 10.1371/journal.pone.001660

[37] A.L. Barabasi, Z.N. Oltvai, "Network biology: understanding the cell's functional organization", *Nat. Rev. Genet.*, vol. 5, no. 2, pp. 101–113, 2004. doi: 10.1038/nrg1272

[38] S. Eum, S.I. Arakawa, M. Murata, "Toward bio-inspired network robustness–Step 1. Modularity", in *Proc. 2nd IEEE Bio-Inspired Models of Network, Information and Computing Systems (BIMNICS)*, 2007, pp. 84–87. doi: 10.1109/BIMNICS.2007.4610087.

[39] T. Meyer, L. Yamamoto, C. Tschudin, "A self-healing multipath routing protocol", in Proc. *3rd International Conference on Bio-Inspired Models of Network, Information and Computing Systems (Bionetics)*, 2008, pp. 1–8. doi: 10.5555/1512504.1512512

[40] H. Jeong, B. Tombor, R. Albert, Z. Oltvai, A.L. Barabási, "The large-scale organization of metabolic networks", *Nature*, vol. 407, pp. 651–654, 2000. doi: 10.1038/35036627.

[41] J. Arnedo-Moreno, K. Matsuo, L. Barolli, F. Xhafa, "Secure communication setup for a P2P-based JXTA-Overlay platform", *IEEE Trans. Ind. Electron.*, vol. 58, no. 6, pp. 2086–2096, 2011. doi: 10.1109/TIE.2010.2047831.

[42] L. Barolli, F. Xhafa, "JXTA-Overlay: A P2P platform for distributed, collaborative and ubiquitous computing", *IEEE Trans. Ind. Electron.*, vol. 58, no. 6, pp. 2163-2172, 2011. doi: 10.1109/TIE.2010.2050751.

[43] A.R. Razavi, S.K. Moschoyiannis, P.J.A. Krause, "A scale-free business network for digital ecosystems", in *Proc. 2nd IEEE International Conference on Digital Ecosystems and Technologies*, 2008, pp. 241–246. doi: 10.1109/DEST.2008.4635166.

[44] V. Conti, S.S. Ruffo, S. Vitabile, L. Barolli, "BIAM: a new bio-inspired analysis methodology for digital ecosystems based on a scale-free architecture", *Soft Comput.*, vol. 23, no. 4, pp. 1133–1150, 2019. doi: 10.1007/s00500-017-2832-z.

[45] V. Conti, B. Lanza, S. Vitabile, F. Sorbello, "BioAnalysis: a framework for structural and functional robustness analysis of metabolic networks", in *Proc. 4th IEEE International Conference on Complex, Intelligent and Software Intensive Systems (CISIS)*, 2010, pp. 138–145. doi: 10.1109/CISIS.2010.136.

[46] S. Vitabile, V. Conti, B. Lanza, D. Cusumano, F. Sorbello, "Topological information, flux balance analysis, and extreme pathways extraction for metabolic networks behaviour investigation", *Front. Artif. Intell. Appl.*, vol. 234, pp. 66–73, 2011. doi: 10.3233/978-1-60750-972-1-66.

[47] C. Damiani, M. Di Filippo, D. Pescini, D. Maspero, R. Colombo, G. Mauri, "popFBA: tackling intratumour heterogeneity with flux balance analysis", *Bioinformatics*, vol. 33, no. 14, pp. i311-i318, 2017. doi: 10.1093/bioinformatics/btx251.

[48] A. Graudenzi, D. Maspero, C. Damiani, "Modeling spatio-temporal dynamics of metabolic networks with cellular automata and constraint-based methods", in *Proc. International Conference on Cellular Automata (ACRI)*, LNCS, Springer, Cham, Switzerland, vol. 11115, pp. 16–29, 2018. doi: 10.1007/978-3-319-99813-8_2.

[49] Rundo, L.; Militello, C.; Russo, G.; Vitabile, S.; Gilardi, M.C.; Mauri, G. GTVcut for neuro-radiosurgery treatment planning: an MRI brain cancer seeded image segmentation method based on a cellular automata model. *Nat. Comput.* 2018, 17(3), 521–536. doi: 10.1007/s11047-017-9636-z.

[50] X. Tang, G. De Micheli, P.E. Gaillardon, "A high-performance FPGA architecture using one-level RRAM-based multiplexers", *IEEE Trans. Emerg. Topics Comput.*, vol. 5, no. 2, pp. 210-222, 2016. doi: 10.1109/TETC.2016.2630121

[51] D. D'Agostino, A. Quarati, A. Clematis, L. Morganti, E. Corni, V. Giansanti, *et al.*, "SoC-based computing infrastructures for scientific applications and commercial services: Performance and economic evaluations", *Fut. Gen. Comput. Syst.*, vol. 96, pp. 11-22, 2019. doi: 10.1016/j.future.2019.01.024

[52] V. Conti, S. Vitabile, C. Militello, B. Lanza, F. Sorbello, "An embedded processor for metabolic networks optimization", in *Proc. 5th IEEE International Conference on Complex, Intelligent and Software Intensive Systems (CISIS)*, 2011, pp. 77–84. doi: 10.1109/CISIS.2011.21.

[53] G.B. Dantzig, "*Linear Programming and Extensions*", Ed. Princeton University Press: Princeton, NJ, USA 1963.

[54] A. Sanaullah, C. Yang, Y. Alexeev, K. Yoshii, M.C. Herbordt, "Real-time data analysis for medical diagnosis using FPGA-accelerated neural networks", *BMC Bioinform.*, vol. 19, no. 18, art. no. 490, 2018. doi: 10.1186/s12859-018-2505-7.

[55] E. Torti, A. Fontanella, G. Florimbi, F. Leporati, H. Fabelo, S. Ortega, G.M. Callicó, "Acceleration of brain cancer detection algorithms during surgery procedures using GPUs", *Microprocess. Microsyst.*, vol. 61, pp. 171-178, 2018. doi: 10.1016/j.micpro.2018.06.005

[56] S. Sowmya, R. Paily, "FPGA implementation of image enhancement algorithms", in *Proc. IEEE International Conference on Communications and Signal Processing (ICCSP)*, 2011, pp. 584–588. doi: 10.1109/ICCSP.2011.5739392.

[57] M. Leeser, S. Coric, E. Miller, H. Yu, M. Trepanier, "Parallel-beam backprojection: an FPGA implementation optimized for medical imaging", *J. VLSI Sign. Process. Syst. Sign. Image Video Technol.*, vol. 39, no. 3, pp. 295-311, 2005. doi: 10.1007/s11265-005-4846-5.

[58] E.W. Wächter, V. Fochi, F. Barreto, A.M. Amory, F.G. Moraes, "A hierarchical and distributed fault tolerant proposal for NoC-based MPSoCs", *IEEE Trans. Emerg. Topics Comput.*, vol. 6, no. 4, pp. 524-537, 2016. doi: 10.1109/TETC.2016.2593640.

[59] E. Abdulhay, V. Elamaran, N. Arunkumar, V. Venkataraman, "Fault-tolerant medical imaging system with quintuple modular redundancy (QMR) configurations", *J. Ambient Intell. Human. Comput.*, pp. 1–13, 2018 (In press). doi: 10.1007/s12652-018-0748-9.

[60] J.T. Oikarinen, L.J. Jyrkinen, "Maximum intensity projection by 3-dimensional seed filling in view lattice", *Comput. Netw. ISDN Syst.*, vol. 30, no. 20-21, pp. 2003–2014, 1998. doi: 10.1016/S0169-7552(98)00177-9.

[61] L. Mroz, A. König, E. Gröller, "Maximum intensity projection at warp speed", *Comput. Graph.*, vol. 24, no. 3, pp. 343–352, 2000. doi: 10.1016/S0097-8493(00)00030-3.

[62] O. Gambino, L. Rundo, V. Cannella, S. Vitabile, R. Pirrone, "A framework for data-driven adaptive GUI generation based on DICOM", *J. Biomed. Inform.*, vol. 88, pp. 37–52, 2019. doi: 10.1016/j.jbi.2018.10.009.

[63] M. Rivera-Acosta, S. Ortega-Cisneros, J. Rivera, "Automatic tool for fast generation of custom convolutional neural networks accelerators for FPGA", *Electronics*, vol. 8, no. 6, article no. 641, 2019. doi: 10.3390/electronics8060641.

[64] R. Zhao, H.C. Ng, W. Luk, X. Niu, "Towards efficient convolutional neural network for domain-specific applications on FPGA", in *Proc. 28th IEEE International Conference on Field Programmable Logic and Applications (FPL)*, 2018, pp. 147–1477. doi: 10.1109/FPL.2018.00033.

[65] V. Conti, L. Rundo, G. Billeci, C. Militello, S. Vitabile, "Energy efficiency evaluation of dynamic partial reconfiguration in field programmable gate arrays: an experimental case study", *Energies*, vol. 11, no. 4, article no. 739, 2018. doi: 10.3390/en11040739.

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