Rad Hard Datacenter for Space

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***Abstract*—A datacenter for use in Space offers high performance computing similar to small terrestrial datacenters, including storage, networking, and cloud computing. When operated using software platforms from commercial Cloud Service Providers, the range of enabled applications is quite similar to terrestrial clouds. The Space datacenter is planned for reliable power-efficient operation for longer than 30 years in any Space environment, employing on-board AI-based FDIR and self-healing. A small version is based on a single 6U-VPX enclosure. The large version is packaged in less than one cubic meter and offers about 13 TFLOP, 100 AI/ML TOPS and 3.5 PB storage while dissipating 12 kWatt.**

Keywords—Datacenter, Space computing, rad hard processor.

I. Introduction

Datacenters for use in Space missions address the need of large Space-based systems and users for general purpose, high-performance, high-throughput computing, storage, and networking services. Such services are similar to cloud capabilities provided on the ground and are designed for seamless integration with such services.

The paper proposes and characterizes a Space datacenter, describes the relevant stakeholders, offers a modular hardware, software, and usage architecture, and discusses modularity, networking, expected performance and power efficiency, as well as Space resiliency.

II. Space Datacenter Overview

Datacenter serviced by Cloud Service Providers (CSPs) are typically architected as shown in Fig. 1 and are organized in three layers:

- The physical system, including hardware (HW) and embedded software (SW), constitutes the *infrastructure* layer. At times, the infrastructure is made available to the market in the form of Infrastructure-as-a-Service (IaaS). For Space use, the physical system is provided by a Space computing manufacturer such as Ramon.Space.
- The Management SW makes up the *platform* layer. It includes hypervisors, operating systems, dockers and security services, as well as multi-user management. This layer is made through collaboration by the infrastructure manufacturer, cloud service providers, users, and multi-cloud service managers. At times, the platform is made available to the market in the form of Platform-as-a-Service (PaaS).
- User *workload* consists of the application code, and libraries and API that are availed by the platform and infrastructure providers. User workloads are offered by either the infrastructure provider, the platform provider, the users themselves or third party application providers, typically tagged as Software-as-a-Service (SaaS).

Space datacenters are planned to have a key role in fusing sensor data, in critical missions (battle management, situational awareness and command and control capabilities over large space / air / ground assets), in ground independence, and in commercial applications. Inspired by terrestrial trends, artificial intelligence applications are expected to consume a growing portion of Space datacenter resources.

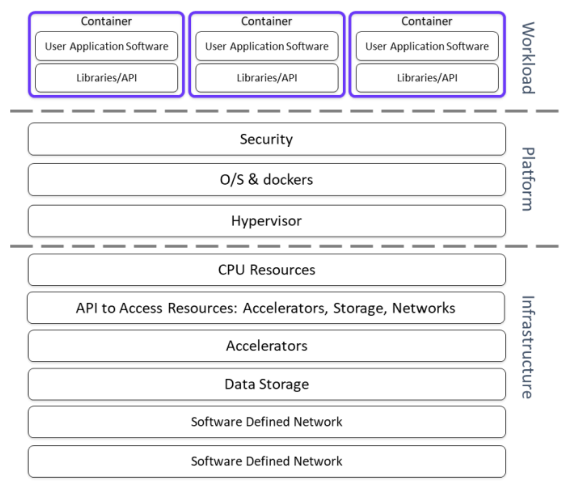

Fig. 1. Typical Datacenter Architecture

Modern datacenters are *disaggregated* and *network-centric*, rather than ‘server-blade centric’. Resources are distributed over many nodes, to provide performance, redundancy, and resiliency. While in the past datacenters focused on the CPU, contemporary datacenters evolve around Datacenter Processing Units (DPU) that offer software defined networking (SDN), offloading control and data tasks from the CPUs, and taking massive connectivity away from the CPU, such as between many accelerators and many storage units. This evolution is readily applicable to Space, where a densely connected network of high-end Space grade multi-purpose components such as high-end FPGA (e.g., Xilinx Versal) and high-end SoC (e.g., RC64 [1]) serve as focal points, to which many CPUs, accelerators, storage and memory units, external interfaces and other modules are connected.

III. Physical Construction

The Space datacenter consists of a rack and multiple compute units (“boxes”) mounted onto the rack, as exemplified in Fig. 2. The rack, measuring about 2.00m × 0.75m × 0.55m

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(smaller than one cubic meter) houses data networking wires and power distribution network cables, as well as interfaces to the spacecraft (2.00m height reflects the physical constraints of certain future Space stations). The goal of inserting these wires and cables within the rack is to eliminate, or minimize, box-front sockets and cabling, in order to reduce labor and maintenance requirements and to enhance reliability. In human mission spacecrafts such as Space stations and in planetary colonies, the rack is part of the fixed structure while the boxes may be swapped in and out for maintenance and upgrade by human or robotic astronauts.

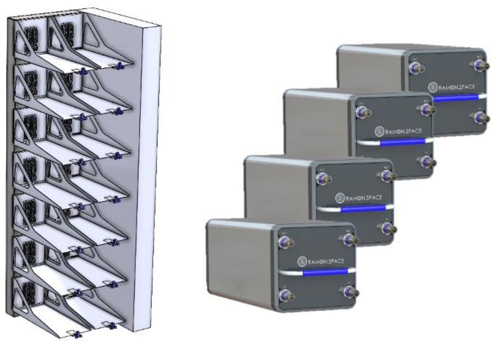

Fig. 2. Left: Back side rack hides wiring for DC power distribution and for networking (example rack capable of carrying 14 boxes). Right: Enclosures (boxes) that can be plugged onto the rack.

When more than four boxes are used, each Box is liquid cooled directly, hence the four "quick disconnect" liquid ports on its front. Fig. 3 shows coolant flow through the box walls, whereas individual cards employ conduction cooling. The rear side of each box is equipped by ARINC-600 (or similar) connectors for push-attachment to the rack.

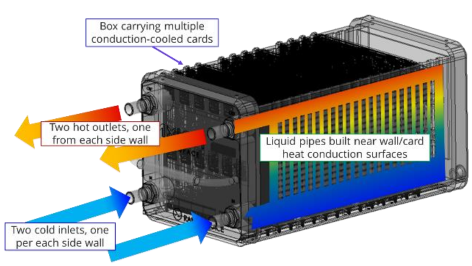

Fig. 3. Liquid cooling applied to side walls of the box. Electronics card are conduction-cooled, transferring heat to the side wall, where heat energy is collected and exhausted by liquid.

Each box is based on SpaceVPX 6U-220 construction, containing from one to five groups, each group comprising four compute cards and one power supply card (Fig. 4).

IV. Compute Card

Each compute card carries the building blocks that are needed in the datacenter, including RC64 DPUs, CPUs, accelerators, storage, interfaces, and control devices, as well as highly reliable power distribution devices (Fig. 5). The two CPUs execute user workloads and the essential parts of the cloud software, such as the kernel of the operating system (O/S). Rad-hard CPUs, such as the up-screened sixteen-core ARM Teledyne e2v LX2160 [2], or the future Microchip HPSC RISC-V [3], or the future FrontGrade Gaisler octa-core GR765 Sparc/RISC-V [4], may be employed. Each CPU may be accompanied by a low power interface FPGA (not shown). The four RC64 DPUs provide AI/ML and DSP acceleration of user applications, manage software-defined network, monitor system health, and control the attached storage. Up to 8 TByte of Space grade storage can be integrated on each card (improving upon Ramon.Space NuStream architecture [5]), possibly requiring FPGA devices for bridging between RC64 DPUs and 3D-NAND flash chips.

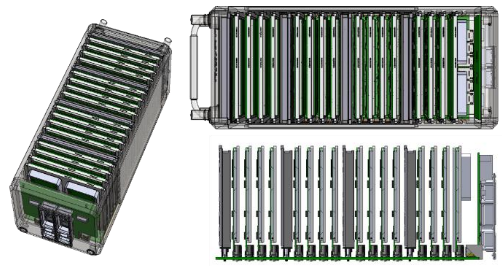

Fig. 4. Views of a box, housing a SpaceVPX-6U backplane, five to 25 VPX-6U-220 size cards, and an interface/bulkhead card carrying ARIC-600 plugs (right).

Networking is designed to enable a variety of modes, including Ethernet (ETH), PCI express (PCIe), SpaceWire (SpW), and SpaceFibre (SpFi). When the design employs only SpW and SpFi, FPGA devices may be required for bridging between CPUs that lack SpW and SpFi support and the network.

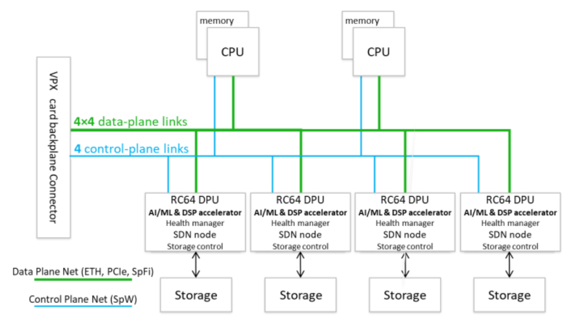

Fig. 5. Compute Card architecture: Four RC64 DPU chips provide high-performance AI/ML and DSP acceleration, on- and off-card software-defined networking and higher-level services, manage health and mitigate faults and failures, and facilitate storage control. Two CPUs execute O/S tasks and user workloads. Each RC64 and each CPU is accompanied by a low power interface FPGA (not shown). Any resource may be connected with any other resource, whether on-card or elsewhere. The compute card may function solitary or in concert with any number of other networked compute cards.

Fig. 6 shows the physical implementation as a SpaceVPX-6U-220 card. A metal cover and a pair of wedgelocks on card sides provide thermal conduction pathways to side walls, as well as enhanced mechanical strength and added radiation and EMI shielding.

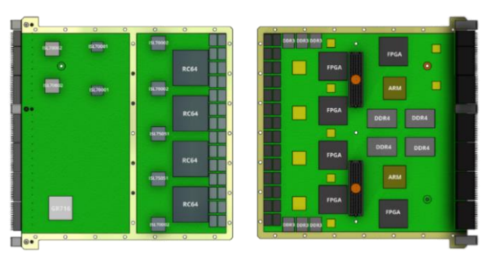

Fig. 6. Compute card physical views

V. NETWORK TOPOLOGY AND SDN

As the Space datacenter is network-centric, every part of it is connected to the network and can communicate with any other part through that network. The physical network provides very high level of connectivity. Routing in the network is determined by software. Two sub-nets are provided, for data plane (preferably ETH, PCIe or SpFi) and for control plane (preferably SpW). For extended reliability, control messages may also be routed, in whole or in part, over the data plane network. Inter-card connectivity within the Box (Fig. 7, top) assures three hops maximum distance over 16 cards and four back-of-box ports, by means of doubly connected 2D torus topology. That topology also facilitates high level of redundancy for fault tolerance, avoiding critical bottlenecks of tree-based architectures, as well as enabling flexible dynamic routing for congestion control.

The network is extended through the back rack in order to interconnect, e.g., fourteen boxes of the Space datacenter. The topology (Fig. 7, bottom) assures eight hops maximum networking distance over the entire datacenter.

For external connectivity, namely networking with the outside of the Space datacenter, each box may contain one card that is equipped with secure interface(s) to external Ethernet. The interface may employ certified encryption devices, for creating the required separation and providing customer-specified levels of security.

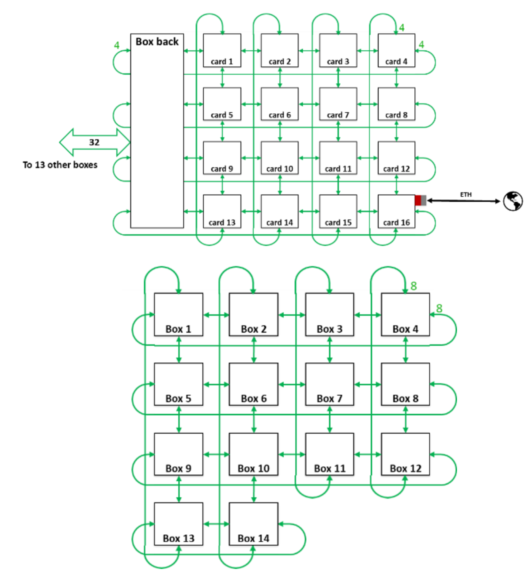

Fig. 7. Physical network topology. **Top**: Box-level inter-card physical connect topology, including external secure network links and links to other boxes. **Bottom**: Datacenter level inter-Box physical connect topology. Both level topologies are based on doubly connected 2D torus and "double-fat pipe" (16 pair) links.

Actual connectivity over the network is driven by Software Defined Network (SDN). Each networking node in the datacenter employs routing software to determine on which egress port to send each received packet. The SDN software also includes a distributed module for Fault Detection, Isolation and Recovery (FDIR), and a distributed module for network discovery and configuration, e.g., according to the evolving Space oriented NDCP protocols [8][9].

Note that there are no dedicated switching or routing cards—all networking functions are distributed over the compute cards. This style of network-centric datacenter design enables using only a single type of card over the entire datacenter, leading to enhanced reliability and significant cost reduction in constructing complex computing for Space.

Note further that Space datacenters are not expected to offer enhanced remote memory access links and switches, such as RDMA operations enabled by InfiniBand and RoCE. Such remote access mechanisms are intended to achieve low latency by means of bypassing standard networking, at a great expense in special silicon devices, dedicated cabling and high power consumption. Such means are considered unjustified in Space datacenters, due to limited financial, engineering and power resources.

VI. SPACE DATACENTER PERFORMANCE

The large version of the Space datacenter comprises a total of 224 compute cards, organized in 14 boxes on a single rack. It achieves peak performance of 13 TFLOPS and 100 AI/ML TOPS. It offers 3.5 PB storage, and dissipates up to 12 kWatt. For comparison, the first time a terrestrial supercomputer achieved similar performance happened in 2012 [6] when IBM presented Sequoia [7]. That supercomputer took up a very large warehouse (see photos in [7]) and dissipated close to 8 MWatt, close to 1000× higher power than the Space datacenter. In the future, AI and DSP upgrades of RC64 DPUs, memories, storage and CPUs will be used, significantly enhancing performance and improving the performance-to-power ratio.

Since the Space datacenter is highly modular, any smaller size (and lower number of compute cards) can be accommodated for lower power dissipation and smaller volume.

VII. SPACE DATACENTER QUALITY AND RELIABILITY

A. *Resiliency*

Resiliency is the ability of the Space datacenter to withstand failures and faults and yet remain functional. In other words, resiliency is the manner in which reliability and graceful degradation are achieved. Resiliency is achieved in the Space datacenter through the following means:

- Every module in the Space datacenter is characterized by very high reliability.
- All components are radiation hardened, in terms of TID, SEU, SEL and SEFI for all relevant Space missions (Earth orbits and planetary colonization). All components are assembled in manners that achieve high board-level reliability (BLR) and resilience to thermal cycles and extreme temperature in all relevant Space missions.
- Every module in the Space datacenter, as well as the entire system, is designed to meet both common Space standards and more stringent proprietary requirements.
- Modular redundancy and redundant networking assure functionality even after a module or a network link fail.
- Quality control system, combining hardware and software, makes an essential part of the Space datacenter, and maintains system health during its entire operational lifetime.
- In periodically serviced Space stations, sub-systems (boxes) are replaced when needed, thus extending operational lifetime beyond predicted and actual lifetime of individual sub-systems, and further enabling upgrades by taking advantage of future technological improvements.

B. HW and SW Fault Detection, Isolation and Recovery

All parts of the Space datacenter are monitored continuously using Fault Detection, Isolation and Recovery (FDIR) set of tools. FDIR is based on a wide range of hardware means for correcting errors, for monitoring status and for gathering indicators, parameters and statistical measures of faults and failures. FDIR also includes a wide range of distributed software modules, executing on all parts of the Space datacenter—CPUs, DPUs, networking nodes, storage controllers, accelerators, and interfaces.

In contrast with common practice in Space [10], FDIR for the Space datacenter is planned for autonomous execution on-board, rather than being split between Space and ground. It is also planned to adopt novel AI-based techniques for autonomous on-board FDIR [11][12].

The first purpose of FDIR is to detect faults and failures, to identify causes (radiation, mechanical, thermal, software bugs, hardware faults, cyber-attacks, etc.), to disseminate and record such findings, and to determine corrective actions.

Second, FDIR is charged with isolating faulty parts and modules that cannot be recovered, as well as kicking redundant units into operation, when possible.

Third, FDIR triggers recovery operations when applicable, such as power restarts and data scrubbing.

The fourth functionality of FDIR relates to self-healing, as described next.

C. Preventive self-healing & maintenance

Each part of the Space datacenter is characterized by reliability assessment and health indicators. FDIR software tracks activity over time for each part. When collected measures indicate that a part approaches the end of its useful life, and the probability of encountering failures surpasses pre-determined (or adaptive) threshold, FDIR software module for preventive maintenance may activate replacement of a part by a redundant part, indicating to the Space datacenter management software that reconfiguration should take place. As noted above, self-healing is key goal of on-board AI-based FDIR [11]. Autonomous on-board FDIR is essential in deep Space applications, such as in Lunar datacenters, due to the extremely restricted bandwidth of links to Earth.

VIII. CONCLUSIONS

A rad-hard, high-resilience Space datacenter is presented. It is highly modular and disaggregated, based on a single type of compute card, reducing cost and supply chain issues. The Space datacenter is highly scalable—many compute cards can be networked together and employed at the same time. The Space datacenter design minimizes cable harnesses; rather, it makes extensive use of printed connectivity, for enhanced reliability and simplicity. The Space datacenter is designed to execute standard cloud platforms, standard cloud applications, and autonomous AI on-board tasks. The Space datacenter reliability and availability are enhanced by means of on-board AI-based FDIR and maintenance, as well as self-healing capabilities. The Space datacenter is designed for high end computing on Space stations and in Lunar communities. Smaller configurations of the Space datacenter are suitable for high-end satellite constellations and other spacecraft, offering software and use uniformity over a wide range of use cases.

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