An Exploration of Openness in Hardware and Software Through Implementation of a RISC-V Based Desktop Computer

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ABSTRACT

Open hardware and open source software platforms bring benefits to both implementers and users in the form of system adaptability and maintainability, and through the avoidance of lock-in, for example. Development of the RISC-V Instruction Set Architecture and processors during the last ten years has made the implementation of a desktop computer using open hardware, including open processors, and open source software an approaching possibility. We use the SiFive Unmatched development board and Ubuntu Linux, and the recorded experiences of system builders using the Unmatched board to explore the extent to which it is possible to create an open desktop computer. The work identifies current limitations to implementing an open computer system, which lie mainly at the interface between the operating system and hardware components. Potential solutions to the challenges uncovered are proposed, including greater consideration of openness during the early stages of product design. A further contribution is made by an account of the synergies arising from open collaboration in a private-collective innovation process.

CCS CONCEPTS

• **Software and its engineering** → *Open source model*; *Software evolution*; • **Social and professional topics** → *Computer manufacturing*; *Economic impact*; Intellectual property; • **Hardware**;

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KEYWORDS

Open Hardware; Open Source Software; RISC-V; Open Collaboration

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1 INTRODUCTION

open source software (OSS) has become an accepted, conventional and important part of software development [7, 29, 44]. Benefits for software intensive businesses include the high availability of software components and a subsequent reduction in time to market and development overheads, as well as a collective approach to software development and maintenance [18, 53]. The increasing availability of open hardware and the development and adoption of RISC-V, an open instruction set architecture (ISA) [15, 58], are creating further opportunities for product development and innovation, as well as processor innovation; particularly in the internet of things (IoT) domain and embedded devices. Because the RISC-V ISA is open, developers are able to prototype processor implementations and extensions in field-programmable gate arrays (FPGAs) and to publish and share processor implementations in a similar way to OSS (e.g. [40, 55]).

While desktop computers and servers with OSS operating systems and user applications are common, the development of RISC-V based, PC form-factor boards — e.g. SiFive's Unleashed [50] and Unmatched[51] — has made the implementation of a desktop computer using open ISA processors, open hardware (OH), and OSS an approaching possibility. An open computing system offers the potential to avoid vendor lock-in, to have designs that can be replicated in the future, supporting system maintainability [26], and, with RISC-V processors, the potential for ongoing processor innovation [3, 15]. Currently, Linux distributions such as Debian, OpenSUSE and Ubuntu are available for RISC-V, as is FreeBSD; so, what barriers are there to the implementation of an open desktop computer?

In this research, we investigate the implemention of desktop computers and servers using the SiFive Unmatched board, and apply that knowledge in the processes of planning to build a desktop computer using the Unmatched board and the Ubuntu distribution of Linux to explore the practical application of openness, including the application of open standards, in both software [26] and hardware. The work focuses on the following research objectives:

- **O1** To understand the current barriers to implementing an open desktop computer;
- **O2** To identify potential solutions to any barriers encountered; and
- **O3** To understand the pragmatic solutions that may be required to implement an open computing system.

To meet the research objectives, we analyse the experiences of building computers with the Unmatched board that system builders have documented in written articles, videos, and SiFive's support forums. The archival analysis is framed in the context of planning to build an "open" desktop computer using the definition of OSS [35] and Open Source Hardware Association's definition of OH [34] and its implementation in the CERN Open Hardware Licence v2 [9] to provide base definitions of openness.

The paper makes two distinct contributions. The first consists of analysis of the experiences of system builders to support an understanding of the practical limits to implementing an open desktop computer. The second contribution is an illustration of the value of open collaboration as a means of identifying and solving technical problems, and developing technology.

The following section provides background on RISC-V, definitions of open hardware and open source software, and related academic research. The research approach used is detailed in Section 3 and our findings are presented in Section 4. The findings are discussed in Section 5, where we also suggest future work, and we draw our conlusions in Section 6.

2 BACKGROUND

Developed initially in 2010, RISC-V is an open ISA [58]. Established ISAs in common use, such as x86, are closed and even though the instruction set is published, licences cannot be obtained to build a processor implementing x86. While licences for ARM's ISAs can be purchased, only a few companies can afford them [3, 15]. In contrast, RISC-V processors can be implemented without the need to purchase a licence. However, the processors need to go through a verification process to ensure that they implement the standard [27, 45]. The standardisation process and the specifications [42] are managed by RISC-V International [1].

The RISC-V ISA is modular and all RISC-V processors implement the core instruction modules. A further, optional, instruction modules have been developed and fifteen were verified in 2021; including vector processor instructions [43] and a scalar cryptography module [11]. Processor implementers are also able to develop their own extension modules for RISC-V. RISC-V processors can be implemented in proprietary, or closed, hardware, and OH. OH processor implementations, sometimes known as *open silicon*, are typically available in a hardware description language, such as SystemVerilog [19], and developed in a similar way to OSS. Examples of open RISC-V processors include those developed by the PULP project [40] and T-Head Semiconductor [55].

The Open Source Hardware Association's (OSHWA) definition of OH [34] is a reworking of the Open Source Initiative's (OSI) definition of OSS [35] applied to hardware. Given the range of objects and substances that might be considered to be "hardware" — e.g. beer, vehicles, and electronics — the definition of OH is broad and needs to accommodate a wide range of components. Examples of components that might be included in a OH design specification are simple, physical objects such as a resistor or a bolt, complex electronic devices that require firmware and software to work, and processor designs in a hardware description language that appear to be similar in nature to software.

Licensing practices and licenses for OH are developing. For example, Creative Commons licences have been used for a long time by Arduino S.r.l. for their microcontroller (MCU) designs [2], and some businesses use the SolderPad Licence [52], which extends version 2 of the Apache License [1] to include hardware. The European Organisation for Nuclear Research (CERN) have developed a licence for OH, and the most recent version has been approved by the OSI. Version 2 of the CERN Open Hardware Licence [9] (CERN-OHL-v2) implements the Open Source Hardware Association's (OSHWA) definition of OH [34] in three types of licence: strongly reciprocal (CERN-OHL-S-v2), weakly reciprocal (CERN-OHL-W-v2), and permissive (CERN-OHL-P-v2). The CERN-OHL-v2 includes the concepts of an *available component* [10, §1.7] and *complete source* [10, §1.8] which places requirements on the components used in the design. Individual components do not themselves have to be OH to be part of an OH design specification; the minimum requirement is that components are *available*. There is complexity in the notion of an available component, as well as scope for interpretation. For the purposes of this work, we consider an available component to be one which is generally available — either freely available or can be purchased — and that any software required to operate the component is available to the user. The CERN-OHL-v2 considers a component's availability to be key, and not the software licence.

In contrast, Lundell and Gamalielsson's dimensions of openness [26] considers OSS to be an integral part of an open system, in conjunction with *open standards* and *open content licences*. The three dimensions of openness provide a model for sustainable systems that are interoperable and maintainable in the long-term and avoid forms of lock-in, including vendor lock-in [26]. OH is a developing area with applications in scientific research, where it can reduce barriers to access and innovation [36], and in business, where similar arguments to OSS concerning reduced duplication of effort, lower cost of innovation, shared intellectual property, shorter time to market and non-traditional business models are relevant [13, 15, 25, 37, 56, 57].

[1] https://riscv.org/

The combination of OH, with open standards, open licensed content, and OSS already provides important scientific and civil infrastructure. For example, the Precision Time Protocol (PTP) [38, 39] is an open standard, also known as White Rabbit (WR) [30], which was developed to support data collection at CERN's Large Hadron Collider [30]. WR is also used in large-scale data gathering projects such as the Square Kilometer Array Telescope [24], in automated trading in financial markets, and to provide fine-granularity time infrastructure services on national networks [31]. CERN researchers and others (for example [20, 23, 24, 46, 54]) continue to develop the protocol and applications, and the networking appliances required to build WR networks are available as OH designs and implementations[2]. There are also proprietary hardware implementations of WR that are used, for example, in mobile telecommunications systems, e.g. MicroChip's SyncE and IEEE 1588 PLLs[3].

RISC-V processors for MCUs have been available from companies such as SiFive for some years, and have been incorporated in microcontrollers (MCUs) manufactured by SiFive and SparkFun, which run OSS MCU operating systems such as Zephyr [60]. More recently, SiFive and other companies, including, Alibaba, have developed 64 bit RISC-V processors that can run Linux [50, 51, 55]. The SiFive Unmatched board brings the RISC-V open ISA to the desktop space and, theoretically at least, allows the combination of OH or OH elements with the three dimensions of openness for software systems [26] in consumer and business computers. Is it possible to implement an open desktop computer? And, if not, what barriers are there to creating an open computer?

3 RESEARCH APPROACH

Initial availability of the HiFive Unmatched boards attracted a lot of attention and around 380 examples were sold[4] before production was discontinued in early 2022. Some purchasers of boards, both companies and individuals, have written and made videos about the process they used to implement computers using the Unmatched boards, to evaluate the boards, and to demonstrate the results of their work. SiFive also provide detailed documentation of the technical specifications, and the consequent constraints placed on the peripherals and components that can be connected to the Unmatched board [49].

We review publicly available accounts of the implementation of computers with the Unmatched board to develop an understanding of the problems encountered and the solutions that implementers discovered and used. The information is analysed using the definition of OSS [35] and the CERN-OHL-v2 [9] to identify solutions that use OH and OSS, to understand the technical and practical problems and solutions, and, where necessary, to support the identification of replacement components that may meet the functional and non-functional requirements.

Potentially relevant sources were identified by using the Google search engine to search with the following two quoted strings: "sifive unmatched" and "sifive unmatched documentation". The former string was also used to search for video content using Google and YouTube. The URLs returned were stored and the web pages read and videos watched to determine their relevance to building a computer with the Unmatched board, and the use of OSS on the computer. Documentation on SiFive's website for the Unmatched was collected. We also reviewed the content of the discussion forums hosted by SiFive related to the Unmatched board. Snowballing was used to find further relevant sources, and to mitigate possible bias in search results. Links in forum posts, documents, web pages reviewed, and videos were used as a source of links to additional blogs, articles and videos, which were used as further sources of information, or to add perspectives to sources we were already aware of.

The definition of OSS and the CERN-OHL-v2 were used as requirements and applied as analytical tools to understand the relationship between the published documentation, conversations in the forum and accounts of system builders, and the idea of an open desktop computer. A simple, semantic coding scheme [6] was developed and used by the first author [28] to identify topics discussed in forums, and written and video accounts of system builds. In total, the content of 120 of the SiFive Forum threads, 8 HiFive Unmatched documents published by SiFive, 15 blog pieces, wiki pages, and news articles, and 22 videos were analysed.

During the process of the research and planning an implementation of a desktop computer, the first author led a series of workshops with the partner companies in the SUDO project[5] (represented by the authors). The workshops were designed as an introduction to RISC-V for company software developers and managers, and explored RISC-V as a technology and as a potentially new way of thinking about software and product development. Each workshop included a discussion of the potential of RISC-V on the desktop and in the data center. The machine planned in this research, progress made, and the challenges encountered were discussed and feedback used to develop analysis and possible solutions to any challenges.

4 FINDINGS

In this section we first review the documentation for the HiFive Unmatched to identify the requirements of a desktop computer. We then examine user experiences in Section 4.2 and how they reflect limitations to openness and might inform plans to build an open desktop computer in Section 4.3.

4.1 Unmatched Documentation

The user documentation published by SiFive for the Unmatched [49] specifies *required* and *optional* hardware and provides a list of components that have been tested by SiFive and work with the board. The required hardware items are an enclosure or case for the board, and a power supply. The requirements for items are clearly specified. Open source hardware cases designs can be found for cases suitable for ITX form factor boards such as the Unmatched[6]. In practice, cases are available components, and, because cases generally do not require software to operate them, an open source case design would be ideal, an off-the-shelf case is an available component.

[2] A list of WR networking equipment vendors is at https://ohwr.org/project/white-rabbit/wikis/WRCompanies
[3] https://www.microchip.com/en-us/products/clock-and-timing/synce-ieee-1588
[4] https://www.crowdsupply.com/sifive/hifive-unmatched
[5] https://www.his.se/forskning/informationsteknologi/software-systems-research-group/sudo/
[6] For example: https://www.colinreay.org/opensource

Qualified power supply units (PSUs) recommended by SiFive for use with the Unmatched boards are:

- FSP Flex Guru 250W PSU (Model: FSP250-50FGBBI(M))
- FSP Dagger Pro 650W PSU (Model: SDA2-650)
- Antec HCG Gold Series 650W PSU (Model: HCG650 Gold)
- EVGA SuperNova G3 550W (P/N: 220-G3-0550-Y1)

All four PSUs are available for purchase in Europe and have no software requirements. Accordingly, they also meet the definition of an available component. Users also report the use of other PSUs with the same connectors and capacity. SiFive's documentation also specifies the PSU requirement more generically as: "ATX or SFX type PSU with a minimum 150 W rating and with a 24-pin power output connector …" [49]. Designs such as AB Open's rack cluster [5] successfully demonstrate different approaches to powering the Unmatched, although that design does not need to supply power to a graphics card on each board, unlike a desktop computer.

The Unmatched board will boot from a microSD card, which is sufficient to establish that the device works and to run a small desktop system. However, greater storage capacity, faster storage, and a shorter boot time, is needed to create a conventional desktop computer. In addition, the Unmatched board requires a graphics processing unit (GPU) card to support a monitor, and a keyboard and pointing device to operate the graphical user interface (GUI) desktop software. The documentation lists the following optional hardware components that can be used to expand the Unmatched board:

- M.2 Key M Connector for NVMe SSD Module (2230, 2260, 2280[7])
- M.2 Key E Connector for Wi-Fi / Bluetooth Module (2230)
- PCIe x16 Slot for graphics cards or other I/O expansion cards (8-lanes useable)
- Human Interface Devices such as Keyboard and Mouse via the USB Type A Ports

For the purpose of a planned build of a desktop computer, we use Ubuntu Linux v21.04 as an operating system for the Unmatched board [8], although it would be possible to build Linux from source if neccessary. Other Linux distributions such as Debian [12] and SUSE [33], and operating systems such as FreeBSD [14], are also available as binary images for RISC-V processors and the Unmatched board. Ubuntu is selected because it is offered as an optional operating system by manufacturers such as Dell and Lenovo, for example, and is thus available to business and public sector organisations.

The documentation does not specify any qualified hardware to be used as human interface devices (HIDs). Given the generic drivers for HIDs — typically a keyboard and a mouse — are OSS, commonly available USB keyboards and mice can be used with the Unmatched board. The first three items on the above list all have specified, qualified hardware items. Our intention is to plan the build of a computer to demonstrate the practicality of an open computing system and we will use all three components in the build. An SSD is used to provide sufficient storage to support a desktop system. A graphics card is needed to support a monitor, and the planned build also includes a WiFi module to allow demonstration of the completed computer where wired Ethernet access is not possible.

The documentation also specifies a CR1220 coin-cell battery to support the real-time clock (RTC) [49]. The battery is a common size and can be purchased easily; accordingly it is also considered to be an available item.

In summary, the required and optional hardware components can be considered to be available components for an OH design, and OSS drivers are available for the qualified components, where drivers are required. The optional WiFi card is discussed below.

4.2 User Experiences

Owners of the Unmatched board describe a variety of uses for the board, the problems encountered and the solutions found. The board is delivered with an SD card containing small footprint Linux operating system (OS) built with SiFive's Freedom U software development kit[8]. The supplied OS boots to the Xfce[9] desktop and provides a working desktop computer. The release of the Unmatched board also saw further development of Ubuntu with contributions from board owners in the form of bug reports (e.g. Thread-10 and Thread-22), as well as Debian (e.g. Thread-11) and FreeBSD (e.g. Thread-69, Thread-61 and Thread-50). Indeed, some Unmatched owners tried to port kernel versions before the Ubuntu core developers completed their work, which led to bugs being discovered and fixed (e.g. Thread-71). Thread-71 also documents a problem with the `shutdown` command where the power cannot be turned off cleanly. Ubuntu developers provide a solution. Ubuntu images were available for Unmatched when the board was delivered to customers, and some users documented their builds and early use of Ubuntu (e.g. Video-1 and Video-2). Work to port Haiku [16] (an OSS implementation of BeOS [59, p26]) to Unmatched is documented in the forums (e.g. Thread-14 and Thread-40). Videos (e.g. Video-3 and Video-4) document some of the work done towards adapting T2 Linux SDE [41] packages for RISC-V and the Unmatched.

A common problem faced by users of all operating systems was the boot sequence, especially when the operating system was installed on the optional M.2 NVMe storage device. One of the developers working on Haiku for RISC-V proposes and improvement to the boot process for Unmatched (Thread-58). The Unmatched uses u-boot[10] which uses configuration files stored on the microSD card or in the onboard flash (Thread-63). Consequently, both the microSD card (or flash memory) and the NVMe drive are required to boot an OS from the latter. Matters are further complicated by a race condition in Ubuntu's boot sequence, that is subsequently resolved (Thread-65).

System builders were interested in a variety of software applications for the Unmatched board. Some chose to run games to test and demonstrate the capabilities of the board. Minecraft is demonstrated in a video linked from Thread-34. The hardware configuration is listed and includes an Nvidia graphics card with closed source drivers. Video-5 documents the installation of Ubuntu on Unmatched, and explores the desktop software, before running some benchmarks, and some games including Doom, Quake, Quake II and Quake III.

[7] The digits refer to the physical dimensions of the cards. The first two digits specify the width of the card in millimeters, and the last two digits, the length of the card including the connector.

[8] https://github.com/sifive/freedom-u-sdk

[9] https://gitlab.xfce.org/xfce

[10] Universal boot loader: https://www.denx.de/wiki/U-Boot

Video players such as mpv (Video-1) and VLC (Video-6) are also shown to be working, though the creator of the former video comments that some software doesn't run well on Wayland, the default graphics server for Ubuntu v21.04. In addition, Canonical, the company behind Ubuntu, demonstrated CAD software running on the Unmatched at the RISC-V summit in December 2021 (Video-9), as well as VLC and the Calligra office suite. One user asks whether BOINC[11] has been built for RISC-V (Thread-117).

Web browsers proved to be a challenge. Gnome Web (also known as Epiphany), the default web browser for the Gnome desktop, runs on Ubuntu, but users wanted a more familiar browser with features such as being able to watch video in web pages (Video-5). Firefox had not been packaged for RISC-V Linux distributions, so some Unmatched users tried to build it. Video-10 shows Firefox being cross-compiled for T2 Linux. The author, and others, identify the lack of a working JavaScript interpreter as an obstacle to Firefox working on RISC-V and Unmatched in the same way as on Windows, MacOS, and distributions of Linux compiled for x86 and ARM processors (Thread-25,Thread-70). Another builder reports having completed a port of Firefox for Unmatched complete with working JavaScript (Thread-35). Their brief account acknowledges the support received from the Mozilla community to complete the task.

When Unmatched was first delivered to customers, the RTC wasn't recognised by the OS. Thread-21 provides a detailed account of the problem and its solution, which requires patching the Linux kernel driver. The RTC is integrated in the DA9063[12] power management integrated circuits (PMIC) and the Linux kernel driver for the device is unable to access the PMIC. Thread-21 includes information that a patch is being prepared for the driver[13]. Given a working driver for the DA9063 PMIC, that resolves the RTC problems, the power management problems reported by other users can also be addressed, and progress is made towards resolving issues with the `shutdown` command. A few months later, Thread-17 documents progress providing a fix for using the RTC as a means of waking the Unmatched and to boot Linux and the patch being added to the Linux kernel[14].

The documentation specifies two series of AMD video cards as qualified for Unmatched. The specified cards can be used with the OSS `amdgpu` Linux kernel driver, as well as AMD's closed source drivers. Most users added specified video cards to their Unmatched boards. However, given the Unmatched was delivered to users during 2021, some had problems sourcing GPU cards because of COVID-19 related supply chain issues and for that reason, or expediency, installed other brands and models of GPU. As noted previously, one user was able to run an Nvidia card (Thread-34), as did AB Open in their build [17] (and Video-7). Others were able to use AMD Radeon GPUs and cheaper clones (Thread-7) successfully.

Thread-42 includes a discussion of how to configure Ubuntu to use the `amdgpu` driver, rather than the closed source radeon driver loaded by default. The discussion highlights some limitations to the OSS driver with more recent GPU cards; in particular that the audio signal is not sent over an HDMI connection. Some more recent video cards lack drivers or require driver modifications to work. One example is the requirement for floating point arithmetic to be available for some AMD GPUs[15] (Thread-43). The time and effort required to implement this functionality in T2 Linux is documented in Video-8. Another problem encountered is caused by a bug in the Mesa rendering library on a Debian system (Thread-11), which the user diagnoses and reports in detail. Subsequently the bug is fixed in Debian and propagated to the next Ubuntu release. Of interest is that some contributors to the SiFive forums are clearly aware that the process of creating systems with the Unmatched board is part of a collaborative development process with the manufacturer, and operating system and software developers (Thread-100 & Thread-108).

The Unmatched has four accessible USB ports which system builders primarily use to attach keyboards and mice, both wired and using wireless receivers (Thread-43). Some users identify intermittent problems with the USB ports (Thread-8, Thread-46, and Thread-43). Other devices are tried in USB ports including WiFi dongles (Thread-59) — the reporter has only tested devices with closed source drivers — and audio devices (Thread-24). There are also some who would like to boot from universal serial bus (USB) devices (Thread-47), which requires additional work with u-boot to modify the boot sequence.

The M.2 and PCIe connectors provide users with additional opportunities to add devices and ports to the Unmatched board. The intended uses are a graphics card for the PCIe slot and storage and communications in the M.2 slots. Both types of connector are versatile. Some users, for example, have mixed success using the PCIe port to add high-speed Ethernet cards (Thread-120). The M.2 connectors provided both opportunities and pitfalls. Some owners were able to add internal USB ports using a card in the M.2 Key E slot, e.g. Thread-48 while others found that the connector's versatility could lead to problems with hardware selection. One example is found in Thread-38 and Thread-101 where questions are asked about using the Intel 9560 WiFi card instead of the recommended Intel 9260 card. The Intel 9560 is a WiFi/Bluetooth card that has the same form factor as the 9260, but, as Intel warn in their technical documentation:

> "Though you can insert these CRF into a standard M.2 Key E socket, they are only compatible with a system designed for the CNVi." [22]
>
> "These CRFs can only be used with select Intel processors/chipset on systems/motherboards that is specifically designed to support it." [22]

Oversimplifying matters, CNVi cards like the Intel 9560 are radio transmitter/receivers and the networking components are situated on the motherboard. In contrast, the Intel 9260 is an expansion card with both networking components and a radio transmitter/receiver that is PCIe compatible.

Conversations in the SiFive Forums provide further insights into the process of developing RISC-V hardware and the software, particularly operating system elements, required to use the hardware. While the SiFive forums have the appearance of a Q&A site to

[11]Berkeley Open Infrastructure for Network Computing

[12]https://www.renesas.com/eu/en/products/power-power-management/multi-channel-power-management-ics-pmic/handheld-computingtablet-power-management-ics-pmics/da9063-programmable-pmic-quad-core-application-processors

[13]https://lkml.org/lkml/2021/11/19/883

[14]https://lkml.org/lkml/2021/11/1/800

[15]Free Desktop issue at: https://gitlab.freedesktop.org/drm/amd/-/issues/1754

support product owners, the forums work as an open collaboration between users, the manufacturer and operating system developers to develop the software and hardware, as well as to improve the user's experiences. The value of the open collaboration is apparent in a discussion of changing the processor's clock frequency (Thread-68) where users exchange information and point to sources of help, while the manufacturer provides additional detail, and corrects misconceptions.

Forum users also discuss openness in relation to Unmatched and the implementation of computers with the Unmatched board. There are differences in expectations. Some users would like open source drivers for all components and more detail about the software and firmware running on the board, this is exemplified by a wish list articulated in Thread-100. The manufacturers' response is that the Unmatched board is not intended to be open hardware, rather its purpose is to get RISC-V hardware into developers' hands so that the software stack, including operating systems, can be developed. Some components on the Unmatched board are licensed intellectual property (IP), and consequently not all details are available to end-users. A similar point is made in response to a query about the PCIe bus in Thread-85.

4.3 Planning to Build an Open Desktop Computer

Before looking more closely at the idea of an open computer and how one might be built, we need a working definition of *open* in this context. In Sections 1 and 2 we refer to the work of Lundell and Gamalielsson[26] who define dimensions of openness in terms of OSS, open standards, and openly licensed content. We have also considered the CERN-OHL-v2 licences as expressions of the concept of open hardware, and in earlier parts of this section, we outline different perspectives of openness in terms of a computing system that are held by the users of the Unmatched. Lundell and Gamalielsson's dimensions of openness apply, in conception, to software systems alone. Accordingly, the use of Ubuntu v21.04 meets their requirements for openness in the use of OSS and open standards, provided selected software meets those requirements. (The dimension of content licensing is a matter for the user and outside the scope of this argument.) Extending Lundell and Gamalielsson's dimensions to the software interfaces between the operating system and computer peripherals, such as GPUs and keyboards, we infer that the selection of peripherals in combination with open source drivers would be consistent with their dimensions of openness. However, as we have already observed, the CERN-OHL-v2 allows for an item of hardware in combination with supplied, closed source drivers to be considered part of an OH design. Consequently, there are two perspectives of *open* that need to be considered, which reflect the different expectations expressed by system builders in the SiFive forums. Accordingly, we consider two approaches to building a computer: one with OSS drivers, and one where binary drivers may be used. It should be noted that the CERN-OHL-v2 is used as an analytical tool, and we do not propose a licensed OH computer design because such a design is so obvious as to be unlicensable.

As outlined in the first part of this section (Section 4.1), the user documentation for the Unmatched board [49] specifies required and optional hardware. The required hardware items are an enclosure or case for the board and a power supply. Neither item requires software, and user experience documented in the forums suggests that other cases and power supplies that meet the requirements may also be used. The optional hardware components to be included in the planned build are: including an M.2 NVMe storage device, an M.2 WiFi module, a graphics card, a USB keyboard and a mouse.

The Linux kernel drivers supplied with Ubuntu Linux v21.04, the operating system used for the planned build, include OSS drivers for keyboards, mice, and NVMe storage devices. SiFive specify qualified GPUs and two WiFi cards. The qualified GPUs are the AMD RX 500 series and the AMD Radeon HD 6000 series. As noted in Thread-42, Ubuntu loads the closed source driver by default, which meets the requirements for the GPU to be an available component according to the CERN-OHL-v2. Similarly, the specified Intel WiFi cards (Intel 9260 and AX200) both use the closed source `iwlwifi` driver, which also meets the requirements of the CERN-OHL-v2.

Some Unmatched owners expressed the desire to use OSS drivers as far as possible. With the caveat of the closed source driver being loaded by default, the qualified GPUs can also be used with the OSS `amdgpu` driver (Thread-42). Some Qualcomm Atheros WiFi cards have the M.2 Key E form factor required for the Unmatched, and, depending on the model, use the OSS `ath9k`, `ath5k`, and `carl9170`[16] drivers. Replacing the qualified Intel WiFi cards with an appropriate Qualcomm device would allow the use of OSS drivers with all optional hardware specified in the documentation [49].

The Unmatched board is an available component for an OH design in the context of the CERN-OHL-v2. The board itself is not intended to be OH (Thread-100,Thread-199) and even though the board schematics [48] and bill of materials (BoM) [47] are available as part of the documentation, core components, such as the FU740 CPU, are not generally available for purchase (Thread-105), and some on-board components are licensed IP.

Accordingly it is possible to propose more than one OH design of an open desktop computer based on the Unmatched board. Designs could follow the conditions of the CERN-OHL-v2 licences[17], and would offer those using the designs choices related to the use of OSS drivers and binary blobs. However, creating a computer where all hardware components are open with fully detailed operating information is not currently possible.

5 DISCUSSION

In the introduction we stated the following three research objectives for this work:

- **O1** To understand the current barriers to implementing an open desktop computer;
- **O2** To identify potential solutions to any barriers encountered; and
- **O3** To understand the pragmatic solutions that may be required to implement an open computing system.

The barriers to creating an open computing system depend on the definition of *open* being used. To create an OH design for a desktop computer is possible (with the caveat given in footnote 17),

[16]https://wiki.debian.org/ath9k, https://wiki.debian.org/ath5k, & https://wiki.debian.org/carl9170
[17]Notwithstanding the point that such a design would lack sufficient intellectual property to be considered licensable.

and using the CERN-OHL-v2 licence a computer using components with OSS drivers can be specified, with constraints on the available components that might be used. The CERN-OHL-v2 requirements for an available component specify that the hardware component and the software required to use it are available to the user; there is no requirement for the software to be OSS, though the author of the design may specify it. In the context of a desktop computer, an OH design licensed using the CERN-OHL-v2 may specify a component that requires a closed source binary driver for the Linux kernel. The Intel 9250 WiFi card is an example because it requires the `iwlwifi` [21] driver supplied by Intel as a binary or *blob*. The designer could specify a WiFi card such as the Qualcomm Atheros family of cards, which use the OSS `ath9k`, `ath5k`, and `carl9170` drivers.

Looking more closely at the notion of an available component, reveals complexity behind the boundary of the component. Discussions in the SiFive forums and the SiFive documentation show that while an open design may be specified, elements within that design — subcomponents of specified components — may not be open. Examples observed include the PCIe bus where an Unmatched owner would like to have more detail about the bus to be able to write drivers for another (unspecified) operating system (Thread-85). It is unclear from the forums whether the information was acquired from the bus manufacturer. However, where a component is supplied with software and considered an available component, there can be a barrier in terms of openness to the creation of third-party software to replace the supplied software.

Two barriers to implementing an open desktop computer are closed source drivers — contingent on the OH license used — and the extent to which hardware is open. The pragmatic solution is to use components with OSS drivers, and licenses such as the CERN-OHL-v2 which define hardware components in ways that can be incorporated into designs. Potential solutions are another matter. One possible solution might be to design a computer board where all components that require firmware and drivers are OH and only physical components such as resistors, for example, are considered to be available components. With RISC-V processors, this model is arguably more achievable than previously. Some MCUs already fulfil this ambition to some extent — e.g. SparkFun's RedV MCUs[18], which have RISC-V processors, and AVR and ARM based MCU boards from Arduino[19], AdaFruit[20], and single-board computers (SBCs) manufactured by BeagleBone and Olimex. A question for future research would concern whether there is an economic model, or models, that would support the development and manufacture of OH PC boards, especially as the BeagleBone Black [4] and OLinuXino [32] systems are both capable of running Linux desktops, although both are SBCs, similar in performance to a Raspberry Pi.

A further complication for the implementor of an open computing system based on the HiFive Unmatched board may come from the terms under which the board is supplied to purchasers. The Getting Started Guide contains the following statement:

> "The HiFive Unmatched Platform is intended for use by end users only, and solely for such end users to test and evaluate SiFive's services and products, including, but not limited to, SiFive's semiconductor components and software applications (the "Intended Use"). The Unmatched Platform may not be resold, redistributed, transferred or otherwise exploited." [49]

Given that the Unmatched board is no longer manufactured, resale or transfer is the only way to obtain the board, and this condition of use appears to preclude the board being *available*. Also intestesting to note is a SiFive forum thread (Thread-1) where a user asks about buying a Unmatched board, and is offered one. The thread ends after the initial two messages, but SiFive management — at least the staff and management involved in the forum — have not deleted the thread. Accordingly there is an open question about how the company perceives resale of Unmatched boards

As noted above, the Unmatched board was part of a process of developing RISC-V computers that provided hardware for system builders to buy with the intention of improving OS and software implementations on production hardware. The open collaborative process in the SiFive forums — an example of private-collective innovation [13, 25, 57] — appears to have been successful. Private-collective innovation is expected to be used when the benefits outweigh the cost [57] and the benefits in the case of the Unmatched board have been broad. SiFive have benefited from a lot of development work undertaken by OS developers and individual users to ensure that the boards they purchased could be put to their intended purposed. For future boards, the company can now be confident that Linux distributions will run on RISC-V. Canonical and the Ubuntu project invested time prior to the manufacturing release of Unmatched to update the distribution from the RISC-V implementation for the earlier Unleashed board, and received bug reports and, in some cases, fixes that improved the distribution. Other distributions and operating systems — Debian, FreeBSD and T2 Linux — were further developed on Unmatched, and the Haiku OS was ported to RISC-V. In addition, there were contributions from users that improved the documentation of Unmatched.

In summary. In meeting the first research objective (**O1**) we identify two principal barriers to implementing an open desktop computer: closed source drivers for hardware components, and the extent to which hardware components are open. The second objective (**O2**) concerns potential solutions to the barriers identified. Potential solutions include constraints on the design of a computer board so that all electronic components are OH with OSS drivers. Pragmatic solutions, the third objective (**O3**), include the use of OSS drivers where they are available, and replacement of components with functionally similar items with OSS drivers. Careful selection of OH licence can also permit the use of components with closed source drivers in open designs.

Limitations. In this study we have analysed technical documentation, forum activity, and accounts of system builders in blogs, news items and videos focused on building a desktop computer using the SiFive Unmatched board. We acknowledge that there are limitations to the transferability of our findings that arise from the

[18] https://www.sparkfun.com/
[19] https://www.arduino.cc
[20] https://www.adafruit.com/

focus of the study on a single case. The SiFive Unmatched, however, is the only PC class, RISC-V computer board that has recently been available for purchase. The barriers to implementation of an open desktop computer identified during the study concern the licensing of electronic, hardware components and the operating system drivers required to use the component. The generic pattern may reasonably be expected to occur in the context of implementing open computer systems. Nonetheless, additional problems may be encountered when using other computer boards and hardware components to implement open systems.

6 CONCLUSIONS

In this paper we have analysed the experiences of system builders using the HiFive Unleashed, a PC form-factor board with a RISC-V processor, to build desktop computers. Our interest lies in trying to understand how possible it is for an open desktop computer to be created, and what barriers system builders face, and the pragmatic solutions adopted to build an open system. In practice, the constraints to creating an open computer system lie in the interface between the OSS operating system and the hardware. The Linux operating system provides both OSS and closed source drivers for motherboard components and peripherals, which allow for the specification of an OH design of a computer based on a CPU with an open ISA — RISC-V — and an OSS operating system. Careful selection of components allows the specification of a computer that uses, as far as possible, OSS drivers. However, many hardware components — both peripherals and on the Unmatched board — are proprietary and rely on proprietary (closed source) firmware to provide an interface to the operating system drivers. Accordingly, open hardware designs, in the sense of the CERN-OHL-v2, are possible, and largely open computing systems are feasible, but completely open systems may not yet be practical. However, we observe that some existing SBCs are examples of OH computer designs, and argue that future research could investigate possible economic models to support the development of OH PC class motherboard designs, where there is an emphasis on the use of OH components with OSS drivers and firmware. This paper makes a further contribution by providing an illustration of the significant impact and value of the synergies arising from open collaboration in private-collective innovation between hardware manufacturers, operating system developers, and early adopters of a technology.

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A REFERENCED SIFIVE FORUM THREADS

Table 1: SiFive forum threads referenced in the text

Thread	URL
Thread-1	https://forums.sifive.com/t/looking-to-buy-your-hifive-unmatched/5672
Thread-7	https://forums.sifive.com/t/my64-mini-itx-case-and-hifive-unmatched/4414
Thread-8	https://forums.sifive.com/t/having-issues-with-gpus/5360
Thread-10	https://forums.sifive.com/t/intermittent-kernel-oops-under-heavy-load/5009
Thread-11	https://forums.sifive.com/t/amd-gpu-suddenly-unusably-slow-mesa-issue/5391
Thread-14	https://forums.sifive.com/t/booting-haiku-on-the-sifive-unmatched/5470
Thread-17	https://forums.sifive.com/t/has-anyone-got-da9063-rtc-working-from-linux/5302
Thread-21	https://forums.sifive.com/t/two-outlying-issues/4926
Thread-22	https://forums.sifive.com/t/unexpected-bugs-and-oops-virtual-memory-related-with-ubuntu-21-04-and-kernel-5-11-10-shown-on-console/5397
Thread-24	https://forums.sifive.com/t/usb-audio-support/5357/4
Thread-25	https://forums.sifive.com/t/usb-audio-support/5357
Thread-34	https://forums.sifive.com/t/minecraft-running-barely/4974
Thread-35	https://forums.sifive.com/t/firefox-first-runs/5211
Thread-38	https://forums.sifive.com/t/intel-9560-m-2-wifi-card-not-detected-solved/5227
Thread-40	https://forums.sifive.com/t/haiku-runs-on-hifive-unmatched/4981
Thread-42	https://forums.sifive.com/t/ubuntu-amdgpu-drivers/4935/8
Thread-43	https://forums.sifive.com/t/unmatched-first-runs/4750/3
Thread-46	https://forums.sifive.com/t/usb-disconnect/5175
Thread-47	https://forums.sifive.com/t/is-it-possible-to-boot-from-usb/5180
Thread-48	https://forums.sifive.com/t/m-2-e-key-to-pci-e-usb2-adapter/5166
Thread-50	https://forums.sifive.com/t/open-issues-for-freebsd-not-the-unmatched-guys/4930
Thread-58	https://forums.sifive.com/t/a-plea-to-desktop-focused-os-distro-creators-on-booting/5083
Thread-59	https://forums.sifive.com/t/usb-wifi-is-ok/4902
Thread-61	https://forums.sifive.com/t/reporting-success-freebsd-on-my-unmatched/4925
Thread-63	https://forums.sifive.com/t/stuck-loading-device-tree/5022
Thread-65	https://forums.sifive.com/t/nvme-not-functioning/4762/7
Thread-68	https://forums.sifive.com/t/testing-unmatched-at-1-4-ghz/4863
Thread-69	https://forums.sifive.com/t/openbsd/4988
Thread-70	https://forums.sifive.com/t/browser-suggestion/4983
Thread-71	https://forums.sifive.com/t/5-12-4-kernel-for-ubuntu/4907
Thread-85	https://forums.sifive.com/t/more-documentation-for-pcie/4769
Thread-100	https://forums.sifive.com/t/remaining-agency-issues-to-be-solved/4578
Thread-101	https://forums.sifive.com/t/unmatched-bluetooth-and-wifi-card-support/4576
Thread-105	https://forums.sifive.com/t/will-the-fu740-chip-be-sold-separately/4432
Thread-108	https://forums.sifive.com/t/can-an-unmatched-board-be-used-as-a-standalone-computer/4353
Thread-117	https://forums.sifive.com/t/does-u740-support-boinc/4201
Thread-119	https://forums.sifive.com/t/is-the-board-open/4175
Thread-120	https://forums.sifive.com/t/problem-with-intel-x520-adapter-cant-be-detected-by-hifive-unmatched/5044

B REFERENCED VIDEOS

Table 2: Videos referenced in the text

Video	URL
Video-1	https://www.youtube.com/watch?v=0ge5H-7h6GQ
Video-2	https://www.youtube.com/watch?v=1YfEKfcF98c
Video-3	https://www.youtube.com/watch?v=wHp-UIGov8c
Video-4	https://www.youtube.com/watch?v=xGr0vmffSa0
Video-5	https://www.youtube.com/watch?v=bqekGqREf9k
Video-6	https://www.youtube.com/watch?v=3o411cQ7XG0
Video-7	https://vimeo.com/644341183
Video-8	https://www.youtube.com/watch?v=Sv4-_a_3BKg
Video-9	https://www.youtube.com/watch?v=HrJi7tX0jE8
Video-10	https://www.youtube.com/watch?v=MiGfP0-g2q0