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Review Article

Best Practice in Open Source Scientific Designs Pre-Covid-19

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Abstract

Before the COVID-19 pandemic, open source hardware development grew steadily. However, the pandemic rapidly accelerated the global acceptance of open source hardware solutions. While open source software has long been vital in the ICT sector, this concept now extends to physical hardware production. Notably, the medical and energy fields have prominently embraced this shift, utilizing 3D printing to actualize open source designs. This study explores pre-pandemic Open Source Scientific practices, aiming to extract insights for a stronger future open source framework. Through an in-depth case study, we illuminate best practices, exemplary applications, and propose a framework for upcoming open source hardware projects. Additionally, this paper categorizes key areas of open source hardware innovation, outlining key sections and areas, thus offering a comprehensive view of the open source hardware landscape.

Introduction

Open source hardware development, while a relatively recent phenomenon, has its roots deeply embedded in the principles of collaboration, transparency, and shared knowledge. The concept of open source, which was initially confined to the realm of software, has gradually expanded to encompass tangible hardware production and development. This shift has been most evident in sectors such as science, engineering, and information and communication technology (ICT), where the principles of open source have been applied to create innovative solutions and products [1].

The history of open source can be traced back to the early efforts at the Massachusetts Institute of Technology (MIT) Artificial Intelligence (AI) Lab in 1971 [2], initially focusing on code access freedom. Evolving principles significantly impacted commercial and custom apps, though challenges like intellectual property and licensing persisted. Open source hardware offers innovation, rapid prototyping, and tailored solutions, reducing development time and improving software optimization. Flexibility in customization is key, addressing computational reproducibility through open policies and standards. The evolution of open source from software to hardware has been a gradual process, marked by a series of significant milestones. Bonvoisin et al, [1] indicated that one of the key factors contributing to this evolution has been the standardization of practices in open source hardware. Standardization contributes to the formation of a recognizable identity and enables interactions with a wider community. Early standardization initiatives focused on aspects such as licensing, intellectual property, and documentation formats.

The advent of 3D printing technology has played a pivotal role in the realization of open source hardware designs, particularly in the medical and energy sectors. The ability to rapidly prototype and manufacture physical objects based on digital designs has opened up new avenues for innovation and collaboration. The introduction of open source Process Development Kits (OpenPDK) by Skywater technologies in June 2020 has further democratized the hardware design process, eliminating barriers to Application-Specific Integrated Circuit (ASIC) design [1].

Despite significant progress in open source hardware, it's still early compared to software. Challenges like open tool chains, modularity, and hardware-specific standards persist. Yet, its potential advantages -quicker development, higher success chances, and optimized software - drive future exploration. However, embracing open source hardware faces obstacles, including rising chip design costs and diminishing Moore's law benefits [3]. Complexity and licensing complexities, especially when contrasted with open source software, are challenges [4]. Additionally, the lack of strong support systems, akin to software repositories, poses another hurdle.

Researchers utilize open source hardware to access advanced technology, particularly in financially and infrastructurally constrained scientific settings [5]. DIY technologies, a type of open tech, are prevalent, especially in underfunded countries. Beyond financial accessibility, open hardware benefits labs through local production and direct knowledge transfer. While it offers opportunities, challenges persist. This paper delves into open source hardware practices in science, engineering, and ICT, aiming to bolster a robust, unified framework for future adoption.

Literature Review

The literature on open source hardware development is vast and diverse, encompassing a range of topics from the standardization of practices in open source hardware [1] to the opportunities and challenges presented by open-source hardware. This literature review aims to provide a comprehensive overview of the key themes and findings from the existing body of research, focusing on the sectors of science, engineering, and ICT.

Open source hardware derived from the software field, particularly from the Open-Source Software (OSS) space, per Heradio [6]. OSSC is software licensed to allow others to modify and distribute its source code. This OSS space has been growing in popularity over the years, achieving significant importance. Consequently, numerous successful initiatives have embraced this ethos, exemplified by prominent projects such as the Linux operating system and the Apache web server. This philosophy has, in turn, spawned an analogous movement that extends the principles of openness to the realm of electronic hardware design, giving rise to what is known as Open-Source Hardware (OSHW). This OSHW field formed the basis for this, and many other studies, with key themes emerging.

One of the key themes in the literature is the standardization of practices in open source hardware. Bonvoisin et al. [1] argue that standardization is a crucial component in the maturation of any field of technology as it contributes to the formation of a recognizable identity and enables interactions with a wider community. Their study reviews past and current standardization initiatives in the field of Open Source Hardware (OSH), focusing on aspects such as licensing, intellectual property, and documentation formats. They also introduce two standards that are currently being released and call for early users and contributors, the DIN SPEC 3105 and the Open Know How Manifest Specification. Another significant theme in the literature is the opportunities and challenges presented by open-source hardware. Gupta et al. [3] argues that while innovation in hardware is slowing due to the rising costs of chip design and diminishing benefits from Moore's law and Dennard scaling, open source can help hardware innovation. However, they note that this has not yet happened due to several reasons, including the need for an open tool chain, modularity, and hardware-specific interface standards.

The literature also discusses the application of open source hardware in various sectors. For instance, Wenzel [5] discusses the use of open source hardware in scientific environments characterized by economic and infrastructural constraints. He argues that DIY technologies, which are a form of open technologies, are already widespread, especially in countries with lower science funding. Beyond financial accessibility, Wenzel suggests that open hardware can be transformational to the technology access of laboratories through advantages in local production and direct knowledge transfer. Also, Fingerhuth et al. [7] review a wide range of open source software for quantum computing, covering all stages of the quantum toolchain from quantum hardware interfaces through quantum compilers to implementations of quantum algorithms. In the context of scientific instruments, there are challenges posed by the explosion in the volume of data produced as spatial and temporal resolutions of scientific instruments improve. They propose a design workflow that allows for the exploration of algorithmically complex hardware designs and the development of reusable hardware libraries for scientific instruments at the edge. Within the realm of the Information and Communication Technology (ICT) sector, the work of Miljković et al, (2021) centres on the nuanced distinctions between the sharing and reutilization paradigms of Free and Open-source Software (FOSS) as opposed to Open Hardware (OH). The authors posit that the differential support between these two domains can be attributed to the inherent intricacies inherent in OH's digital structure and licensing arrangements. In light of this, they propose that the utilization of the FAIR principles, which encompass the enhancement of Open Hardware's findability, accessibility, interoperability, and reusability, holds the potential to effectively address this substantial challenge [4].

In conclusion, the literature on open source hardware development is rich and diverse, however, there are still gaps in our understanding, particularly in relation to the best practices in open source hardware development across the sectors of science, engineering, and ICT. This paper aims to contribute to filling these gaps by providing a detailed exploration of the best practices in these sectors.

Methodology

The methodology employed in this study is designed to facilitate a high-level categorization of open source hardware to support further development and easier access for users. This approach is underpinned by a comprehensive review of the literature and analysis of existing open source hardware projects.

Literature Review

The first step in our methodology involved a comprehensive review of the literature on open source hardware development, with a particular focus on best practices in the sectors of science, engineering, and ICT. This review provided valuable insights into the opportunities, challenges, and best practices in this field, and helped to identify gaps in our understanding, particularly in relation to the categorization of open source hardware.

Analysis of Existing Open Source Hardware Projects

Following the literature review, we conducted an analysis of existing open source hardware projects. This involved collecting data on a wide range of projects, including their objectives, the sectors they operate in, the technologies they use, and the communities they serve. This data was then analyzed to identify common themes and patterns, which informed the development of our categorization framework.

Categorization Framework

The categorization framework developed in this study is designed to provide a structured approach to understanding and navigating the diverse landscape of open source hardware. The framework is based on two key dimensions, sector and area of application.

Sector: This dimension relates to the sector in which the open source hardware project operates, such as science, engineering, or ICT. Understanding the sector can provide insights into the specific needs and challenges that the project is designed to address.

Area of Application: This dimension relates to the area that the open source hardware project serves. This can include cross sector areas such as medical devices, machinery and energy, as well as sectoral specific areas such as production tool.

By categorizing open source hardware projects along these dimensions, we can create a structured and accessible framework that supports further development and easier access for users.

Categorization of Open Source Hardware Innovation

Open source hardware innovation can be generally categorized into three high-level vertical sectors: Science, Engineering, and ICT. Each sector presents unique opportunities and challenges for open source hardware development, and understanding these can help to inform the design and implementation of open source hardware projects. A number of cross-sectoral areas are proposed namely, communications, electronics, machinery, other engineering, energy, environmental, production tools, scientific hardware and medical devices. These classifications, and the cross sectoral areas of relevance can be seen below in figure 1.

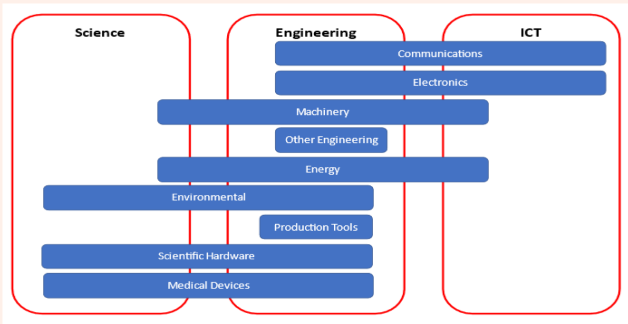

Figure 1: Proposed catagorisation of Open Source Hardware Innovation.

Science

The science sector encompasses a broad range of disciplines, from physics and chemistry to biology and earth sciences. Open source hardware in this sector often involves the development of scientific instruments and equipment, such as microscopes, spectrometers, and environmental sensors. For example, the Open Science Drone Toolkit [8] demonstrates the potential of using affordable, accessible, and customizable open source software and hardware for capturing research-grade aerial data. Similarly, the OpenMetBuoy-v2021 [9] offers an easy-to-build, affordable, and customizable open-source instrument for oceanographic measurements, emphasizing its adaptability in both sea ice and open ocean environments. In healthcare, the development of an Arduino-based heartbeat detection device for real-time ECG analysis represents a significant innovation in the field of medical science [10].

The democratization of design in scientific innovation has also been explored, with case studies highlighting the design and social impact of collaboratively designed open source hardware instruments [11]. Furthermore, tools for public participation in science have been developed to support the efficient and inclusive dissemination of Open Science Hardware (OSH), fostering greater community involvement in scientific endeavours, In the realm of material identification, the potential of low-cost hardware combined with open source software has been utilised in reality [12], emphasizing its utility not just for professional researchers but also for citizen science initiatives. Additionally, the introduction of COSI Measure, [13] an automated open source measurement system, showcases the capability of open source hardware to offer sub millimetre resolution for a diverse range of applications.

Engineering

The engineering sector involves the application of scientific and mathematical principles to design and build structures, machines, and systems. Open source hardware in this sector can range from mechanical devices and electrical circuits to complex systems like robots and drones [3]. Demir et al [14] discuss the use of flexible radio platforms in telecommunications training represents a significant innovation in the field of engineering education. As discussed, 3D printing was drive ben the development of open source hardware in the engineering sector. 3D printing has become an integral part of the engineering sector, offering innovative solutions and applications. In the realm of tissue engineering, 3D printing techniques have been employed to fabricate complex structures, such as scaffolds, that can be used for various biomedical applications [15].

Additionally, the integration of the Internet of Things (IoT) with 3D printing has been explored, with Aradhya [16] showcasing the potential of open source hardware and software tools in enhancing the efficiency of 3D printing processes and enabling remote engineering capabilities. Furthermore, the educational aspect of engineering has also embraced 3D printing. Tutorials have been developed to impart knowledge and skills related to 3D printing to undergraduate engineering students [17], categorizing the learning outcomes into primary, secondary, and tertiary levels. This not only equips students with practical skills but also fosters an understanding of the potential applications of 3D printing in real-world engineering scenarios.

ICT

The ICT sector involves the use of computers and telecommunications to store, retrieve, transmit, and manipulate data. Open source hardware in this sector can range from computer components and networking devices to complex systems like servers and data centres [3]. For example, the growth of a community that shares digital 3D designs has created an opportunity to study, encourage and stimulate innovation in the ICT sector [18].

The implementation of TEMPEST, a technique developed that involves receiving electromagnetic signals from a video interface to infer the image displayed on a monitor, showcases the potential of software-defined radio in the ICT sector. Similarly, the adoption of FIWARE, an open-source standard platform, has been explored by Rodriguez et al [19] in the context of smart farming, indicating its potential applicability in various ICT domains. ICT support tools for hardware development in the open source sphere have also emerged, tools for example e Sim, offering open-source solutions for mixed-signal and microcontroller simulations, catering to a diverse audience from students to startups. Similarly, innovations such as Hecatonquiros showcase the adaptability of open-source hardware, providing platforms for developing robotic manipulators suitable for various applications, including aerial manipulations in the ICT domain [20].

Cross-Sectoral Areas

In addition to these three vertical sectors, there are a number of cross-sectoral areas that are relevant to open source hardware innovation. These include communications, electronics, machinery, other engineering, energy, environmental, production tools, scientific hardware and medical devices. These areas represent key domains of application for open source hardware and offer unique opportunities for innovation and collaboration. This groupings can help collected, organise and refine the developments in the open source hardware field. The categorization of open source hardware innovation into these vertical sectors and cross-sectoral areas provides a structured approach to understanding and navigating the diverse landscape of open source hardware.

Standout Applications in the Proposed Sectors and Subcategories

Standout applications in the key sectors and areas include the following:

Communications

Amateur Radio

The Homebrew D-STAR Radio and HackRF One are standout examples of open source hardware projects in the field of amateur radio. These projects provide amateur radio enthusiasts with the tools and resources they need to experiment with radio communication and contribute to the amateur radio community [21].

Video Electronics

In the field of video electronics, the Milkymist One video synthesizer and the Neuros OSD digital video recorder are examples of open source hardware projects that have made significant contributions (Zhang & Wawrzynek,2011). These projects provide users with the tools and resources they need to experiment with video production and distribution.

Networking

In the field of networking, the NetFPGA hardware platform and the OpenPicus platform [22,23] for smart sensors and Internet of things are examples of open source hardware projects that have progressed this area according to Mitola & Maguire [24]. These projects provide users with the tools and resources they need to experiment with networking and IoT technologies. The NetFPGA platform facilitates the swift prototyping of networking devices, offering a cohesive environment for open-source applications in software-defined networking (SDN) across both hardware and software realms [22]. This platform empowers users to innovate and pioneer new networking technologies and protocols. Conversely, the OpenPicus platform is tailored for smart sensors and IoT applications, presenting a modifiable open-source foundation for the creation and launch of smart sensor networks [23].

Wireless Networking

In the field of wireless networking, projects like the Sun SPOT hardware-software platform for sensor networks, the USRP universal software radio peripheral, the PowWow Power Optimized Hardware and Software FrameWork for Wireless Motes, the Twibright RONJA free-space optic system, and the SatNOGS software-hardware project for a global low Earth orbit satellite ground station, as discussed by [25] are examples of open source hardware projects that have made significant contributions.

Electronics

Cameras

Open-source cameras, constructed using transparent hardware and software components, have revolutionized the realm of photography and videography, granting users unparalleled flexibility to tailor them to specific requirements. This adaptability, coupled with cost-effective innovation, has been pivotal in advancing scientific methodologies. The integration of open-source hardware designs with economical optoelectronic and robotics elements has spurred the creation of bespoke lab equipment, including cameras [26].

A great example of this is the ESP32-CAM module. This device amalgamates a 2MP camera with a dual-core 32-bit processor, supplemented by Wi-Fi, Bluetooth connectivity, and diverse I/O interfaces. Supported by the Arduino programming language and an array of open-source libraries, it's an ideal candidate for programmable camera research and has been adapted for various experimental camera configurations [27]. The versatility of open-source cameras extends beyond mere hardware. In digital image forensics, they've been instrumental in employing deep learning techniques for open-set source camera device identification, a process that discerns the originating camera model of a digital image [15].

Computer Systems

Open-source computer hardware systems, grounded in the principles of collaboration, transparency, and accessibility, have emerged as transformative forces in the technological landscape. A primary draw of open-source computer hardware lies in its cost-effectiveness. The democratization of hardware designs allows individuals and organizations to sidestep the hefty expenses tied to proprietary systems. This cost advantage has propelled platforms like Arduino and Raspberry Pi to the forefront, especially in educational arenas, enabling students to delve into hardware development and swiftly craft prototypes [28]. Beyond affordability, the inherent flexibility of open-source hardware stands out. Users are empowered to tailor and adapt designs to their unique requirements, fostering innovation and paving the way for novel applications [29]. This adaptability, coupled with the spirit of collaboration, accelerates technological progression [30].

The rise of open-source hardware has also catalysed the expansion of the Internet of Things (IoT). Platforms built on open-source foundations offer economical and user-friendly avenues for crafting IoT devices and applications. When integrated with protocols like MQTT, these devices seamlessly weave into the broader internet fabric, enabling real-time control and connectivity [28]. Notably, the computer systems sector has been enriched by trailblazing projects such as Arduino, Raspberry Pi, OpenPOWER, RISC-V, and Parallella, among others. These initiatives equip users with the tools to explore and innovate in computing, underscoring the transformative potential of open-source hardware [28,30].

Peripherals

In the field of peripherals, the Nitrokey USB [31] key for data and email encryption is an example of an open source hardware project, which helped to provide open solutions for a secure and customizable solution for data and email encryption. It offers features such as strong encryption algorithms, secure key storage, and support for various encryption protocols, all of which are in demand in the space [32]. The open-source nature of the project allows users to review and verify the security of the hardware and software components, ensuring transparency and trustworthiness.

Robotics

Open-source robotics includes the integration of transparent software and hardware in crafting robotic systems. This approach champions the dissemination of designs, programming, and resources, fostering a culture of collective innovation in the robotics realm, as per Kehoe et al. [33]. The best representation of this is the Arduino initiative, a revered microcontroller platform pivotal for numerous robotic projects [34]. On the software front, frameworks like the Robot Operating System (ROS) equip developers with essential libraries and tools, streamlining the creation of robotic applications, as discussed by Connolly et al. [35].

The embrace of open-source robotics brings a wide variety of benefits to the table. It supports improved transparency and inclusivity with such an environment encouraging swift prototyping and evolution, with developers augmenting pre-existing designs and reciprocating with enhancements for the broader community. This ethos not only stimulates collaboration but also paves the way for significant cost reductions. By sidestepping proprietary avenues, developers can harness cost-effective solutions, exemplified by the Raven laparoscopic surgery robot, which offers a more economical alternative to its commercial counterparts [36].

Machinery & Production Tools

Automotive

In the automotive domain, the open-source movement has been instrumental in fostering innovation and expanding the boundaries of vehicular technology. Noteworthy projects such as Rally Fighter (Figure 8), Riversimple Urban Car, OpenXC, OScar, Wikispeed, and OSVehicle Tabby have been at the forefront of this revolution. These initiatives offer enthusiasts and professionals alike access to open-source hardware tools, facilitating experimentation and the development of novel automotive solutions. For instance, Kochanthara et al [37] highlight active the landscape of automotive software on platforms like GitHub providing insights into the multidisciplinary nature of this industry, traditionally dominated by closed-source development. Moreover, the Open Source Hardware (OSHW) Maker Movement, as discussed by Richardson [38] has been pivotal in democratizing the tools for creating sophisticated automotive parts and products, suggesting a future where domestic production tools might even allow for printing cars at home.

Aircraft

Open-source aviation encompasses both hardware and software that are openly available and developed, allowing for modifications and adaptations. This methodology champions collective innovation, customization, and collaboration within the aviation sector. A prime example of this open-source ethos in aviation software is the FAST-OAD platform, a brainchild of ONERA and ISAE-SUPAERO [39]. This platform facilitates the scrutiny, dimensioning, and fine-tuning of aircraft blueprints. Designed with user adaptability and modularity in mind, it empowers global researchers and industry stakeholders to diversify the aircraft design trajectory, encompassing novel configurations and models. Notably, FAST-OAD has been instrumental in explorations centred on the conceptualization of hydrogen-powered commercial aircraft [40]. OpenAP also stands out in open-source aviation software, offering a holistic aircraft performance model tailored for aviation studies and simulations [41]. Rooted in transparent aircraft surveillance data and established literature models, OpenAP delivers an exhaustive model encapsulating aircraft attributes, performance metrics, and utility libraries. Beyond software, the aviation sector is witnessing a surge in open-source hardware initiatives. A case in point is AWEsome (Airborne Wind Energy Standardized Open-source Model Environment), a benchmarking platform for airborne wind energy mechanisms [42]. Comprising cost-effective hardware and underpinned by open-source software, AWEsome offers a platform for research entities and emerging ventures to evaluate control methodologies, design paradigms, and flight operations.

Electric Vehicle Chargers

Open source electric vehicle charger systems play an important role in electric vehicle (EV) infrastructure. These systems can play a crucial role in the charging process and can have a significant impact on the efficiency and cost-effectiveness of EVs. One study by Sioshansi & Denholm [43] highlights the value of plug-in hybrid electric vehicles (PHEVs) as grid resources. The study demonstrates that a PHEV fleet can provide benefits to the power system, particularly through the provision of ancillary services, which can reduce the need for conventional generator capacity. Another study by Cetin & Yaz [44] focuses on the design aspects of an integrated and isolated unidirectional lithium-ion battery charger for a small-scale electric vehicle. The study presents a three-step approach involving simulation, prototype development, and the final product. In addition to traditional charging systems, there are innovative approaches being explored. The infrastructure for EV charging systems is crucial for the growth and revitalization of the EV market, as highlighted by Kim & Joung [45]. Furthermore, the use of renewable energy sources for charging infrastructure is explored in a study by [46]. The authors propose a smart charging infrastructure that can accumulate, store, and transfer surplus energy to the power grid.

3D Printers

In the field of 3D printers and scanners, projects like the RepRap project, LulzBot, and Thingiverse have made significant contributions [47]. These projects provide users with open source hardware tools that enable them to experiment with 3D printing and scanning technologies. Since the early days of development, a series of open-source endeavours have played a transformative role in advancing the technology's capabilities and reach. The RepRap project stands out as a foundational effort in democratizing 3D printing, emphasizing the importance of distributed manufacturing and cost-effective solutions [48]. LulzBot, another key player, embodies the spirit of open-source, offering a platform that encourages users to delve deep into the intricacies of 3D printing technologies [49]. Thingiverse serves as a collaborative hub, providing a space for enthusiasts to share and access a plethora of design files (Taubin, Moreno, & Lopes, 2014). Moreover, the fusion of the Internet of Things (IoT) with 3D printing has ushered in novel opportunities, particularly in the realm of remote engineering, enhancing the predictability and efficiency of the printing process [16]. Additionally, innovations such as open-source syringe extrusion heads have expanded the scope of 3D printers, facilitating the printing of specialized materials like gels and bio-inks, which holds immense potential for sectors like bio fabrication and tissue engineering [50].

Other Traditional Engineering

Architecture and Design

In the area of architecture and design, open-source initiatives have been instrumental in revolutionizing the way people approach construction and spatial design. Projects such as WikiHouse, Opendesk, and OpenStructures [51] stand as testaments to this transformative shift. These platforms empower users with open-source hardware tools, fostering an environment where architectural and design innovations can be explored and refined.

WikiHouse, in particular, has emerged as a beacon for sustainable and accessible construction. Founded by Parvin and LeRodiaconou in 2011, this project was unveiled at the Gwanju Design Biennale in South Korea and has since garnered global attention [52]. With its emphasis on resource-light sustainable homes, WikiHouse champions the democratization of construction. The platform thrives on a collaborative ethos, with contributors from around the world adding creative-commons licensed designs to its digital repository. This encourages the adaptation and evolution of these designs using open-source tools, such as Sketchup and CNC router systems. The Wiki House project is distinguished by its transparent approach to design. It offers comprehensive open-source plans, encompassing images, material descriptions, part lists, and detailed files for each construction component.

Domotics

Home automation, often termed as "domotics" or "smart home technology," encompasses a suite of systems and innovations designed to automate various household functions [53]. Its core objectives include optimizing economic efficiency, enhancing well-being, mitigating domestic hazards, and judiciously harnessing natural resources like sunlight. By combining control and automation technologies, domotics helps raise the levels of comfort, security, and energy conservation within residences.

While "domotics" is frequently used synonymously with "home automation" and "smart home," it also denotes the concept of machines that can substitute human intervention in household tasks [54]. The evolution of domotics has been driven by breakthroughs in telecommunication and the emergence of open-source technological solutions. It holds large promise in potentially elevating quality of life, fostering independence, and tailoring care for users [55]. According to Simonet & Noyce [55] The spectrum of domotics technologies spans from stationary sensors and automated gadgets to wearable tech, all capable of autonomously gathering data and taking actions.

Scholars from diverse fields such as computer science, engineering, healthcare, and physics have shown keen interest in domotics [53-56]. Their explorations have delved into its applications in areas like smart home environments, energy demand modulation, and managing specific health conditions, including Parkinson's disease.

Defence & Weaponry

A controversial area of open source hardware development is in the defence and weaponry production area. In addition to evidence indicating the production and use of 3d printed open source parts and equipment in conflicts globally, including Myanmar [57], Syria (All 3DP, 2016), Ukraine [58] and Europe [59], more formalised organisation have emerged to support the production of open-source weaponry such as Defense Distributed. This organisation, founded in 2012, controversially launched an online open-source organization that developed and distributed digital plans and files to allow the production of DIY firearms, known as "wiki weapons" or "Ghost Guns", using 3d printing and CNC milling based machinery. The company was at the centre of controversy for developing and releasing the "Liberator" [60], the self-purported "first completely 3d printed gun" in 2013, by providing publicly available 3d printable STL files to the public, which within days were subjected to a removal demand from the United States Department of State [61] for violations of the International Traffic in Arms Regulations.

In 2018, Defense Distributed released an additional 10 CAD files for public download at DEFCAD, a publicly searchable 3d printing repository launched by Defence Distributed known as "The Pirate Bay of 3D Printing" [62], adding further controversy to the space. Legal battles and lawsuits are ongoing in relation to these organisations and files, highlighting the critical importance of regulation, national and international laws and general public & governmental perception of open-source hardware, in the adoption and conflict resulting from open-source ideologies in traditional sectors.

Open StreetMap

OpenStreetMap (OSM) has emerged as a groundbreaking platform in the geospatial sector, offering user-generated street maps that adhere to the peer production model, akin to the collaborative spirit of Wikipedia [63]. This open-source project has been vital to numerous applications, from providing a foundation for routing services in R [64] to enabling the development of innovative vehicle localization methods without the need for prior LiDAR maps [65].

The humanitarian sector has particularly benefited from OSM, with large-scale mapping efforts being undertaken to support disaster preparedness and response [66]. In regions where comprehensive mapping data is scarce, OSM has been leveraged to detect missing buildings, enhancing the efficiency of humanitarian mapping campaigns (Li et al., 2022). The academic community has also recognized the multidisciplinary potential of OSM, with studies exploring its applications, data quality, and community dynamics.

Environmental & Energy

Renewable Energy

In the realm of renewable energy, numerous open-source initiatives have significantly influenced the advancement of sustainable energy solutions. Notably, the creation of GEA (Geophysical and Environmental Applications) [67], an open-source framework for modelling atmospheric and oceanic phenomena within the finite volume C++ library OpenFOAM [68] has been pivotal. This framework has facilitated a deeper comprehension of the dynamics of renewable energy sources by introducing a non-hydrostatic atmospheric model that employs a pressure-based solver for the Euler equations. The accuracy and reliability of this approach have been validated through comparisons with existing numerical data, underscoring its potential in the renewable energy sector [67].

Building on the drive towards a sustainable future, numerous other open-source solutions have emerged to further bolster the renewable energy sector. An innovative IoT-based SCADA system has been developed to monitor and supervise renewable energy generation units, offering a cost-effective and efficient approach to energy management [69]. Additionally, educational tools like an open-source solution for simulating variable speed wind turbines have been introduced to enhance the understanding and application of sustainable energy in academic settings [70].

Plastic Recycling

Open-source plastic recycling is a rapidly developing concept, aiming to tackle the environmental and economic hurdles posed by plastic waste. Pioneering work by Baechler et al. [48] introduced a concept for distributed recycling of waste polymers, facilitated by 3D Printers, into RepRap feedstock. This comprehensive study assessed prior designs of waste plastic extruders, commonly termed Recycle Bots (Figure 10), using a weighted evaluation matrix. From this assessment, they proposed and meticulously detailed an enhanced design, encompassing component summaries, testing methodologies, basic life cycle analysis, and extrusion outcomes. Their findings revealed that the recycled plastic filament averaged a mass of 0.564 g/100mm length, consuming 0.06 kWh/m of energy. This underscored the technical viability of crafting feedstock filament for the RepRap from waste plastic using a decentralized recycling apparatus.

The real-world ramifications of Baechler et al.'s research are significant, opening up new concept in waste recycling. The Recycle Bot's proficiency in curbing RepRap's operational expenses paved the way for decentralized in-home plastic recycling, and subsequent concepts such as the Precious Plastic's recycling tools initiative [71], and causing ripple effects on municipal waste management strategies, potentially diminishing costs, greenhouse gas emissions from waste collection and transportation, and the environmental footprint of fabricating bespoke plastic components.

Water Systems

Open-source innovations in water filtration and irrigation offer transformative solutions for sustainable and economical water management in farming. Utilizing open-source principles combined with hands-on (DIY) techniques, these systems promote widespread community participation in their refinement and customization (Ahmad et al., 2018). A distinctive feature of these systems is their emphasis on micro-irrigation practices, which include methods such as drip, spray, jet, and bubbler watering techniques , as outlined by Marella et al. [72]. These techniques direct water straight to the plant's root zone, minimizing evaporation losses and optimizing water usage [73]. Payero et al. [74] discusses how their intuitive design makes them particularly appealing to farmers, especially in resource-constrained environments. In terms of agricultural output, these open-source methodologies have demonstrated positive results. Studies suggest that crops irrigated using drip methods often produce superior yields in both volume and quality [73].

Communities

Open source communities are collaborative groups where individuals and entities collaboratively contribute to the enhancement of open source initiatives. These ecosystems thrive on the mutual exchange of code, insights, and resources, underpinned by values of openness, teamwork, and recognition based on merit [75].

A notable instance of such an initiative is the Global Village Construction Set (GVCS) by Open Source Ecology. The GVCS comprises 50 distinct industrial tools, all built from openly accessible designs and schematics. Designed to be affordable, adaptable, and modular, the GVCS empowers individuals and groups to craft tools essential for sustainable lifestyles [75]. Lerner & Tirole [75] delved into the motivations of solo developers and corporate entities participating in open source activities. Their findings suggest that aspects of labour economics, particularly the notion of "career aspirations," coupled with theories of industrial organization, shed light on the nuances of open source contributions. They also highlighted intriguing avenues for further exploration in the realm of open source. The organizational structures steering open source ecosystems have also been scrutinized.

Scientific Hardware

Open-Source Lab

The Open-Source Lab initiative emphasizes the creation and documentation of open-source hardware instruments tailored for scientific research . Unlike proprietary projects, this venture is rooted in the open-source ethos, offering users a platform to explore scientific tools that are open and modifiable [76]. Open-source hardware is characterized by designs and documentation that are publicly accessible, granting everyone the freedom to analyse, adapt, distribute, and utilize the hardware [77]. By aligning with these principles, the Open-Source Lab offers tools that champion modification and dissemination.

The adoption of open-source hardware in the scientific domain has seen a surge, presenting benefits such as cost-effectiveness when juxtaposed with commercial equipment [11]. Utilizing digital fabrication methods, researchers have crafted top-tier scientific instruments at costs significantly lower than their commercial counterparts. The Open-Source Lab champions the widespread accessibility of scientific tools, making them both affordable and available. By offering these tools, the initiative equips scientists and researchers to craft tailored sensing and data collection systems, catering to distinct research objectives [29].

OpenBCI

OpenBCI is a pioneering open-source EEG amplifier that has significantly impacted neuroscience research , according to Storzer et al. [78]. This platform offers open-source tools, empowering users to delve into EEG methodologies. The core of OpenBCI is a compact EEG amplifier adept at capturing local field potentials (LFPs) from the brain. Numerous research projects have utilized this amplifier to gather EEG data at an impressive 2,048Hz sampling rate [78]. The data acquired can be further refined and interpreted using open-source software solutions like OpenBCI and Svarog.

Open Source Imaging in Biology

The evolution of sophisticated 3D imaging, design, and printing methodologies has profoundly enriched the realm of biological sciences. A notable initiative in this domain is the creation of open-source hardware instruments tailored for 3D visualization, design, and printing. The primary objective of these activities is to democratize access to these groundbreaking tools, making them both affordable and user-friendly for researchers [79]. 3D modelling, and 3D printing have ushered in a transformative era for the study and presentation of biological specimens. A study by Keaveney et al [80], show that these advancements not only enhance research capabilities but also revolutionize educational approaches, providing students and educators with hands-on tools to explore and understand the complexities of life in three dimensions, via the impactful applications in the field.

Medical Devices

Open Prosthetics Project

The Open Prosthetics Initiative is a pioneering effort focused on creating and disseminating open-source blueprints for prosthetic equipment. This initiative is rooted in the broader open design (OD) philosophy, which champions collective efforts and the free exchange of expertise and tools [81]. By harnessing the power of modern computer-aided design (CAD) tools, additive production methods, and graphic software, the initiative aims to overcome the challenges and exorbitant costs linked to conventional prosthetics. The primary goal is to make prosthetics more accessible, especially for those in economically challenged settings or in regions with limited healthcare infrastructure. The Open Prosthetics Initiative exemplifies the transformative potential of open design in crafting intricate tools like prosthetics (Freire et al., 2021). By promoting remote teamwork and pooling diverse skills, the project accelerates innovation. By offering prosthetic designs as open-source resources, the initiative encourages a collaborative spirit and the broader adoption of open design principles in prosthetics.

Open-source Ventilator

During the COVID-19 pandemic, the global demand for mechanical ventilators surged, prompting the emergence of open-source ventilators as a potential solution, especially in underserved areas [82]. These cost-effective ventilators were developed with the primary goal of assisting critically ill COVID-19 patients who needed respiratory support [81]. Notable examples include the RepRapable Automated Bag Valve Mask-based Ventilator, crafted by Michigan Technological University, which is designed using easily obtainable materials, offering a practical option for healthcare centres facing a deficit of standard ventilators and the TeamOSV ventilator systems developed by an open source global team centred in Ireland [83].

E-Nable Project

The E-Nable initiative is a community-driven effort dedicated to creating 3D-printed upper-limb prosthetic devices for those in need , as outlined by Rivard et al. [84]. Its mission focuses on offering cost-effective and easily accessible alternatives to conventional prosthetics, especially for those hindered by financial constraints or other challenges. Harnessing the power of open-source platforms, E-Nable promotes a collaborative spirit among its contributors, emphasizing user-centric designs and enhanced accessibility. The project's commitment to user-led and open methodologies has garnered praise, with many healthcare innovators endorsing such approaches for their transformative potential. E-Nable stands as a testament to how user-centric, open innovations can elevate healthcare standards and patient safety [84].

Conclusion

Exploring pre-COVID open source scientific designs unveils innovation, collaboration, and knowledge democratization. This paper delves into best practices across Science, Engineering, and ICT, spotlighting standout applications that showcase open source hardware's potential [85-90].

Open source principles drive scientific design innovation, enabling shared progress and cost-effective alternatives. Modifications tailored to specific research needs enhance appeal. Community support and funding bolster open source design development. However, challenges exist. Ensuring design quality and reliability amidst variability is a hurdle. Standardized documentation lacks, complicating replication and modification. Legal and regulatory complexities add further layers.

Yet, undeniable potential surfaces through case studies - EEG amplifiers, 3D-printed prosthetics - advancing research and lives. This journey blends triumphs and challenges, reflecting collaboration's power. COVID-19 spotlighted open source hardware's role in crises, like rapid ventilator development. Future holds promise, aligning with interconnected world needs. Open source principles will steer research's future amid challenges.

In summary, exploring best practices in open source scientific designs reveals insights and lessons. Open source spurs innovation, access, and crisis response. As we forge ahead, these insights guide open source hardware, fuelling research's future despite challenges.

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References

1. Bonvoisin J, Bowman R, Chagas A, Emanuel K, Haeuer M, et al. (2020) The Open Know-How Manifest Specification.
2. Sherlock J, Muniswamaiah M, Clarke L, Cicoria S (2018) Open Source Software Opportunities and Risks.

3. Gupta G, Nowatzki T, Gangadhar V, Sankaralingam K (2016) Open-source Hardware: Opportunities and Challenges.
4. Miljković N, Trisovic A, Peer L (2022) Towards FAIR Principles for Open Hardware p. 90-101.
5. Wenzel T (2023) Open hardware: From DIY trend to global transformation in access to laboratory equipment. PLoS Biol 21(1): e3001931.
6. Heradio R, Chacon J, Vargas H, Galan D, Saenz J, et al. (2018) Open-Source Hardware in Education: A Systematic Mapping Study. IEEE Access 6: 72094-72103.
7. Fingerhuth M, Babej T, Wittek P (2018) Open source software in quantum computing. PLoS ONE 13(12): e0208561.
8. Pereyra IG, Bernaldo P, Velázquez L, Pérez A, Molina FC, et al. (2023) Open Science Drone Toolkit: Open source hardware and software for aerial data capture.
9. Rabault J, Nose T, Hope G, Müller M, Breivik Ø, et al. (2022) OpenMetBuoy-v2021: An Easy-to-Build, Affordable, Customizable, Open-Source Instrument for Oceanographic Measurements of Drift and Waves in Sea Ice and the Open Ocean. Geosciences 12(3): 110.
10. Möller T, Voss M, Kaltwasser L (2022) An Arduino based heartbeat detection device (ArdMob-ECG) for real-time ECG analysis.
11. Frangos M, Pearce J, Brastaviceanu T, Mahmoud A, Khalid A (2016) Democratising design in scientific innovation: application of an open value network to open source hardware design. SSRN Electronic Journal.
12. Hobbs S, Paull D, McDougall T (2018) Evaluating low-cost spectrometer designs for utility in reflectance and transmittance applications. International Journal of Remote Sensing.
13. Han JH, Mundkur P, Rotsos C, Antichi G, Dave N, et al. (2015) Blueswitch: Enabling Provably Consistent Configuration of Network Switches. In Proceedings of the 2015 ACM/IEEE Symposium on Architectures for Networking and Communications Systems (ANCS), Oakland, CA, USA, pp. 17-27.
14. Demir A, Pekoz B, Kose S, Arslan H (2019) Innovative Telecommunications Training through Flexible Radio Platforms.
15. Manisha N, Li C, Karunakar A (2022) Open-set source camera device identification of digital images using deep learning. IEEE Access 10: 110548-110556.
16. Aradhya V (2020) Implications of IoT in 3D Printing and Remote Engineering - Using Open-Source Hardware and Software. REV Proceedings.
17. Ullah AS, Tashi KA, Harib KH (2020) Tutorials for Integrating 3D Printing in Engineering Curricula. Educ Sci 10: 194.
18. Kyriakou H, Nickerson J (2014) Collective Innovation in Open Source Hardware. SSRN Electronic Journal.
19. Rodriguez MA, Cuenca L, Ortiz A (2018) FIWARE Open Source Standard Platform in Smart Farming - A Review. In 19th Working Conference on Virtual Enterprises (PRO-VE), Cardiff, United Kingdom pp. 581-589.
20. Perez JM, Ramon SP, Arrue B, Ollero A (2020) Hecatonquiros: Open-source hardware for aerial manipulation applications. International Journal of Advanced Robotic Systems.
21. Wyglinski AM, Nekovee M, Hou YT (2009) Cognitive Radio Communications and Networks: Principles and Practice. Netherlands: Elsevier Science.
22. Han J, Antichi G, Zilberman N, Rotsos C, Moore A (2015) An integrated environment for open-source network softwarization.
23. Song H, Choi W, Jeon T, Oh J (2022) Recent advances in smart organic sensors for environmental monitoring systems. Acs Applied Electronic Materials 5(1): 77-99.
24. Mitola J, Maguire GQ (1999) Cognitive radio: making software radios more personal. IEEE Personal Communications 6(4): 13-18.
25. Newman TR, Shepard DP, Reed JH (2014) A Software-Defined Radio for Wireless Networking Research. In: IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC).
26. Needs S, Bull S, Lindley DA, Ray P, Edwards A (2019) Exploiting open source 3d printer architecture for laboratory robotics to automate high-throughput time-lapse imaging for analytical microbiology. Plos One 14(11): e0224878.
27. Henry D, Dillon A, Paul E, Nick S, William D, et al. (2022) Esp32-cam as a programmable camera research platform. Electronic Imaging 34(7).
28. Cgseong C, Kim J, Park D (2020) Real-time object control system using open source platform. Indonesian Journal of Electrical Engineering and Computer Science 20(1): 313.
29. Fisher D, Fletcher R, Anapalli S (2021) Python software integrates with microcontrollers and electronic hardware to ease development for open-source research and scientific applications. Advances in Internet of Things 11(01): 42-58.
30. Boujut J, Pourroy F, Marin P, Dai J, Richardot G (2019) Open source hardware communities: investigating participation in design activities. Proceedings of the DSI Conference on Engineering Design 1(1): 2307-2316.
31. Nitro Key (2023) Accessed via https://www.nitrokey.com/.
32. Grinias J, Whitfield J, Guetschow E, Kennedy R (2016) An inexpensive, open-source usb arduino data acquisition device for chemical instrumentation. Journal of Chemical Education 93(7): 1316-1319.
33. Kehoe B, Patil S, Abbeel P, Goldberg K (2015) A survey of research on cloud robotics and automation. IEEE Transactions on Automation Science and Engineering 12(2): 398-409.
34. Jagtap V, Agarwal S, Strong D, Gennert M (2020) Transportable open-source application program interface and user interface for generic humanoids: tough. International Journal of Advanced Robotic Systems, 17(3): 172988142092160.
35. Connolly L, Deguet A, Leonard S, Tokuda J, Ungi T, et al. (2022) Bridging 3D Slicer and ROS2 for image-guided robotic interventions. Sensors 22(14): 5336.
36. Clark A, Mathivannan V, Rojas N (2021) A continuum manipulator for open-source surgical robotics research and shared development.
37. Kochanthara S, Dajsuren Y, Cleophas L, Van Den BM (2022) Painting the landscape of automotive software in GitHub. In Proceedings of the 19th International Conference on Mining Software Repositories (MSR '22), pp. 215-226.
38. Richardson M (2012) Designer/Maker: The Rise of Additive Manufacturing, Domestic-Scale Production and the Possible Implications for the Automotive Industry. Computer-Aided Design and Applications, PACE, p. 33-48.
39. Sy O (2023) Overall aircraft design: from the open-source fast-oad to its training branch. Journal of Physics Conference Series 2526(1): 012029.
40. Oak M, Fabre A, Delavenne M, Van E, Benard E, Defoort S (2022) Spectral project - application of fast-oad code to the conceptual design of a hydrogen fuelled commercial aircraft. Iop Conference Series Materials Science and Engineering 1226(1): 012027.
41. Sun J, Hoekstra J, Ellerbroek J (2020) Openap: an open-source aircraft performance model for air transportation studies and simulations. Aerospace 7(8): 104.
42. Bechtle P, Gehrmann T, Sieg C, Udo Z (2017) Awesome: an open-source test platform for airborne wind energy systems.
43. Sioshansi R, Denholm P (2010) The value of plug-in hybrid electric vehicles as grid resources. The Energy Journal 31(3).
44. Çetin E, Yaz M (2021) Built-in Isolated Level 1 Unidirectional Battery Charger Design Aspects for a Small-Scale Electric Vehicle. International Journal of Automotive Science and Technology 5.
45. Kim C, Joung H (2018) Model-based predictive control of dc-dc converter for ev applications. International Journal of Engineering & Technology 7(12): 308.
46. Pronozin Y, Anisimov I (2020) Assessment of the use of renewable energy sources for the charging infrastructure of electric vehicles. Emerging Science Journal 4(6): 539-550.
47. Bowyer J (2018) The RepRap project: Open source and the democratisation of industrial production. Robotica 36(7): 995-1001.
48. Baechler C, DeVuono M, Pearce JM (2013) Distributed recycling of waste polymer into RepRap feedstock. Applied Sciences 3(2): 1179-1191.
49. Liu J, Jiang H, Jiang P (2017). Embedded-web-based remote control for RepRap-based open-source 3D printers. IECON Proceedings.
50. González GJ, Cano S, Schuschnigg S, Kukla C, Sapkota J, et al. (2022) Open-source syringe extrusion head for shear-thinning materials 3D printing. Rapid Prototyping Journal.

51. Dortheimer J, Margalit T (2020) Open-source architecture and questions of intellectual property, tacit knowledge, and liability. The Journal of Architecture 25(3): 276-294.

52. Firth P, Rees T (2011) Grand Designs: Open-source platform comes to housing. Life Style: News: Global.

53. Bonino D, Castellina E, Corno F (2008) The dog gateway: enabling ontology-based intelligent domotic environments. IEEE Transactions on Consumer Electronics.

54. Hong Y, Wang Z, Cho J (2022) Global research trends on smart homes for older adults: bibliometric and scientometric analyses. International Journal of Environmental Research and Public Health 19(22): 14821.

55. Simonet C, Noyce A (2021) Domotics, smart homes, and parkinson's disease. Journal of Parkinson S Disease 11(s1): S55-S63.

56. Babar M, Nguyen P, Cuk V, Kamphuis I, Bongaerts M, et al. (2018) The evaluation of agile demand response: an applied methodology. IEEE Transactions on Smart Grid 9(6): 6118-6127.

57. France-24 (2022) https://observers.france24.com/en/asia-pacific/20220114-3d-printed-weapons-myanmar-rebels.

58. 3d Printing UK (2022) https://3dprintinguk.com/3d-printed-weapons-go-to-war/.

59. Europol (2022) https://www.europol.europa.eu/media-press/newsroom/news/printing-insecurity-tackling-threat-of-3d-printed-guns-in-europe.

60. Hutchinson L (2013) The first entirely 3D-printed handgun is here. Ars Technica.

61. Nozowitz D (2013) U.S. State Department Tells Defense Distributed To Take Down 3-D Printed Gun Plans. Popular Science.

62. BBC News (2013) Pirate Bay' for 3D printing launched. Archived from the original on April 25.

63. Haklay M, Weber P (2008) OpenStreetMap: User-Generated Street Maps. IEEE Pervasive Computing 7(4): 12-18.

64. Giraud T (2022) osrm: Interface Between R and the OpenStreetMap-Based Routing Service OSRM. Journal of Open Source Software 7(78): 4574.

65. Cho Y, Kim G, Lee SJH (2022) OpenStreetMap-Based LiDAR Global Localization in Urban Environment Without a Prior LiDAR Map. IEEE Robotics and Automation Letters 7(2): 4999-5006.

66. Herfort B, Lautenbach S, Porto DAJ, Anderson J, Zipf A (2021) The evolution of humanitarian mapping within the OpenStreetMap community. Scientific Reports 11: 3037.

67. Girfoglio M, Quaini A, Rozza G (2023) GEA: a new finite volume-based open source code for the numerical simulation of atmospheric and ocean flows.

68. Jasak H (2009) OpenFOAM: Open source CFD in research and industry. International Journal of Naval Architecture and Ocean Engineering 1(2): 89-94.

69. Ndukwe C, Iqbal MT, Khan J (2022) An Open Source LoRa Based, Low-Cost IoT Platform for Renewable Energy Generation Unit Monitoring and Supervisory Control. Journal of Energy and Power Technology 4(1): 7.

70. Fernández GA, Molina GÁ (2021) Simulation of variable speed wind turbines based on open-source solutions: Application to bachelor and master degrees. International Journal of Electrical Engineering & Education.

71. Precious Plastic (2023), Accessed via: https://preciousplastic.com/.

72. Marella R, Berry D, Dixon J (2017) Agricultural irrigated land-use inventory for polk county, florida.

73. Machado R, Oliveira M (2005) Tomato root distribution, yield and fruit quality under different subsurface drip irrigation regimes and depths. Irrigation Science 24(1): 15-24.

74. Payero J, Mirzakhani NA, Khalilian A, Qiao X, Davis R (2017) Development of a low-cost internet-of-things (iot) system for monitoring soil water potential using watermark 200ss sensors. Advances in Internet of Things 7(3): 71-86.

75. Lerner J, Tirole J (2003) Some simple economics of open source. Journal of Industrial Economics 50(2): 197-234.

76. Pearce J (2012) Building research equipment with free, open-source hardware. Science.

77. Bonvoisin J, Mies R, Boujut J, Stark R (2017) What is the "source" of open source hardware? Journal of Open Hardware 1(1).

78. Storzer L, Butz M, Hirschmann J, Abbasi O, Gratkowski M, et al. (2017) Bicycling suppresses abnormal beta synchrony in the parkinsonian basal ganglia. Annals of Neurology 82(4): 592-601.

79. Ozbolat I, Hospodiuk M (2016) Current advances and future perspectives in extrusion-based bioprinting. Biomaterials 76: 321-343.

80. Keaveney S, Keogh C, Gutierrez HL, Reynaud EG (2016) Applications for advanced 3D imaging, modelling, and printing techniques for the biological sciences. In: 22nd Int Conf Virtual Syst Multimed, IEEE, Kuala Lumpur, Malaysia, pp. 1-8.

81. Panchal J, Fathianathan M (2008) Product realization in the age of mass collaboration.

82. Acho L, Vargas A, Pujol VG (2020) Low-cost, open-source mechanical ventilator with pulmonary monitoring for covid-19 patients. Actuators 9(3): 84.

83. Keogh (2021) Open Innovation in Response to Covid 19: A case study of the Open Source Ventilator Ireland Project. Qeios.

84. Rivard L, Lehoux P, Alami H (2020) It's not just hacking for the sake of it: a qualitative study of health innovators' views on patient-driven open innovations, quality and safety. BMJ Quality & Safety, 30(9): 731-738.

85. All 3DP (2016) https://all3dp.com/3d-printed-bombs-isis/.

86. Aubrey LW, McCaslin JR, Pringle AM, Pearce JM (2018) RepRapable Recyclebot: Open source 3-D printable extruder for converting plastic to 3-D printing filament. Hardware X 4.

87. Freire R, Levänen J, Bonvoisin J (2021) Challenges of open design in low-income communities: a case study of residential rainwater harvesting systems. Codesign 18(3): 303-321.

88. OpenBCI (2023) Accessed via: https://openbci.com/.

89. Pattisapu S, Ray S (2023) Stimulus-induced narrow-band gamma oscillations in humans can be recorded using open-hardware low-cost eeg amplifier. Plos One 18(1): e0279881.

90. Zhang P, Wawrzynek J (2011) High-Performance Software Radio using a General-Purpose Multi-core Processor. In 2011 49th ACM/EDAC/IEEE Design Automation Conference (DAC) 54(1).