

Open Robot Hardware: Progress, Benefits, Challenges, and Best Practices

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Abstract—Technologies from open-source projects have seen widespread adoption in robotics over recent years. The rapid pace of progress in robotics is in part fueled by open-source projects, providing researchers with resources, tools, and devices to implement novel ideas and approaches quickly. Open-source hardware in particular lowers the barrier of entry to new technologies, and can further accelerate innovation in robotics. But open hardware is also more difficult to propagate in comparison to open software because it involves replicating physical components, which requires users to have sufficient familiarity and access to fabrication equipment. In this work, we present a review on Open Robot Hardware (ORH), by first highlighting key benefits and challenges encountered by users and developers of ORH, and then relaying some best practices that can be adopted in developing successful ORH. To accomplish this, we survey over 80 major ORH projects and initiatives across different domains within robotics. Finally, we identify strategies exemplified by the surveyed projects to further detail the development process and guide developers through the design, documentation, and dissemination stages of an ORH project.

Index Terms—Robotics, Open-source Technologies, Open Hardware, Robot Design, Documentation

I. BACKGROUND

THE open-source paradigm of disseminating new technologies has gained traction over the last several decades, particularly in rapidly evolving deep tech fields such as robotics, for its benefits in expediting innovation through the sharing of knowledge, tools, resources, and technical solutions with a community of researchers, citizen scientists, hobbyists, and technology enthusiasts. The rapid pace of progress in robotics has been in part due to the availability of high quality open-source software and hardware solutions that allow roboticists to easily use, adapt, and improve them in their own applications, subsequently accelerating the implementation and testing of novel ideas in a variety of robotics domains. Particularly, open-source software has seen widespread proliferation in robotics [1, 2], in the form of middleware suites [3, 4], computer vision libraries [5], robot control packages [6], simulation environments [7, 8], robot motion planning platforms [9], among others.

In comparison, open-source hardware projects have trailed software in the number and type of hardware available [10]. In general, hardware is more challenging to propagate than

software because of the difficulties encountered when replicating physical components as opposed to using and modifying code. Researchers often choose to purchase commercially available, expensive, closed-source hardware that is hard to modify, repair and maintain, or dedicate resources and time to creating their own hardware from the ground up. But recent advancements in rapid-prototyping (e.g. 3D printing, laser or waterjet cutting) have enabled mechanical fabrication with minimal specialized expertise, easy-to-use equipment, and at relatively low cost, especially compared to alternatives such as CNC machining. These technologies, while still in their infancy, have made it so that many parts can be fabricated with sufficient durability and mechanical strength to be functionally used in a range of robotics applications. As a result, building an open-source mechanical hardware project has become much more feasible, and there are now a range of high-quality open-source hardware projects that create new technologies and deliver impact to the robotics community. The objective of this review is to highlight such robot hardware by identifying the key characteristics and effective development practices, surveying widely adopted projects in various robotics domains, and organize an open-source hardware development process with best practices and strategies derived from the surveyed projects.

Few previous reviews of open-source hardware have been conducted, and to the authors' knowledge, none has taken an all-encompassing look at hardware across the various fields within robotics. Reviews have looked at open-source projects in specific fields of robotics, such as the design of medical devices [11], Unmanned Aerial Vehicles [12], hardware in research labs [13], and in educational applications [14, 15]. Initiatives such as the Open Robot Hardware website [16], and the Open Source Hardware Association's (OSHWA) directory host a compilation of open-source mechanical and electrical hardware [17]. In addition to their directory of projects, OSHWA also promotes open-source hardware use to general audiences, establishes shared principles of the open-source hardware movement, and certifies projects that meet their standard of open-source compliance. More recently, academic journals dedicated to open-source design in science [18–20], and special issues [21] have recognized the impact of open-source hardware specifically in robotics.

The remainder of this paper is organized as follows. Section II focuses on what constitutes Open Robot Hardware (ORH) as well as on the characteristics of such hardware, noting the advantages and challenges it brings to both users and developers, along with best practices for developers to create

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effective ORH projects. Section III presents a survey of over 80 major ORH projects categorized by the robotics sub-field they are applied within. Finally, Section IV describes the different stages in the process of developing new ORH projects, highlighting the strategies adopted by successful ORH projects. The characteristics, best practices, and surveys from this paper will also be made available through the Open Robot Hardware website [16].

II. OPEN ROBOT HARDWARE (ORH)

In this work, we review projects that can be ascribed as **Open Robot Hardware (ORH)**, which we define as satisfying the following inclusion criteria.

- 1) **Open-source:** Design and auxiliary part files required for redesign, fabrication and assembly are made public, along with documentation that facilitates replication of the work. The work should be disseminated with a license that allows use, replication, modification, and sharing of the various project components under the license's terms and conditions.
- 2) **Robotics oriented:** The project has applications in a robotics domain, either as a complete robot system, or constituent of a robot system.
- 3) **Mechanical hardware oriented:** The project focuses on physical items with tangible mechanical components, such as structural framework, mechanisms, actuators, and sensors. Projects with supplementary electronics or software elements that support the hardware are included, but projects with solely electronics or software elements are excluded from the scope of this review.

We also define the **user** of an ORH in the context of this review as an entity replicating, using, modifying, or even simply drawing inspiration from an ORH project. The user is then at the receiving end of the content output by the ORH's **developer**, defined here as the designer, distributor, author, or any entity involved in the development, design, documentation, or dissemination of the project. It is possible for the developer to also take on the role of the user, if they are redesigning or adapting an existing open-source project. It is also possible for a user to become part of the development team, which can occur when the community actively engages with the developers of popular open-source hardware projects.

A. Characteristics of Open Robot Hardware

To understand why someone would consider developing or using an ORH project, it is important to delve into the advantages and challenges associated with such hardware from the perspective of both the users and the developers separately (summarized in Table I and also available on the Open Robot Hardware website [16]).

1) *Advantages to User:* One of the primary goals of open-source projects is to allow a community of users to build on a specific work, sharing knowledge, know-how, resources, tools, technical solutions, and documenting all the issues and problems encountered during the development process. The key advantage that an ORH project offers over commercially

available alternatives is customization. Users have the flexibility to understand how the system works, modify it, and improve it to meet their requirements or the specifications for a particular application. Particularly in a rapidly growing field such as robotics, where new applications are regularly identified, hardware adaptability can significantly help condense the development timeline. While creating their own hardware from scratch might offer even more flexibility, the time and human labour allocated to the development can prove to be prohibitive. Commercial robot hardware products on the other hand are significantly costlier to purchase or license in comparison to ORH, with additional servicing fees for repair and upgrades. An ORH project thus presents a more economical option for the user to quickly test if the hardware is appropriate for their implementation without any long-term commitment.

Another advantage ORH offers users over commercial products is repairability. A purchased product might either require a service person visit or a return to manufacturer, a limitation magnified in hardware components in comparison to software, which could be patched remotely. Similarly, commercial hardware often does not allow users to perform maintenance on their own. On the other hand, the ORH could be repaired and maintained on site by the user. Although this might require sufficient knowledge of the hardware components, popular ORH projects further benefit from their strong user community and developer input, which can offer quick support for common repairs and hardware fixes. In this regard, ORH can notably reduce downtime and expense of restoring the robot or robot component back to function.

The swift pace of development in robotics often renders components of the robot unusable and out-of-date within a few years. Robot software developers may be able to remotely ship updates on their products to maintain compatibility and patch issues. Whereas, robot hardware manufacturers often require users to purchase a new version of their product. In contrast, ORH allows the user to decide if and when they want to upgrade. ORH users can also choose to only upgrade specific components or functions of the hardware. In commonly used ORH, the active user community as well as the developer regularly release these updates to the hardware through design changes or extending alternative component options.

2) *Challenges for User:* Most ORH require the user to fabricate and assemble parts on their own, possibly while using unfamiliar tools and processes (such as molding with 3D printed parts for Hybrid Deposition Manufacturing [22]). The knowledge barrier of reproducing hardware can be more pronounced for some users, especially when replication of the hardware relies on sophisticated equipment, resources, tools or on significant skills and expertise of the users. ORH developers may release bad documentation, and insufficient fabrication and assembly instructions, which further raises the barrier for the non-expert user. This lack of subject area expertise is one of the key hurdles ORH users face in the early stages of hardware implementation. Even if users have the expertise and access to requisite manufacturing tools, they may not be able to afford the time required to fabricate and assemble the components. Some developers will sell pre-

TABLE I: Characteristics of Open Robot Hardware.

	User	Developer
Advantages	<ul style="list-style-type: none"> • Easy to use, modify, and repurpose • Lower cost to acquire and service • Easy to repair and maintain • Upgradable on site in future • Access to user community for large projects 	<ul style="list-style-type: none"> • Decentralized co-development & co-validation • Gaining valuable and quick user feedback • New applications of technology explored • Engaging a large user community • Exposure by delivering impact to community
Challenges	<ul style="list-style-type: none"> • Needs appropriate tools, equipment, and skills • Requires time and labour for replication • Lack of guaranteed long-term support • Lack of comprehensive documentation • Lack of guaranteed reliability or robustness 	<ul style="list-style-type: none"> • Preparing comprehensive documentation • Guarantee design and fabrication simplicity • Keep cost low for affordability • Selecting license and dissemination strategy • Nurturing the engaged user community • Capturing value from hardware

fabricated parts or even completely pre-assembled versions of their hardware to bypass the user knowledge and time required to put their hardware together. Well-funded research groups typically choose the route of buying the part kits, whereas other teams would try to replicate the parts themselves with any available resources. But even with these purchased ORH kits and components, the user retains the advantages of ORH such as repairability, upgradability, and adaptability outlined in the previous section, while circumventing the challenges of recreating the hardware on their own.

Once an ORH project is developed, tested and, disseminated, users create small or large communities that inform the core development team about issues that may arise and may also contribute to the further development or modification of the hardware to suit different needs. Unlike commercially available hardware that might offer service contracts and maintenance assistance, an ORH component can suffer from inadequate long-term support if the community becomes inactive over time, or even loss of access to the original files if the developer takes down the project website or stops maintaining the project (e.g., CAD files may no longer be supported). Although ORH enables the user to repair the hardware on site as mentioned previously, guidance required to perform that repair may be lacking without a formal support team setup to help debug and tackle potential failures over long-term use of the ORH. In fact, components of the ORH might not be suitable for extended use, in comparison to commercially available products that come with a warranty and would have been tested beforehand to meet a certain number of hours in operation and to acquire particular certifications. The upside of reliability and robustness from commercial hardware is often compensated by the repairability of ORH, but still, the long-term support and reliability of ORH could be another challenge for users.

3) *Advantages to Developer:* A robot hardware developer needs to decide if they envision their end product to be open-sourced, so that they can make design and fabrication choices compatible with releasing their designs for even a novice user to implement. Some of the main benefits motivating a developer to open-source their hardware is that their

technology reaches more people, delivering more impact to the community, attracting more citations to their work, and establishing the developer as a leader in the field. In order to achieve this, developers should aim to design their hardware with reproducibility in mind, such as by incorporating rapid prototyping techniques and off-the-shelf components. The ORH is more likely to spread through the community in this manner, and more users may adopt the hardware to use in their own projects, or modify and release their own derivatives. Users may also demonstrate new promising applications for the hardware in other areas of robotics. So, the more widely adopted an ORH becomes, the more exposure it generates for the developer established through the vibrant user community. Thus, this can present the developer with new opportunities for collaborations such as through updates and patches recommended by users, and create a base for the developer to release more ORH in the future.

Since the design, fabrication, and auxiliary files of an ORH are all released to the public, the hardware and its function are more thoroughly validated through implementation by a number of users. Effectively, this decentralizes the research and development (R&D) process of the hardware among the user community. In comparison, for instance, the developer could only run a few experiments to test every component on their own. Whereas, open-sourcing the hardware practically recruits lots of co-testers and co-developers quickly, who will utilize the hardware in their own disparate application areas and notify the developer about issues with the hardware that might not have been foreseen. The transparent nature of ORH improves the hardware by evaluating it more rigorously and co-developing it with numerous users. The decentralization of the R&D is also much faster and cheaper than R&D conducted only by the developer. However, this does not mean that the developer may release incomplete or poorly designed hardware, expecting that user community will identify all the problems with the hardware, because in such a case, the technology will not be adopted at all and the community will never be formed.

4) *Challenges for Developer:* A good open-source project should be accompanied by comprehensive documentation and

detailed user guides that can help the user replicate, use, repair, and maintain the hardware. Writing such an in-depth documentation and directions requires the developer to devote substantial time and effort, and can be particularly challenging if the developer lacks prior experience in doing so. Although the developer can simply release just the design files without any guides or details, such an ORH project is much less likely to be picked up and widely used by the user community. So, to recover the benefits of an ORH outlined previously, the developer must also dedicate resources and time to prepare a well-documented ORH. It should also be noted that such documentation is not required in closed source projects which are typically accompanied by a very basic user guides that only cover the operation of the device.

While supporting documentation can be written towards the end of the development process, the developer should consider open-sourcing the project early on in order to incorporate simplicity in the design and the required fabrication processes, and make the released ORH accessible to as many users as possible. Evaluating the complexity of the hardware early in development can prevent the developer from having to redesign components and modify features to be compatible with common fabrication processes. Simplicity of design also extends to avoiding lots of custom parts, which could be replaced with readily available alternatives. The developer needs to actively consider how their design choices, fabrication processes, and component selection affect the accessibility of the ORH. And doing so early on can temper some of these challenges in creating hardware that gets implemented by large number of users.

In addition to documenting the hardware and including easily sourced components, the developer should also assess the total cost of building and operating their ORH. One of the main advantages of using open hardware is the lower cost compared to purchasing commercial products, which may come with licensing or service fees on top. However, if the combined cost of components in the ORH along with the time and effort required to manufacture and assemble parts reaches or even exceeds the cost of the commercially available hardware alternative, users are less likely to adopt the ORH. Keeping the total price of off-the-shelf parts, calling for simple fabrication processes, and requiring common materials and tools for assembly can aid affordability of the ORH, and improve its ability to reach to new users.

Once the hardware has been designed and documented, developers face the challenge of selecting a dissemination strategy and an appropriate license that will help them reach as many potential users as possible. Even after users adopt the hardware, developers need to continue engaging and nurturing the community around the project. This might require them to regularly communicate through forums, incorporate user feedback, update files for compatibility, or prepare additional documentation. For all the time and labor required, prospective developers considering open-sourcing their project may be put off by the unclear opportunities to capture value for themselves through the released hardware. There isn't a straightforward commercialization strategy for open-source hardware, which may be a significant challenge especially for developers with

limited funding to continue the R&D on their project. In such cases, developers could choose to apply certain licenses to capitalize on any commercial distribution of their hardware in the future.

B. Best Practices for Open Robot Hardware

A successful ORH project maximally leverages the developers' efforts in preparing documentation, maintaining design simplicity and budget, and publishing regular updates by extracting all the benefits that come with open-source technologies. As such, the developer should try to gain widespread adoption of their project and sustain it over a long period of time. OSHA lays out steps developers can take to persuade users to use their open-source project and help build a community around it [17]. In this section, we briefly outline some of these best practices relevant to ORH that developers could follow after they've decided to open-source their robot hardware (Figure 1). Later in Section IV, we further detail the pipeline of requisite methods and considerations at these different stages of developing an ORH project from scratch, along with examples from effective ORH projects.

- The ORH development process begins with the *design* of the hardware components. As an open-source hardware project, the original and editable – preferably, made with open-source CAD tools like FreeCAD or Onshape – design files for the various custom components in the assembly should be released for the user to reference and fabricate the parts. This includes 3D CAD files and 2D part files for planar parts, in various editable and interchange formats like .step.
- These design files should be prepared with a range of user expertises in mind, i.e. the design features should be purposeful simple, and consistent through the parts. In addition to part files, supplementary files like circuit

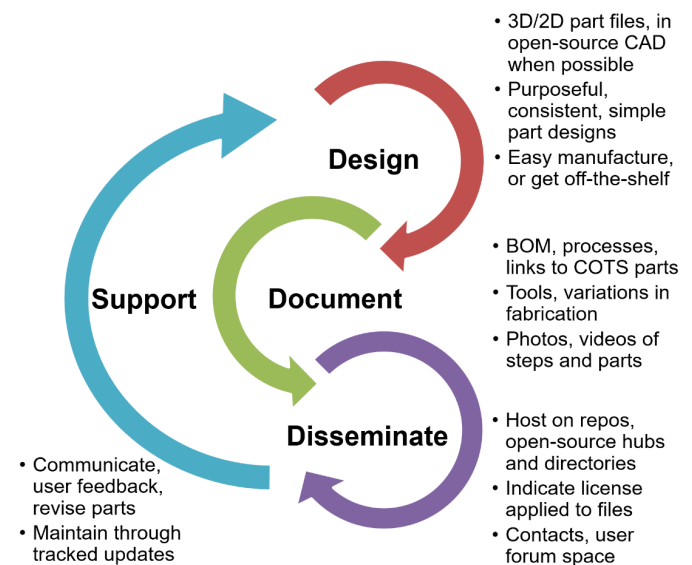


Fig. 1: Development process of an ORH with some best practices developers can follow to make their project as widely adopted and retained as possible.

diagrams and technical drawings may also be useful for the user to replicate the components easily on their end.

- Off-the-shelf components should be utilized as much as possible to relieve some of the manufacturing load of replicating an ORH. If custom fabricated parts are absolutely required, then the design of these parts should account for easy manufacturability at the users end and the variability in fabrication from different types of manufacturing equipment.
- Although the source part files are a crucial part of an ORH project, they are not sufficient on their own to ensure the hardware's reproducibility. Thorough *documentation* describing the various manufacturing and assembly steps needed to build the hardware makes open-source projects so lucrative. Bills of materials (BOM) and lists with links to off-the-shelf parts are very useful for users to acquire components.
- Before prospective users commit to an ORH, they might also want to know if they have access to the required equipment and if they can use the fabrication processes needed to replicate all the components of the project. The documentation should list fabrication methods next to the components as well as any tools needed for post-fabrication and assembly, allowing for alternate methods and equipment where possible.
- While more information for the user is better than less, a good documentation package ensures that the instructions are presented in a logical and clear manner. To this effect, annotated images or videos can go a long way in communicating complex and multi-step building processes effectively to even the novice user.
- Once the design files and documentation packages have been prepared, developers can *disseminate* the project through online repositories or project websites to reach as many users as possible. There are also several open-source project hubs (such as the OSHWA and Open Robot Hardware directories).
- For disseminating within academic communities, journals dedicated to open-source hardware can further spread the reach of the ORH. Sending emails on popular research mailing lists, publishing research papers, and participating in conferences and workshops can also help increase the user base.
- Indicating the license applied to the ORH files prominently on the site can inform prospective users early on and prevent any breach of user agreement.
- Developers can also *support* and nurture their user community by creating forum spaces for users to interact with each other as well as provide feedback on the project. An active user base for the ORH amplifies the previously mentioned advantages of open-sourcing the project for the developer.
- With the pace of progress in rapidly growing fields like robotics, it is crucial to update and revise the ORH files regularly to support current users. Updates should be tracked and released to add compatibility for new versions of off-the-shelf parts, or account for novel fabrication methods. Users can inform the developer when and

what updates may be needed to the project, and even prepare these revisions themselves if the project files are modifiable in freely available CAD software.

The development of a successful ORH is thus continually iterative – using the feedback from support provided to users in informing design changes, that subsequently get documented and disseminated on the platform in a process that gets repeated through the lifetime of the ORH. Thus, an ORH project can be made vastly more effective employing these best practices at the different stages of the process. In Section IV, we further detail these stages of the development process, focusing on the tangible steps prospective developers can take when building their ORH.

III. SURVEY OF OPEN ROBOT HARDWARE PROJECTS

The development and dissemination of open hardware can vary depending on its scope and purpose within the application area. Since robotics encompasses a wide range of fields, each requiring unique hardware and using distinct design and fabrication methods, the primary attribute used for the categorization of ORH below is that of the hardware's **application domain within robotics**. The list of ORH projects classified here is certainly not exhaustive, but rather aims to identify practices of some of those projects that led to their widespread adoption within the user community.

The surveyed projects for which the files are still accessible are listed in Table II, and also published through the Open Robot Hardware website [16]. In this table, we note the ORH properties and practices followed by each project in order for prospective developers to identify current ORH with desired attributes.

A. Robot Arms and Hands

Applications in grasping and manipulation requires the robot to be outfitted with different end-effectors depending on the task and objects used. The choice of end-effector is often limited by compatibility with the robot arm. Open-source robot hands seek to expand the robot systems' functionality by offering inexpensive and customizable robot hands that users can implement for their own use cases. The Yale OpenHand project [23] sought to create a library of such low-cost, 3D printed hand designs for researchers to use. The source design files are made available to public, along with a fabrication guide and videos to aid users in reproducing the hands on their end [27]. The Baxter EasyHand [28] draws from the OpenHand designs to offer an even cheaper and easy-to-build robot hand that functions with existing actuators on the Baxter robot arm. The EasyHand project exemplifies an instance of a derivative ORH project modifying and redistributing another ORH project. Similarly, the OpenBionics initiative [29], initially inspired by the OpenHand project, releases several open-source robot and prosthetic hands, such as a series of modular robot hands [30]. Open robotic hand platforms also present users with an opportunity to standardize evaluations of algorithms through benchmarking test setups. Several such platforms have been developed for testing learning algorithms for dexterous manipulation such as the ROBEL D'Claw [31]

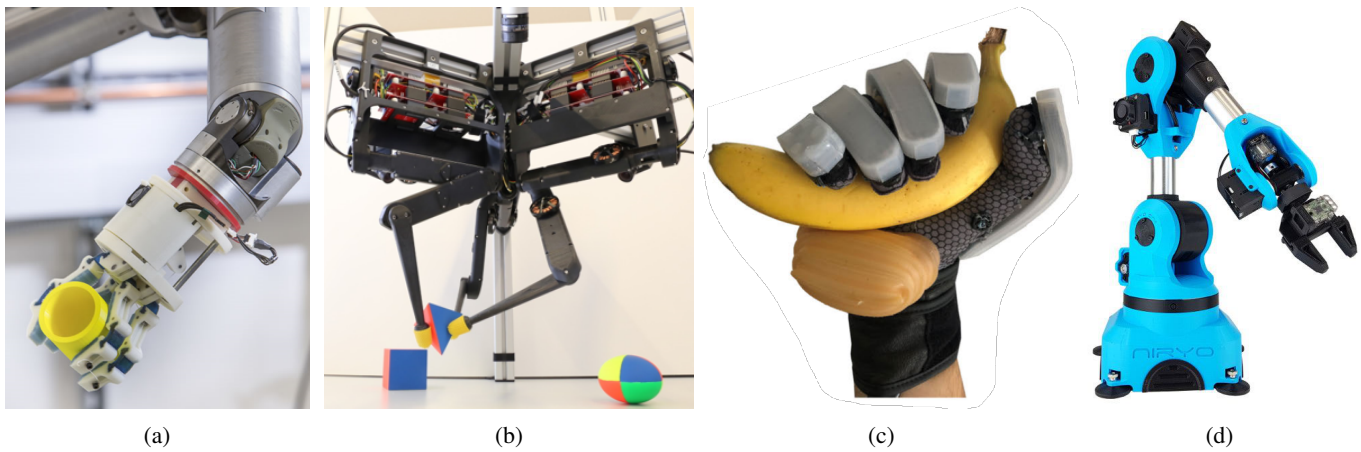


Fig. 2: Robot arm and hand ORH projects. (a) Model T robot hand from Yale OpenHand [23]. (b) TriFinger robot platform [24]. (c) Hybrid hand exoskeleton glove [25]. (d) Niryo One robot arm [26].

and TriFinger [24] platforms. Both of these 3-fingered hands aim to lower the cost barrier for experimentation with a full commercial robot system, and are intended to be used on standalone mounts without a robot arm.

Anthropomorphic hands form a large portion of robot hand designs used to carry out grasping and manipulation tasks in human spaces. The HRI hand [32] presents an anthropomorphic end-effector as a research platform for collaborative robotics, that can be built for a lower cost than acquiring a commercial gripper. A derivative version of the adaptive anthropomorphic hand of OpenBionics [33] aims to be capable of carrying out more dexterous manipulation tasks with fingers that can also move in the abduction/adduction direction. Human-like robot hands are also pivotal to prosthesis hand development. Such hand designs are often open-sourced for affordability compared to commercially available prostheses, and provide a research platform for evaluating control algorithms, human machine interfaces, and operation schemes in powered prosthetics. In order to achieve these objectives, open prosthetic hand designs maintain low-complexity of design so that the hands are easily reproducible. The OpenBionics prosthetic hand [34] uses just a single actuator with a lockable differential mechanism to permit locking different fingers in position. Anthropomorphic hands such as the Open Source Hand [35] can also be created with the aim of serving as a testbed to implement different prosthetic control strategies on a six degrees-of-freedom (DOF) hand. The PUT hand [36] combines fully-actuated and underactuated fingers in its anthropomorphic design with the goal of manipulating elastic objects. Similarly, the Brunel Hand [37] can be used as a platform for researchers in prosthetics, grasping, manipulation, and human-robot interaction. This hand is available for purchase from Open Bionics Labs, but can also be fabricated using the design files provided by the developer.

Similar to prostheses, open-source exoskeletons for arms and hands serve to increase accessibility to wearable, assistive devices for those who have lost some upper-limb functionality. The low-cost ExoArm [38] exoskeleton aims to assist elderly or disabled individuals in lifting objects and in rehabilitation of

arm motion. Exoskeletons for hands, or exo-gloves, can restore grasping capabilities and finger mobility in the hand. The exo-glove in [39] can be either body-powered or motor-driven, and Sparthan [40] features 3D-printed ring structures. These type of hand exoskeletons are often tendon-driven, but some have also added pneumatic actuation for modulating stiffness and inflating a telescoping thumb [25]. Linkage-based actuation is also common in hand braces and orthoses, such as the purely passive wrist-driven orthosis that was open-sourced in [41], and inspired the adapted motor-driven version [42]. Beyond assistive devices, exo-gloves also have a lot of applications in virtual reality and haptics. In [43, 44], finger motions and pinch gestures are used to manipulate objects in virtual reality and simulations. Exo-gloves can be used to transmit haptic feedback to the wearer triggered by a variety of sensors, such as underwater ultrasonic range data indicated by micropumps varying pressure at the fingertips [45], or spatial position observed through a camera translated to vibration stimuli [46].

In comparison to robot hands, prostheses, and exo-gloves, open-source multi-DOF robot arms are less commonly shared, likely due to the size and complexity of the whole arm design. Larger arms capable of carrying heavier payloads would also need components to be fabricated using metal machining or other manufacturing processes that may not be accessible to many users. The Niryo One [26], Thor robot arm [47], and CM6 compliant arm [48] with six DOFs attempt to bridge the fabrication gap by requiring mostly 3D printed components. And, other robot arms such as the OpenManipulator-X [49] are made entirely from off-the-shelf components from Robotis. Neither of these robot arms have a payload of more than 500-750 grams. In comparison, the 3-DOF PARA [50] and 5-DOF Dexter [51] robot arms have higher payloads of 1-3 kg, and use acrylic tubes and carbon fiber plates for structure, respectively. Still, larger 6 or 7-DOF robot arms are particularly absent from the open hardware space. While users might not be able to fabricate components for heavier payload arms, open-sourcing the design files and releasing documentation still has benefits of allowing the users to repair, modify, and upgrade the hardware as outlined previously in Section II-A.

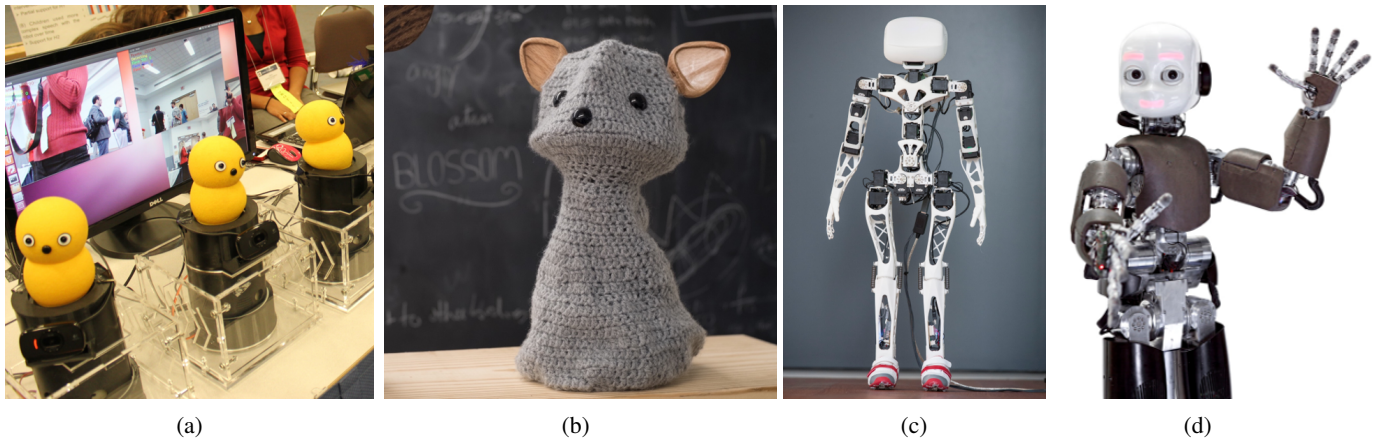


Fig. 3: Social robot and humanoid ORH projects. (a) MyKeepon toy robot [52]. (b) Blossom handcrafted robot [53]. (c) Poppy Humanoid [54]. (d) iCub humanoid robot [55].

B. Social Robots

Human-robot interaction (HRI) is an active area of research in robotics, and social robot platforms are a central apparatus that researchers have used to test expressive gestures and behaviors in real-world experimental settings. Commercially available products may not be suitable to the type of empirical evidence researchers hope to collect, and this could often require the researchers to develop or adapt their own hardware. The MyKeepon project [52] modified an off-the-shelf toy product and released a programmable, low-cost platform that could be built and repaired by users, allowing even multiple instances of MyKeepon robots to be deployed for comparative studies. On the other hand, some HRI experiments may call for customized and unique social robots. The open-source social robot platform (OPSORO) [56] allows the user to produce novel embodiments of social robots from a set of modules atop a skeletal frame for an accelerated design cycle. Users can incorporate different modules of the platform to enact facial features and design distinct outer layers allowing for wide variety of robots to be created with the platform. In similar vein, the Blossom social robot [53] can be custom-built with novel handcrafted exteriors and outfitted with a range of crafted parts such that no two robots have to look alike. Both the internal and outer structures of Blossom are fabricated from soft materials to add compliance in the natural motions of the robot. Soft actuators and compliant mechanisms are also employed in the CASTOR social robot [57]. CASTOR has partially humanoid-like appearance and is intended for use in therapy for children with autism spectrum disorder. Humanoids deployed as social robots and beyond are discussed in the subsequent section in more detail. All of these open social robot platforms can be constructed using cheap materials and accessible components, and associated control software and assembly instructions are made available for users to implement the robots easily, such as the well-organized wiki for CASTOR [58]. Social robots thus represent a model subsection of the wider ORH community, where commercially available products may not appropriately match the type of physical robot embodiment that researchers might

seek, and novel robot implementations are required to enable expressive capabilities in HRI settings. That said, the number of non-humanoid social robots trails in comparison to other robotics domains, likely due to the novelty of the field.

C. Humanoids

Humanoids are distinguished from social robots discussed above because they are often used in applications beyond human-robot interaction and embodied social behaviour. Humanoid platforms have been used in robotics research for studying grasping and manipulation, bipedal locomotion, multi-robot collaboration, motion planning, perception, and more. However, building a new humanoid robot is a resource intensive process, and might not be desirable if the research field requires to employ the robot simply as platform to build and validate algorithms on. The RoboCup soccer competition spawned several such open humanoid platforms such as DARwin-OP (subsequently followed by ROBOTIS-OP2 and -OP3) [59], and NimbRo-OP and -OP2X [60, 61] for researchers to deploy in their own specific applications. The hardware and software for all of these platforms was released open-source to aid users in modifying and repairing the robots, and have since been used in additional research areas of developmental psychology, cognitive science, and education.

Rapid prototyping fabrication techniques such as 3D printing have enabled users to manufacture components for open hardware more easily, and open humanoid platforms have capitalized on the proliferation of these techniques. The Poppy project [54] and InMoov [62] were some of the first 3D-printed open-source humanoid robots that could be entirely built and then programmed by the user. Both of these projects have also created a strong community centered around the robot, where users utilizing the robots in different applications can ask questions and share their adaptations and suggestions [63, 64]. The more recent Epi humanoid platform [65] is also assembled with 3D printed components, and focuses on developmental robotics research with its childlike impression and a fixed base. Similar to Epi, the NICO robot [66] provides yet another platform for multi-modal human-robot interaction

research in developmental robotics and embodied cognition. Lastly, the adult-sized humanoid face Eva [67] is designed to communicate using facial expressions and head movements, and comprised of 3D printed skeletal structure and a molded exterior.

One of the most popular humanoid platforms that has found application in several research domains such as locomotion, cognition, haptics, grasping, vision, and learning is the iCub humanoid robot [55]. The hardware and software for the robot were open-sourced along with relevant accompanying documentation for both, and has fostered a strong community of iCub users that help resolve issues, share their work, and suggest improvements [68]. The iCub robot is an example of an ORH that is not directly intended for the user to fabricate and assemble in its entirety on their own, but the access to documentation and hardware files in the form of CAD drawings and circuit diagrams allows users to modify, service, or upgrade the robot as necessary. Even though iCub was one of the earliest open humanoid platforms and was released over a decade ago, the open-source nature of the project has allowed researchers to continue using it as a development platform in an evolving field like robotics, where hardware can fall out of date quickly. The popularity of iCub might also have paved the way for other open humanoid robot platforms mentioned above, and typifies the benefits of ORH for both users and developers.

D. Legged Robots

Evaluating complex control and learning strategies for legged locomotion in robotics requires testing the algorithms on physical legged robot hardware. But, developing an advanced legged robot can need significant time and resources, and custom fabricated components that might not be easily and cheaply accessible. Several open-source quadruped projects have recognized this challenge and tried to address it by creating robots that use minimal custom machined pieces, inexpensive components, and off-the-shelf parts. The Open Dynamic Robot Initiative [69] is built with low-cost 3D-printed components and widely available brushless DC motors for the actuator modules. This actuator assembly allows for high-performance torque and impedance control, previously limited only to complex legged robots like Anymal [73] or the MIT Cheetah [74]. Moreover, this same actuation module has been implemented in the TriFinger robot hand [24] previously mentioned. Other morphologies of quadrupeds that offer a low-cost entry into legged locomotion research include the Stanford Doggo [75], Pupper, and Woofer [76] robots. The Doggo boasts performance metrics comparative to state-of-the-art quadrupeds, while keeping the total cost of the robot under \$3,000. Using similar architecture, the Woofer and Pupper robots incorporate high-power, and hobby actuators respectively, to offer even more options of robust, low-cost legged robot hardware to researchers in this field. The popularity of Boston Dynamics' quadrupeds has also spawned smaller-scale open-source versions such as SpotMicro [77], which in turn inspired OpenQuadruped [78], an inexpensive legged robot with an accompanying in PyBullet simulator and OpenAI

gym environment to test learned gait policies [79]. Another quadruped platform for legged locomotion study, Oncilla [70], enables simplified control in rough terrain locomotion via compliant spring-loaded pantograph legs. In addition to releasing the blueprints of the robot, a simulated model of Oncilla is also created in Webots for users to test control strategies before executing them on the hardware.

Some quadruped platforms have been developed with a specific application in consideration. The Metabot robot [80] was designed as an educational robot platform, allowing educators and learners to experience building a legged robot, and subsequently program it to walk or dance. The Aracna robot [81] was developed to promote research in evolutionary robotic algorithms that can generate robot behaviours automatically. To this end, Aracna deliberately embodies unconventional kinematics that require non-intuitive motor commands for generating a successful gait. Similarly, the Dynamic Robot for Embodied Testing, or DyRET [82] robot was designed to test the evolution of both control as well as morphology of the robot in the real world, and not just in simulation. This four-legged robot is able to modify and reconfigure its legs to adapt to different tasks and environments.

Smaller meter-scale or centimeter-scale legged robots might be even more suitable than their larger counterparts for an open-source release, since they are typically fabricated with simple materials and processes, and consequently cost less to build. The OpenRoACH [83] hexapedal platform can be built with benchtop machines and ubiquitous rapid prototyping methods within two hours. It can be integrated with a variety of sensors, the data from which can be processed through the ROS-capable computer on board. Taking the idea of simple fabrication further, the \$20 chassis of the BigANT robot [84] requires only a foam board and minimal hand tools to craft the structure of the robot. The plate and reinforced flexure (PARF) joints in this design can be employed into any number of functional robot designs, and facilitates quick and inexpensive fabrication of robot bodies.

In addition to the applications and morphologies discussed above, legged robotics research also spans domains of kinematics and dynamic control, as well as lower-limb prostheses and exoskeleton designs. The HOPPY kit [71] for robotics education allows students to experiment hands-on with topics in robotics that range from control and trajectory generation to simulation and kinematics on modular and robust physical hardware. The low cost of the kit eases access for researchers and educators studying dynamic behavior in robotic systems. The Open-Source Leg (OSL) [72] likewise aims to lower barriers of entry in leg prosthesis research, by eliminating the time and resources required in developing one's own robotic leg system from scratch, and presenting a common testbed across the field for benchmarking control approaches. The OSL project also demonstrates some developer practices that can encourage adoption within the community such as creating an online forum [85] for users to share modifications and ask questions, and a step-by-step video assembly guide [86]. Users also have the option to purchase a fully-built OSL from a vendor, and the released design and documentation files can help users with future upgrades and repairing the leg. Similar

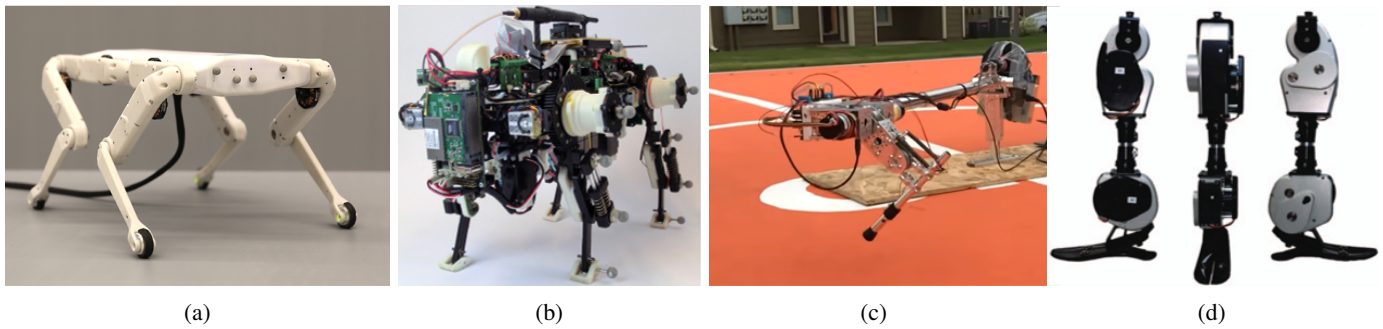


Fig. 4: Legged robot ORH projects. (a) Open Dynamic Robot Initiative quadruped [69]. (b) Oncilla quadruped [70]. (c) Hoppy kit [71]. (d) Open-Source Leg (OSL) prosthesis [72].

to OSL, the Alice pediatric exoskeleton [87] was developed with the goal of improving access to lower-limb assistive technologies. Alice can be controlled with simple, low-cost electronics and the physical components of the exoskeleton are 3D printed or purchased off-the-shelf, and Alice has even been clinically validated on patients with different medical conditions. That said, lower-limb exoskeletons for adults are still missing from the open-source landscape, likely because they would require fabrication with the metal and other high-strength material in order to sustain the heavier loads during use.

Legged robotics research and education can be cost prohibitive, especially if the robots require advanced manufacturing methods or rely on domain-specific knowledge to build and operate. However, these ORH projects are improving access to physical robot platforms in their respective fields through their comparatively lower cost of entry and minimal fabrication requirements. Across the different robotic leg systems, one can now find an ORH morphology that is suitable for their application, either as it is from the developer, or after some modifications permitted by the open-source license.

E. Mobile Robots

Mobile robots are an effective low-cost and versatile platform in robotics education and research, and a number of mobile robot platforms at every scale have been proposed, some of which have also been open-sourced. One of the most popular mobile robots, E-puck [88] was designed with robotics education in mind, and teaches students concepts in signal processing, embedded programming, autonomous control, and distributed systems. The simple structure of the robot equipped with a micro-controller and a wide variety of sensors makes for an easy-to-use robot that also has a lot of flexibility for implementation. While the E-puck robot may be directly purchased from vendors, the part files for the robot are also made publicly available for users to make design changes or build on their own. Other small two-wheeled open-source mobile robots such as Mona [89] and Miniskybot [90] have also been successfully implemented in educational settings, both of which offer lots of flexibility in programming and an inexpensive construction. Tracked mobile robot with 3D printed structures and mostly off-the-shelf components have also been proposed as benchmarking tools in computer vision

and artificial intelligence research in addition to education – the Zumi [91], Veter [92], and Nanosaur [93] robots are furnished with more capable on-board computing for users in these domains to test their software on a physical platform which can be quickly and easily built. To provide students interested in mechanics, electronics, and programming hands-on experience in building and operating a robot, the European Space Agency (ESA) and NASA JPL have also released their own scaled down versions of 6-wheel Mars rover designs, along with detailed instruction guides of the fabrication and assembly processes on their websites [94, 95].

Beyond educational applications, robot vehicles have also been used as popular testbeds in a range of robotics research fields. A popular family of robot vehicles, the TurtleBot3 [96] offers a low-cost mobile robot kit that can be adapted to be employed in a range of research applications. While users commonly purchase the TurtleBot3 hardware directly from distributors, developers have released the design files for the robot so that users can customize and modify the robot as needed. A lot of open-source mobile robots rely heavily on off-the-shelf components, so that the hardware can be effortlessly put together by the user. The Zumi [91] mobile platform is built mostly from off-the-shelf components, and is intended for development of multi-robot systems and computer vision. Lastly, scaled down mini-racecars like the MIT RACECAR [97] and the Multi-agent System for non-Holonomic Racing (MuSHR) [98] can serve as powerful platforms for implementing autonomous navigation, localization, and planning algorithms in real-world environments for robotics research and education. But users can also modify these open hardware cars to adapt the testbeds, for instance, by adding a gripper to MuSHR in order to investigate collaborative multi-robot manipulation [98].

Mobile robots serve as a very effective tool for testing implementations of software algorithms in a range of robotics domains quickly with a reduced cost of materials, and a simple construction requiring nominal expertise and tools. Their ease of use and adaptability to different applications also make them suitable for educational settings in addition to robotics research.

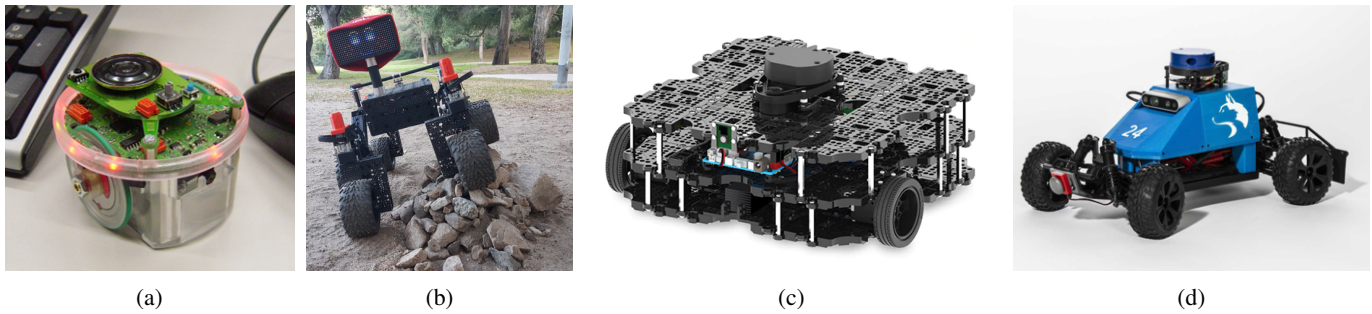


Fig. 5: Mobile robot ORH projects. (a) E-puck two-wheeled robot [88]. (b) NASA JPL Open Source Rover [95]. (c) Turtlebot3 Waffle platform [96]. (d) MuSHR mini-racecar [98].

F. Component Modules and Tool Kits

In some of the newest domains of robotics, building one's own hardware might be the only option available to a researcher since no similar off-the-shelf products are commercially available for purchase. For such domains, ORH can provide valuable tools for users to iterate and test new robot structures instead of developing hardware from scratch.

Soft robotics is one of these fields in robotics that has grown rapidly over the last few years, and researchers have been open-sourcing their hardware to allow other researchers to create their own soft robotic devices. One such core component in a soft robotic mechanism is the actuator, and PneuFlex [99] was one of the early soft actuators that the developers had released publicly along with CAD models, 3D printing files, and a detailed fabrication guide [100]. The actuator was later used in the compliant RBO hands [101]. A lot of soft robot component technologies have also been compiled on open platforms that host tools and guides to test new soft mechanisms quickly, further accelerating the development of novel applications for soft robots. The Soft Robotics Toolkit [102] offers instructions and guides on several common components of soft robots to enable speedier development of soft devices. The toolkit is developed with contribution from a number of research groups, and has even been used to support educators in hands-on robotics courses. Another such platform supporting fast development of articulated soft robots is the Natural Machine Motion Initiative (NMMI) [103]. NMMI is composed of hardware modules that users can put together to create complex and novel robotic structures. Both of these platforms are continually updated with the latest developments in soft robotics and grow with more contributions from developers and other research groups.

The practice of open-sourcing the tools and components required to build a robot hardware has gained traction not only in soft robotics, but has also seen prevalence in other evolving domains of robotics, such as modular and swarm robotics. The Molecubes [104] platform was openly distributed to promote new developments in reconfigurable and modular robotics. The project underwent multiple iterations, and invited modifications and enhancements from the user community [105]. Swarm robot hardware has similarly been made publicly available in projects like the centimeter or millimeter-sized Jasmine [106] and Kilobot [107] robots. The Swarm Robotics

Construction System (SRoCS) [108] is another open-source swarm robot platform released for studying multi-robot coordination specifically in construction tasks.

Lastly, hardware that spans multiple areas in robotics can also significantly benefit from open-source technologies. Electronics platforms like Arduino [109] and Raspberry Pi [110], common components such as tactile sensing arrays like TakkTile [111] and Digit [112], and soft tactile grippers in Punyo [113] are constituent in robot hardware for many different areas. Electronics hardware, in particular, has a long sustained history of open-source communities and repositories like Open Electronics [114], Kitspace [115], Hackaday [116] and many more, surveyed in field-specific academic reviews [117] and special issues of journals [118]. While the wide breadth of open-source electronic platforms and components is beyond the scope of this review, their widespread adoption and thriving community can inspire best practices and methods in disseminating ORH projects. Moreover, the success of these repositories also confirms that ORH projects that release component modules and technologies can notably expedite prototyping and testing of new robot structures, which can be especially vital for identifying novel applications in fast-moving domains of robotics.

G. Miscellaneous

1) *CNC Robots*: Open-source hardware has been pervasive in a lot of other robotics domains in addition to the ones outlined above. CNC robots are so called for their similarity to Computerized Numeric Control (CNC) machines. These simple 3-axis robots with orthogonal actuation DOFs are potent tools for automating a variety of 2-dimensional tasks. They can be equipped with any suitable end-effector for the task. For instance, the tiny Piccolo CNC bot [119] applies this architecture as a drawing robot with a distal pen attachment. Piccolo is often used in educational workshops to give users hands-on experience in building and programming robots. The FarmBot [120] employs the CNC robot framework to automate small farms in home agriculture spaces. Developers of FarmBot sell the hardware, but the source files for the robot are freely available and can be modified or repaired as per the users' needs.

2) *Haptic and Teleoperation Interfaces*: Haptic and robot teleoperation interfaces have also seen ORH solutions that

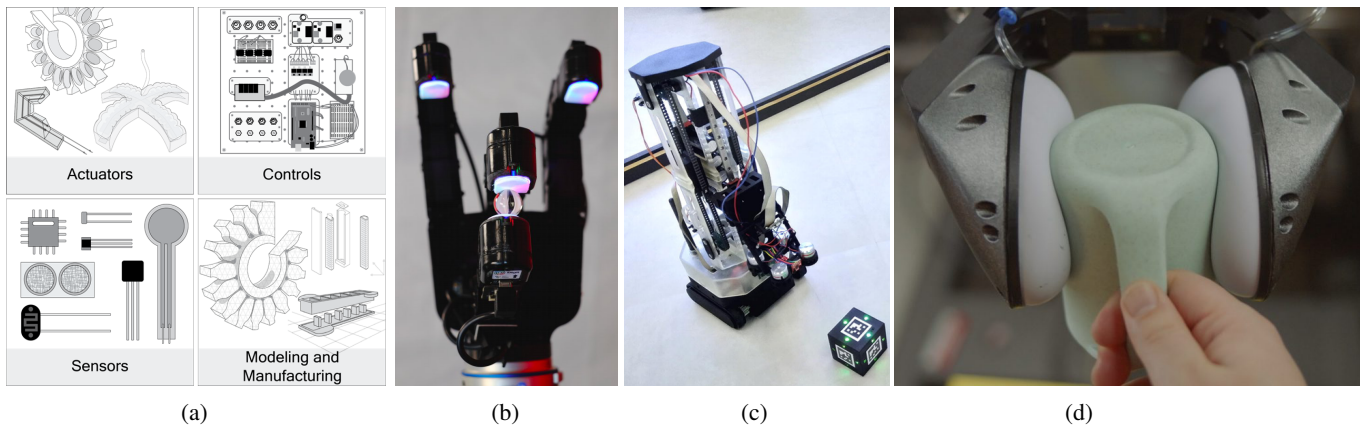


Fig. 6: Component module and tool kit ORH projects. (a) Components of Soft Robotics Toolkit [102]. (b) Digit sensor on a multi-fingered hand [112]. (c) SRoCS swarm robot system [108]. (d) Punyo soft bubble gripper [113].

users can build on their own. The HapKit [121] platform is a single-DOF device that can be used as an input and also generate forces experienced by the user. The kit is quite inexpensive (costing less than \$50), and can be intuitively built and used by a novice user, which is ideal for learning environments. Similar in goal of being easily fabricated, WoodenHaptics [122] is a 3-DOF haptic device, the structure of which is made from laser-cut stacked plywood sheets. The design of the device also focuses on the ease of making modifications to the device for different applications requiring spatial haptic interactions. While haptic devices have been commonly used as interfaces in teleoperating a robot, the ROBOPuppet [123] takes an alternate kinesthetic approach to simplify teleoperation by creating a scaled down replica of the target robot. The operator is expected to be able to more intuitively control the motion of the robot by manipulating the table-top robot model, whose joint angles are duplicated exactly in the target robot.

3) *Medical Robots*: Open-sourcing hardware in medical robotics can be challenging particularly because of the stringent requirements placed on robot systems in this field. While open-source platforms such as the da Vinci Research Kit (DVRK) [124] and the Raven-II [125] have markedly improved the accessibility to the control software of commercial surgical robots, the hardware of medical robot systems remains relatively more exclusive. Some ORH in medical robotics targets peripherals around the open-software surgical robots, such as the SPRK platform [126] that simulates body organ motion for studies with the DVRK robot. Medical robot hardware itself has started to become publicly available through initiatives like Open Source Medical Robots [127] and Pillforge medical capsule robots [128]. The ENDO robot presented in [127] is a continuum manipulator designed to lower the barrier of entry in surgical robotics research. And in [128], a platform for rapid development for medical capsule robots is proposed, with hardware and software component modules that can be assembled for quickly testing prototypes. However, ENDO and Pillforge are just a few ORH in medical robotics, and more open-source hardware should be explored that can further lower barrier to new robotic technologies in this field.

4) *Aerial Robots*: ORH for unmanned aerial vehicles (UAVs) has been widely popular among researchers for their flexibility and ease of implementation, similar to ORH for mobile robots discussed previously. Lim et al. [12] present a survey of open-hardware for quadrotor UAVs, so those projects are not detailed here again for brevity. Hardware for other types of UAVs, like lighter-than-air (LTA) crafts have also been open-sourced – a design for a robotic gondola attached underneath a balloon is proposed in [129] as an indoor LTA airship that can be employed in research and education. Similar to medical robots, open-source projects in UAVs have been explored more as software platforms and flight controllers. But as more applications for UAVs are discovered and with the increased convenience of fabrication from rapid-prototyping methods, ORH for UAVs can be expected to also become just as abundantly available as mobile robots.

IV. DEVELOPING AN OPEN ROBOT HARDWARE PROJECT

Many of the ORH projects categorized in the previous section exemplify a development process that can lead to a widely used and retained ORH with an active user community. Prospective developers can better understand the steps involved in creating an ORH through these projects, especially if they work in a similar robotics domain. In the discussion below, we detail the pipeline of developing successful ORH through the stages of design, documentation, and dissemination that will help an ORH project to be widely adopted by a lot of users for a long period of time. We also discuss how developers can determine fabrication methods most suitable for their ORH. And along the way, we will refer to some useful strategies from ORH projects previously surveyed that new developers can implement themselves.

A. Design and Fabrication

1) *Design and Part Files*: An ORH project vitally shares the design files for the hardware so users can manufacture components as well as modify and share their adaptations. To this end, the developer should publish all part documents including 3D CAD files (for any machined, 3D printed, or

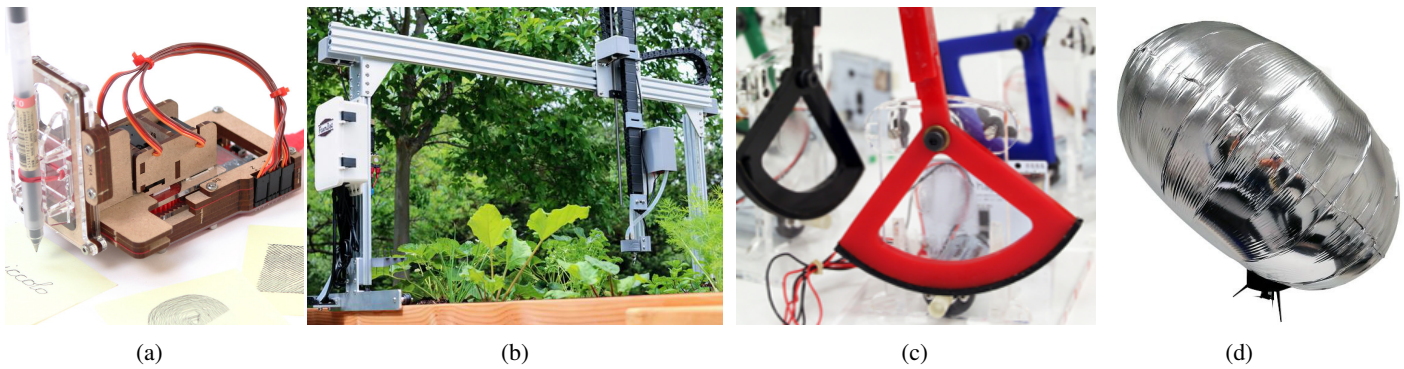


Fig. 7: Miscellaneous ORH projects. (a) Piccolo CNC bot [119], (b) Farmbot CNC robot [120], (c) HapKit haptics platform [121], and (d) Robotic gondola for an LTA airship [129].

molded parts), 2D fabrication files (for laser cutting, waterjet cutting, or similar process), and any auxiliary files required for fabricating components (for example, machine drawings, or circuit board layouts). If any of the part files have special software requirements, the developer should highlight those in the shared documentation. As such, open-source projects should rely on freely available software, so that cost of meeting the software requirements don't prohibit users from accessing the released design and part files. That said, the majority of ORH are developed in proprietary CAD systems like SolidWorks or Autodesk Fusion, usually due to the lack of free advanced 3D modelling software that are suitable for the design complexity of some mechanical components. Nonetheless, projects like Metabot [80], Mushr [98], Veter [92], and Miniskybot [90] use free and open-source 3D modelling tools like OpenSCAD, FreeCAD, or Blender, and others like Farmbot [120] use free versions of design platforms like Onshape. Even if editable design files are made with these freely available modelling tools, they might still remain out of reach of many users who do not have access to expensive computers capable of opening and modifying large projects with lots of components and sub-assemblies. In contrast, programs like OnShape and Autodesk Fusion have the benefit of being cloud-based, which eliminates the requirement of having sufficient local computing power in order to run CAD software, and allows users to flexibly work on design files from any computer with a good internet connection.

It is worth noting that simple replication of an ORH may not require editable CAD files. For instance, if a robot only requires 3D printed components, STL files may be sufficient. However, editable 3D CAD models of the components allow users to adapt designs and make changes as necessary, which can then be shared with the rest of the user community or even released as another ORH. Editable CAD files could be in formats directly saved by programs (like .sldprt from SolidWorks). But, most major CAD programs are not able to easily import file formats native to other programs. So, designs can be made even more accessible by exporting files to neutral interchange formats like .step or .iges because of their cross-platform compatibility. The .step format is regularly updated to include more solid model data (such as geometry, configurations, colors, layers, GD&T and more), and is thus

preferred over the older .iges format, which retains surface model data only. The EasyHand [28] project is an example of ORH redistribution after modification of the Yale OpenHand project [23], because the 3D models were made available for OpenHand. Sharing of files in modifiable formats also applies to 2D part files, such as laser or vinyl cutting files, as well as electronics components of the hardware, such as schematics for circuit board layouts.

To encourage adaptations of the design and contributions from users, the features in part files should be added such that they clearly convey purpose and function of the design choices. Breaking the top-level intricate assembly down into simple, understandable sub-assemblies can further help improve the ease of parsing through the files. The ESA ExoMy [94] and NASA JPL Open Source Rover [95] both have an involved top-level assembly with several off-the-shelf components and 3D printed parts. The ExoMy project details a part naming convention for its mechanical design files, along with a folder structure guide to navigate the assemblies and 3D printed parts. The Open Source Rover provides a similar folder structure guide, but also outlines a subsystem road map to provide users with a high level view of the sub-assemblies, and where along the fabrication and assembly process the user is at any point [95].

Another reason for ORH projects to share editable design files is to account for inconsistencies in fabrication processes. Processes like 3D printing vary depending on the printers and materials used, and developers should consciously avoid designing hard-to-fabricate features in their custom parts. One way to avoid such variations altogether from fabrication processes is to rely more on commercial off-the-shelf (COTS) components. But, even for purchased components, developers should consider alternatives to components that may not be in stock or discontinued in the future. Users with access to editable CAD files can tweak the part designs on their end to accommodate alternative components in such cases. This allows the developer to off-load creating design variations to the users, who can add compatibility for different COTS parts on their own, given that the design files are understandable and the file repository is easily navigable.

2) *Fabrication Methods Selection*: One of the main hurdles that open-source hardware has to overcome is that it requires

fabrication of physical components to reproduce the hardware. So, the fabrication methods that developers choose for their components can have a significant impact on the accessibility of their ORH project. Developers should identify the requisite processes in parallel with the design of the components, and modify any parts that might be hard to manufacture or source. Most ORH projects heavily rely on additive manufacturing approaches such as fused deposition modelling, and more modern techniques like stereolithography, polyjet, and digital light process. These are quite approachable nowadays even through desktop 3D printers, and are generally appropriate for small parts that may have complex geometries. The range of materials that can be 3D printed has grown a lot over the recent years [130], but most of these printed polymers are not suitable for very high-force or long-duration applications. Metal 3D printing is starting to become more accessible, particularly through on-demand prototyping services, but it is still limited in terms of material choices and sometimes cost prohibitive [131]. There are also several other fabrication techniques that use 3D printing as one of its steps. Printed parts can be used as molds for different resins, and are commonly used to make components for soft elastic actuators [132]. Other techniques have taken the idea of molding with 3D printed parts even further, such as shape deposition manufacturing [133], which alternates deposition and removal of material to create embedded structures with different materials. Hybrid deposition manufacturing (HDM) [22] builds on this concept by including both permanent and sacrificial parts in the mold, and has been used in making the robot grippers and hands of the OpenHand [23] and OpenBionics [29] projects.

For larger parts, developers can consider subtractive methods such as laser cutting, laser etching, CNC routing, and water-jet cutting. These are often very fast, inexpensive, and can work with a variety of materials. Although they are limited to extruded planar geometries, lots of projects have found ways to fabricate components with these methods – Piccolo [119] and early HapKit version [121] use mostly laser cut acrylic or fiberboard, the legs and frame of the quadruped Stanford Doggo [75] are made with water-jet aluminum sheets, and the Pupper [76]. The skeleton of OPSORO robot [56] is also mostly made up of laser-cut foam pieces that can be snapped together. These pieces are also designed with assembly error-proofing in mind, for example, with connectors of different widths that only fit together in a specific way. Another laser cutting-based technique stacks multiple layers of cut 2D parts to create thick structures, as seen in WoodenHaptics [122]. The OpenRoach robot [83] is made with etched wooden sheets with flexure joints that serve as creasing patterns, so that the 2D sheets can be folded to create 3D robot structures. Laser cut parts have also been used as stencils for painting different dot patterns onto latex sheets in the Punyo tactile gripper [113]. Even without laser cutters or waterjet cutters, rigid sheets of foam, plastic, cardboard, fiberboard, or other material can be scored and cut with common tools to easily construct structures for robots. The fabrication of BigANT robot [84] presents such a versatile technique (called, plate and reinforced flexure (PARF) fabrication) of building robots with rigid plate materials connected by fiber-reinforced tape

joints. These types of versatile fabrication methods that rely on minimal tooling and cheap materials can help ORH projects reach a much wider audience of users.

Depending on the functional requirements of the components in a robot, certain materials properties may be desired, which then inform the choice of fabrication method. Soft robots use a number of different approaches to manufacture elements of their robotic systems [134]. Many social robots are also designed with soft, deformable materials because they need to be compliant to external contacts, or blend with household objects. The Blossom [53] robot's exterior is made from knitted fabrics that are used to convey warmth as the robot is intended to be stationed in people's homes. The OPSORO robot [56] also uses flexible textiles as well as foam patterns that are stitched together to make the 3D shell. Just as some robots need highly deformable components, others may need high-strength components to sustain large loads. The Open-Source Leg (OSL) [72] is one such project that requires several machined metal parts. But machine tools like CNC mills and lathes might be out of reach for many users who may not be trained to use them. To mitigate that, the OSL project offers the option of purchasing a pre-built leg, or suggests users to outsource the fabrication to machine shops. When possible, developers should still try to recommend easy-to-use fabrication methods for their components. And if no existing method is suitable, they could rely on COTS components such as extruded frames, tubes, or patterned plates, which can be readily adapted into large-sized robot builds. For example, Farmbot [120] and HOPPY [71] both use metal extrusions; the linkages of the PARA robot arm [50] are made from acrylic tubes; ROBEL [31] is mostly made up of off-the-shelf brackets; and, Zummy [91] and HOPPY are mostly made of COTS parts.

Even for users with no access or expertise to use manufacturing equipment, obtaining custom fabricated parts is becoming easier with the rise of on-demand prototyping and manufacturing services [135]. Developers could utilize the wide range of manufacturing options available with popular services (like Protolabs, Shapeways, Fictiv, Xometry, and many more) to recommend to users as an alternative to fabricating parts on their own.

B. Documentation and Instruction

The design and part files on their own do not suffice easy reproduction of the ORH – thorough documentation along with visual guides for fabrication and assembly are essential to ensure accessibility for users with a range of expertise in the processes required to build and operate the robot hardware. The ORH projects that are widely adopted have detailed and clear instruction sets that indicate each step of the manufacturing and assembly process. The documentation package of the OpenHand project illustrates some of these good documenting techniques. A list of all the fabricated and purchased components in the form of a bill of materials is listed at the top of each subsection of the assembly guides as shown in Figure 8 [27]. The instructions for building OpenBionics hands [34] is also exemplary of some best practices

[136]. For instance, each section has accompanying list of materials and annotated images of the parts for users to quickly reference assembly steps and requisite components at hand. The bills of materials for Piccolo bot [119] and Punyo gripper [113] helpfully link where each component can be sourced, or alternately, specify the fabrication process if it is a custom component [137, 138]. However, a user might have acquired all the requisite components, and realize midway through the build process that they do not have a particular tool. Projects like Poppy [54], WoodenHaptics [122], and ExoMy [94] avoid such a situation by listing and visually showing all the tools and equipment required to carry out the assembly [139, 140].

Once all the components and tools are obtained by the user, the documentation should then direct the user through each step of the assembly process. Visual guides are very effective in conveying the process in addition to textual instructions. The InMoov project uses images of the partially assembled components after every step for users to compare their output with that in the guide [62]. A number of other projects – Yale OpenHand [23], Punyo gripper [113], Open-Source Leg [72], Poppy [54], and more – have videos of an individual assembling the components so users can conveniently follow along, e.g. [141] shows videos for fabricating an actuator body in the Soft Robotics Toolkit [102]. Such assembly videos, even more than still photos, can unambiguously communicate the minute details of the process that a user just reading the text may overlook; for instance, the user may pick up on how much clamping force to apply through the individual's actions in a video. The HOPPY project [71] and CASTOR robots build instructions [58] instead use video animations of the various CAD model's exploded views, which also effectively articulate how parts connect with one another.

Inconsistencies at the user's end depending on the type of fabrication equipment, tools used for assembly, or alternative off-the-shelf components sourced are likely to occur, and need to be addressed when the developer prepares the documentation packet for the ORH. The previous subsection detailed how design of the hardware can account for such variations. Documentation and the instruction guides can also aid the user's ability to identify discrepancies by highlighting what design features the user should check before proceeding with the assembly, and then compare with the developer's setup for differences (for example, make of the 3D printer, or model number of actuator). The Yale OpenHand instruction documents have annotated images and schematics to call user's attention to evaluate specific features on their molded and 3D printed parts [27]. This helps debug any issues in fabrication early on in the assembly, so users can reproduce well-functioning robot hands.

Developers are also strongly encouraged to provide as much information to users as possible about the appropriateness of various fabrication technologies, including specific machine models used for the project's components. For example, the ExoMy rover project lists all the 3D printers that their rover has been successfully manufactured with [142], and users are encouraged to notify the developers if they printed the rover with a different 3D printer, so that the developers can update this list. For more multi-step fabrication processes,

such as those for the Punyo gripper [113], the documentation thoroughly guides the user through the process steps, and most importantly, includes safety precautions and fabrication errors to look out for along the way [143]. Projects that require more advanced fabrication steps, like CNC machined parts, should be aware of the level of complexity and cost that would discourage potential users. The Open-Source Leg project [72] has several machined parts due to functional requirements of the hardware, but the developers provide all the necessary files to outsource the machining fabrication such as drawings, part quotes, and even sample emails to send to manufacturers.

Thoughtfully created documentation packages are thus critical to accompany the chosen fabrication technologies. The practices typified in the ORH projects discussed above significantly lower the barrier of entry for novice users, and they should be referenced by prospective developers intending to create ORH documentation that improves the reproducibility of their hardware.

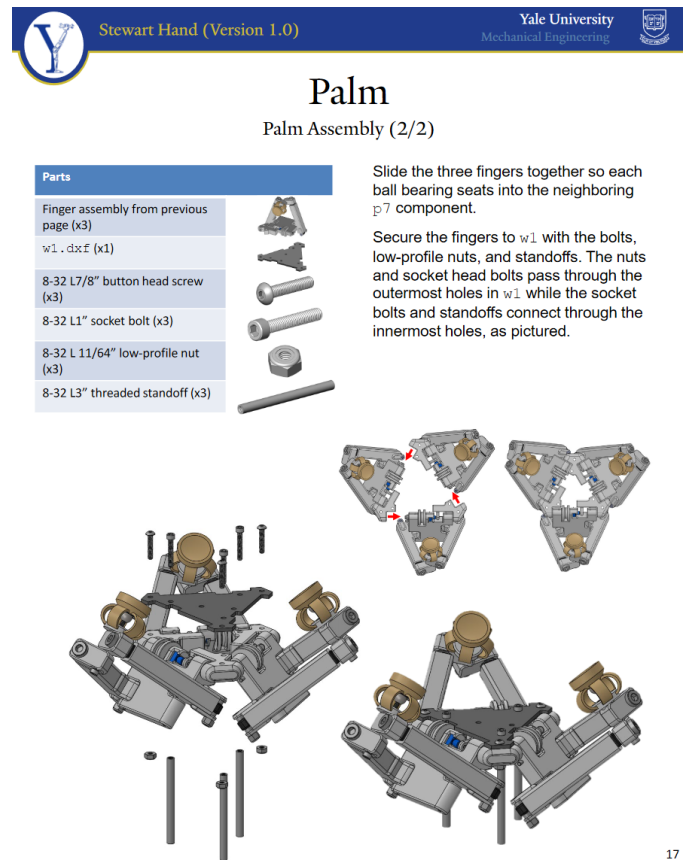


Fig. 8: Bill of materials visually shown and annotated images of the exploded assembly view in the documentation of Yale OpenHand's Stewart Hand [27].

C. Dissemination

The key characteristic of an ORH project is that the prepared design files and documentation packet are disseminated in an open manner for potential users to find and access them. For this purpose, a lot of ORH projects host project repositories on platforms like GitHub or the Open Science Framework (OSF)

that allows public dissemination of the project along with an ability to version control files for any necessary updates. More hardware-focused platforms like Thingiverse and Hackaday are popular with maker communities, but have also been used for distributing new research hardware [29]. Wherever the developer decides to host the project files, they should track revisions and updates to convey changes in the latest version to users. In fact, the developer should try to ensure proper maintenance of the ORH project over its active duration of time by releasing patches and fixing persistent issues that users may be encountering. To publicize an ORH, developers can utilize academic journals on open-source hardware such as HardwareX [18], Journal of Open Engineering [19], and Journal of Open Hardware [20], which can serve as valuable tools for broadcasting one's work within the research community. ORH projects such as the Eva humanoid face [67], HRI Hand [32], and Swarm Robotics Construction System (SRoCS) [108] were all published through these open hardware journals. Other dissemination strategies for advertising ORH specifically to reach academic and research communities can also be used such as sending emails to popular robotics mailing lists, publishing papers field-specific journals, and participating in conferences, workshops, and tutorials. Developers should also contact directories like the Open Robot Hardware initiative [16] that compile ORH projects. The Open Source Hardware Association (OSHW) [17] maintains a similar directory of open-source hardware projects, but requires developers to undergo a certification process beforehand. Certifying the project with OSHWA ensures that it complies with the requirements set for their open-source hardware standard, further adding credibility to an ORH with the OSHWA certification logo.

When releasing an open-source project, the developers need to decide what type of license should be applied to their original design files, as well as the accompanying software and documentation. Different parts of the project can have distinct licenses applied to them; for example, the bill of materials for HRI Hand [32] and SRoCS [108] note the open-source license next to each part in the table. The applied license stipulates if users need to attribute the original work (attribution), if they can modify or adapt the work (derivative), if they can distribute the adapted work under a different license (permissive, as opposed to copyleft or viral), and if they can use the original open-source work for a monetary advantage (commercialization). There are several open-source licenses with different characteristics that developers can choose from to apply to their designs [144]. Some of the most commonly applied licenses are from Creative Commons [145], which has several licenses with different provisions on attribution, use of derivatives, copyleft, and commercial use. A comprehensive comparison of the Creative Commons licenses can be found in [146, 147]. Popular open-source software licenses like GNU General Public License (GPL) [148], MIT license [149], and BSD license [150] are often applied to open-source hardware, primarily as a way to waive liability and warranty. They differ from each other in one major way – the GPL is copyleft and requires any future modifications to be released under the same license, whereas the MIT and BSD licenses are far more permissive and do not have many licensee requirements.

The Apache license [151] is similar to MIT, but has explicit provisions for patents on derived projects. While all of these licenses are written with software projects in mind, some licenses have also been written to specifically protect hardware. TAPR [152] and CERN [153] both have copyleft licenses for hardware similar to GPL (CERN even has different variants), and the Solderpad license [154] is a permissive hardware license derived from Apache.

Explicit and clear mention of the license on the project's repository and documentation conveys to prospective users how they can implement and use the work, and should thus be carefully considered by the developer. Some repositories like GitHub even provide the option to select a license when creating a new project. In general, developers should include the license information in every file or at least in the README [17]. Similar licensing principles also apply to non-hardware files of the project such as any accompanying code and even supporting documentation packages, and developers can choose to apply different licenses to each of these elements. Overall, it is strongly encouraged that developers pick an open-source license with as few restrictions as possible to attract users to their projects [155], and consider that a lot of users would like to customize and build upon the project.

D. Support

Previously, one of the challenges identified by users of open-source hardware was the lack of sustained support for technical issues users may run into during the build process or in later stages of operating the hardware. While developers should nurture ORH projects through updates that resolve issues encountered by users, some of this responsibility can be undertaken by an active user community. Repositories or project websites should at the least allow users to contact developers in order to report issues and suggest modifications. But a thriving user community can be generated if developers create a forum space for users to log issues, ask questions, share updates, and even offer support to each other. Popular ORH projects like iCub [55] have a strong community forum with lots of users of the iCub robot participating in discussions ranging from low level software questions to announcing new research conducted with the robot [68]. The ExoMy [94] and NASA JPL rover [95] projects similarly setup forum spaces and message boards for users to seek solutions to common problems as well as invite contributions to the project by proposing changes and updating project files. Robotics toolkits and component platforms like Soft Robotics Toolkit [102] and Natural Machine Motion Initiative (NMMI) [103] in particular benefit from highlighting opportunities to their communities to contribute to their projects, because these improve the collection of modules offered on the platform. Several other ORH projects like WoodenHaptics [122], InMoov [62], and Farmbot [120] allow users to interact with each other through mailing lists, discussion spaces, and blogs, which can lead to a more engaged user base that subsequently helps the project stay relevant to progress in the wider robotics community over a longer duration through “cooperative development” [156]. These practices facilitate the creation of a thriving and

engaged user community for a successful ORH, and discussion forums and message boards are cornerstones in building and maintaining cooperation in the project's community. Through these communication channels, users can share feedback, frequently encountered issues, contribute design updates and modifications, share new project ideas and implementations, and offer support to each other – all of which enhance the ORH's usability and compatibility, far more effectively in comparison to only the developer working to sustain those ORH attributes.

V. FUTURE OF OPEN ROBOT HARDWARE AND CONCLUSIONS

With just the sheer magnitude of projects that are released every year, the momentum behind ORH will certainly sustain over the coming years, and still has the potential to revolutionize access to new hardware in robotics [21]. That said, releasing robotics hardware in an open-source manner is still far from standard, and trails behind open-source software and electronics. But robotics research can greatly benefit if open-sourcing hardware became a more common norm, as is currently the case with published algorithms and software. Computational researchers release their software code for purposes of reproducibility, benchmarking, verification, and more [157], and releasing hardware that can be replicated by others would promote research in the same way. This is evident in emerging fields of robotics, such as social and soft robotics, where more and more projects are being released open-source. Commercially available hardware is somewhat scarce for these new fields, which may also instigate researchers to release their projects as well as seek out other researchers' ORH. But even beyond these novel areas, the proportion of ORH will continue to grow, facilitated by intersection of the new domains with the established fields of robotics, for instance, as soft actuators make their way into grippers, mobile manipulators, and assistive devices.

The future of ORH will also be fueled by the shrinking barrier of entry for novice users and the steadily improving quality of available ORH. The practical challenges of ORH, for both users and developers, are already being eased up by technological advancements on several fronts. First, new fabrication techniques are more accessible than ever, and are able to generate complex and durable parts in a variety of material options, such as metals and soft polymers. On-demand manufacturing services have also helped outsource the fabrication step for users without access to costly equipment, further boosting the accessibility of ORH in many domains [135]. Secondly, free and open-source CAD software are becoming more feature-rich, especially cloud-based CAD, which make creating and modifying 3D parts significantly easier without the need for expensive computers [158]. Next, communication spaces, like online forums setup on Slack or Discord, are more ubiquitous today and being used more often by developers, which encourages collaborations and future development of the project [156]. And lastly, repositories for disseminating project files are being more commonly utilized and these platforms continue adding functionality for managing and

controlling versions of design and documentation files. Even the more hardware-focused platforms such as Thingiverse and Hackaday, which have been previously popular in the open-source communities, are gradually being used for sharing new ORH projects [29, 48, 62, 77].

While quality and abundance of ORH are important, future ORH projects also need to be supported for a sufficiently long duration of time. Reliability of long-term access and support is one of the reasons that drives prospective users away from open-source hardware. But the growing utility of development platforms for collaboration, hardware repositories, and project management tools can aid in extending the life of future ORH projects [159]. These platforms help invite new users, engage experienced users, and encourage potential developers to share their own adaptations. In this way, sustaining and continually iterating the ORH is distributed within the community and simplified for the developer. Eventually, this cycle of sharing ORH can also stimulate more sharing, thus compounding the advantages for both users and developers.

One of the crucial areas in which the ORH community needs to invest more resources and effort in the future is in properly documenting and updating their projects. From the surveyed projects in Table II, only about a third of the projects have been updated in the last 2 years. While the repositories may still be accessible and have ample supporting documentation, dormant ORH projects may be unlikely to be adopted by users, especially if there is no active community or forum around the project. Moreover, robotics is a field that moves quite fast, and, the longer a project remains dormant, the more likely it is to become obsolete. Some other vital aspects of the documentation and instruction / user guide missing in a lot of existing ORH projects are detailed fabrication instructions, and a comprehensive, regularly updated bill of materials. A few do offer the alternative option of purchasing the components from a vendor, but the majority of ORH projects do not have much guidance on how to fabricate or acquire the required components. This can be a critical barrier to adoption of an ORH project, particularly for users who might be new to a field, or for prototyping methods that might not be widely used yet. Thus, in the future, the role ORH projects play in uplifting robotics research will be vastly amplified if they are regularly supported and updated over a much longer time period, and accompanied by a comprehensive documentation package that covers a wide range of instructions from fabrication to operation.

A. Conclusion

In this review, we focused on open robot hardware (ORH), which we defined as projects having open-sourced their design and auxiliary files accompanied by proper documentation, addressing a need in some robotics-specific domain, and centering around mechanical or electrical hardware components. The characteristics of ORH projects were discussed by highlighting the advantages and challenges encountered by both the users and the developers of ORH. For the users, open-source projects allow flexibility to adapt the hardware, and make modifications, repairs, and upgrades with support from

the wider user community. On the other hand, the replication of ORH requires some knowledge in fabrication and assembly from the user, which can be especially challenging for projects without good documentation. For the developer, open-sourcing the project ensures reproducibility of their hardware, verification of the designs, and valuable exposure to the community when the hardware gets widely adopted. But developing an ORH can be quite demanding too, requiring preparation of supplemental documentation and instruction guides, and maintaining simplicity in the designs. Furthermore, the different domains within robotics can necessitate unique hardware and distinct design and fabrication methods, further diversifying the range of ORH projects.

To both summarize the state of the art as well as investigate best practices from current ORH, we surveyed over 80 projects and classified them by their application domain within robotics. While not an exhaustive list, the survey aims to highlight the properties of ORH that are characteristic to each of the domains. Moreover, the strategies applied by popular ORH projects classified are noted. These best practices and common fabrication methods are then relayed so developers can follow them through the design, documentation, and dissemination phases of new ORH projects. We will make these ORH features, development practices, and survey available online on the Open Robot Hardware website [16].

Open-source projects have proliferated throughout robotics, aiding progress and innovation from accelerated implementations of novel ideas. This has been evidenced by the growing availability and widespread adoption of open hardware over the recent years. We believe Open Robot Hardware will continue to have a lasting and notable impact across the robotics landscape, and its development warrants further exploration efforts.

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TABLE II: Open Robot Hardware Surveyed Projects

Project	Design and Fabrication					Documentation and Instruction						Dissemination and Support				
	Editable CAD	CAD SW	Fabrication Methods	Can Purchase?	Cost	Fabrication Instruct.	Assembly Guide	BOM / COTS Links	Annotated Images	Videos / Animations	Tools Required	Online Repository	OS License	Software / Control	Community Forum	Updates since 2020
Robot Arms & Hands																
OpenHand [23]	*	SolidWorks	3D Print, HDM		\$150-200 plus motors	*	*	*	*	*	*	GitHub, Website	CC BY-NC 3.0	*		*
OpenBionics [29]	*	Solidworks, FreeCAD	Laser Cut, HDM, 3D Printing, Stitching		<\$100-200 plus motors	*	*	*	*	*	*	GitHub, Website	CC BY-SA 4.0	*		*
ROBEL [31]	*	SolidWorks	3D Print, Laser Cut	*	\$3,500	n/a	*	*	*			GitHub, Website	Apache 2.0	*		
TriFinger [24]		Unknown	3D Print, Machining		\$5,000	*	*	*	*		*	GitHub, Website	BSD 3-Clause	*	*	*
HRI Hand [32]	*	Fusion 360	3D Print		\$500-900		*	*	*			OSF, GitHub	MIT License	*		
Open Source Hand [35]	*	SolidWorks	3D Print		\$2,500							Website	Unknown			
PUT Hand [36]	*	Inventor	3D Print, Machining		Unknown							Github	CC BY-NC 4.0	*		
Brunel Hand [37]		Unknown	3D Print	*	\$1,500							GitHub, Website	CC BY-SA 4.0	*		
ExoArm v2 [38]		Unknown	3D Print		Unknown			*				Hackaday, GitHub	Unknown	*		
WDO [41]	*	SolidWorks	3D Print		\$15	*	*	*	*		*	Pinshape	CC BY-NC 4.0			
OMG VR Gloves [43]		Unknown	Sewing, 3D Print		\$50-100	*	*	*	*	*	*	Instructables	CC BY-SA 4.0			
Lucid VR Gloves [44]		Unknown	3D Print		\$60	*	*	*		*	*	Hackaday, GitHub	MIT License	*	*	*
IrukaTact [45]	*	TinkerCAD	3D Print		Unknown			*				Website	Unknown	*		
Unfolding Space Glove [46]	*	STEP	Sewing		\$500	*	*	*	*			Website, GitHub, Hackaday	CC BY 4.0	*		*

Thor Arm [47]	*	FreeCAD	3D Print		\$400	*	*	*	*	*	*	Website, GitHub, Hackaday	CC BY-SA 4.0	*	*	*
CM6 Arm [48]	*	STEP	3D Print		\$1,000		*	*	*			Hackaday, GitHub	MIT License	*		
OpenManipulator-X [49]	*	Onshape	3D Print	*	\$1,500		*	*	*	*		Website, Thingiverse	CC BY 4.0	*		*
PARA Arm [50]	*	SolidWorks	3D Print		\$3,400	*	*	*	*		*	OSF, GitHub	MIT License	*		
Niryo One [26]		Unknown	3D Print	*	\$1,600		*	*	*	*	*	GitHub, Website	CC BY-NC-SA 4.0	*		
Dexter Arm [51]	*	Onshape	3D Print	*	\$3,000		*	*		*		GitHub, Hackaday	GPL v3	*	*	*
Social Robots																
Opsoro [56]	*	Rhino3D	3D Print, Laser Cut		Unknown		*	*	*		*	Website, GitHub	MIT License	*		
Blossom [53]	*	2D, SolidWorks	Laser Cut, Knitting, 3D Print		<\$250	*	*	*	*		*	GitHub	MIT License	*		*
CASTOR [57]		Unknown	3D Print, Sewing		Unknown		*	*	*	*		GitHub	CC BY-NC-SA 4.0	*		*
Humanoids																
DARwin-OP, Robotis-OP2 [59]	*	SolidWorks	CNC Mill, Band Saw, Dremel, Bending Break	*	\$9,600	*	*	*	*		*	GitHub, SourceForge	Apache 2.0	*		
Robotis-OP3	*	STEP	3D Print	*	\$12,000							GitHub	Apache 2.0	*		
NimbRo-OP2X [61]	*	STEP, IGES	3D Print, Machining		Unknown			*				GitHub	CC BY-NC-SA 3.0	*		
Poppy [54]	*	SolidWorks	3D Print		\$9,000		*	*	*	*	*	Website, GitHub	CC BY-SA 4.0	*	*	*
InMoov [62]		Unknown	3D Print	*	\$1,500	*	*	*	*	*		Website	CC BY-NC 3.0	*	*	*
Epi [65]	*	STEP	3D Print		\$8,500				*			GitHub	CC BY-SA 4.0	*		
NICO [66]	*	Inventor	3D Print, Laser Cut	*	Unknown		*	*	*	*		GitHub, Website	CC BY-SA 3.0	*		
Eva [67]	*	SolidWorks	3D Print, Laser Cut, Molding		\$900	*	*	*	*			Zenodo	BSD 3-Clause	*		
iCub [55]	*	PTC Creo	Machining, Molding	*	\$260,000		*	*	*	*		Website, GitHub	BSD 3-Clause, GPL v2	*	*	*

Legged Robots																
Open Dynamic Robot Init. [69]		Unknown	3D Print		\$4,200	*	*	*	*		*	GitHub, Website	BSD 3-Clause	*	*	*
Doggo [75]	*	Fusion 360	Waterjet, 3D Print, Machining, Routing		\$3,000		*	*	*			GitHub	MIT License	*	*	
Pupper [76]	*	Fusion 360	3D Print, Routing	*	\$900		*	*	*	*	*	ReadTheDocs	MIT License	*	*	
SpotMicro [77]		Unknown	3D Print		Unknown		*	*	*	*	*	Thingiverse, ReadTheDocs	CC BY 4.0	*	*	
OpenQuad. [78]	*	STEP	3D Print		\$600		*	*				GitHub	MIT License	*		
Oncilla [70]	*	SolidWorks	3D Print		Unknown							c4science	GPL v3	*		
Metabot [80]	*	OpenSCAD	3D Print, Laser Cut	*	\$400			*	*			GitHub	CC BY-NC 3.0	*		
Aracna [81]	*	SolidWorks	3D Print		\$1,400			*				GitHub	GPL v3	*		
DyRET [82]		Broken Link	3D Print		\$6,500							GitHub	CC BY-SA 4.0	*		
OpenRoACH [83]	*	SolidWorks	3D Print, Laser Cut		\$150	*	*	*	*			Website, Google Drive	Unknown	*		
HOPPY [71]	*	SolidWorks	n/a		\$500	n/a	*	*		*		GitHub	Unknown	*		
Open-Source Leg [72]	*	STEP	Machining	*	\$23,000	*	*	*		*	*	Website	GPL v3	*	*	*
Alice Exo [87]		STL	3D Print		\$1,600			*				Website, Hackaday	CC BY-NC 3.0	*		*
Mobile Robots																
E-puck [88]	*	STEP, IGS	Injection Molded	*	\$550 to \$850			*				Website	Open Source Hardware License v1.0	*	*	
Mona [89]	n/a	Unknown	3D Print	*	\$100							GitHub	Unknown	*		
Miniskybot [90]	*	OpenSCAD	3D Print		Unknown		*	*	*			GitHub, Website, Thingiverse	CC BY-SA 3.0	*		
Zumy [91]	*	SolidWorks	Laser Cut		\$400	n/a	*	*	*		*	Website	Unknown	*		
Veter [92]	*	Blender	3D Print	*	\$1,500		*	*	*			Website, GitHub	GPL v2	*	*	
Nanosaur [93]		Unknown	3D Print		\$300	*	*	*	*		*	Website, GitHub	CC BY-NC-SA 4.0	*	*	*
ESA ExoMy [94]	*	SolidWorks, STEP	3D Print		\$600	*	*	*	*		*	GitHub	GPL v3	*	*	*
NASA JPL OS Rover [95]	*	SolidWorks, STEP	3D Print, Laser Cut		\$2,500	*	*	*	*		*	GitHub	Apache 2.0	*	*	*

TurtleBot3 [96]	*	Onshape	3D Print	*	\$549		*	*	*	*		Website	Open Source Hardware License v1.0	*	*	
MIT Racecar [97]	*	STEP	Laser Cut		\$1,000		*	*	*			GitHub	MIT License	*		
MuSHR [98]	*	OpenSCAD	3D Print		\$610-930		*	*	*	*	*	GitHub	BSD 3-Clause	*	*	*
Component Modules & Tool Kits																
PneuFlex [99]		Unknown	3D Print, Molding		Unknown	*	*	*	*	*	*	Website	CC BY-SA 4.0	n/a		
Soft Robotics Toolkit [102]	*	SolidWorks, STEP	Depends on project		Depends on project	*	*	*	*		*	Website	Unknown	*	*	
NMMI [103]	*	STEP	Depends on project		Depends on project							Website, SourceForge, GitHub	Depends on project	*		
Jasmine [106]		Unknown	Machining		\$130		*	*	*			Website	GPL	*		
SRoCS [108]	*	FreeCAD	3D Print		\$7500 per robot/block		*	*		*		OSF	MIT License	*		
Digit [112]	*	STEP	3D Print, Laser Cut, Molding	*	\$300	*	*	*	*		*	GitHub	CC BY-NC 4.0	*	*	*
Punyo [113]	*	SolidWorks, STEP	3D Print, Laser Cut		Unknown	*	*	*	*	*	*	Website	CC BY-NC 4.0	n/a		*
Miscellaneous																
Piccolo [119]	*	n/a	Laser Cut		\$80	*	*	*	*			GitHub	CC BY-SA 4.0	*		
Farmbot [120]	*	Onshape	3D Print	*	\$1,700-5,300		*	*	*			Website	CC0 1.0	*	*	*
HapKit [121]	*	SolidWorks	3D Print, Laser Cut		\$50-100	*	*	*	*	*	*	Website	CC BY-SA 3.0	*	*	
Wooden Haptics [122]	*	SolidWorks	Laser Cut	*	\$3,600	*	*	*		*	*	Website, GitHub	CC BY-SA 4.0	*	*	
ROBO Puppet [123]		Unknown	3D Print		\$85	*	*				*	Website	Unknown	*		
SPRK [126]	*	SolidWorks	Laser Cut		\$250		*	*	*			GitHub	MIT License	*		
ENDO [127]	*	SolidWorks	3D Print		\$100			*				GitHub	GPL v3	*		*
Pillforge [128]	n/a	n/a	n/a		Unknown	*	n/a	*	n/a	n/a	n/a	GitHub	MIT License	*		
LTA Gondola [129]	*	SolidWorks	3D Print		\$90		*	*	*			GitHub, Hackaday	CC BY 4.0	*		*