Improving instrument reproducibility with open source hardware

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Laboratory hardware is often custom made or significantly modified. To improve reproducibility, it is imperative that these novel instruments are properly documented. Increasing adoption of Open Source Hardware practices can potentially improve this situation. This article explores how open licenses and open development methodologies enable custom instrumentation to be reproduced, scrutinised, and properly recorded.

[H1] Introduction

Reproducibility is a major issue in scientific research. It is often addressed by conducting the same experiment, independently, in more than one laboratory. Work developing cutting-edge instrumentation typically invites interested parties to contact the authors for details or cites efforts to make an instrument commercially available. While ready-made laboratory instruments have vastly improved scientific progress, it is important that novel instruments are properly scrutinised and replicated [1]. A growing community of scientists are using and developing Open Source Hardware with the aim of improving reproducibility [2]. This approach adopts practices from open source software, where full designs and associated documentation are shared under a license permitting redistribution and modification.

Open source software was dismissed for many years by commercial providers, but has now become the gold standard for software security due to the benefit of free code scrutiny. Similarly, open licensing and good documentation have vastly improved the performance and reproducibility of scientific software [3]. Many disciplines have adopted open source solutions, like ImageJ or R, as their computing standard. Like open source software, open hardware has been viewed as a budget DIY alternative to high-end instrumentation. However, this does a disservice to many projects where reproducibility, rather than cost, is the primary motivation for openness. For example, OpenSPIM [4] and MesoSPIM [5] — light-sheet microscopes costing tens to hundreds of thousands of dollars respectively — or CERN's White Rabbit timing system are shared under open licenses to encourage scientists and companies outside the originating group to replicate the instrument. The documentation enabling this rapid sharing of technology also ensures that instruments can be recreated in the future, even after staff and students leave the project.

[H1] The importance of good documentation

New techniques and custom instruments are often shared between laboratories through visits, secondments, and joint projects. While this is a good way to share knowledge and skills — particularly for seemingly inconsequential details that are never written down —

it does not scale well. Sharing techniques through personal interactions eliminates the possibility of independent replication, which is essential for truly reproducible research. Transcribing every detail necessary to reproduce an instrument requires significant effort, particularly if the design evolved over time. Ideally, hardware documentation should be verified by starting with an empty lab bench and a colleague who follows the written instructions to the letter, producing a new copy of the instrument. This represents a significant investment of time and resources and may require a working instrument to be stripped down for parts. In practice, this ideal is usually approximated. The best documented open hardware projects have been assembled independently, leading to improved instructions based on feedback.

The documentation challenge in open software projects is simplified by tools that automatically or semi-automatically produce documentation based on comments and metadata embedded in the code. This tooling is often integrated with version management platforms such as GitHub or GitLab, vastly reducing the effort required to share consistently documented code. Fewer automation toolchains exist to support open hardware projects, although projects including GitBuilding are starting to change this [6]. Expectation, however, is a big driver. It is expected that a high-profile publication relying on custom software will include a reasonable level of software documentation. By contrast, instructions and design files enabling full replication of hardware are much rarer.

[H1] Open hardware and commercialisation

The absence of hardware documentation is not just due to high production effort. There is also a trade secrets approach applied in many laboratories, which may have arisen from fears about lost citations or co-authorships if a reproducing laboratory doesn't need to contact the authors of the original design. Furthermore, many universities encourage researchers not to share details of potentially patentable research, but are reluctant to file patents. Combined, these two factors can lead to instrument details being incompletely shared to avoid prejudicing a future patent that is never filed. Such instruments are often re-invented many times by different laboratories.

Open source hardware is compatible with commercial production, but requires a different approach. Most open hardware licenses permit commercial use, meaning they are non-exclusive licenses to sell a product. The manufacturer has no guarantee that they will not encounter competition. Companies such as Adafruit, Arduino, OpenTrons, OpenQCM and Prusa Research have built successful businesses selling their own open hardware designs, while Adafruit and LabMaker sell open hardware designed by others.

Scientific instruments are not a typical consumer goods market, with specialist products, small sales volumes, and a heavy emphasis on quality. The ability to order a particular instrument will always speed up scientific progress. If that instrument is a known quantity, assessed and improved by multiple independent research groups, there is greater confidence that it produces reproducible results. Many scientists are prepared to pay a premium for well-documented instruments that can be inspected and customised, as demonstrated by the success of the OpenTrons OT2 pipetting robot.

[H1] Scalability

Many scientific instruments are shared as open hardware designs, from inexpensive and easily reproduced devices under $100, to cutting-edge systems costing hundreds of thousands of dollars. The former is more likely to be replicated. Many projects, such as the OpenFlexure Microscope [7], have seen hundreds or thousands of replications globally. Replicating an expensive instrument requires strong scientific motivation and a sizeable research grant. However, if the instrument is sufficiently useful, even these do get replicated. Both kinds of project have much to offer. Easily replicated instruments provide useful workhorse tools, enable valuable insights into what makes for high quality documentation, and help to develop working practices and software tools to readily produce documentation. This work reduces the time spent verifying documentation of high-end projects that are less amenable to reconstruction. It also helps the community reach a consensus about what documentation is required for an instrument to be considered reproducible.

[H1] Accessibility and automation

An open hardware approach enables and encourages independent replication. However, it also allows laboratories to build their own hardware when it is difficult to obtain, for example due to lack of funds, poor infrastructure, or international logistics. The ability to customise instruments, or link them with open software tools, means automated experiments are increasingly used in laboratories with modest resources. Automated experiments can improve throughput and reproducibility, as documenting a protocol for a machine to perform requires a complete experimental description in machine-readable form [8]. This record, if shared properly, is a valuable part of describing methods fully.

[H1] Conclusion

Custom instrumentation is often left out of the discussion on scientific reproducibility. Being able to recreate a particular piece of apparatus and inspect its design and performance is as crucial as knowing the details of a particular protocol. Current practice is less open in this area than for software or protocol development, but there is a growing community of scientists and engineers developing and sharing open hardware for use in research laboratories. This is accompanied by tools and resources encouraging others to adopt open development as best practice. A number of community groups have emerged to support this, for example GOSH, Open Neuroscience, Open Hardware Makers. With a rapidly growing community of instrument developers across many disciplines, open hardware will have an increasingly important role in making sure instruments are repeatable and accessible.

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Competing interests

Richard Bowman was formerly a director and shareholder of OpenFlexure Industries, a microbusiness selling open hardware products based on the OpenFlexure Project.

Related links

GitBuilding: https://gitbuilding.io/

Adafruit: https://www.adafruit.com/

Arduino: https://www.arduino.cc/

OpenTrons: https://opentrons.com/

OpenQCM: https://openqcm.com/

Prusa Research: https://www.prusa3d.com/

LabMaker: https://www.labmaker.org/

OpenFlexure Microscope: https://openflexure.org/projects/microscope/

GOSH: https://openhardware.science/

Open Neuroscience: https://open-neuroscience.com/

Open Hardware Makers: https://openhardware.space/