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INVITED REVIEW

3D printing in core facilities – Low pain, high gain

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Abstract

Three-dimensional (3D) printing has rapidly developed from a niche hobbyist activity into a widely accessible and indispensable technology across multiple scientific disciplines. Within microscopy, optical engineering laboratories and imaging core facilities, 3D printing enables creating customised solutions for sample holders, optical components and everyday laboratory tools that traditionally required specialised machining. By providing rapid prototyping, low-cost production and reproducibility, 3D printing facilitates innovation and efficiency in facility operations. This article provides a perspective on the possibilities, challenges, and practical aspects of implementing 3D printing within microscopy core facilities. Instead of providing technical review about 3D printing, we focus on service organisation, user engagement, resource management and community-driven repositories for design dissemination. Our aim is to share insights with those considering the implementation of 3D printing as a service for developing add-on components to ease the operation of different aspects of the machine-park driven services and those who are managing advanced instrumentation within research groups.

KEYWORDS

3D-printing, core facility, rapid prototyping

1 | INTRODUCTION

3D printing offers substantial advantages for assay troubleshooting and customisation on imaging instrumentation and provides benefits to ease the use of advanced instrumentation in both core facilities as well as research groups, especially when rapid turnaround times are critical. Staying up to date with new technologies and implementing new instrumentation, additional modalities, or services is one of the overarching goals that should be met by core facilities to accommodate research in centralised services.[1] Here, 3D printing is an emerging technology that deserves consideration for implementation into a core facility, either as a service, or to accommodate custom adaptations to the user needs. However, the implementation of 3D printing as a new service requires initial investments in hardware, materials, and personnel training[2], just like the implementation of any other technology does. Operators must gain familiarity with printing technologies, knowledge of choice of materials and basic device maintenance requirements. For smaller facilities, this may pose challenges; yet, ownership of a 3D printer is not a

prerequisite for benefiting from 3D printing either as a service, or for internal use. Institutions or facilities should consider sharing 3D printing resources, such as central fabrication facilities, or creation labs, which can support the needs of multiple core facilities or research groups in the institution efficiently, while ideally being open for direct interactions between fabrication and facility staff. A low threshold for initial trials with 3D printing activities can be achieved by the use of external services for the reproduction of validated parts from online resources or published studies.

2 | RAPID PROTOTYPING FOR CORE FACILITY APPLICATIONS

One of the major incentives for introducing 3D printing into microscopy core facilities is rapid prototyping and offering a high degree of ad-hoc flexibility for assay establishment. Customised 3D-printed components, such as sample holders, slide inserts, or imaging chambers, can be designed to meet specific user needs or to upgrade existing equipment in a time efficient manner.[2] Compared with conventional metal machining, 3D printing allows inexpensive, fast, and easily modifiable fabrication. Importantly, 3D printing also provides additional relevance for modification, repair and adaptation of parts for older or incompatible parts that are out of production or are difficult to obtain (e.g., camera adapters, hardware-mounts or -connectors).

Material choice remains a pivotal factor: while machined inserts typically offer low thermal expansion and consequently better optical stability, plastic prototypes afford quick testing of functional designs and offer cheaper solutions for lower technical demands.[3, 4]

Although in many scenarios 3D-printed parts might already suffice requirements, for high-precision applications, such as nanoscale imaging, material stability and thermal behaviour must be considered and evaluated. For this reason, most parts demanding high precision and stability are milled from aluminium or stainless steel, which increases the costs, but often provides additional advantages by offering a reduced material surface roughness and improved resistance to solvents. Rapid prototyping using 3D printing prior to final production by milling may circumvent potential drawbacks, reducing overall costs and project delays, while additional iterations might introduce delays as well. In some cases, the low-cost 3D-printed version is already sufficient and no milled parts are required. We provide a short list of selected manuscripts that provide a compelling introduction to the topic of 3D printing in life science research and microscopy applications (Table 1). Nevertheless, for each adaptation it is advised to evaluate the requirements of the parts. Direct production of a final milled version remains an option that might be more beneficial in specific cases.

3 | 3D PRINTING AS A SERVICE IN CORE FACILITIES

Providing 3D printing as a service adds considerable value to imaging cores. On-site access to such a service enables fast, or even ad-hoc, production of adapters, replacement parts, or nonstandard sample holders. In imaging techniques such as light-sheet microscopy, where unconventional samples and sample holders are used, sample mounting can be cumbersome and custom parts can greatly simplify the experimental workflow (Figures 1 and 2). Such modifications range from bent wires, hooks and syringes, via creative holders including but not limited to LEGO adapters up to sophisticated casts.[14–16]

Specifically, the Zeiss Lightsheet was one of the earliest commercially available lightsheet microscopes. It was widely used in imaging core facilities and research groups. Sample mounting on the Lightsheet 7 and its predecessor, the Lightsheet Z1, often required application specific solutions. Consequently, users and service providers have been exploring possibilities to ease the use of this imaging platform by devising novel sample chambers and various adapters and sample holders.[19] However, even when commercial add-ons are available, they might not fulfil all requirements. Furthermore, custom in-house developed adapters can be highly useful for conducting quality control and performance monitoring routines (Figure 1 and Textbox 1).[20–22]

Similarly, 3D printing allows the iterative approach of sample holder generation and development. Figure 2 shows several iterations of sample holders for the Zeiss Lightsheet 7 'smart sample holder' (Figure 2F). To minimise the interference with the illumination light path, each version serving a slightly different sample such as small organoids (Figure 2A), Arabidopsis seedlings or cleared mouse spinal cord (Figure 2B), whole cleared mouse embryonic heads or isolated cleared mouse brains (Figure 2C–E). Such sample holders are not designed for a specific sample, but rather allow researchers to explore the best sample mounting procedure for their sample, or as part of the testing and iteration cycle.

Specific environmental requirements of the sample can be met by the integration of gas-mixers, microfluidics and might require the designs of customised sample-holder and adapters to improve experimental handling. In the particular case to create hypoxia conditions, the availability of commercial solutions is limited, and several custom adaptations have been reported.[23, 24] Here we showcase

TABLE 1 A selection of resources that provide accessible entry points for life-science researchers wishing to implement 3D printing, including educational introductions toward highly specialised guides integrating microfluidics, microscopy accessories, and bio-compatible prototyping.

Author/year	Title	Key distinguishing point
Mustafa, et al., 2025[5]	A comparative review of 3D printing technologies and their applications: A systematic review for future of medicine fabrication	The review explores the diverse additive manufacturing methods applicable to drug delivery systems, including Fused Deposition Modelling (FDM), Stereo Lithography (SLA) and others.
Kalkal et al., 2025[6]	Harnessing the potential of emerging additive manufacturing technologies as a game-changer for chemical and biosensing innovations	A comprehensive summary of cutting-edge developments in additive manufacturing is provided, alongside an examination of future directions for refining and inventing 3D printing techniques in biosensing applications.
Zang et al., 2025[7]	3D printing of micro-nano-devices and their applications	3D printing technologies for fabricating nano- and micro-scale devices, using high-resolution printing methods – such as two-photon polymerisation and DLP-based systems – enable the creation of complex microfluidic networks, micro-mixers, and electrochemical monitoring platforms.
Christopher et al., 2024[8]	A 3D-printed optical microscope for low-cost histological imaging	Describes the development and evaluation of a fully 3D-printed optical microscope designed as a low-cost, open-source solution for histological imaging.
Pamidi et al., 2024[9]	A practical guide to 3D printing for chemistry and biology laboratories	Highlights the access to and expertise in 3D printing for chemists and biologists, and emphasises the need for standardised reporting principles to ensure that 3D-printed inventions can be reliably reproduced and iteratively improved by other scientists.
Saggiomo, 2022[4]	A 3D printer in the lab: Not only a toy	The article emphasises that low-cost FDM 3D printers are valuable laboratory tools, describing four stages – printing, designing, making materials, and automating – to show how they boost research efficiency, customisation, and accessibility across scientific fields.
*Del Rosario et al., 2021[3]	The field guide to 3D printing in optical microscopy for life sciences	Provides an in-depth tutorial and reference compendium for microscope hardware; compares materials and printers suited for optical precision applications.
Heuer et al. 2021[10]	3D printing in biotechnology – An insight into miniaturised and microfluidic systems for applications from cell culture to bioanalytics	Focuses on 3D printing technologies for microfluidic systems of transparent, precisely structured microfluidic devices that are compatible with optical analysis, enabling real-time imaging of cells and biological processes.
McDermott et al., 2021[11]	autohaem: 3D printed devices for automated preparation of blood smears	3D-printed devices used to prepare consistent blood smears for microscopy-based malaria diagnosis and research.
Alessandri et al., 2017[12]	All-in-one 3D printed microscopy chamber for multidimensional imaging, the UniverSlide	An example of a fully 3D-printed microscopy chamber designed for versatile and multidimensional imaging. It integrates sample preparation, culture, and observation within a single standardised and reusable device.
Lambert et al., 2018[13]	Advances in optical sensing and bioanalysis enabled by 3D printing	Highlights 3D printing fabrication of complex microfluidic architectures that make use of specialised optical materials and printing techniques allowing tailoring of refractive indices, transparency, and scattering properties to replicate biological tissues and improve imaging contrast.

*Highly recommended.

the advantages of in-house development by presenting the design of a generic hypoxia sample chamber and its multi-phase, iterative workflow utilising 3D-assisted prototyping. The final product meets the requirements for achieving hypoxic to anoxic oxygen levels for sample conditioning (Figure 3 and Textbox 2).

To offer a service for the production and integration of custom parts, core facilities will need to establish structured service models that might contain several project-phases, which include standardised request forms, design consultations, prototyping, and documentation.[25, 26] A project-based workflow for custom parts and services promotes transparency, facilitates user communication, and provides a clear framework for authorship or acknowledgment when applicable (see Table 2).

TABLE 2 A multi-phase workflow for project-based 3D printing services, aimed to be used as inspiration to customise the workflow to provide reliable, safe, and transparent 3D printing support in an (microscopy) core facility. By embedding standardised documentation, version control, and community sharing, the service not only accelerates problem-solving but also enhances reproducibility and cross-facility collaboration within the life-science imaging community.

	Project phase	Objective /description	Responsibilities and deliverables	Suggested tools /resources
1	Project initiation and user consultation	Define the research need and assess feasibility. Identify the functional requirements (e.g. stage adapter, sample holder, environmental chamber).	• User submits a standardised request form. • Initial meeting to clarify objectives, geometry, and functional constraints (optical path, space and weight limits, temperature, chemical resistance).	Consultation templates; previous design repository; sketching and measurement tools; internal ticket or request system.
2	Concept design and risk assessment	Translate requirements into an initial CAD sketch while evaluating mechanical, optical, and safety considerations.	• Assess load, precision, and potential impact on microscopes. • Select suitable printing materials (PLA, PETG, ABS, resin) and determine biocompatibility if applicable. • Ensure compliance with safety and equipment warranty policies.	CAD software (FreeCAD, Fusion 360, SolidWorks); optical layout drawings; materials database.
3	Digital modelling and version control	Develop detailed CAD files with appropriate documentation of dimensions and tolerances.	• Create digital models under version control. • Include tagging, part numbers, and compatibility metadata. • Track revisions of designs within a repository system.	Cloud repositories (GitHub, GitLab, SeaTable, Airtable) or local database; institutional file naming convention.
4	Prototype fabrication	Produce a first-iteration print for fit and functional testing.	• Print using appropriate resolution and infill parameters. • Visually inspect and test on the intended instrument. • Document print settings and printer model for reproducibility.	FFF/SLA printer; slicing software (Cura, PrusaSlicer); safety and maintenance checklist.
5	Testing and iteration	Validate mechanical fit, optical alignment, chemical resistance, and usability.	• Perform bench-top and microscope integration tests. • Collect user feedback and adjust design accordingly. • Document issues and corrective changes in the repository.	Test log sheets; comparison photographs; revision reports; collaborative feedback (issue tracker).
6	Final design approval and production	Approve the optimised design for regular use or distribution.	• Print validated parts in chosen materials. • Label each part with version and compatibility information. • Prepare safe-use instructions for end-users.	Quality-checked printing setup; labelling/engraving; short technical datasheet.

(Continues)

TABLE 2 (Continued)

	Project phase	Objective /description	Responsibilities and deliverables	Suggested tools /resources
7	Documentation and repository submission	Archive the final design following FAIR (Findable, Accessible, Interoperable, Reusable) principles.	• Upload finalised models, documentation, and licensing details to institutional or public repositories. • Provide reference images, printer settings, and validation data.	Institutional repository or community platforms (e.g. Thingiverse, Printables, MicroscopyDB, Open Know-How).
8	User delivery and training	Ensure users can safely and correctly apply the printed part.	• Brief user on installation and safety. • Offer training on design reproduction or modification. • Gather post-use feedback.	Quick-start guide; training session or digital tutorial.
9	Acknowledgment and tracking	Recognise facility contributions and maintain service metrics.	• Encourage citation or acknowledgement in publications. • Monitor requests, print volume, and maintenance logs for service evaluation.	Service statistics database; publication tracking spreadsheet.
10	Continuous improvement and community sharing	Promote iterative refinement, innovation, and communal learning.	• Publish and publicise high-impact designs. • Contribute to shared repositories and forums. • Review feedback and incorporate technological advances.	Discussion platforms (Image.sc, μForum, Mastodon, Bluesky); Several 'makers discussion groups'.

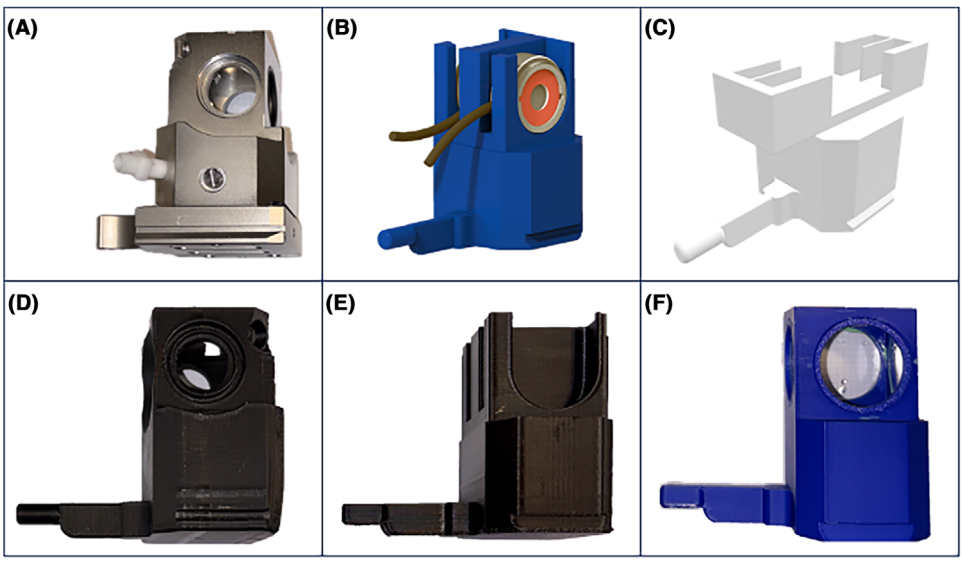

FIGURE 1 Examples of iterative prototyping, with community engagement. (A) Original large sample chamber for the Zeiss Lightsheet 7; (B) 3D render image of sample holders adaptation to fit a diode 'circular photodiode power sensor'[17]; (C) 3D-render of a design iteration of the initial photodiode power sensor design to be compatible with a 'microscope-slide photodiode power sensor[18] (Imaging Core Facility, Biozentrum University of Basel); (D) initial 3D-printed initial Prototype fabrication of the sample chamber; (E) final design production of the design presented in panel B; (F) ongoing 3D-printing, from the 'testing and Iteration-phase' of an a custom designed chamber for larger samples.

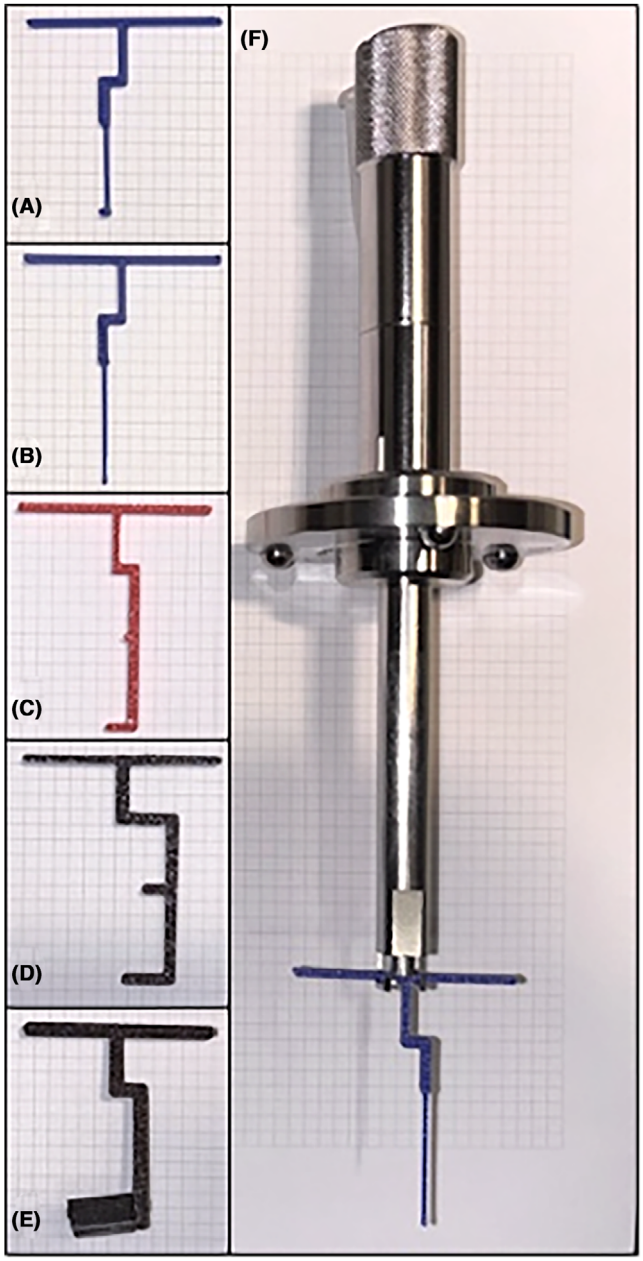

FIGURE 2 Rapid production of diverse sample holders for lightsheet imaging. (A–E) Different sample holders for the Zeiss Lightsheet 7 'Smart Sample Holder' are quickly produced and a wide variety can be promptly produced per request; (F) the Zeiss 'Smart Sample Holder' for the Lightsheet 7, with one of the 3D-printed sample holders mounted. Sample-holders can be further optimised by choosing transparent or RI-matched materials for production.

Textbox 1

As an example, in order to simplify laser power measurements and laser linearity monitoring consistently, the original design of the sample chamber of the Zeiss Lightsheet 7 was reproduced (Figure 1D) and adapted to hold a circular photodiode power sensor (Figure 1B shows the 3D reconstruction of the design, Figure 1E shows the 3D-printed version). The design was shared with the community via MicroscopyDB which inspired other facilities to adapt the design to their need and for microscope-slide photodiode power sensors (Figure 1C). Similarly 3D-printed variants of the Zeiss Lightsheet 7 sample chamber with thinner walls and larger inner volume can overcome limitations imposed by milling metal parts (in progress, Figure 1F). For completeness, we include a cost evaluation for the production of the sample chamber shown in Figure 1F, comparing in-house (self) 3D printing with external services.

Material/price (€)	Self-3D-printed	Institutes' workshop	Shop 1 International	Shop 2 International	Shop 3 Europe
Resin	—	—	10	11.7	–
ABS	0.7	30	21	23	—
Aluminium*	—	200	52	59	313.44

*Price for aluminium milling.

Maintaining an internal repository that stores designs, version histories, and metadata ensures traceability and supports reproducibility (see also Section 10). Several repository options are available to core facilities for managing and organising 3D printing resources. Cloud-based solutions such as *GitHub*, *GitLab*, *SeaTable*, or *Airtable* allow centralised storage, version control, and collaborative access, which can be useful for multi-user environments or institutions with distributed teams. Additional features, such as compatibility-selection tools on internal websites, can assist users in identifying which parts are suited for specific instruments or experimental setups. Alternatively, smaller facilities may prefer locally stored options, where even a simple, well-maintained table or spreadsheet may suffice for basic record keeping.

Ideally, creations are shared in repositories that allow public dissemination, but the choice of repository system is best guided by the intended level of accessibility, particularly whether the stored information is to be shared with users or maintained for internal facility management only. Thoughtful implementation of repository-based tracking guidelines will ensure consistent documentation, enhance communication, and strengthen the overall reliability of

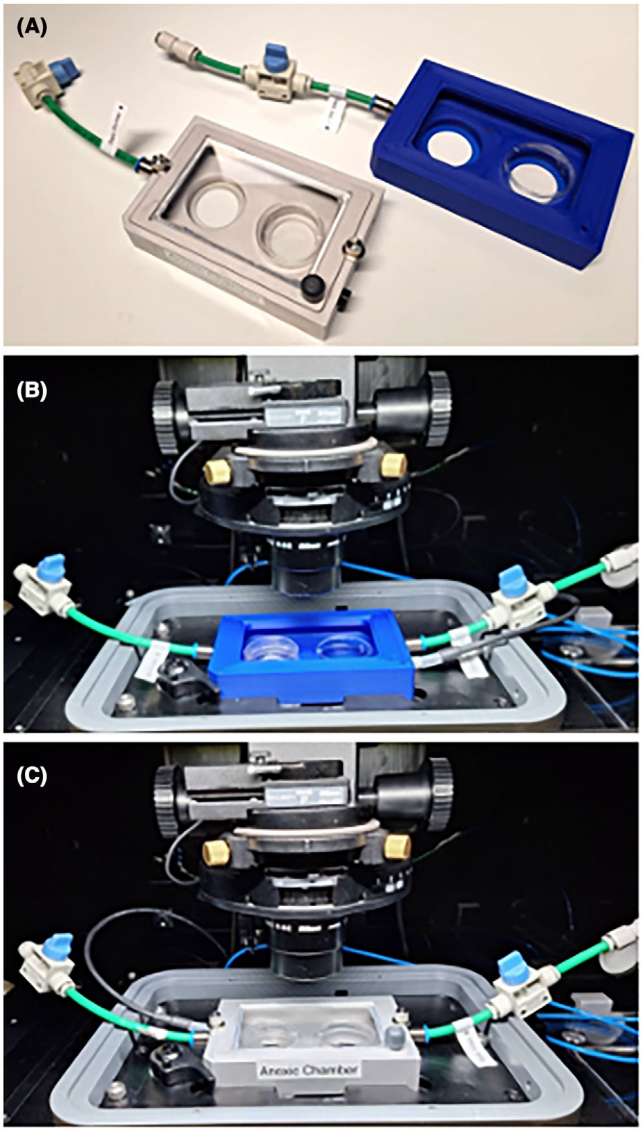

FIGURE 3 In-house developed anoxic chamber, based on 3D-printed prototyping. Where other stage adapters and sample holders only provide hypoxic environments, the anoxic sample chamber allows for rapidly conditioning of the sample on the microscopy to oxygen depleted conditions when connected to a CO_2, N_2, and compressed air gas-mixer. Several iterations were produced based on 3D models to ensure the size, positioning and functionality. (A) The final design milled from aluminium (left) and 3D-printed prototype (right). (B) The prototype was used to determine the placement of sensors, tubing and initial tests. (C) The final version of the anoxic chamber was milled from aluminium with integrated tube-connections and sensor placement, and did not require further adaptations or design iterations.

3D printing as a service within microscopy core facilities. Challenges exist in the overall instrument compatibility management: 3D-printed items might be designed for specific instrumentation and are therefore not compatible across the whole machine park of a core facility.

Textbox 2

The in-house developed generic 'anoxia' sample chamber (Figure 3) prevents the need to place a whole instrument in an anoxic environmental incubator, and overcomes limitations of commercially available gas-mixes in achieving rapid anoxic conditions in the sample. To address this limitation, a project was initiated to produce an air-tight sample chamber. The concept was digitally concept designed, with the aim to minimise oxygen influx. Further design iterations were done to include a a FireSting-O_2 optical oxygen meter (PyroScience FSO2-C4) to enable precise monitoring of O_2 concentrations. Initial prototypes of the chambers were fabricated by 3D printing with PLA filament to optimise dimensions and component placement. Additionally, plugs for the oxygen sensor were produced via 3D printing with TPU filament to ensure proper airtightness when not in use. After three design iterations, the final version was approved and submitted for production by milling from aluminium. The final design and instructions for use were uploaded to the institutional repository to enable eventual further version-controlled development. This also facilitates the distribution of the design for as well as sharing, citing and reproduction. It allows to manage acknowledgements or citations of the object in full detail. As a final step, the user received instructions on the autonomous use of the anoxic chamber autonomously on imaging instrumentation, to minimising health risks and avoid potential instrument damage.

4 | HARDWARE, SOFTWARE AND DATA-FORMAT CONSIDERATIONS

As 3D printing technologies mature, numerous reliable systems are now available for facility environments. Selecting an appropriate printer requires evaluating both performance and practicality.[3] Fused deposition modelling (FDM) deposits molten thermoplastic filament layer by layer and is currently considered as the most versatile 3D printing method for core facilities, since it is capable of processing a wide range of materials. FDM is suitable for rapid prototyping of holders, adapters, spacers, and other non-critical utility parts, because it combines low cost, fast iteration, and broad material availability. However, the layered build process limits surface smooth-

TABLE 3 An overview of commonly used materials for filament 3D printing. Whether a material is easy or hard to print is judged by how well the print has to be planned in the slicer software (print temperature, base plate temperature, ventilation, nozzle speed, etc.), how easy the printed object can be removed from the base plate of the printer or how much post-processing is usually required. The common print artefacts refer to problems that often occur when a certain material is used. The durability refers to the longevity of the material, and also to the mechanical stability. The resistance against temperature fluctuations, chemicals (organic solvents, acidic or alkaline), UV light and the sensitivity to moisture is also stated to give an idea in which environments a material should be preferred over another. For applications in the lightpath, autofluorescence of the materials should also be considered. For 3D-printed objects in direct contact with living specimens or culture medium, additional factors such as biocompatibility and leaching must to be evaluated.

Material	PLA	PETG	ABS	ASA	TPU
Easy or hard printing	Easy to print[28]	Difficult to print[28]	Difficult to print[28]	Difficult to print	Difficult to print[28]
Common print artefacts	Generally not prone to artefacts[3]	Prone to stringing and oozing	Prone to warping and shrinking[28]	Prone to warping and shrinking	Prone to stringing and oozing[28]
Durability	Moderate[19]	High[19]	High	High[17]	Moderate
Temperature resistance	Low[20]	High[20]	Moderate[19]	High	High[20]
Sensitivity to moisture	Hygroscopic	Hygroscopic[19]	Not sensitive	Not sensitive	Hygroscopic[19]
Chemical resistance	Low[18]	High[16]	High[3]	General high, moderate against organic solvents[18]	High
UV resistance	Moderate	Moderate [3]	Low	High	Low[30]

ness, water tightness, and the reliable fabrication of very small or delicate features. FDM printer configurations with dual print heads add flexibility by enabling the simultaneous deposition of different polymers, such as combining structural filaments with dissolvable supports to produce fine, complex geometries. Stereolithography (SLA) forms parts by selectively curing liquid photopolymer resin with light, producing smoother surfaces and finer feature resolution than FDM. However, FDM typically requires more expensive and hazardous materials, including additional washing steps, post-curing with UV light, resin handling, and waste management, which together can make it less suitable for routine use in shared laboratory spaces.[3, 5, 9]

One of the most crucial factors in 3D printing, apart from the design of an object and the decision of the specific 3D printing technology, is the material selection.[27] Several factors need to be considered in this decision: The required detail influences material selection, as some materials tend to warp, shrink, or adhere poorly to the base plate.[3] Other print artefacts require post-processing of the printed object, such as sanding of surfaces and edges.[28] Environmental stability is equally important, particularly if the object must withstand moisture, temperature fluctuations, UV light, or chemical exposure, as well as mechanical stress.[3, 27] Finally, if the printed part is in direct contact with a sample or culture medium, potential biocompatibility must be evaluated. Other factors, in particular toxic fumes during printing, autofluorescence of the material, the environmental impact and costs should also be considered during the material selection.[3] Table 3 lists some commonly used filament types and mentions some of the important properties to be considered when the printed object is used in a microscopic system. PLA is a filament optimal for initial prototyping since it is easy to handle, but it does not have the best durability under certain conditions.[3, 27–29] Materials like PETG[3, 17, 27–29] or ABS are more robust in most conditions and can be considered for the final version if a 3D-printed part is to be used PLApermanently.[3, 17, 27–29] ASA is a very durable material suited for most environments, but relatively hard to handle as it tends to adhere very strongly to a standard printer base plate and can produce shrinking and warping artefacts, if the settings for the print are not optimally chosen.[17]

More recently, metal 3D printing, or metal additive manufacturing, provided a main benefit in the ability to generate complex geometries. Several manufacturing technologies are available (Powder Bed Fusion, Binder Jetting, Directed Energy Deposition or Metal Extrusion), the use of metal 3D printing comes with high costs, additional post-processing requirements and imposes challenges when tight tolerances or surface smoothness are required.[18]

For 3D parts design, a variety of mature software options are available. While commercial packages offer extensive functionality, most microscopy facilities require only the reprinting of existing designs, and basic modelling capabilities for small projects or single-part designs. In such cases, open-source tools such as FreeCAD (for parametric

modelling) or Blender (for non-parametric, surface-based modelling) are often sufficient and cost-effective.

Attention to data format compatibility is equally important. Proprietary software often relies on unique file types that limit future interoperability, whereas open formats support long-term accessibility. For designs intended to be modified or parameterised, the STEP (.stp or .step) format is recommended, as it preserves editable geometric parameters and enables easy scaling or adaptation (e.g. adjusting dimensions or repeating structural elements). For distributing fixed designs not meant for alteration, the STL (.stl) format remains widely accepted, though its mesh-based nature restricts fine editing and can affect print quality depending on mesh resolution. Maintaining standardised file formats fosters adaptability, reproducibility, and effective sharing of 3D resources across microscopy facilities and user communities.

5 | USER PERSPECTIVES AND ACKNOWLEDGMENT PRACTICES

Balancing custom services with other facility duties requires diligent management and clear prioritisation. In addition to a tight coordination for compatibility of 3D-printed items with the instrument machine park, additional aspects should be considered when a 3D-printing service is to be provided. Table 2 can serve as inspiration for back-end coordination and project management, including milestones such as project initiation, design iterations, fabrication, testing, final deliveries, and documentation. Role-clarification of the requester and service providers during the different steps of the fabrication process should be carefully defined and agreed upon.

Specifically, tolerances requirements and material choice should be evaluated. For a provided service, it is important to clearly communicate the limitations to the requester and manage expectations. When 3D-printed parts are to be used as a final 'delivery', clear information on potential shortcomings like temperature stability, surface roughness, reproducibility tolerances should be communicated earl on. Very often, these shortcomings can be tolerated as a trade-off for the benefits of the services. The tests for the 3D-printed custom parts should align with the agreed aims of the project-based 3D printing services. Besides the functional production and implementation process, one needs to give thought to the challenges of compatibility and maintenance need to be addressed, including the usage of the 3D-printed parts on other instruments; the use by other users and the wider distribution of parts.

As with any service-oriented activity, authorship and intellectual property considerations arise. Who is the creative mind behind the invention? Is the user request specific, as it rather describes a solution to 'the problem', or is a more complete service and strongly relies on the facility staff expertise and creativity to provide a solution to the proposed problem required. Transparent project documentation and consistent criteria for acknowledgment can strengthen professional recognition of facility staff. Beyond technical benefits, structured 3D printing services reinforce the facility's role as an innovation hub within the research ecosystem.

6 | ENABLING NOVEL RESEARCH THROUGH PROTOTYPING

Access to 3D printing, and offering expert project-based support, can transform existing instruments into more versatile imaging-platforms, which can be used for experiments that might otherwise be unfeasible, in-field observations,[8] or exploration and educational purposes.[31] The accommodation of novel research applications can be mitigated by low threshold reimplementation of available tools from the scientific community, but relies on specific expertise for the integration of these tools, such as: providing support for sample-holder integration, or stage inserts, with for instance sample-environment control (Figure 3).

Combining printed components and simple electronics allows the development of cost-effective peripheral devices, such as: light stimulation modules, sample-orientation stages, or flexible microscopy toolboxes that can be assembled into functional imaging platforms.[31] Elaborating the electronics and peripheral instrumentation will increase the complexity of the overall integration, but offers enormous potential for customisation. The integration of gas-mixers or fluid pumps for instance, allows event triggered sample stimulation by changing environmental conditions or adding specific drugs treatments. Such applications often require adapters to integrate the peripheral instrumentation to be compatible with the sample and the microscope platform. Controlling peripheral instrumentation directly from the microscope software, synchronising microscope acquisition with the external device control enables tighter integration between experimental manipulation and image acquisition. Such further automation will not rely on more advanced 3D printing implementation, but rather demonstrates the possibilities that can be unlocked by the ability to integrate bridging hardware components.

Finally, combining the automated hardware control with the analysis of the captured images in real time will be the entry-point to 'Smart Microscopy'. Smart microscopy can begins with instrument control based on integrated (entry-level) image properties of the last acquisition, such

as intensities. The level of complexity can be increased by using feature triggered decision making to either steer the imaging protocol, like zooming in on a dedicated feature, or to control up to the peripheral instrumentation, for example, by adding a drug exactly when the cell of interest enters mitosis. These different levels of complexity can be utilised to explore technologies or design prototypes, which can then serve as proof-of-concept to underpin larger funding strategies or motivate investment requests in advanced instrumentation.[4] Thus, 3D printing expands the experimental possibilities available to users and promotes methodological innovation.

7 | CHALLENGES: COMPATIBILITY AND MAINTENANCE

Custom designs must be carefully managed to ensure compatibility across the equipment park. Ad hoc or incompatible components may introduce risks if they interfere with sensitive optical or mechanical systems. Besides the previously mentioned consideration in tolerances, 3D-printed parts are more prone to deformation, which can lead to mechanical damage, optical misalignment, or more subtle issues such as temperature drift or vibration, all of which may affect instrument calibration. At best, these aspects are already evaluated in the testing and iteration phase of the 3D printing project-workflow (see Table 2). As In addition, non-compatible parts may pose a potential risk of contaminating optical systems, for instance by releasing plastic shavings, emitting chemical compounds (for example, from incompletely cured resins used in UV-cured 3D printing), or attracting dust through static surface charges.

Careful material selection and documentation is essential. Parts designed for specific instruments might also be mistakenly used on other systems for which they were not intended, thereby introducing the same risks described above and discussed previously. Moreover, enthusiastic users might attempt to install their own 3D-printed parts without consulting facility staff.

Furthermore, the need for additional training or introduction on usage of the fabricated tools might needs to be considered. Although this will likely not be required for simpler 'problem-solving' parts, even incompatibilities of simpler items might cause a risk of damage in some cases. Therefore, facilities are encouraged to implement compatibility matrices and to embed identifiers such as part numbers or instrument names directly into printed objects. Maintaining metadata and version control in a central repository assists in tracking designs and minimising redundancy. Although such organisation requires additional effort, it ensures long-term utility and safety of printed components. A general consideration is to check whether the use of third-party, or self-produced components might void warranty. Strict compatibility checks and housekeeping of the custom parts are strongly recommended (see also Tables 2 and 4).

8 | INTEGRATION WITH EXISTING FABRICATION RESOURCES

Institutions hosting fabrication laboratories or mechanical workshops should assess the balance between in-house 3D printing and centralised manufacturing. Imaging cores possess unique expertise: their staff are familiar with the operational and safety requirements of high-value microscopy systems and understand the constraints of optical quality and stability. Consequently, 'do-it-yourself' fabrication within the imaging core can complement existing infrastructure by addressing application-specific needs with rapid iteration cycles. Alternatively, collaboration between core facility and mechanical workshop staff can be very effective.

On the organisational level, the use of external or parallel services may impose an additional challenges. These challenges are not integrated in Table 1, as they will likely differ too broadly across institutions and are therefore difficult to integrate in a general context.

9 | COMMUNITY COLLABORATION AND RESOURCE SHARING

To maximise efficiency and dissemination, the microscopy community benefits from shared repositories and collaborative development platforms.[26, 30] Publicly accessible databases enable exchange, validation, and version control of 3D designs (Figure 4) while ensuring that creators receive appropriate recognition.[32] Initiatives such as the MicrocopyDB-based 'Community Tools' section on the ELMI website aim to centralise distributed resources across repositories such as GitHub, GitLab, Thingiverse, and others (Table 4). However, a unified, microscopy-specific platform remains a community goal.

Discussion forums further complement these repositories by providing opportunities for interaction and feedback. For example, μForum hosts a dedicated 'Builders & Tools' category, which has the potential to develop into a central hub for knowledge exchange and collaboration that will enable creators and innovators to rate, evaluate, and troubleshoot community-based parts. With continued growth, it might mature into a structured knowledge base similar to existing exemplary forums such as Image.sc forum.

TABLE 4 Repositories differ in purpose and scope – from large open public databases to curated or internally managed resources. For facility management (e.g. GitHub, GitLab, SeaTable, Airtable) or local repositories (such as spreadsheets or institutional databases) can also be employed to catalogue 3D printing activities, designs, and version control. The choice of solution should depend on whether access is intended solely for internal tracking or extended to users for transparency and reproducibility.

Repository / platform	Website	Description / relevance to microscopy
Thingiverse	https://www.thingiverse.com	One of the largest public repositories for 3D-printable designs; includes community-made microscope stage inserts, sample holders, camera adapters, and optical component mounts.
GitHub	https://github.com	Cloud-based version-control platform hosting many open-source microscopy and instrumentation projects, including CAD files and design documentation for custom parts and modular imaging tools.
GitLab	https://gitlab.com	Similar in functionality to GitHub; supports institutional or private repositories for controlled access to internal 3D printing projects and shared design development.
Printables (Prusa)	https://www.printables.com	Community platform maintained by Prusa Research, hosting general scientific 3D models including microscope accessories, laboratory fixtures, and mechanical adapters.
GrabCAD	https://grabcad.com/library	Professional engineering library containing CAD models for optical, mechanical, and laboratory components; useful for parametric design and integration of microscope stages and accessories.
NIH 3D Print Exchange	https://3dprint.nih.gov	Curated repository supported by the US National Institutes of Health, focused on biomedical and laboratory tools. Includes validated models of sample holders, imaging support tools, and cell-culture accessories.
Hackster.io	https://www.hackster.io	Platform for open hardware and electronics projects; hosts a growing set of microfluidics, imaging, and automation projects integrating 3D-printed and electronic components.
Open Know-How Registry	https://openknowhow.org/registry	Metadata registry that catalogues open hardware projects, helping link microscope component designs from various repositories and ensure design reproducibility and traceability.
OpenMicroscopy	https://github.com/HohlbeinLab/OpenMicroscopy	A community-maintained directory of curated, projects and resources related to open microscopy hosted in the GitLab repository from the Hohlbein Lab
Instructables	https://www.instructables.com	A community website emphasising detailed, step-by-step tutorials and 'how-to' guides; includes a large number of 3D-printing and laboratory hardware projects, often adaptable for microscopy applications.
MicroscopyDB – Community Tools (ELMI)	https://elmi-embl.org/tools	Microscopy-specific initiative aggregating community-developed tools and 3D designs from multiple repositories; aims to centralise and curate imaging-related open hardware resources.

Moreover, hardware production projects that involve 3D printing should align with project-based workflows and repository-driven documentation, as recommended for image analysis, hardware coding, and CAD-based design.[33] Informal exchanges also thrive on social media platforms such as *Bluesky* and *Mastodon*, where groups are now forming to share recommendations, design files, and even 'starter packages' for new users entering the 3D printing field.

Despite these initiatives, a single centralised microscopy-specific hub, functioning as a repository capable of hosting 3D models, validating designs, enabling version control, and integrating communication tools for user feedback and collaboration, does not yet exist. Establishing such a platform would streamline the exchange of designs, improve interoperability, and create a structured pathway for acknowledging contributors.[34]

A more proactive involvement from microscope manufacturers and related component producers is encouraged to share resources and help realise this vision. Although there are ample cases where technical drawings are accessible, the availability of interoperable 3D models is still sparse. By providing detailed, but non-sensitive and license-protected, 3D renders of microscope stands, stage models, incubators, optical components, and other peripheral equipment, companies can catalyse innovation within the community while maintaining intellectual property boundaries. Such contributions would greatly enhance the

FIGURE 4 Life-cycle of (community-) developed 3D-printed tools for microscopy core facilities. Created parts experience a life-cycle through which they are conceived, manufactured, evaluated, and disseminated within the microscopy community. These steps can be supported by hosting designs, tracking versions, and promoting peer review. Active participation by both researchers and instrument manufacturers, through sharing verified 3D models of microscope stands, stages, incubators, and optical components, fosters an iterative, collaborative ecosystem that drives innovation and reproducibility in the microscopy community.

ability of the microscopy community to design compatible accessories, streamline instrument integration, and develop novel applications more efficiently. Questions remain to be answered about the appropriate models for hosting such information and viable solutions on how to share scaffolds that are not provided by the original vendor. Opening a dialog about these current bottlenecks in finding, sharing and reusing existing designs and product information, for (re-)creating and adaptation will hopefully lead to lowering the threshold for creativity driven problem solving for creators and builders.

The search for a mutually beneficial model, where manufacturers share verified component models and the community co-develops extensions or improvements, would need to build on trust, recognition, and synergy between academia and industry. Ultimately, collective participation will promote standardisation, reproducibility, and creativity across imaging disciplines.

10 | COPYRIGHT AND PATENTS

Copyright primarily protects creative and digital works, including CAD files, 3D models, technical drawings, and accompanying documentation. When a researcher, facility staff or designer creates a 3D model, they generally hold the copyright to that digital design. This means that the model cannot be copied, distributed, or modified without permission unless the creator has released it under an appropriate license. Many online repositories used by the scientific community (e.g. GitHub or Thingiverse) provide designs under open-source or Creative Commons licenses, which define how others may use the files. When depositing new models, facility staff are encouraged to select an appropriate license and record authorship and usage terms. Similarly, tracking the license and origin of externally sourced designs ensures both legal compliance and proper attribution.

In contrast, patents protect technical inventions and functional mechanisms. Re-creating patented components via 3D printing, whether for commercial or research use, may still constitute infringement. Core facilities should therefore verify that printed parts do not replicate protected designs, particularly when reproducing commercial accessories. Conversely, facility developers who create innovative components may consider patenting novel functions before public release, in accordance with institutional intellectual-property policies.

In summary, mindful handling of copyright and patents enables microscopy facilities to integrate 3D printing responsibly, ensuring legal use, recognition of creators, and sustainable open sharing within the research community.

11 | DISCUSSION AND CONCLUSIONS

3D printing has become a transformative tool for microscopy core facilities and general for technology driven laboratories, enabling rapid problem-solving, supporting innovation at comparatively low production costs. Despite initial setup requirements, the long-term benefits outweigh the challenges. Services can be implemented on different levels of complexity, thereby allowing facilities to tune the service integration to available resources. Nevertheless, effective integration requires dedication to implement a structural service organisation, resource management, appropriate training, validation procedures, documentation and collaborative frameworks for knowledge sharing.

Expanding community repositories, supported by academic contributors, facility networks, and industrial partners, will drive broader adoption to use 3D printing for innovation in microscopy. An improved unified platform for 3D-printable microscopy resources could make community-developed designs more FAIR: easier to find, accessible under clear (licence) conditions, interoperable through standard file formats and metadata, and reusable

through documentation, version control, and validation records. Establishing such an open, FAIR,[34] yet safeguarded ecosystem for design exchange will strengthen the microscopy community's collective capacity for creativity, efficiency, and scientific advancement.

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