Printegrated Circuits: Personal Fabrication of 3D Printed Devices with Embedded PCBs

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Figure 1: *Printegrated Circuits* is a new approach that leverages multi-material 3D printers to create seamless interactive objects with embedded circuitry. (A) Interactive objects are designed with conductive elements and traces with cavities for embedded PCBs (B). During fabrication, the 3D printing process is paused to allow PCBs to be inserted inside an object. (C) Four example Printegrated Circuit designs that detect touch interactions and communicate over USB.

Abstract

Consumer-level multi-material 3D printing with conductive thermoplastics enables fabrication of interactive elements for bespoke tangible devices. However, large feature sizes, high resistance materials, and limitations of printable control circuitry mean that deployable devices cannot be printed without post-print assembly steps. To address these challenges, we present Printegrated Circuits, a technique that uses traditional electronics as material to 3D print self-contained interactive objects. Embedded PCBs are placed into recesses during a pause in the print, and through a process we term *Prinjection*, conductive filament is injected into their plated-through holes. This automatically creates reliable electrical and mechanical contact, eliminating the need for manual wiring or bespoke connectors. We describe the custom machine code generation that supports our approach, and characterise its electrical and mechanical properties. With our 6 demonstrations, we highlight how the Printegrated Circuits process fits into existing design and prototyping workflows as well as informs future research agendas.

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CCS Concepts

• **Human-centered computing → Interaction devices**.

Keywords

3D printing, conductive thermoplastics; prototyping; PCBs; personal fabrication

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1 Introduction

3D printers are now ubiquitous and are frequently used by makers, designers, students and researchers. Breakthroughs in print speed, price, and reliability of fused filament fabrication (FFF) 3D printers have led to much greater consumer adoption and applications [18]. Increasingly common multi-material printers now allow practitioners to go beyond making parts of a single homogeneous material and combine thermoplastics of different colours and material properties in the same print. This unlocks a body of work exploring combining standard and conductive thermoplastics [24, 56]. This research includes the creation of free-form capacitive touch sensors [9, 10, 77], extensions of existing touch interfaces [46, 50, 51, 59], deformation sensing [71, 78], and electric field sensing [2, 29, 48, 79, 105], as well printed passive and active circuitry [12–14] and displays [35].

Echoing the revolution in desktop publishing enabled by the personal computer, rumblings of a revolution in "desktop manufacturing" [28] enabled by digital fabrication tools are now louder than ever. Access to these tools rewrites the rules of production of digital devices, suggesting a way to unlock the long tail of hardware manufacturing [40], supporting the fabrication of customised products suited for individual needs.

In and beyond HCI, the goal of many of these developments is to support the fabrication of high-fidelity research prototypes [41, 62] or customised interactive objects for a market of one [27]. Current demonstrations of 3D printed electronic interactive devices are still limited by the resistance of materials and the resolution of available machines [81]. Printegrated Circuits presents an approach that harnesses existing consumer FFF 3D printers, electronics, and materials to create self-contained printed prototypes. The key to Printegrated Circuits is confining high-resolution and resistance-dependent circuitry to traditional electronic material in the form of PCBs, and using the printer itself to automatically form connections between these PCBs and the free-form and customisable object.

The Printegrated Circuits process comprises two steps: 1) the automated pausing of the 3D printing process on a multi-material 3D printer, to allow manual insertion of a PCB-mounted microcontroller into a pre-designed cavity; and 2) the novel *Prinjection* step we have developed, which extrudes conductive filament directly into plated-through holes (PTHs) of the inserted PCB. This creates robust electrical and mechanical connections to the microcontroller before the print continues.

This process can be adopted by researchers, designers and makers without the expertise or access to specialised 3D printed electronics machines, but who do already use local consumer-level 3D printers. This will allow these innovators to benefit from rapid iteration cycles needed to develop bespoke and high-fidelity interactive prototypes with existing tools.

To implement the Printegrated Circuits process, we have developed a slicer post-processing plug-in to allow users to specify the layer and position within the 3D printing process for PCBs to be inserted. The script splices the machine instruction file with commands to pause the print job and subsequently issue Prinjection movements to connect the 3D print and the PCB. The Prinjected filament also allows subsequent layers to form stable electrical and mechanical connections with the PCB. Through a series of described tests, we optimise and characterise the Prinjection movements, on boards that simulate inserted PCBs that would traditionally be used with breadboards, or soldered into projects. The process produces enclosed free-form devices with microcontrollers robustly fixed and connected within the device itself. The process is designed to be accessible to existing users of 3D printing technology through its easy integration into existing tool flows and use of tools already in the hands of makers. The process also supports recovery of embedded circuits to allow for iterative design and sustainable re-use of valuable components.

Our 6 demonstrations show how the technique works with different previously presented printed input modalities; custom, as well as off-the-shelf printed circuit boards; and haptic centralised applications. These demonstrations also provide the grounds for our discussion, where we highlight the opportunities and challenges in printing high-fidelity interactive prototypes, expressing the craft-like dialogue between the creative designer and the precise and repeatable machine.

2 Related Work

2.1 High Fidelity Prototyping with Electronics as Material

Personal fabrication in HCI supports democratised tangible device creation with a growing body of work incorporating electronics as material in craft-like prototyping. For instance, Little Bits [5] presented the "electronics as material" abstraction to facilitate non-expert crafting of interactive devices with magnetic electronic modules that could be incorporated in all sorts of projects. Circuit Stickers [70] took this further by re-packaging electronics as adhesive stickers to seamlessly integrate with hand-drawn paper-based circuits. Supported by the diverse ecosystem of prototyping kits and development platforms [55], electronics are now integral to any prototyper's workflow at every level.

Paired with accessible electronics, digital fabrication machines have allowed individuals to create robust and appealing enclosures for crafted electronics [3, 73, 80, 99]. However, increasing interest in supporting scalability and low-volume production of devices [8, 40, 53] has drawn focus to the manual nature of this kind of making and the reliability needed for deployment. One approach to overcome this challenge is to directly harness the intrinsic scalability and reliability of outsourced production. Hartley et al. explore supporting the transition between prototyping module-based electronics and assembled PCBs in MakeDevice [36, 37]. Others have gone further and used the PCB substrate itself as material to support the fabrication of complex and high fidelity devices [20, 30, 31, 49].

This work addresses a key tension in interactive device creation: the trade-off between outsourced manufacturing and local fabrication. While outsourced production offers reliability and scalability, it lacks the tangibility, rapid iteration, and deep customisability inherent to hands-on, local making. Printegrated Circuits aims to resolve this tension by harnessing the best of both worlds, using commercially manufactured PCBs as material for rapid customisation with local digital fabrication tools.

2.2 3D Printed Electronics for Interactive Devices

3D printing technologies are expanding beyond the creation and replication of mechanical components to encompass rapid fabrication of electronics too. Commercial electronics printing techniques include multi-layered inkjet printing with conductive materials [7, 21], direct ink writing with silver paste [1, 93], multi-jet fusion with conductive powders [38], and aerosol jet systems [64]. The development of these approaches suggests a future where high-fidelity interactive devices can be rapidly prototyped, produced and customised to the needs of any individual. However, these specialised electronics printers remain out of reach of many designers, researchers, and makers, with machines requiring trained operators, being prohibitively expensive, or only existing in research and development settings, and not on the maker’s desk [28].

In response to this, and towards the goal of democratising the use of digital machines to fabricate interactive devices, researchers have hacked and modified existing fabrication devices [26, 47, 52, 61, 72, 103] and built alternatives [63, 67, 68, 83, 92, 97, 108]. Others have augmented 3D prints made on low-cost machines to make resulting objects functional through post-print augmentation [11, 45, 66, 74, 87, 90, 101, 106, 107], or mid-print part insertion [19, 80].

Material developments in printable thermoplastics have enabled researchers, designers, and makers to harness increasingly prevalent and reliable multi-material fused filament fabrication (FFF) 3D printers to print with carbon composite rigid thermoplastics [56, 69, 84], conductive TPU [71], and copper-based materials [24]. Multi-material devices demonstrate functionality that can be incorporated into interactive devices such as capacitive touch sensors [9, 10, 77], deformation sensors [71, 78], and position sensing through electric fields [2, 29, 48, 79, 105].

FFF printing of functional logic or driver circuitry to pair with these interactive structures, while currently being investigated [14], is limited by materials and resolution. Printed conductive structures are therefore commonly paired with traditional electronics. This has been done by wiring directly between print and electronic circuit by melting wires into the surface [69], using silver paste [84], or copper plating combined with press-fit connections [44, 58], introducing technical manual steps to the making process. Oh Snap! [77] overcomes this challenge with a custom piece of electronics to interface between the PCB and print, with additional magnetic elements and pogo pins. Thermopixels [60] prints directly over plated pads with vias and uses the same circuitry used to thermally activate the pixels to force high current through the print in order to heat the filament and ensure sufficient electrical connection to the metal.

These approaches support the reliability of connections through the use of custom-designed elements in the connected circuitry. The Printegrated Circuits approach uses an un-modified 3D printer, accessible tools and can combine them with traditional prototyping electronics hardware through the use of custom automated print paths.

2.3 Custom 3D Printer Workflows for Interactive Devices

Going beyond the fabrication of homogeneous plastic parts requires custom design and fabrication workflows and explorable parameter spaces [82, 88] unconstrained by abstractions that traditionally encapsulate domain-specific knowledge [25].

Bespoke CAD tools support the design of specific elements that allow for interactivity within 3D prints. In *A Series of Tubes* [74], Savage et al. demonstrate a tool for routing pipes through 3D models to add interactivity through conductive pathways and air-filled pipes. X-Strings [57] is a tool to design and print string-actuated mechanisms straight off the printer. *Capricate* [75] presents a design tool to add capacitive touch pads and automatically place conductive traces.

Some workflow modifications involve mid-print part-insertion-based interventions [96]. For example, to reduce print time and wasted material, Substiports [95] and Scrappy [94] use existing objects for support and internal media. Medley [16] and Encore [17] combine existing materials and objects into 3D prints to augment their function. To make traditionally static 3D printed objects interactive, Folded Printgami [19] inserts folded paper-based circuits mid-print. Rhapso creates functional string-based mechanisms [4] and uses a custom thread-placing mechanism to integrate new material properties into prints. Liquido [76] prints cavities and manually inserts liquid to allow for different tilt sensing modalities by creating contacts between thermoplastic electrodes.

Creating tools to generate domain-specific tool-paths for FFF printers is also an interesting avenue of research, allowing researchers to think of 3D prints as more than homogeneous parts, and imparting qualities through printing that can’t be described in the design stage. Hong et al. extend traditional 3-axis FFF printing to a 5-axis system that allows conformal extrusion beyond horizontal planes, increasing strength and conductivity [42, 43]. Wasserfall et al. [98] suggest a way to integrate wire generation into a slicing program, and Duty et al. [23] suggest injecting molten filament into infill gaps to increase the vertical strength of parts.

Printegrated Circuits adds to this body of work by suggesting mid-print intervention and domain-specific tool-path generation: PCBs are inserted during a pause in printing, and custom tool-paths we call "Prinjection" allow for conductive filament to be vertically injected into the plated-through holes of the PCB. This workflow enables the fabrication of fully self-contained interactive devices.

Table 1: Chronological overview of related work in interactive device creation with custom and consumer-level 3D Printers

Work	Printed Device Functionality	Printer	Connection Type	Post-Processing Steps	Functional Materials
Capricate [75]	Capacitive touch sensing	Multi-material FFF	Extend existing capacitive touch	None	Conductive ABS (Torwell Technologies)
PrintPut [10]	Capacitive and resistive sensing	Multi-material FFF	Alligator clips/ Z-tape	Make connections	Conductive ABS (Maker Geeks)
Electronics Integration in FDM Fabrication [97]	Wiring and Placement of SMD components	Modified industrial printer with vacuum gripper and extruder for conductive ink	Self-connecting with silver ink	None	Silver ink
Botfactory [7]	PCB printing	Custom inkjet	Soldering	Traditional PCB assembly	Proprietary inkjet materials
Voxel 8 [1]	Sensing and power distribution	FFF with silver ink direct write	Self-connecting	None	Proprietary silver ink
Flexibles [78]	Capacitive deformation sensing	Multi-material FFF	Extend existing capacitive touch	None	Conductive PLA (Protopasta)
Electrick [105]	Electric field tomography touch sensing	FFF	Copper tape	Make connections	Static dispersing ABS (Zen Toolworks)
FiberWire [84]	Wiring and capacitive and resistive sensing	Markforged	Silver epoxy	Laser etch, drill and silver epoxy	Continuous carbon fiber filament (Markforged)
./trilaterate [79]	Capacitive hover, touch and deformation	Multi-material FFF	Thermo-press-fit	Make connections	Conductive PLA (Protopasta)
Protospray [35]	Electroluminescent display	Multi-material FFF	Thermo-press-fit	Make connections and spray	Conductive PLA (Protopasta) + electroluminescent paint
FFF wire embedding [108]	Internal copper wiring	Custom-hot end and filament	Threaded inserts	Make connections to components	Custom PLA with embedded copper wire
OhSnap! [77]	Capacitive sensing	Multi-material FFF	Pogo-pins + magnets	Snap custom board	Conductive PLA + magnetic PLA (Protopasta)
Thermoformed Circuit Boards [44]	Capacitive touch, power transfer to LEDs and power	Multi-material FFF	Press-fit / silver paste	Electroplating	Electrifi copper (Multi3d)
Metasense [29]	Capacitive deformation	Multi-material FFF	Thermo-press-fit	Make connections	Electrifi copper (Multi3d)
LaserFactory [61]	Power distribution and sensing	Heavily modified laser cutter	Self soldering	None	Silver ink
ModElec [38]	Various with touch sensing and power distribution	Multi jet fusion technology	Snap fit / silver conductive adhesive	Make connections	Proprietary conductive agent
Lattisense [71]	Resistive deformation sensing	Multi-material FFF	Thermo-press-fit	Make connections	Conductive TPU (jaTek)
MechSense [2]	Rotation sensing through capacitance	Multi-material FFF	Thermo-press-fit	Make connections	Electrifi copper (Multi3d)
Thermopixels [60]	Thermochromic display	Multi-material FFF	Print over pad	Joule heating	Conductive PLA (Protopasta)
E-Joint [58]	Capacitive and contact sensing, wireless charging	Multi-material FFF	Press-fit / custom connections	Electroplating	Carbon nanotube PLA (Hangzhou ZhuoxinUniversal Materials)
Impedius [22]	Single line capacitive and resistive sensing	Multi-material FFF	Alligator clips	Make connections	Conductive PLA (Protopasta)

3 Printegrated Circuits

Drawing from the related work, Printegrated Circuits presents a solution to locally fabricate high-fidelity prototypes using electronics as material, using an unmodified multi-material 3D printer with conductive materials and custom tool-paths.

As illustrated in Figure 2, the Printegrated Circuits fabrication process involves: pausing the print for parts to be manually inserted; injecting conductive filament into the plated-through holes normally used for soldering, a process which we call Prinjection; and connecting conductive sensing structures with the PCB.

Printegrated Circuits use manually designed recesses and conductive traces modelled within the objects to seamlessly accommodate integration of conventional electronics that are inserted during the print process. The Prinjection process is automatic, with custom g-code movements spliced into the print file with a slicer post-processing script directing the printer to form robust mechanical and electrical connections to the PCB and creating anchors for further layering of traces with conductive filament.

Printegrated Circuits dovetails with existing device prototyping paradigms, allowing for the insertion of off-the-shelf and custom-designed PCBs to be used in the process. These PCBs are treated as reusable materials, where plastic can be softened with a heat gun and high-value modular electronics recovered for future use in design iterations, or altogether new devices.

3.1 The Printegrated Circuits Workflow

In Figure 3, we present each workflow stage for an example scenario creating an illustrative "ABC 123" USB capacitive touch HID keyboard device with arbitrary characters using the Printegrated Circuit Board introduced in Section 5.1. Here, we give a high-level overview of the most important details of the process. In our supplementary material, we provide in-depth details of specific constraints and design recommendations.

3.1.1 Electronic CAD. The workflow uses the digital design files of the embedded PCB. Therefore, the first stage is to export a STEP model (.step) of the PCB and drill file (.drl) to represent the positions of the plated-through holes. These can be exported from electronic CAD platforms, or open-source designs can typically be downloaded directly from the supplier of prototyping PCBs.

3.1.2 Mechanical CAD. Printegrated Circuits are modelled around recesses for the embedded PCBs, which are designed using the .step file exported from ECAD. PCBs must be placed parallel to the printing surface with the unpopulated face pointing upwards. Sensing structures and traces are also manually designed at this stage. This design is realised within parametric timeline-based CAD programs like Onshape[1] and Autodesk Fusion[2]. The process is not dependent on any specific CAD platform, giving practitioners autonomy over the design of novel features. Conductive elements are modelled as separate parts and exported from the CAD platforms as a 3MF file.

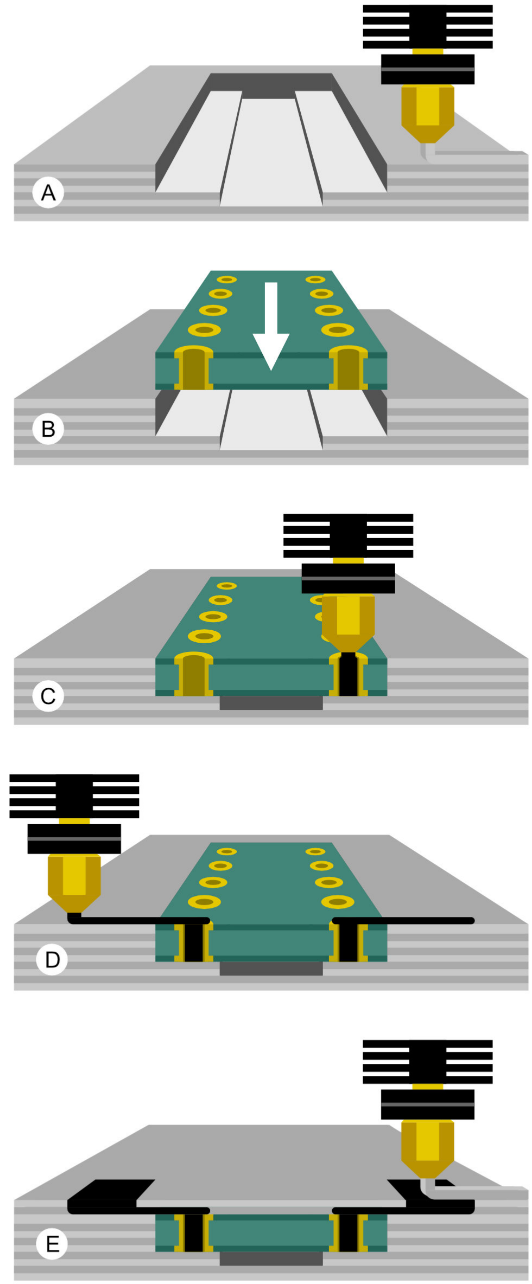

Figure 2: The Printegrated Circuits process (A) The object is printed with non-conductive material following commands generated by slicing software. (B) The printer pauses for manual insertion of the PCB. (C) The printer injects a fixed amount of conductive filament directly into plated-through holes in the PCB, in a process we term *Prinjection.* (D) Conductive traces are printed from the Prinjected contacts. (E) The rest of the object and its interactive structures are completed.

[1]Onshape, https://onshape.com/, Accessed 2025-03
[2]Autodesk Fusion, https://www.autodesk.com/ca-en/products/fusion-360, Accessed 2025-03

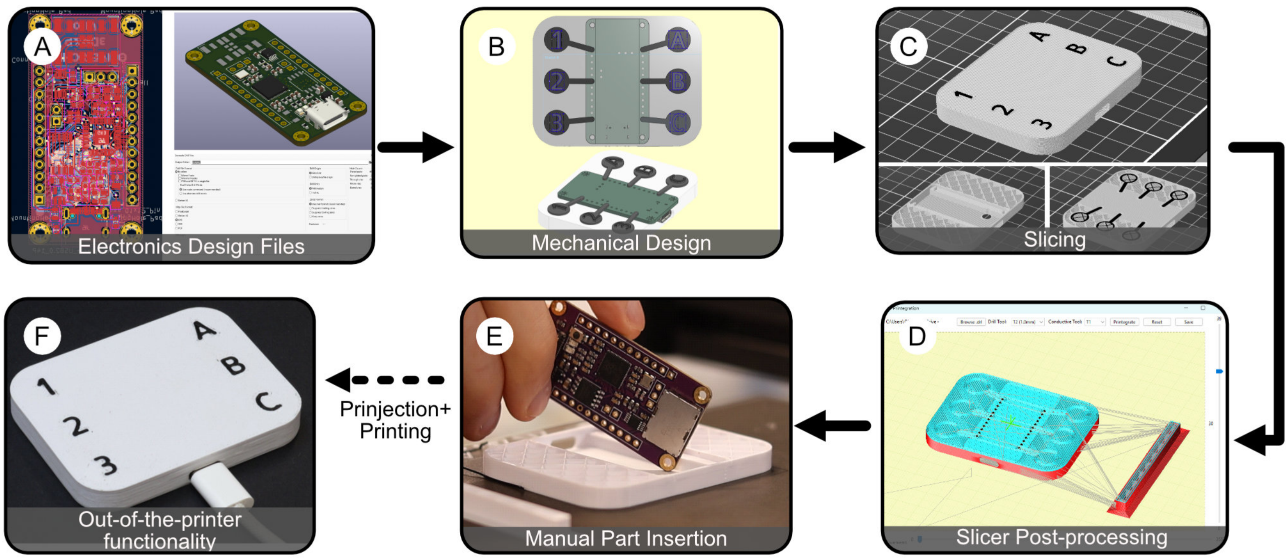

Figure 3: The Printegrated Circuit workflow: (A) PCB designs in EDA exported as STEP with .drl file. (B) In-context CAD modelling of an interactive object with embedded PCB (C) The slicing step (D) The sliced file is re-interpreted in a post-processing script, merging in instructions to support the necessary Prinjection steps (E) Designs are printed with a mid-print pause for part insertion followed by Prinjection (F) Printegrated Circuits work out-of-the-printer.

3.1.3 Slicing (CAM). We perform slicing using Prusa Slicer V2.7.4[3]. Each part of the model is assigned either a conductive or non-conductive material at this stage. This is a standard feature of slicing software, normally used to set the colour of different parts of a model. Printing infill is set to 100% for conductive parts to increase conductivity, and internal interface layers between parts are enabled to ensure high fidelity of the internal structure. We include a slicer configuration file with all of the settings in our supplementary material.

3.1.4 Printegrated Circuits Post-processing Script. We use the post-processing script setting in Prusa Slicer. The source code for this work is hosted on our GitHub repository: https://github.com/ollyoid/Printegrated-Circuits. On g-code export of print files, the slicer runs a script that opens our graphical program based on Pronterface[4] allowing the user to specify the position and layer of the to-be-inserted PCB and its associated plated-through holes on a representation of the sliced print. After selecting the board and placing the holes, the user clicks the 'Printegrate' button, and g-code lines are inserted into the print file specifying the pause, tool changes, extra nozzle priming movements, and the Prinjection steps. We describe the specific stages of Prinjection in more detail in Section 3.2.

3.1.5 Printing (CNC). Our examples and demonstrations were built with a Prusa XL 5T tool-changing FFF 3D printer with 0.4mm nozzle diameters[5]. This printer is supplied with 5 print heads at around 4000 USD, targeting 3D printing hobbyists as well as professionals.

We used Protopasta Conductive Composite PLA (90 USD/kg)[6], for conductive traces and white eSUN PLA+ (20 USD/kg)[7] as the structural material, but other non-conductive thermoplastics would work equally well.

In striving to make the Printegrated Circuits process more adoptable by the maker and research community, a discussion of the practicality of using other machines and materials is included in the supplementary materials of this paper.

3.2 Prinjection

The Prinjection technique uses custom-generated g-code to inject conductive filament into the plated-through holes of an embedded PCB. PCBs are embedded during a user-specified pause in the printing process, and Prinjection locations are calculated using the user-specified PCB insertion position and the plated-through hole coordinates retrieved from the PCB's original manufacturing or footprint files. Prinjection uses the pressure of the injected molten plastic to conform to the edges of the surrounding metal, similar to injection moulding. The large contact area reduces contact resistance and improves the mechanical reliability of the formed

[3]Prusa Slicer, https://www.prusa3d.com/page/prusaslicer_424/, Accessed: 2025-03
[4]Pronterface, https://www.pronterface.com/, Accessed: 2025-03

[5]Prusa XL 5T, https://www.prusa3d.com/en/product/original-prusa-xl-semi-assembled-5-toolhead-3d-printer/, Accessed: 2025-03
[6]Protopasta Electrically Conductive Composite PLA https://proto-pasta.com/products/conductive-pla, Accessed: 2025-03
[7]eSUN PLA +, https://www.esun3d.com/pla-pro-product/, Accessed: 2025-03

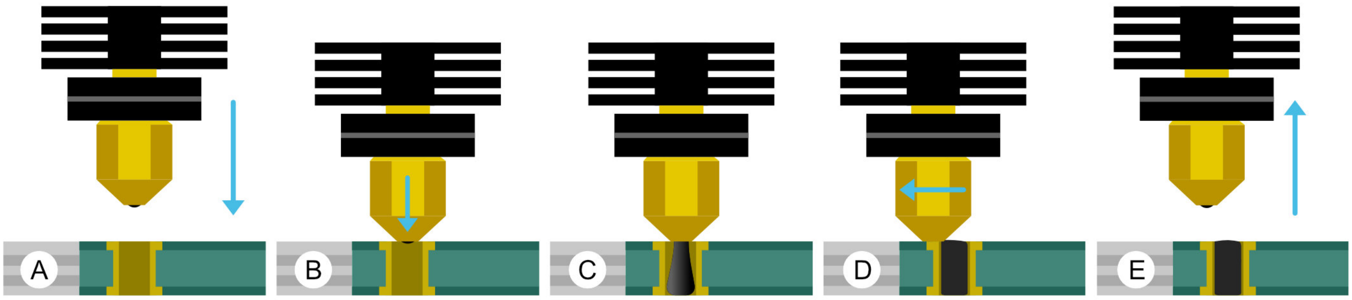

Figure 4: Prinjection Movements: After priming the nozzle, (A) the tool moves over each plated-through hole, (B) lowers onto the surface, (C) injects conductive plastic into the through hole, (D) wipes the nozzle against the surface of the PCB, before (E) lifting the tool back up.

connections. Prinjection also creates a mechanical anchor for conductive traces, overcoming the challenges faced by low adhesion to the PCB's solder mask.

Figure 4 demonstrates a simplified version of the individual Prinjection steps, each movement controlled by a series of g-code instructions written below.

Prinjection Commands

```
for each hole in PTHs do
    gcode += "G0 X" + hole.x_coord + " Y" + hole.y_coord
    gcode += "G0 Z" + board_height
    gcode += "G1 E" + (retract_amount + extrude_amount)
    gcode += "G1 E" + (-retract_amount)
    gcode += "G0 X" + (hole.x_coord + sweep)
    gcode += "G0 Z" + (board_height + lift)
end for
```

Figure 5 shows the cross-section of a successful Prinjection of a plated-through hole in a prototyping board against a non-Prinjected sample, where both samples have had a conductive trace laid over the top of the through hole. The samples were potted in resin, cut, and repeatedly sanded and polished following the process described by Schlaepfer and Oskay [65].

4 Characterisation and Calibration of Prinjected Contacts

The goal of these characterisations and tests was to optimise and show how prinjection could be used to make reliable electrical and mechanical contact between 3D printed object and metal contacts on an embedded PCB. The tests used PCBs with 2.54 mm or 1/10" spaced 1mm diameter plated-through holes, as this is what is common in prototyping settings, where boards are traditionally inserted in breadboards.

4.1 Optimising Prinjections

We identified a set of optimal printer movements and parameters for the injection of conductive material into plated-through holes on a PCB to form the base of electrical connections to the rest of a 3D printed object. The key goals were to adequately fill the holes with conductive material so that there was surface contact on all sides and to provide a surface for the next planar layers of conductive material to adhere to without too much excess extruded material or strings that could cause unwanted paths between neighbouring contact points.

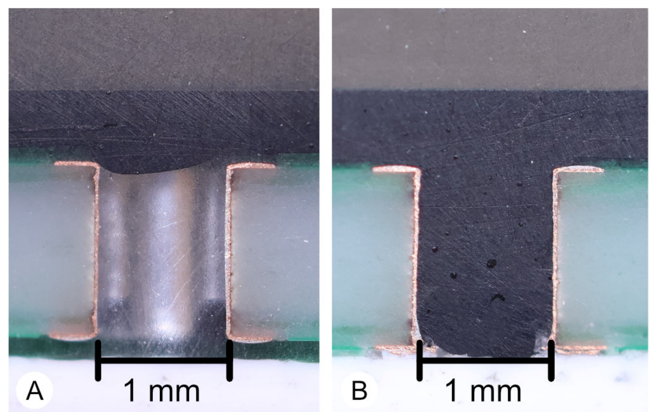

Figure 5: Cross-sections of the plated-through holes of a test PCB cast in resin, sanded and polished. (A) Conductive filament is printed onto the PCB surface without Prinjection; it lies on the surface making little contact with metal. (B) Prinjection leaves holes fully filled and ensures reliable connectivity.

To explore optimal parameters, we used blank prototyping boards[8] with 14 columns of 20 plated-through holes typical of a breakout board, coupled with a 3D printed frame to hold the prototyping board in place, as shown in Figure 6A. Samples were prepared to test one parameter at a time. After placing the board in the frame, we instructed the 3D printer to perform Prinjection steps on each of the through holes with conductive filament. For each column, the printer would first perform a wipe movement that would prime the

[8]Universal prototyping boards, https://shop.pimoroni.com/products/universal-proto-board-pcbs-3-pac, Accessed 2025-04

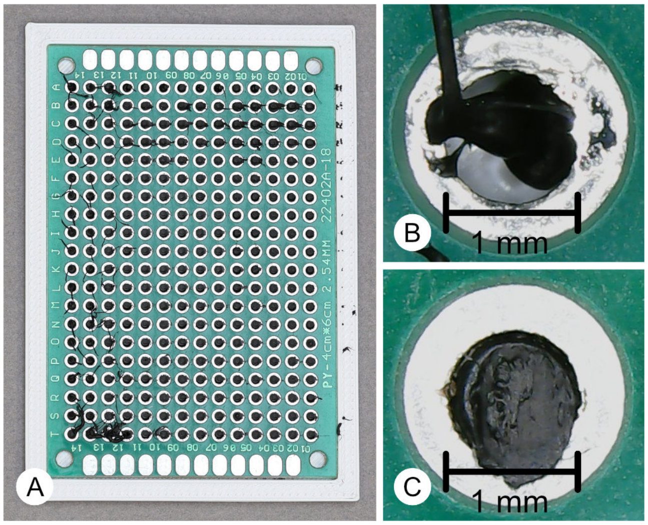

Figure 6: Prinjection optimisation tests using a prototyping board. (A) The holes in a column are filled using identical Prinjection commands, before making a single parameter change for the next column. (B) An under-filled plated-through hole compared with (C) a perfectly-filled hole.

nozzle with conductive material, then perform Prinjection movements for each plated-through hole in that 20 hole column. This was repeated for each column of holes with the same parameter incremented by a set amount for each column. The parameters we varied were: extrusion amount, retraction amount, and wipe length. The same movement with the same values was repeated for a whole column of 20 holes because we wanted to understand whether changes in pressure in the nozzle were occurring. After each test, we inspected the samples and visually identified which holes were most uniformly filled with minimum stringing like the example in Figure 6C.

Extrusion length. Our first test determined the correct extrusion volume. We tested extrusion amounts from 0.2mm to 0.9mm of standard 1.75mm diameter filament in increments of 0.05mm. We selected this range because the theoretical total volume of a 1.0mm diameter cylindrical plated-through hole in a standard 1.6mm thick PCB is 1.6mm * π * 0.5mm^2 = 1.26mm^2. This volume constitutes a length of around 0.74mm of 1.75mm diameter filament. For each extrusion length, a column of 20 consecutive holes was filled. After each row, the printer performed a wipe move to re-prime the nozzle ready for the next column of holes.

An extrusion length of 0.65mm gave the best results, just below the theoretical through hole volume. However, significant stringing was still apparent in all tests, including when using the optimal length. Our next test, therefore, focused on reducing stringing.

Retraction. The second test explored retraction of the filament, with the goal of reducing the stringing that was apparent in the previous test. Pulling back filament before moving the nozzle can help reduce stringing.

While we found that stringing is not often a catastrophic issue in Printegrated Circuits - subsequent print head passes when printing conductive traces will normally fragment and remove the strings - but there is still a small risk that residual filament between adjacent holes could cause unintended crosstalk or other signal integrity issues, if not a complete short circuit.

We performed retraction tests from 1mm to 8mm in increments of 0.5mm. Higher retractions resulted in less stringing. However, we did not exceed 8mm of retraction because above this value the nozzle became clogged. Too much retraction also decreases the overall print duration and causes temperature creep as heat travels back up the extruder. When plastic passes its glass transition temperature and cools too far up the nozzle, it can cause the filament to jam. After visually inspecting the results, we determined a retraction amount of 7.5mm gave the least stringing without negative side-effects.

Wiping. The third test explored nozzle wiping. After each injection, we dragged the nozzle at the same z-height off to the side of the hole. This was to try and 'cut off' any strings of filament and produce a cleaner pattern.

Following a similar approach to the above optimizations, we filled in a grid of plated-through holes, gradually increasing the wipe length. A longer wipe length proved more reliable, but we balanced this against increased print duration and the risk that, for a more realistic PCB, long wipes might interfere with nearby components and features. From our tests we determined a wipe length of 2mm was enough for the nozzle to completely clear the plated-through hole.

4.2 Contact Resistance

We also explored the contact resistance of the Prinjected material. Contact resistance is a measure of the additional impedance introduced by the interface between adjacent conducting materials. Poor adhesion, low contact surface area and unstable mechanical connections can all increase contact resistance, limiting the functionality of fabricated devices. Traditional metal-metal contacts of solder and clean connectors like jumper wires and breadboards have negligible contact resistance, whereas metal-conductive composite contacts can have significant contact resistance [91].

We calculated the contact resistance at the PCB-to-PLA interface by measuring the difference between the resistance across the length of a conductive trace and the resistance of the length of the trace connected to a plated-through hole. Direct resistance measurement with a multimeter is inaccurate as it varies with the pressure applied to the probes, which themselves introduce a variable contact resistance. We obtained accurate measurements using the 4-point probe technique, eliminating the resistance of the probes and the contact between the probe and the material. While the resistance of the probes themselves was relatively low, the contact resistance between the probe and the material was highly variable.

We took measurements with a Keithley 2614B source measurement unit (SMU) connected to a bespoke 4-point probe assembly, which we designed and built. The probe used 4 dome-capped pogo pins mounted in a linear arrangement. We also developed a custom contact resistance characterisation PCB shown in Figure 7A. The characterisation PCB comprised 20 traces with a plated-through

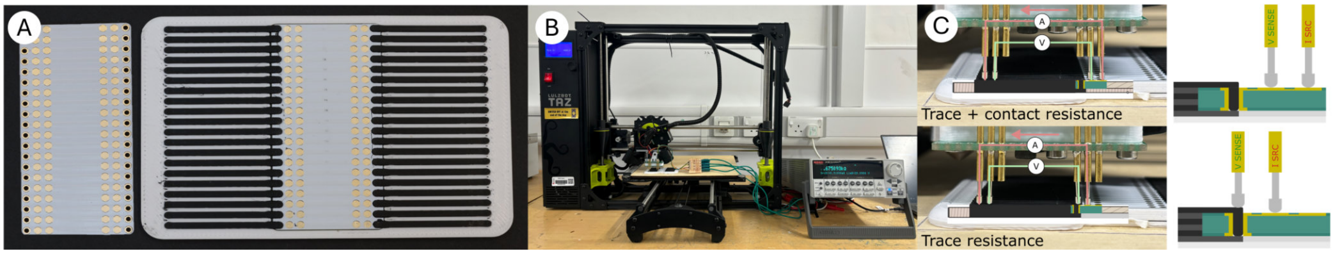

Figure 7: Contact resistance characterisation: (A) Custom PCB with contacts for 4-point probe. (B) Automated testing of contact resistance using an upcycled Lulzbot 3D printer, (C) Two different configurations of pogo pins in a custom probe for a 4-point probe.

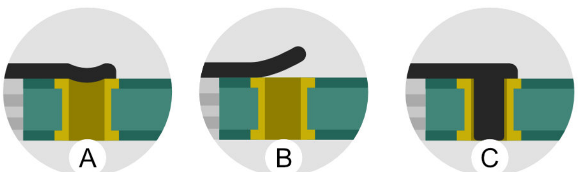

Figure 8: Without Prinjection (A, B), the printed conductive trace has nothing to anchor to, resulting in the printed trace peeling up from the surface. With Prinjection (C) printed traces become anchored and do not peel up.

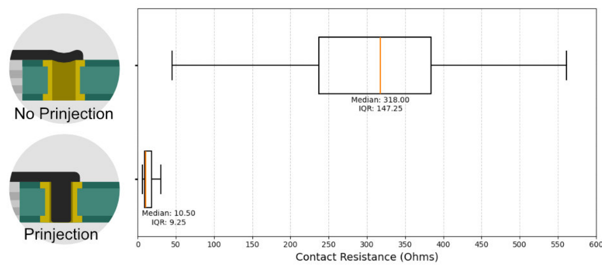

Figure 9: Characterisation of the contact resistance of a planar print vs. with Prinjection, see Section 4.2 for details.

hole, and two surface pads at either end. We designed the PCB with the same pitch as the pogo pins, so that from the end of each trace one pad could be used for the low force pin, the other for the low sense, and the through hole for the Prinjection process. The high sense and high force pins were then connected via the pogo pins at the other end of the characterisation board as shown in Figure 7C. To ensure repeatable and consistent sensing, a re-purposed 3D printer stage was used to lower the probe assembly to a set height for each trace as shown in Figure 7B. The modified 3D printer combined with the SMU could then take resistance measurements for a whole row of traces automatically. Changing the position of the force and sense pins on the PCB side of the probe by swapping pogo pins between connections supported a comparison between total resistance (trace + contact) and trace resistance alone as shown in 7C. Both types of measurement were taken for each trace, and then the contact resistance was calculated by taking the difference between the two readings.

Two samples were prepared with Protopasta's conductive PLA with 3 mm deep, 25 mm long traces with a width of 1.5 mm. One sample was sliced with default slicer settings, a 0.2mm layer height and a pause command inserted through the slicer's interface at layer 13 for PCB insertion. The other sample was sliced in the same way but then underwent splicing with Prinjection commands, with the optimally selected movement settings from the previous tests.

An independent samples one-tailed T-test revealed a significant difference in contact resistance distribution between the planar and Prinjection samples, $t(74)=7.06$, $p<0.001$. The Prinjection contact resistance was the same order of magnitude as the trace resistance of the material, while the resistance of the planar connection was significantly higher. Importantly, the Prinjection contact resistance also showed much lower variance, useful for ensuring predictable electrical properties at the modelling stage, and when optimising or calibrating a particular Printegrated Circuit design. In contrast, only 36 of the 40 planar traces formed an electrical connection (i.e. there was a 10% failure rate). The smooth surface of the PCB and the lack of anchoring offered by a Prinjection plug meant that in the 4 failed cases, the overlaid conductive trace peeled up during printing, as depicted in Figure 8B. This peeling effectively resulted in an open circuit.

Our test validates the benefit of Prinjection over the planar layering which has been used in previous work to print conductive filament over PCBs, such as ThermoPixels [60]. The greater mechanical reliability and consistently stable electrical properties allow repeatable production of Printegrated Circuits using the parameters described above.

4.3 Robustness

Building on the consistency of our contact resistance measurements, we further explored the physical robustness of Printegrated Circuits. Robustness is a multifaceted concept; our approach was to further explore the quality of electrical contact by taking measurements before and after repeated stress testing, and comparing samples created using Prinjection with planar printing.

Method. Two samples were printed, one with planar printing and one with Prinjection. Both used contact resistance characterisation

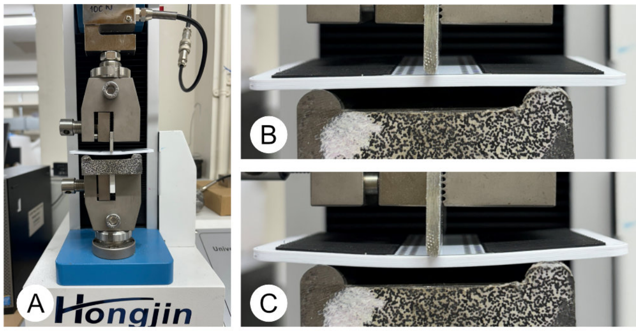

Figure 10: Robustness testing with a universal testing machine in a three-point bending setup (A) and applying 75 N of force repeatedly to the sample board (B-C)

PCBs as in the previous test. A Hongjin universal testing machine[9] equipped with a 3-point bend fixture and 100N strain gauge was used. For each sample, 100 bend cycles were performed with a 75N force. After 50 cycles the sample was turned over to perform the remaining 50 bend cycles from the other side. Contact resistance measurements were taken before and after these cycles.

Results. An independent samples one-tailed T-test compared changes in contact resistance before and after bending across the Prinjected and planar samples. Our test showed a significant difference in contact resistance $t(78)=-1.67$, $p<0.05$). The test showed that the Prinjected sample was significantly more robust to bending than the planar sample.

We were surprised that, unlike the planar sample, the Prinjected sample actually showed a reduced average contact resistance following repeated bending, demonstrating remarkable electromechanical robustness. Further study is required, but it appears that mechanical manipulation actually improved surface-to-surface contact of the Prinjected material.

4.4 Summary of Results

Our tests provide optimal measures for the Prinjection technique, and demonstrate its importance in providing robust electrical and mechanical connections with significantly lower and more predictable resistance when interconnecting conventional and 3D printed electronics.

The evaluation work was conducted with a simple sample assembly which does not represent the breadth of design or fabrication space of the Printegrated Circuits approach. The characterisation board and experiments were optimised to identify fundamental characteristics of the Printegrated Circuits. In the following section, we go beyond test scenarios and show some example demonstrations that we have built to give a sense of the opportunities and potential that this robust 3D printed device workflow provides.

[9]Hongjin Universal Testing Machine, https://www.hongjin-group.net/good-quality-universal-testing-machine-universal-tensile-testing-machine-hongjin-3-product/, Last Accessed: 2025-04

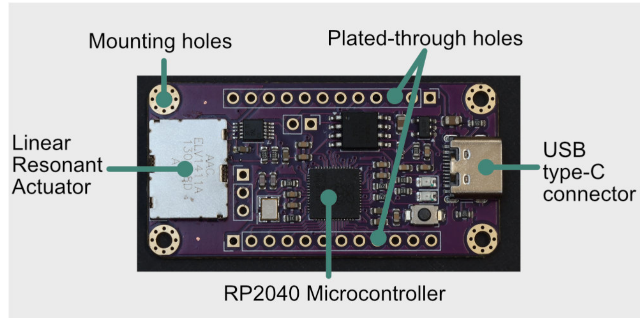

Figure 11: Our Printegrated circuit board combines the RP2040 microcontroller with a linear resonant actuator, allowing for capacitive touch sensing paired with centralised vibrotactile response. The Printegrated Circuits process can use this board or off-the-shelf prototyping boards.

5 Demonstrations and Properties of Printegrated Circuits

In this section, we present six demonstrative devices we have built during the development of Printegrated Circuits. These demonstrations are shown in Figures 1, 12, 13 and 14, and are summarised in Table 2. Printegrated Circuit devices are inherently user-ready through seamless design, off-the-printbed functionality, freedom of form and no required post-assembly. Through specific demonstrations we provide examples of integration within personal fabrication ecosystems, enabling fully customisable device creation (5.2), supporting iterative design (5.3), integration within existing design processes (5.4), support for low volume production (5.5) and compatibility with established fabrication workflows (5.6). We further evidence Printegrated Circuit's inherent capacity to overcome material challenges (5.7), the robustness of fabricated devices (5.8) and their highly sensitive functionality (5.9). Through these demonstrations, we highlight the approach's advantages and aim to inspire further exploration by underlining opportunities and challenges.

5.1 The Printegrated Circuit Board

An advantage of Printegrated Circuits is that they work with both existing prototyping PCBs, such as those available from suppliers like Adafruit[10] and Seeed Studio[11], as well as custom platforms that can be designed using conventional electronics design tools and readily available components.

However, to support our demonstrations, we developed our own open-source general-purpose PCB, which enables the fabrication of objects that combine capacitive touch and haptic feedback, shown in Figure 11. This Printegrated Circuit Board combines an RP2040 microcontroller[12] and a Linear Resonant Actuator (LRA) to create haptic effects.

[10]Adafruit Industries, https://www.adafruit.com/, Accessed: 2025-03
[11]Seeed Studio, https://www.seeedstudio.com/, Accessed: 2025-03
[12]RP2040 Microcontroller, https://www.raspberrypi.com/products/rp2040/, Accessed: 2025-03

Table 2: Demonstrations of the Printegrated Circuits method with fabrication information

Device	Function	Interaction Modalities	Embedded Circuit	PLA (g)	Conductive PLA (g)	Print Time
Slug	Scrolling device/slide clicker	Cap Touch & Vibrotactile	Printegrated Circuit Board	32	6	2h15
Ladybird	Media controller	Cap Touch & Vibrotactile	Printegrated Circuit Board	33	13	2h35
Isopod	Stroke sensitive emoji keyboard	Cap Touch & Vibrotactile	Printegrated Circuit Board	29	7	2h39
TuneShroom	USB MIDI Keyboard	Cap Touch	Seeed Xiao ESP32-S3	73	23	8h22
SnailSense	IOT Plant Pot Moisture Sensor	Resistance Sensing	Seeed Xiao ESP32-S3	31	25	3h59
Lego Data Physicaliser	Block Sensing Bar Graph	Resistive & Contact	Seeed Xiao ESP32-S3	78	77	7h25

Capacitive touch sensing through loading mode self-capacitance [33] is implemented with a single pin with precisely timed capacitance measurements carried out using the microcontroller's Programmable IO (PIO). Using the microcontroller's pins directly means that they can be easily reconfigured for other output and sensing too.

The board uses a surface mount haptic actuator[13], which is well suited to Printegrated Circuits because like the microcontroller they can be centralised and placed on a PCB embedded in the part and have actuation projected onto the surface. Single sources of vibrotactile stimulation can create a number of illusions [54].

The example we have already shown in Figure 3 uses our Printegrated Circuit Board for a general-purpose application. In the demonstrations below, we show how it is re-used in more complex devices.

5.2 Printegrated Circuits are Customisable

The IO-creatures (Figure 12) are a series of capacitive touch USB human interface devices (HID) with haptic feedback. They all use the Printegrated Circuits board described earlier. The design of the devices stem from the same origin, the enclosed ABC123 board also presented in the earlier sections. Designers can customise devices for specific uses through digitally designed form, and firmware controlled function. The IO-creatures demonstrate how Printegrated Circuits prioritises customisation and freedom of form.

Specifically, each of the IO-creatures has a different behaviour or function. Using CircuitPython running on the Printegrated Circuit Board, different keystroke behaviours can be programmed when capacitive touch events are registered. These can be mapped to any of the pins on the Printegrated Circuit Board, from which channels to the conductive pads are printed.

The Slug (Figure 12A) has two capacitive touch pads mapped to the up and down arrows so that it can be used as a presentation clicker, with the vibration providing non-visual feedback.

The Ladybird (Figure 12B) behaves as a media controller with different capacitive spots controlling volume, play/pause, and skip forward/backwards.

The Isopod (Figure 12C) measures consecutive touches along its back to detect stroking. When stroked down its back it prints happy emojis, but when stroked backwards, it sends keystrokes encoding angry emojis to the host machine. It also makes use of the haptic actuator to "purr" through vibration effects when stroked.

5.3 Printegrated Circuits Support an Iterative Design Process

The TuneShroom (Figure 13) is a mushroom-shaped MIDI instrument. Finger touches on the black spots of the cap are registered through capacitive touch sensing. The embedded board, a Seeed Studio Xiao ESP32-S3[14], uses USB MIDI to send notes to a host device such as a smartphone or computer running a MIDI synthesiser application or digital audio workstation (DAW).

The TuneShroom is an example of a more complex design, with challenging 3D routing between the base of the stem, where the microcontroller is inserted, and the pads on the cap of the mushroom. Printegrated Circuits supports iterative processes that are required when designing complex objects, harnessing local digital fabrication practices rather than outsourced production.

Like the other demonstrations, the Tuneshroom was designed in the browser-based CAD platform, Onshape. The platform uses a parametric, timeline-based workflow which allows for modification of previous features, supporting this iterative design workflow where early versions or sections of the design can be printed to inform design choices and changes.

While other researchers have presented tools for 3D routing specifically for the integration of interactive elements into 3D prints [74], we chose to route our models by hand. This decision was made for three primary reasons: When testing existing solutions, they weren't able to correctly resolve the complex geometries we were working with more than two traces; routing by hand allows

[13] ELV1411a LRA, https://nfpshop.com/product/lvm-series-linear-vibration-motors-elv-1411a, Accessed 2025-03

[14] Seeed Studio Xiao ESP32 S3, https://www.seeedstudio.com/XIAO-ESP32S3-p-5627.html, Accessed 2025-03

Figure 12: The slug, ladybird and isopod are all USB HID devices derived from the same base functional design, but each is customised to have a unique form and function. (A) the slug is a haptic presentation clicker, (B) the ladybird is a media controller, (C) the isopod is a stroke-sensitive desk pet.

for the application of domain-specific knowledge to the specific scenario, e.g. understanding the impact of layer heights and anisotropic properties of materials and; finally automatic routing would constitute an independent step outside of the parametric design tools the rest of the model was designed in, which means that manual designs had the benefit that small design changes do not require re-performing any routing.

The physical design of the TuneShroom took several iterations to get right. A specific consideration was the design of the gills. We wanted to use the natural droop of unsupported molten filament to create organic-looking curved gills. This involved printing the device a number of times with manually designed supports. As a designer, having direct access to 3D printing tools meant that several iterations could be made in the time that it would take to have one version outsourced.

With this approach to making interactive devices, iteration is just as easy at all design stages. After the initial creation stage, and some use of our original design, we discovered that the TuneShroom had a flaw: the small base meant that when placed on a surface and a touch pad at the edge was tapped to play a note, it was unstable and prone to falling. The timeline-based CAD model made it easy to edit one of the original shape-defining sketches to stretch out the base and re-print the device with a wider base, as shown in Figure 13.

5.4 Printegrated Circuits Enable Integration within Existing Design Processes

SnailSense (Figure 14) is a plant pot moisture sensor based on Thingiverse user 3Dmon's snail model[15]. It uses resistance sensing to measure soil moisture. Dry soil has a high resistance and, when soaked, the resistance decreases. In contrast with the capacitive touch sensing devices, this device uses a voltage divider circuit that is designed into the object for sensing, as opposed to simple one-pin electrodes. The soil acts as a resistor between reference ground (0V) and an analogue pin on the microcontroller, a thin winding trace is designed into the print between sense and the high level (3V3) pin. The winding trace is designed to be comparable to the resistance of the soil, so the voltage read on the analogue pin is proportional to the resistance of the soil.

Before designing and printing a full object with embedded circuitry, iterative steps using existing prototyping tools like Arduinos and jumper cables can be performed. For example, in order to optimise the resistive sensing of the snail, different electrode designs shown in Figures 14 A and B were first printed, tested and modified as stand-alone parts before combining as one in the snail. Specifically, we varied the length of the fixed resistor trace that had to be in a range similar to the resistance of the soil to maximise sensitivity. In the test pieces, the electrodes were manually connected through wires to an Arduino. Since robustness and minimising assembly time were not critical at this stage, making a full printegrated circuit wasn't necessary. Once optimised, though, these features could all be integrated into a single design, allowing for a fully integrated and repeatable print.

5.5 Printegrated Circuits Enable Fabrication of Modular and Scalable Devices

The Lego Data Physicaliser (Figure 15) is a personal habit tracker, designed to record the number of daily achievements through a tangible medium. The circuit measures the changes in resistance of each tower as bricks are added. The tower of bricks adds resistors in parallel to the circuit, which can be sensed through an analogue pin on the microcontroller. Daily counts are then recorded, allowing for seamless interactions between tangible control and digital tracking. Modular tangible interactive devices are an attractive avenue for researchers exploring the intersection of physical and digital, offering novel ways to explore data [15, 104]. One of the challenges in getting these devices into users' hands is the difficulty of fabricating many of the same modules. We present this device to show how

[15] 3DMON Snail Thingiverse, https://3d-mon.com/, CC BY-SA, Accessed: 2025-03

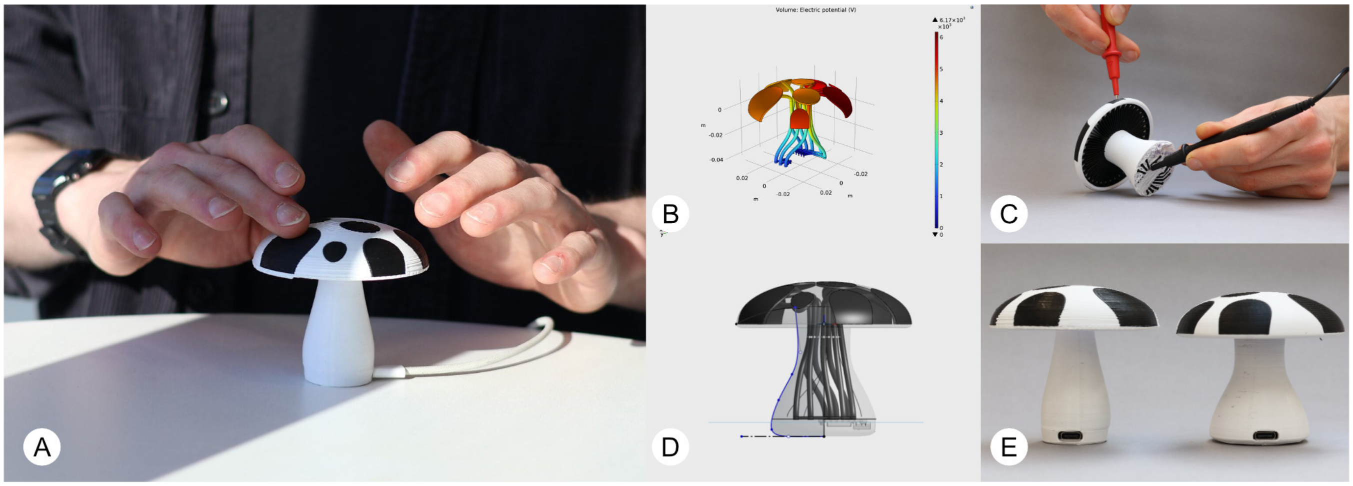

Figure 13: The TuneShroom is a MIDI instrument. Its digital design means that it can be both simulated and tested in the physical world with the ability to make rapid modifications to the design.

passive electronic elements can be scaled to make duplicates and extensions to modular sensing systems without extra effort. In the context of personal fabrication for prototyping, we suggest a key benefit of Printegrated Circuits is that it enables simple scaling-up in the production of tangible interactive devices for user studies.

5.6 Printegrated Circuits Integrate within Existing Workflows

When printing the SnailSense, the electrodes are printed flat on the printbed, however, for their application shown in Figure 14, they need to be pointing downwards to be inserted into the soil. In order to achieve this, we heated the relevant point in the model with a heat gun and folded it using an approach similar to Thermoformed Circuit Boards [44]. Unlike that prior work, however, the high resistance of the traces in our application is not a challenge, so no copper plating step is required. In fact, the high resistance allows for the design of passive resistors into the model that give rise to the voltage divider network needed for this application. This demonstrates that Printegrated circuits can harness the advantages of existing workflows to enable the fabrication of free-form devices.

5.7 Printegrated Circuits Overcome Material Challenges

The high resistance of carbon-black-based conductive filaments can be measured physically as well as simulated. In Comsol Multiphysics[16] we can use the 3D geometry of the TuneShroom's traces and the material's anisotropic resistances to perform Finite Element Analysis to calculate the resistance of the traces.

The physics simulation was set up to calculate the resistance between the contact points on the PCB and the surface of the touch pads on the TuneShroom's cap. The conductive material's anisotropic resistance, caused by the 3D printer's layering of material, is used in the simulation by defining its conductivity with a diagonal matrix. We performed these simulations using the earlier measured resistance values.

$$\sigma = \begin{bmatrix} 5.55 & 0 & 0 \\ 0 & 5.55 & 0 \\ 0 & 0 & 3.33 \end{bmatrix} \quad \text{(S/m)}$$

Figure 13 (B) shows the voltage potential through the geometry of the TuneShroom's traces. The simulation results showed that the different conductive geometries all had a resistance between 4.5-6.1 kΩ. These were compared with the directly measured resistances, which were all higher than the simulations (mean +1.1 kΩ). This could be due to variations in print line orientations. This high resistance, however, doesn't pose an issue for the capacitive touch measurement as the low-resistance dependent control circuitry is all confined to the conventional PCB.

5.8 Printegrated Circuits are Robust

While the robustness of prinjected contacts was demonstrated through rigorous tests in Section 4.3, the TuneShroom's durability has been evidenced through its use at multiple in-person events, where it was carried loosely in a backpack or pocket without any protective enclosure. Its robustness was further illustrated in an informal drop demonstration, where it was dropped from a height of around 2 meters ten times at various angles. Despite the repeated impacts, all touch pads remained fully functional, showing that the internal connections held up well.

5.9 Printegrated Circuits are Sensitive

The ESP32-S3 found in the Xiao microcontroller board used in the TuneShroom has native touch peripherals capable of 16-bit capacitance readings. The design guidelines[17] recommend using an insulating cover over electrodes; to avoid extra coating steps and increase sensitivity with high resistance traces (recommended

[16]Comsol Multiphysics, https://www.comsol.com/, Accessed: 2025-08

[17]ESP32 Touch Sensor Application Note, https://github.com/espressif/esp-iot-solution/blob/release/v1.0/documents/touch_pad_solution/touch_sensor_design_en.md, Accessed: 2025-03

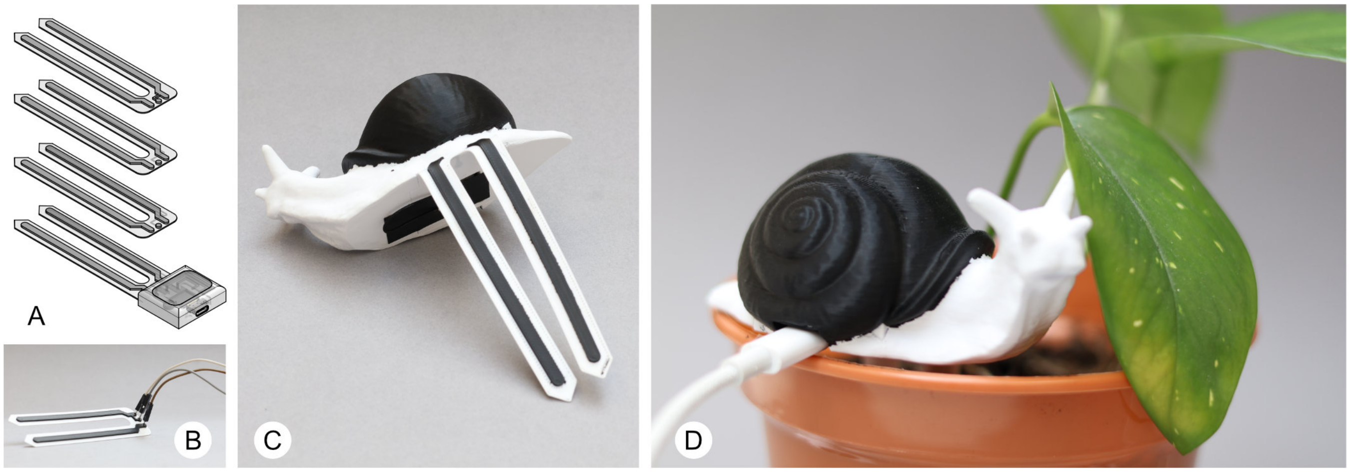

Figure 14: SnailSense is a plant pot moisture sensor that uses the resistance of the soil to track watering. It demonstrates how Printegrated Circuits allow iterative design through prototyping of sensing elements (A) and (B) before integration in a fully Printegrated 3D form (C) and (D).

max of 2 kΩ), we just use the bare conductive filament. This results in high capacitance readings when the pads are touched, up to the maximum readable value. Using the calculation described in the application note, where the sensitivity is (non-trigger value − trigger value)/non-trigger value × 100% we measured the average sensitivity of 110%, for our electrodes, despite the high resistance of the traces. To detect touch events, capacitance readings overcome a threshold. We found that this does not need to be calibrated per-pad or across devices.

5.10 PCB Recovery and Material Downcycling

The novel fabrication process introduces challenges surrounding repair and recyclability due to the enclosed nature of Printegrated Circuits. However, we demonstrate both that the high-value PCB can be recovered to be used in new Printegrated Circuits, and that the printed material, a mixture of conductive and non-conductive PLA, can be down-cycled to fabricate non-interactive objects.

The high value PCB can be recovered for re-use, as shown in Figure 16 A-D: by heating up the prototype with a heat gun, cutting it open with a scalpel, and pulling out the PCB with pliers. The heat gun is used to bring the temperature of the plastic surrounding the PCB to the plastic's glass transition temperature of 60°C. Care should be taken not to overheat the part above the melting point of the solder at around 220°C, at which point components may be susceptible to being knocked off the PCB.

Prinjected material usually fuses to the top printed surface and remains adhered when peeled off, leaving the plated-through holes clear. However, if it remains lodged after extraction, it can be reheated and removed with a fine toothpick.

We also illustrated in Figure 16 E-G that the mixed conductive and non-conductive PLA can be shredded down and re-extruded to produce new filaments and printed into new objects. Using the mixed blend of conductive and non-conductive PLA from the shredded Printegrated Circuit housings and a 67:33 ratio of virgin to recovered material, we were able to extrude new filament with a Felfil filament extruder[18] and use it to print new objects. The resulting parts made from our recycled filament are non-conducting; this is due to the concentration of conductive filler being below the percolation threshold [85]. However, as can be seen in Figure 16F and G, the recycled filament and resulting part appear black despite only a small amount of the black conductive material in the blend.

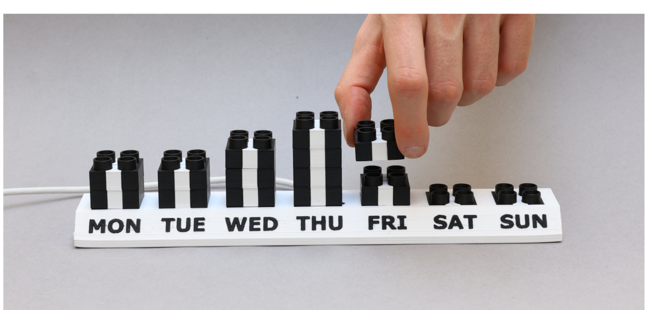

Figure 15: The Data Physicalisation Device uses the resistance of Lego-inspired towers to calculate height, allowing users to record information through tangible media.

6 Discussion

Printegrated Circuits extends work around 3D printing interactive structures using available materials and tools to create self-contained devices so that they can be adopted and deployed by the community. In this section, reflecting on the work, we identify several areas that require further investigation to fully realise this goal.

[18] Felfil filament extruder, https://felfil.com/, Accessed: 2025-04

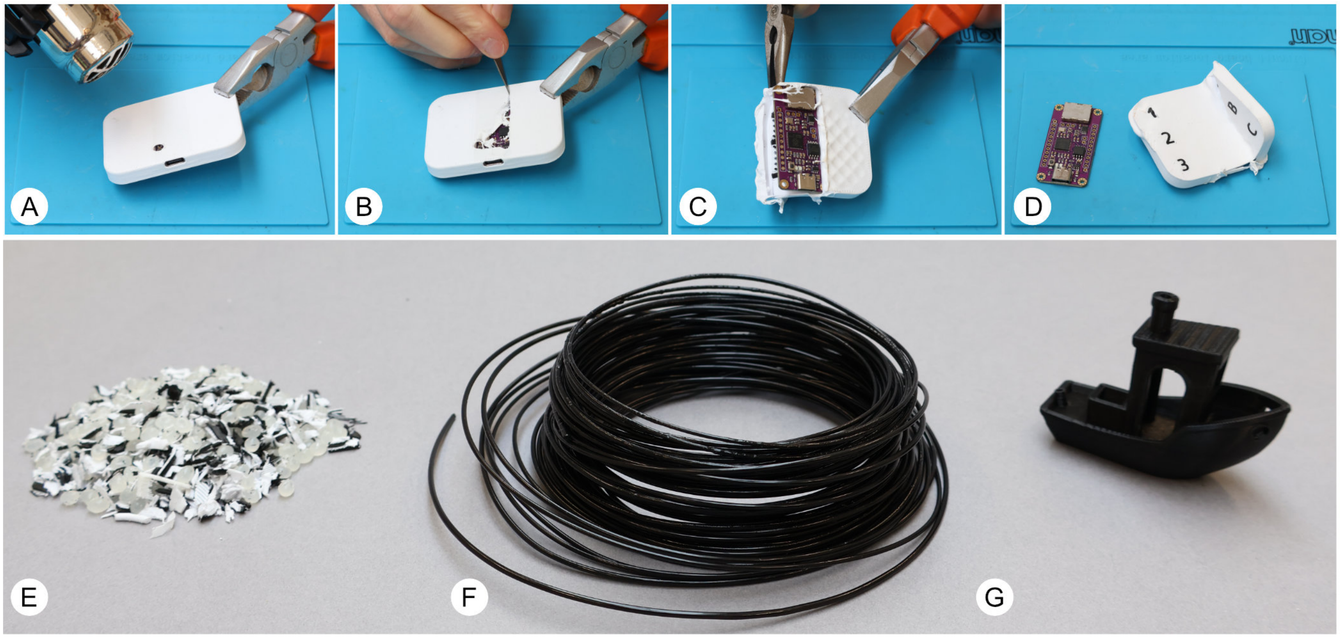

Figure 16: The process of recovering PCBs and filament from Printegrated Circuits: heating with a heat gun (A), using a scalpel to cut layers (B), using pliers to bend material when malleable (C) and freeing the circuit (D). Shredded parts are mixed with virgin PLA pellets at a 33:67 ratio (E) to extrude new filament (F) that can be used to print new non-interactive objects like this Benchy (G).

6.1 Design and Workflow Challenges

The Printegrated Circuits process presents a distinct set of challenges to existing digital fabrication workflows. While the technique relies heavily on existing tools, the novel requirements introduced during design, slicing, and printing highlight the need for more flexible and extendable software. To support newcomers to electronics or 3D printing in designing new Printegrated Circuits, further work is required to encapsulate the domain-specific expertise traditionally gained from direct interactions with materials and machines. This would allow for extending existing tools to better support automation in this kind of workflow.

Bridging the gap between experts and newcomers is crucial for the wider adoption of these technologies. While printing existing designs and inserting PCBs mid-print is achievable for many, the end-to-end design and fabrication process requires much better support. Integrating post-processing scripts and automated routing to some extent could support this [74, 75, 98], but opportunities also lie in developing flexible and extendable tools that actively guide users through new workflows [82, 86, 89]. For instance, such tools could:

- Support the creation of user-customisable objects, similar to Thingiverse Customizer[19].
- Provide interactive guidance for PCB placement and layer selection.
- Automate model-aware firmware generation for the embedded electronics.

[19]Thingiverse Customizer, https://www.thingiverse.com/customizer, Accessed 2025-10

6.2 Material Limitations

Printegrated Circuits overcomes some limitations posed by high resistance printable conductive material by using traditional electronics as material. Challenges still remain when considering modular embedded electronics, active sensing and actuation, or embedded energy storage, which all would require interconnects capable of carrying current between elements. While more conductive specialised filaments such, such as Multi 3D's Electrifi copper filament [24], exist, they are more difficult to print with, requiring precise temperature ranges, having poor adhesion characteristics, and remaining considerably more resistive than bulk copper. High resistances have led researchers to explore the use of wet electroplating processes to improve conductivity [44]. This kind of process comes with its own set of design and fabrication constraints, introducing new barriers to entry. Looking forward, we seek to explore embeddable electronic interconnects as well as functional electronics.

6.3 Material-centred Free-form Personal Fabrication

As additive manufacturing capabilities become increasingly accessible, designers and makers look to use these tools to fabricate more elements of their devices. DisplayFab [34] categorises interactive devices distinctly as input, output and control and distinguishes material-centric fabrication methods from component-based fabrication methods. It postulates the convergence of personally fabricated input techniques and the divergence of visual outputs or displays, with integration of control within material-centric methods being unattainable with current personal fabrication means. In Printegrated Circuits, we provide a hybridised approach offering a step beyond this limitation by spanning the integration of component-based control with material-centric 3D printing. We suggest that, using Printegrated Circuits as a baseline method, future work can explore the seamless integration of material-centric methods with component-based work. This harnesses the strengths of both systems to enable free-form multi-material structures with extended digital functionality within existing fabrication processes.

6.4 Reversibility and Sustainability

It is impossible to present the Printegrated Circuits technique without addressing the challenges around sustainability, specifically, the reversibility of the process in the form of disassembly for iteration and repair. We have demonstrated that the high-value general-purpose electronic elements can be recovered in a useful form and reused in new devices, and that the plastic can be partially recycled.

Disassembly is destructive to any previously printed part of the object, and although the raw PLA material is derived from renewable resources, it does not break down freely in the environment. Other work overcomes some of these challenges with the use of screws [102] and magnets [77]. Improved recycling techniques for multi-material prints [100] suggest that with increased access to fabrication and recycling tools, destructive recovery and full recycling of materials could be considered as a practical alternative to repair altogether. We also look to new and exciting work in extruded biomaterials [6] and consider how techniques to combine these with conductive material like charcoal could be used to build interactive devices with disposable and decomposable casings combined with re-usable embedded electronic elements.

6.5 Future Printed Device Interaction Modalities

In this paper, we presented a number of simple input modalities for Printegrated Circuits, however, existing research has covered many other 3D printed examples that could be augmented using our approach. We specifically look towards integrating output modalities within Printegrated Circuits, for example, embedding electroluminescent driver circuits within devices [35] or integrating custom segmented electrophoretic 'Eink' display film as demonstrated by Grosse-Puppendahl et al. [32]. We are also interested in exploring techniques for combining flexible materials and electrostatic valves [30] to create actuated soft robotics.

We also imagine that the fully enclosed nature of these devices offers a wealth of opportunities beyond the creation of robust demonstrations. Paired with wireless power transfer or energy harvesting techniques, and if necessary, a rechargeable battery or supercapacitor, fully dust-proof and water-resistant devices could be crafted for a range of interaction scenarios.

7 Conclusion

Personal fabrication research continues to democratise access to tools and processes, offering individuals new ways of turning their ideas into physical devices. In particular, 3D printed electronics has the potential to decentralise the production of interactive devices. However, challenges often emerge when taking these solutions beyond one-off demonstrations; limitations in robustness, materials and design tools present barriers to sustained deployment and scaling. This, in turn, limits sharing and adoption.

Printegrated Circuits lowers these barriers by embedding PCBs into the 3D printing workflow with the help of new tooling. Our approach circumvents the limited current-carrying capacity of established conductive filaments by only using them for sensor structures and connections, keeping the remaining digital device interconnections, including power, within a traditional PCB. This technique enables the fabrication of interactive devices that are fully functional out-of-the-printer, allowing an initial prototype to be replicated reliably without significant manual intervention. This supports the recently-proposed process of *isotyping* [39] and enabling small-batch production. Through a series of characterisations and demonstrations, we have presented that this approach is robust and ready to use within the existing digital fabrication workflow. We hope that Printegrated Circuits will inspire the fabrication of robust and fully integrated interactive devices with the tools we already have available to us as researchers, designers and makers, and we look forward to working with the community to extend the concept in future work.

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References

[1] Voxel8 . 2019. https://www.voxel8.com/. Last accessed September 2019. archiveurl: https://web.archive.org/web/20160112091937/http://voxel8.co/ archivedate=14 December 2016.

[2] Marwa Alalawi, Noah Pacik-Nelson, Junyi Zhu, Ben Greenspan, Andrew Doan, Brandon M Wong, Benjamin Owen-Block, Shanti Kaylene Mickens, Wilhelm Jacobus Schoeman, Michael Wessely, Andreea Danielescu, and Stefanie Mueller. 2023. MechSense: A Design and Fabrication Pipeline for Integrating Rotary Encoders into 3D Printed Mechanisms. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3544548.3581361

[3] Vicente Arroyos, Maria L K Viitaniemi, Nicholas Keehn, Vaidehi Oruganti, Winston Saunders, Karin Strauss, Vikram Iyer, and Bichlien H Nguyen. 2022. A Tale of Two Mice: Sustainable Electronics Design and Prototyping. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems (CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, 1–10. doi:10.1145/3491101.3519823

[4] Daniel Ashbrook, Wei-Ju Lin, Nicholas Bentley, Diana Soponar, Zeyu Yan, Valkyrie Savage, Lung-Pan Cheng, Huaishu Peng, and Hyunyoung Kim. 2024. Rhapso: Automatically Embedding Fiber Materials into 3D Prints for Enhanced Interactivity. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24)*. Association for Computing Machinery, New York, NY, USA, 1–20. doi:10.1145/3654777.3676468

[5] Ayah Bdeir. 2009. Electronics as material: littleBits. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction (TEI '09)*. Association for Computing Machinery, New York, NY, USA, 397–400. doi:10.1145/1517664.1517743

[6] Fiona Bell, Camila Friedman-Gerlicz, and Leah Buechley. 2025. Biomaterial Recipes for 3D Printing: A Cookbook of Sustainable and Extrudable Bio-Pastes. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '25)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3689050.3704427

[7] Botfactory. 2025. BotFactory Inc. Last Accessed 2025. https://www.botfactory.co/

[8] Andy Boucher. 2023. Research Products at Scale: Learnings from Designing Devices in Multiples of Ones, Tens, Hundreds and Thousands. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3544548.3581540

[9] Caio Brito, Gutenberg Barros, Walter Correia, Veronica Teichrieb, and João Marcelo Teixeira. 2016. Multimodal augmentation of surfaces using conductive 3D printing. In *ACM SIGGRAPH 2016 Posters (SIGGRAPH ’16)*. Association for Computing Machinery, New York, NY, USA, 1–2. doi:10.1145/2945078.2945093

[10] Jesse Burstyn, Nicholas Fellion, Paul Strohmeier, and Roel Vertegaal. 2015. PrintPut: Resistive and Capacitive Input Widgets for Interactive 3D Prints. In *Human-Computer Interaction – INTERACT 2015*, Julio Abascal, Simone Barbosa, Mirko Fetter, Tom Gross, Philippe Palanque, and Marco Winckler (Eds.). Springer International Publishing, Cham, 332–339. doi:10.1007/978-3-319-22701-6_25

[11] Moritz Bächer, Benjamin Hepp, Fabrizio Pece, Paul G. Kry, Bernd Bickel, Bernhard Thomaszewski, and Otmar Hilliges. 2016. DefSense: Computational Design of Customized Deformable Input Devices. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI ’16)*. Association for Computing Machinery, New York, NY, USA, 3806–3816. doi:10.1145/2858036.2858354

[12] Jorge Cañada, Hyeonseok Kim, and Luis Fernando Velásquez-García. 2024. Three-dimensional, soft magnetic-cored solenoids via multi-material extrusion. *Virtual and Physical Prototyping* 19, 1 (Dec. 2024), e2310046. doi:10.1080/17452759.2024.2310046 Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/17452759.2024.2310046.

[13] Jorge Cañada and Luis Fernando Velásquez-García. 2023. Monolithically 3D-Printed, Miniature Solenoids with Soft Magnetic Core for Compact Systems. In *2023 13th International Conference on Power, Energy and Electrical Engineering (CPEEE)*. IEEE, Tokyo, Japan, 116–120. doi:10.1109/CPEEE56777.2023.10217558

[14] Jorge Cañada and Luis Fernando Velásquez-García. 2024. Semiconductor-free, monolithically 3D-printed logic gates and resettable fuses. *Virtual and Physical Prototyping* 19, 1 (Dec. 2024), e2404157. doi:10.1080/17452759.2024.2404157 Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/17452759.2024.2404157.

[15] Liwei Chan, Stefanie Müller, Anne Roudaut, and Patrick Baudisch. 2012. CapStones and ZebraWidgets: sensing stacks of building blocks, dials and sliders on capacitive touch screens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’12)*. Association for Computing Machinery, New York, NY, USA, 2189–2192. doi:10.1145/2207676.2208371

[16] Xiang ’Anthony’ Chen, Stelian Coros, and Scott E. Hudson. 2018. Medley: A Library of Embeddables to Explore Rich Material Properties for 3D Printed Objects. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI ’18)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3173574.3173736

[17] Xiang ’Anthony’ Chen, Stelian Coros, Jennifer Mankoff, and Scott E. Hudson. 2015. Encore: 3D Printed Augmentation of Everyday Objects with Printed-Over, Affixed and Interlocked Attachments. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST ’15)*. Association for Computing Machinery, New York, NY, USA, 73–82. doi:10.1145/2807442.2807498

[18] Context. 2024. 3d_printing. https://www.contextworld.com/research-updates/3d_printing

[19] Claudia Daudén Roquet, Jeeeun Kim, and Tom Yeh. 2016. 3D Folded PrintGami: Transforming Passive 3D Printed Objects to Interactive by Inserted Paper Origami Circuits. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS ’16)*. Association for Computing Machinery, New York, NY, USA, 187–191. doi:10.1145/2901790.2901891

[20] Artem Dementyev, Hsin-Liu (Cindy) Kao, and Joseph A. Paradiso. 2015. SensorTape: Modular and Programmable 3D-Aware Dense Sensor Network on a Tape. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST ’15)*. Association for Computing Machinery, New York, NY, USA, 649–658. doi:10.1145/2807442.2807507

[21] Dragonfly. 2025. DragonFly IV | A new era in 3D electronics printing, Last Accessed 2025. https://www.nano-di.com/dragonfly-iv

[22] Bhaskar Dutt, Yixuan Chen, Daniel Ashbrook, and Valkyrie Savage. 2025. Impedius: A Signal-Space Multiplexing Technique Using Individual Elements of Impedance for Chained Passive Sensors. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’25)*. Association for Computing Machinery, New York, NY, USA, 1–11. doi:10.1145/3689050.3704949

[23] Chad Duty, Jordan Failla, Seokpum Kim, Tyler Smith, John Lindahl, and Vlastimil Kunc. 2019. Z-Pinning approach for 3D printing mechanically isotropic materials. *Additive Manufacturing* 27 (May 2019), 175–184. doi:10.1016/j.addma.2019.03.007

[24] Patrick F. Flowers, Christopher Reyes, Shengrong Ye, Myung Jun Kim, and Benjamin J. Wiley. 2017. 3D printing electronic components and circuits with conductive thermoplastic filament. *Additive Manufacturing* 18 (Dec. 2017), 156–163. doi:10.1016/j.addma.2017.10.002

[25] Frikk H Fossdal, Vinh Nguyen, Rogardt Heldal, Corie L. Cobb, and Nadya Peek. 2023. Vespidae: A Programming Framework for Developing Digital Fabrication Workflows. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS ’23)*. Association for Computing Machinery, New York, NY, USA, 2034–2049. doi:10.1145/3563657.3596106

[26] Wei Gao, Yunbo Zhang, Diogo C. Nazzetta, Karthik Ramani, and Raymond J. Cipra. 2015. RevoMaker: Enabling Multi-directional and Functionally-embedded 3D printing using a Rotational Cuboidal Platform. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST ’15)*. Association for Computing Machinery, New York, NY, USA, 437–446. doi:10.1145/2807442.2807476

[27] Neil Gershenfeld. 2012. How to Make Almost Anything: The Digital Fabrication Revolution Essay. *Foreign Affairs* 91, 6 (2012), [i]–57. https://heinonline.org/HOL/P?h=hein.journals/fora91&i=1081

[28] Neil A. Gershenfeld. 2005. *Fab: The Coming Revolution on Your Desktop–from Personal Computers to Personal Fabrication*. Basic Books. Google-Books-ID: Oil3bH6fKBkC.

[29] Jun Gong, Olivia Seow, Cedric Honnet, Jack Forman, and Stefanie Mueller. 2021. MetaSense: Integrating Sensing Capabilities into Mechanical Metamaterial. In *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST ’21)*. Association for Computing Machinery, New York, NY, USA, 1063–1073. doi:10.1145/3472749.3474806

[30] Jesse T. Gonzalez and Scott E. Hudson. 2022. Layer by Layer, Patterned Valves Enable Programmable Soft Surfaces. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6, 1 (March 2022), 12:1–12:25. doi:10.1145/3517251

[31] Jesse T Gonzalez, Sonia Prashant, Sapna Tayal, Juhi Kedia, Alexandra Ion, and Scott E Hudson. 2023. Constraint-Driven Robotic Surfaces, At Human-Scale. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST ’23)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3586183.3606740

[32] Tobias Grosse-Puppendahl, Steve Hodges, Nicholas Chen, John Helmes, Stuart Taylor, James Scott, Josh Fromm, and David Sweeney. 2016. Exploring the Design Space for Energy-Harvesting Situated Displays. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST ’16)*. Association for Computing Machinery, New York, NY, USA, 41–48. doi:10.1145/2984511.2984513

[33] Tobias Grosse-Puppendahl, Christian Holz, Gabe Cohn, Raphael Wimmer, Oskar Bechtold, Steve Hodges, Matthew Reynolds, and Joshua Smith. 2017. Finding Common Ground: A Survey of Capacitive Sensing in Human-Computer Interaction. doi:10.1145/3025453.3025808

[34] Ollie Hanton, Mike Fraser, and Anne Roudaut. 2024. DisplayFab: The State of the Art and a Roadmap in the Personal Fabrication of Free-Form Displays Using Active Materials and Additive Manufacturing.. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI ’24)*. Association for Computing Machinery, New York, NY, USA, 1–24. doi:10.1145/3613904.3642708

[35] Ollie Hanton, Michael Wessely, Stefanie Mueller, Mike Fraser, and Anne Roudaut. 2020. ProtoSpray: Combining 3D Printing and Spraying to Create Interactive Displays with Arbitrary Shapes. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI ’20)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3313831.3376543

[36] Kobi Hartley, Aron Eggens, James Hahn, , Steve Hodges, Andrew Scott, Joe Finney, Charly Olivier, Mannu Lambrichts, Lorraine Underwood, and Jan Hollinshead. 2025. MakeDevice: Easing the path from hardware prototyping toolkits to manufacturable devices. In *Proceedings of TEI 2025*.

[37] Kobi Hartley, Joe Finney, Steve Hodges, Peli De Halleux, James Devine, and Gabriele D’Amone. 2023. MakeDevice: Evolving Devices Beyond the Prototype with Jacdac. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’23)*. Association for Computing Machinery, New York, NY, USA, 1–7. doi:10.1145/3569009.3573106

[38] Liang He, Jarrid A. Wittkopf, Ji Won Jun, Kris Erickson, and Rafael Tico Ballagas. 2022. ModElec: A Design Tool for Prototyping Physical Computing Devices Using Conductive 3D Printing. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 5, 4 (Dec. 2022), 159:1–159:20. doi:10.1145/3495000

[39] Steve Hodges. 2025. SenseCam and Isotyping: The Challenges and Benefits of Working with New Hardware. In *Proceedings of the 33rd ACM International Conference on Multimedia* (Dublin, Ireland) *(MM ’25)*. Association for Computing Machinery, New York, NY, USA, 3–4. doi:10.1145/3746027.3758124

[40] Steve Hodges and Nicholas Chen. 2019. Long Tail Hardware: Turning Device Concepts Into Viable Low Volume Products. *IEEE Pervasive Computing* 18, 4 (Oct. 2019), 51–59. doi:10.1109/MPRV.2019.2947966 Conference Name: IEEE Pervasive Computing.

[41] Steve Hodges, Nicolas Villar, James Scott, and Albrecht Schmidt. 2012. A New Era for Ubicomp Development. *IEEE Pervasive Computing* 11, 1 (Jan. 2012), 5–9. doi:10.1109/MPRV.2012.1 Conference Name: IEEE Pervasive Computing.

[42] Freddie Hong, Steve Hodges, Connor Myant, and David E Boyle. 2022. Open5x: Accessible 5-axis 3D printing and conformal slicing. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems (CHI EA ’22)*. Association for Computing Machinery, New York, NY, USA, 1–6. doi:10.1145/3491101.3519782

[43] Freddie Hong, Borut Lampret, Connor Myant, Steve Hodges, and David Boyle. 2023. 5-axis multi-material 3D printing of curved electrical traces. *Additive Manufacturing* 70 (May 2023), 103546. doi:10.1016/j.addma.2023.103546

[44] Freddie Hong, Connor Myant, and David E Boyle. 2021. Thermoformed Circuit Boards: Fabrication of highly conductive freeform 3D printed circuit boards with heat bending. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI ’21)*. Association for Computing Machinery, New

York, NY, USA, 1–10. doi:10.1145/3411764.3445469

[45] Jonathan Hook, Thomas Nappey, Steve Hodges, Peter Wright, and Patrick Olivier. 2014. Making 3D printed objects interactive using wireless accelerometers. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems (CHI EA '14)*. Association for Computing Machinery, New York, NY, USA, 1435–1440. doi:10.1145/2559206.2581137

[46] Kaori Ikematsu and Itiro Siio. 2018. Ohmic-Touch: Extending Touch Interaction by Indirect Touch through Resistive Objects. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–8. doi:10.1145/3173574.3174095

[47] Yuhei Imai, Kunihiro Kato, Norihisa Segawa, and Hiroyuki Manabe. 2019. Hot Stamping of Electric Circuits by 3D Printer. In *Adjunct Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 128–130. doi:10.1145/3332167.3356895

[48] Vikram Iyer, Justin Chan, and Shyamnath Gollakota. 2017. 3D printing wireless connected objects. *ACM Trans. Graph.* 36, 6 (Nov. 2017), 242:1–242:13. doi:10.1145/3130800.3130822

[49] Jaakko T. Karras, Christine L. Fuller, Kalind C. Carpenter, Alessandro Buscicchio, Dale McKeeby, Christopher J. Norman, Carolyn E. Parcheta, Ivan Davydychev, and Ronald S. Fearing. 2017. Pop-up mars rover with textile-enhanced rigid-flex PCB body. In *2017 IEEE International Conference on Robotics and Automation (ICRA)*. 5459–5466. doi:10.1109/ICRA.2017.7989642

[50] Kunihiro Kato, Kaori Ikematsu, and Yoshihiro Kawahara. 2020. CAPath: 3D-Printed Interfaces with Conductive Points in Grid Layout to Extend Capacitive Touch Inputs. *Proc. ACM Hum.-Comput. Interact.* 4, ISS (Nov. 2020), 193:1–193:17. doi:10.1145/3427321

[51] Kunihiro Kato and Homei Miyashita. 2016. 3D Printed Physical Interfaces that can Extend Touch Devices. In *Adjunct Proceedings of the 29th Annual ACM Symposium on User Interface Software and Technology (UIST '16 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 47–49. doi:10.1145/2984751.2985700

[52] Yoshihiro Kawahara, Steve Hodges, Benjamin S. Cook, Cheng Zhang, and Gregory D. Abowd. 2013. Instant inkjet circuits: lab-based inkjet printing to support rapid prototyping of UbiComp devices. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing (UbiComp '13)*. Association for Computing Machinery, New York, NY, USA, 363–372. doi:10.1145/2493432.2493486

[53] Rushil Khurana and Steve Hodges. 2020. Beyond the Prototype: Understanding the Challenge of Scaling Hardware Device Production. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–11. doi:10.1145/3313831.3376761

[54] Johan Kildal. 2010. 3D-press: haptic illusion of compliance when pressing on a rigid surface. In *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction (ICMI-MLMI '10)*. Association for Computing Machinery, New York, NY, USA, 1–8. doi:10.1145/1891903.1891931

[55] Mannu Lambrichts, Raf Ramakers, Steve Hodges, Sven Coppers, and James Devine. 2021. A Survey and Taxonomy of Electronics Toolkits for Interactive and Ubiquitous Device Prototyping. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 5, 2 (June 2021), 70:1–70:24. doi:10.1145/3463523

[56] Simon J. Leigh, Robert J. Bradley, Christopher P. Purssell, Duncan R. Billson, and David A. Hutchins. 2012. A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors. *PLOS ONE* 7, 11 (Nov. 2012), e49365. doi:10.1371/journal.pone.0049365 Publisher: Public Library of Science.

[57] Jiaji Li, Shuyue Feng, Maxine Perroni-Scharf, Yujia Liu, Emily Guan, Guanyun Wang, and Stefanie Mueller. 2025. Xstrings: 3D Printing Cable-Driven Mechanism for Actuation, Deformation, and Manipulation. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, 1–17. doi:10.1145/3706598.3714282

[58] Xiaolong Li, Cheng Yao, Shang Shi, Shuyue Feng, Yujie Zhou, Haoye Dong, Shichao Huang, Xueyan Cai, Kecheng Jin, Fangtian Ying, and Guanyun Wang. 2024. E-Joint: Fabrication of Large-Scale Interactive Objects Assembled by 3D Printed Conductive Parts with Copper Plated Joints. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24)*. Association for Computing Machinery, New York, NY, USA, 1–18. doi:10.1145/3654777.3676398

[59] Karola Marky, Martin Schmitz, Verena Zimmermann, Martin Herbers, Kai Kunze, and Max Mühlhäuser. 2020. 3D-Auth: Two-Factor Authentication with Personalized 3D-Printed Items. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3313831.3376189

[60] Kongpyung (Justin) Moon, Zofia Marciniak, Ryo Suzuki, and Andrea Bianchi. 2024. 3D Printing Locally Activated Visual-Displays Embedded in 3D Objects via Electrically Conductive and Thermochromic Materials. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3613904.3642537

[61] Martin Nisser, Christina Chen Liao, Yuchen Chai, Aradhana Adhikari, Steve Hodges, and Stefanie Mueller. 2021. LaserFactory: A Laser Cutter-based Electromechanical Assembly and Fabrication Platform to Make Functional Devices & Robots. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3411764.3445692

[62] William Odom, Ron Wakkary, Youn-kyung Lim, Audrey Desjardins, Bart Hengeveld, and Richard Banks. 2016. From Research Prototype to Research Product. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, New York, NY, USA, 2549–2561. doi:10.1145/2858036.2858447

[63] Hyunjoo Oh, Tung D. Ta, Ryo Suzuki, Mark D. Gross, Yoshihiro Kawahara, and Lining Yao. 2018. PEP (3D Printed Electronic Papercrafts): An Integrated Approach for 3D Sculpting Paper-Based Electronic Devices. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3173574.3174015

[64] Optomec. [n. d.]. Optomec - 3D PRINTING SOLUTIONS FOR AN ADDITIVE MANUFACTURING WORLD. https://optomec.com/

[65] Windell Oskay and Eric Schlaepfer. 2022. *Open Circuits: The Inner Beauty of Electronic Components*. No Starch Press. Google-Books-ID: StOQEAAAQBAJ.

[66] Gianpaolo Palma, Narges Pourjafarian, Jürgen Steimle, and Paolo Cignoni. 2024. Capacitive Touch Sensing on General 3D Surfaces. *ACM Trans. Graph.* 43, 4 (July 2024), 103:1–103:20. doi:10.1145/3658185

[67] Huaishu Peng, François Guimbretière, James McCann, and Scott Hudson. 2016. A 3D Printer for Interactive Electromagnetic Devices. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. Association for Computing Machinery, New York, NY, USA, 553–562. doi:10.1145/2984511.2984523

[68] Narjes Pourjafarian, Marion Koelle, Fjolla Mjaku, Paul Strohmeier, and Jürgen Steimle. 2022. Print-A-Sketch: A Handheld Printer for Physical Sketching of Circuits and Sensors on Everyday Surfaces. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, 1–17. doi:10.1145/3491102.3502074

[69] Protopasta. [n. d.]. 3D Printing a Multi-Material Conductive Touch-Sensitive 3D Printed Controller for Makey Makey With a Single Extruder 3D Printer. https://www.instructables.com/Single-Extruder-Multi-Material/

[70] Jie Qi, Andrew "bunnie" Huang, and Joseph Paradiso. 2015. Crafting technology with circuit stickers. In *Proceedings of the 14th International Conference on Interaction Design and Children (IDC '15)*. Association for Computing Machinery, New York, NY, USA, 438–441. doi:10.1145/2771839.2771873

[71] Rei Sakura, Changyo Han, Yahui Lyu, Keisuke Watanabe, Ryosuke Yamamura, and Yasuaki Kakehi. 2023. LattiSense: A 3D-Printable Resistive Deformation Sensor with Lattice Structures. In *Proceedings of the 8th ACM Symposium on Computational Fabrication (SCF '23)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3623263.3623361

[72] John Sarik, Alex Butler, Nicolas Villar, James Scott, and Steve Hodges. 2012. Combining 3D printing and printable electronics. In *Proceedings of TEI 2012 Works in Progress*. https://www.microsoft.com/en-us/research/wp-content/uploads/2016/02/07-sarik.done_.pdf

[73] Valkyrie Savage, Sean Follmer, Jingyi Li, and Björn Hartmann. 2015. Makers' Marks: Physical Markup for Designing and Fabricating Functional Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. Association for Computing Machinery, New York, NY, USA, 103–108. doi:10.1145/2807442.2807508

[74] Valkyrie Savage, Ryan Schmidt, Tovi Grossman, George Fitzmaurice, and Björn Hartmann. 2014. A series of tubes: adding interactivity to 3D prints using internal pipes. In *Proceedings of the 27th annual ACM symposium on User interface software and technology (UIST '14)*. Association for Computing Machinery, New York, NY, USA, 3–12. doi:10.1145/2642918.2647374

[75] Martin Schmitz, Mohammadreza Khalilbeigi, Matthias Balwierz, Roman Lissermann, Max Mühlhäuser, and Jürgen Steimle. 2015. Capricate: A Fabrication Pipeline to Design and 3D Print Capacitive Touch Sensors for Interactive Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. Association for Computing Machinery, New York, NY, USA, 253–258. doi:10.1145/2807442.2807503

[76] Martin Schmitz, Andreas Leister, Niloofar Dezfuli, Jan Riemann, Florian Müller, and Max Mühlhäuser. 2016. Liquido: Embedding Liquids into 3D Printed Objects to Sense Tilting and Motion. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 2688–2696. doi:10.1145/2851581.2892275

[77] Martin Schmitz, Jan Riemann, Florian Müller, Steffen Kreis, and Max Mühlhäuser. 2021. Oh, Snap! A Fabrication Pipeline to Magnetically Connect Conventional and 3D-Printed Electronics. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery,

New York, NY, USA, 1–11. doi:10.1145/3411764.3445641

[78] Martin Schmitz, Jürgen Steimle, Jochen Huber, Niloofar Dezfuli, and Max Mühlhäuser. 2017. Flexibles: Deformation-Aware 3D-Printed Tangibles for Capacitive Touchscreens. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1001–1014. doi:10.1145/3025453.3025663

[79] Martin Schmitz, Martin Stitz, Florian Müller, Markus Funk, and Max Mühlhäuser. 2019. ./trilaterate: A Fabrication Pipeline to Design and 3D Print Hover-, Touch-, and Force-Sensitive Objects. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3290605.3300684

[80] Corey Shemelya, Fernando Cedillos, Efrian Aguilera, David Espalin, Danny Muse, Ryan Wicker, and Eric MacDonald. 2015. Encapsulated Copper Wire and Copper Mesh Capacitive Sensing for 3-D Printing Applications. *IEEE Sensors Journal* 15, 2 (Feb. 2015), 1280–1286. doi:10.1109/JSEN.2014.2356973 Conference Name: IEEE Sensors Journal.

[81] Yu Song, Roy A. Boekraad, Lampros Roussos, Adrie Kooijman, Charlie C. L. Wang, and Jo M. P. Geraedts. 2017. 3D Printed Electronics: Opportunities and Challenges From Case Studies. American Society of Mechanical Engineers Digital Collection. doi:10.1115/DETC2017-67503

[82] Blair Subbaraman, Nathaneal Bursch, and Nadya Peek. 2025. It's Not the Shape, It's the Settings: Tools for Exploring, Documenting, and Sharing Physical Fabrication Parameters in 3D Printing. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, 1–19. doi:10.1145/3706598.3713354

[83] Lingyun Sun, Yitao Fan, Boyu Feng, Yifu Zhang, Deying Pan, Yiwen Ren, Yuyang Zhang, Qi Wang, Ye Tao, and Guanyun Wang. 2024. MagneDot: Integrated Fabrication and Actuation Methods of Dot-Based Magnetic Shape Displays. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24)*. Association for Computing Machinery, New York, NY, USA, 1–18. doi:10.1145/3654777.3676427

[84] Saiganesh Swaminathan, Kadri Bugra Ozutemiz, Carmel Majidi, and Scott E. Hudson. 2019. FiberWire: Embedding Electronic Function into 3D Printed Mechanically Strong, Lightweight Carbon Fiber Composite Objects. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–11. doi:10.1145/3290605.3300797

[85] Reza Taherian and Ayesha Kausar. 2018. *Electrical Conductivity in Polymer-Based Composites: Experiments, Modelling, and Applications*. William Andrew. Google-Books-ID: wuR8DwAAQBAJ.

[86] Jasper Tran O'Leary, Gabrielle Benabdallah, and Nadya Peek. 2023. Imprimer: Computational Notebooks for CNC Milling. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3544548.3581334

[87] Tiffany Tseng and Yoshihiro Kawahara. 2021. Circuit Assemblies: Electronic Modules for Interactive 3D-Prints. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference (DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1115–1128. doi:10.1145/3461778.3462024

[88] Hannah Twigg-Smith, Jasper Tran O'Leary, and Nadya Peek. 2021. Tools, Tricks, and Hacks: Exploring Novel Digital Fabrication Workflows on #PlotterTwitter. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3411764.3445653

[89] Hannah Twigg-Smith and Nadya Peek. 2023. Dynamic Toolchains: Software Infrastructure for Digital Fabrication Workflows. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23)*. Association for Computing Machinery, New York, NY, USA, 1–20. doi:10.1145/3586183.3606802

[90] Nobuyuki Umetani and Ryan Schmidt. 2017. SurfCuit: Surface-Mounted Circuits on 3D Prints. *IEEE Computer Graphics and Applications* 37, 3 (May 2017), 52–60. doi:10.1109/MCG.2017.40 Conference Name: IEEE Computer Graphics and Applications.

[91] César M. A. Vasques, João P. R. Ferreira, Fernando A. V. Figueiredo, and João C. C. Abrantes. 2025. On the Electrical Resistivity Measurement Methods and Properties of Conductive 3D-Printing PLA Filaments. *Engineering Proceedings* 87, 1 (2025), 26. doi:10.3390/engproc2025087026 Publisher: Multidisciplinary Digital Publishing Institute.

[92] Joshua Vasquez, Hannah Twigg-Smith, Jasper Tran O'Leary, and Nadya Peek. 2020. Jubilee: An Extensible Machine for Multi-tool Fabrication. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3313831.3376425

[93] Voltera. [n. d.]. Voltera: Pioneering Prototyping Solutions for Additive Electronics. https://www.voltera.io/

[94] Ludwig Wilhelm Wall, Alec Jacobson, Daniel Vogel, and Oliver Schneider. 2021. Scrappy: Using Scrap Material as Infill to Make Fabrication More Sustainable. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3411764.3445187

[95] Ludwig Wilhelm Wall, Oliver Schneider, and Daniel Vogel. 2023. Substiports: User-Inserted Ad Hoc Objects as Reusable Structural Support for Unmodified FDM 3D Printers. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23)*. Association for Computing Machinery, New York, NY, USA, 1–20. doi:10.1145/3586183.3606718

[96] Ludwig Wilhelm Wall, Oliver Schneider, and Daniel Vogel. 2025. Intermittent Interaction in Digital Fabrication: User Perception of Periodic Intervention in Semi-Automated Creation Tasks. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, 1–16. doi:10.1145/3706598.3713692

[97] Florens Wasserfall, Daniel Ahlers, Norman Hendrich, and Jianwei Zhang. 2016. 3D-Printable Electronics - Integration of SMD Placement and Wiring into the Slicing Process for FDM Fabrication. (2016). https://hdl.handle.net/2152/89717 Publisher: University of Texas at Austin.

[98] Florens Wasserfall, Norman Hendrich, Daniel Ahlers, and Jianwei Zhang. 2020. Topology-aware routing of 3D-printed circuits. *Additive Manufacturing* 36 (Dec. 2020), 101523. doi:10.1016/j.addma.2020.101523

[99] Christian Weichel, Manfred Lau, and Hans Gellersen. 2013. Enclosed: a component-centric interface for designing prototype enclosures. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI '13)*. Association for Computing Machinery, New York, NY, USA, 215–218. doi:10.1145/2460625.2460659

[100] Xin Wen, S. Sandra Bae, and Michael L. Rivera. 2025. Enabling Recycling of Multi-Material 3D Printed Objects through Computational Design and Disassembly by Dissolution. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, 1–21. doi:10.1145/3706598.3714080

[101] Zeyu Yan, SuHwan Hong, Josiah Hester, Tingyu Cheng, and Huaishu Peng. 2025. DissolvPCB: Fully Recyclable 3D-Printed Electronics with Liquid Metal Conductors and PVA Substrates. doi:10.1145/3746059.3747604 arXiv:2507.22193 [cs].

[102] Zeyu Yan, Jiasheng Li, Zining Zhang, and Huaishu Peng. 2024. SolderlessPCB: Reusing Electronic Components in PCB Prototyping through Detachable 3D Printed Housings. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 1–17. doi:10.1145/3613904.3642765

[103] Zeyu Yan, Anup Sathya, Sahra Yusuf, Jyh-Ming Lien, and Huaishu Peng. 2022. Fibercuit: Prototyping High-Resolution Flexible and Kirigami Circuits with a Fiber Laser Engraver. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3526113.3545652

[104] Arika Yoshida, Buntarou Shizuki, and Jiro Tanaka. 2015. Capacitive Blocks: A Block System that Connects the Physical with the Virtual using Changes of Capacitance. In *Adjunct Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 85–86. doi:10.1145/2815585.2815731

[105] Yang Zhang, Gierad Laput, and Chris Harrison. 2017. Electrick: Low-Cost Touch Sensing Using Electric Field Tomography. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3025453.3025842

[106] Junyi Zhu, Lotta-Gili Blumberg, Yunyi Zhu, Martin Nisser, Ethan Levi Carlson, Xin Wen, Kevin Shum, Jessica Ayeley Quaye, and Stefanie Mueller. 2020. CurveBoards: Integrating Breadboards into Physical Objects to Prototype Function in the Context of Form. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3313831.3376617

[107] Junyi Zhu, Yunyi Zhu, Jiaming Cui, Leon Cheng, Jackson Snowden, Mark Chounlakone, Michael Wessely, and Stefanie Mueller. 2020. MorphSensor: A 3D Electronic Design Tool for Reforming Sensor Modules. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. Association for Computing Machinery, New York, NY, USA, 541–553. doi:10.1145/3379337.3415898

[108] Fabian Ziervogel, Lukas Boxberger, André Bucht, and Welf-Guntram Drossel. 2021. Expansion of the Fused Filament Fabrication (FFF) Process Through Wire Embedding, Automated Cutting, and Electrical Contacting. *IEEE Access* 9 (2021), 43036–43049. doi:10.1109/ACCESS.2021.3065873 Conference Name: IEEE Access.