Oh, Snap! A Fabrication Pipeline to Magnetically Connect Conventional and 3D-Printed Electronics

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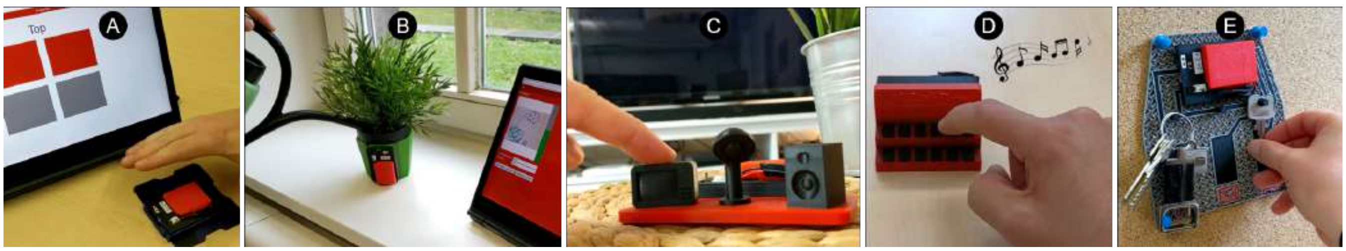

Figure 1: By magnetically connecting conventional electronics with 3D-printed objects, the *Oh, Snap!* fabrication pipeline can be used to explore a large variety of interactions with 3D-printed objects, ranging from hovering (A), water level sensing (B), touch (C/D), or object presence (E).

ABSTRACT

3D printing has revolutionized rapid prototyping by speeding up the creation of custom-shaped objects. With the rise of multi-material 3D printers, these custom-shaped objects can now be made interactive in a single pass through passive conductive structures. However, connecting conventional electronics to these conductive structures often still requires time-consuming manual assembly involving many wires, soldering or gluing.

To alleviate these shortcomings, we propose *Oh, Snap!*: a fabrication pipeline and interfacing concept to magnetically connect a 3D-printed object equipped with passive sensing structures to conventional sensing electronics. To this end, *Oh, Snap!* utilizes ferromagnetic and conductive 3D-printed structures, printable in a single pass on standard printers. We further present a proof-of-concept capacitive sensing board that enables easy and robust magnetic assembly to quickly create interactive 3D-printed objects. We evaluate *Oh, Snap!* by assessing the robustness and quality of the connection and demonstrate its broad applicability by a series of example applications.

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CCS CONCEPTS

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

KEYWORDS

3D printing; capacitive sensing; prototyping; proximity; touch

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1 INTRODUCTION

3D printing is revolutionizing the creation of complex and customized objects. With continuously evolving multi-material 3D printers, it is now feasible to combine multiple different materials (e.g. conductive or deformable) in a single printing pass, often even without requiring assembly in the inside of an object anymore. This considerably lowers the time and effort for the creation and enables many new types of custom-shaped interactive objects. As such, research already has started to explore this interaction space, contributing a plethora of new interaction possibilities that range from 3D-printed custom-shaped touch [3, 38] or deformation input [1, 40] to optical [2, 48] or auditory output [17].

While the interactive objects are often fully 3D-printed, the active electronics still need to be placed manually either during the printing process or directly after printing via soldering or gluing. These approaches still either require manual wiring and complicated hardware setups (which slows down rapid prototyping, despite using 3D printing) or permanently buries valuable electronic components inside printed objects (which often is a waste of components and increases the total printing costs).

To address these limitations, we propose *Oh, Snap!*: an interfacing concept and fabrication pipeline to create 3D objects with internally printed sensing structures that magnetically connect to conventional electronics. Objects that are 3D printed with *Oh, Snap!* consist of insulating, ferromagnetic, and conductive structures, printable on standard printers in a single pass. This approach eases the complex and time-consuming assembly of wires and active electronics that is usually required to create interactive 3D-printed objects. Moreover, we contribute a fabrication pipeline for capacitive sensing that enables users to design, print, and use interactive objects without expert knowledge in computer-aided design. To this end, we also present a prototyping board that can be easily and robustly snapped to the printed objects using the aforementioned interfacing concept and pipeline. We conclude with an evaluation of the snapping performance and the corresponding user experience, and a set of example applications.

While the *Oh, Snap!* interfacing concept operates with generic electrical connections, the fabrication pipeline intentionally focuses on capacitive sensing as a widely-used sensing technique for rapid prototyping, which has been proven to be versatile, not only for touch detection but also for detecting proximity [9, 12], deformations [40], different users [11, 14], touch gestures [33], or movement of liquids [39].

In summary, the contributions of this paper are:

(1) an open concept for magnetic interfacing 3D-printed objects with conventional electronics without requiring assembly at the 3D-printed object (an aspect not covered by consumer products)
(2) a fabrication pipeline for widely-used capacitive sensing
(3) an exploration of the fundamental properties and a validation of the practicability and robustness of the connection between 3D-printed objects and conventional electronics
(4) a set of exemplary use cases illustrating the applicability of *Oh, Snap!*.

2 RELATED WORK

This paper is situated in prototyping platforms and digital fabrication of interactive 3D objects.

2.1 Platforms for Rapid Prototyping of Interactive Objects

With the advent of the maker scene, building custom hardware devices and prototypes has become increasingly common for both, professional and hobbyist use. As a result of this trend, various *rapid prototyping* frameworks and hardware platforms have been proposed to ease the assembly and use of varying electrical components. Among many others (e.g. [32, 44]), some of the most prominent platforms are Arduino [27], Phidgets [6], and .NET Gadgeteer [13, 46]. Moreover, low-cost sensor platforms emerged that allow using electrical components on tape [4, 5] or provide means to sketch [28] or construct [16] physical user interfaces rapidly with low-cost materials.

While hardware platforms and frameworks ease the use of electrical components, they often constrain the possible 3D geometries of the interactive object as the modules have a predefined form-factor. This is especially severe considering the possible complexity of 3D-printed geometries. While research explored using 3D printing for the enclosing object [35, 47], the integration of electronics still requires soldering or insertion of cables and electrical components during the printing process, which is cumbersome, time-consuming, and error-prone.

Probably most closely related to our approach are LittleBits' bitsnaps [23] and SnapBot [19]. In general, LittleBits enables the fast creation of electronic circuits. In particular, LittleBits' bitsnaps enable to connect two conventional electronics component by snapping. Moreover, SnapBot contributes a reconfigurable legged robot that, while housed in 3D-printed parts, still magnetically connects two conventional electronics components. In contrast, *Oh, Snap!* is, to the best of our knowledge, the first paper that contributes a magnetic connector that is 3D-printable on the object's side and, hence, does not require any post-assembly steps compared to solutions such as littleBits' bitsnaps or Snapbot's conventional electrical parts. Both approaches would have to be lavishly integrated into the 3D printing process by gluing or soldering, whereas *Oh, Snap!* bridges precisely this gap.

2.2 Digital Fabrication of Interactive Objects

Many works embed electrical components in non-interactive 3D objects to make them interactive. This can be achieved by mounting of components [45, 51] such as capacitive [33, 49] and acoustic [30] sensors, or by embedding cameras [34], accelerometers [15], or mobile devices [21]. Although these approaches require only a few components, they require a lot of assembly work, alter the surface properties of the objects, or only work on the surface or with hollow molded parts that have to be opened again after printing.

Further research concerns the custom-made digital fabrication of interactive structures. This includes the creation of input and output functions in 3D-printed objects through light pipes [2, 48], through manually filling of inner pipes with media after printing [36], or through pipes that transmit sound [20]. Other approaches print touch-sensitive objects with a conductive spray [17], conductive plastic [3, 18, 22, 25, 26, 37, 38, 40, 42] or conductive paint [7, 8, 29, 50]. To achieve high resolution, these approaches require many sensors, each of which must be lavishly connected to a single trace via soldering or gluing.

In contrast, the *Oh, Snap!* interface connects conventional and 3D-printed electronics with less assembly effort and enables, through our fabrication pipeline and board, easy and robust creation of interactive 3D-printed objects.

3 MAGNETICALLY CONNECTING CONVENTIONAL AND 3D-PRINTED ELECTRONICS

To efficiently create and prototype interactive 3D-printed objects, not only the creation of custom-shaped objects with passive internal interactive structures but also the attachment and removal of

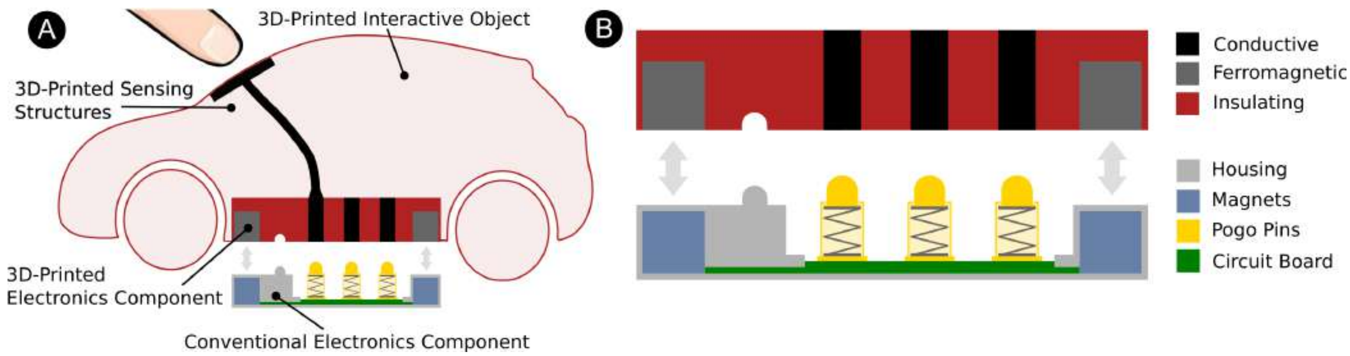

Figure 2: A user integrates the 3D-printed component of the *Oh, Snap!* interface in a 3D object that they have also equipped with a touch electrode (A). The conventional electronics component of the *Oh, Snap!* interface is then magnetically attached to the object after printing (B).

conventional active electronics should be fast, robust, and easily repeatable. Although magnetic connectors for conventional electronics have been available for a long time (e.g. Apple's MagSafe or Little Bits), it is still unclear how they can be integrated into 3D-printed objects.

In this section, we, therefore, present an approach to extend 3D-printed interactive objects in such a way that a robust magnetic connection to conventional electronics can be established.

As detailed below, the concept consists of (1) a 3D-printed electronics component connected to 3D-printed sensing structures, and (2) a conventional electronic component connected to conventional electronics (see Figure 2).

3.1 3D-Printed Electronics Component of the Interface

The 3D-printed electronics component is a material composite, which consists of three main material structures (see the top of Figure 2B):

- ■ The *conductive structure* connects the 3D-printed passive sensing structures inside the 3D-printed object through conductive traces to the conventional electronics component. It is embedded within the 3D-printed object and made of a conductive polymer.
- ■ The *ferromagnetic structure* is printed near the point of attachment of the conventional electronics component to allow magnetic interfacing without using screws or connector plugs. It is made of a ferromagnetic polymer.
- ■ The *insulating structure* forms the overall 3D object and also electrically separates conductive structures. It is made of a standard insulating polymer.

This component can be easily integrated into any 3D-printable model as it only requires a flat subsurface and does not require a certain printing orientation. If required, multiple of these components can be embedded within one object. In Section 4, we propose a fabrication pipeline including a design tool to further ease this process for users.

3.2 Conventional Electronics Component of the Interface

The conventional electronics component consists of three main parts (see the bottom of Figure 2B):

- ■ Two *magnets* embedded in the housing attract the ferromagnetic structure of the 3D-printed electronics component. This mechanism prevents accidental detachment of the conventional electronics component.
- ■ The *housing* itself has at least two hemispherical bumps that exactly fit into respective 3D-printed notches. This mechanism prevents (lateral) displacement (other than pulling apart). In the event of misalignment, the height of the bumps prevents sufficient magnetic adhesion and, thus, physically avoids wrong snapping.
- ■ The active *circuit board* is equipped with standard pogo pins ■ (i.e. spring-loaded electrical connectors), that establish a direct connection between the conductive structure of the 3D-printed electronics component and the conventional electronics component. The latter may contain any active electrical device, ranging from simple components (e.g. resistors or capacitors) to advanced microcontrollers (e.g. for capacitive and resistive sensing or wireless communication).

We opted for pogo pins due to their improved resilience and durability against many attachment cycles (as proven, e.g. by Apple's MagSafe power connectors), while at the same time compensating for slight irregularities of the 3D-printed component. For simplicity, the conventional electronics component is referred to as the "board" in the remainder of this paper.

4 FABRICATION PIPELINE FOR OBJECTS FEATURING CAPACITIVE SENSING

As an exemplary implementation and to prove the applicability of the *Oh, Snap!* concept, we propose a fabrication pipeline (see Figure 3) focused on capacitive sensing aimed at non-expert users with only basic experience in computer-aided design. We focus on capacitive sensing because of two reasons: First, it is a widely-used and well understood sensing technique capable of detecting various interactions beyond touch [9, 11, 12, 14, 33, 39, 40].Second, a

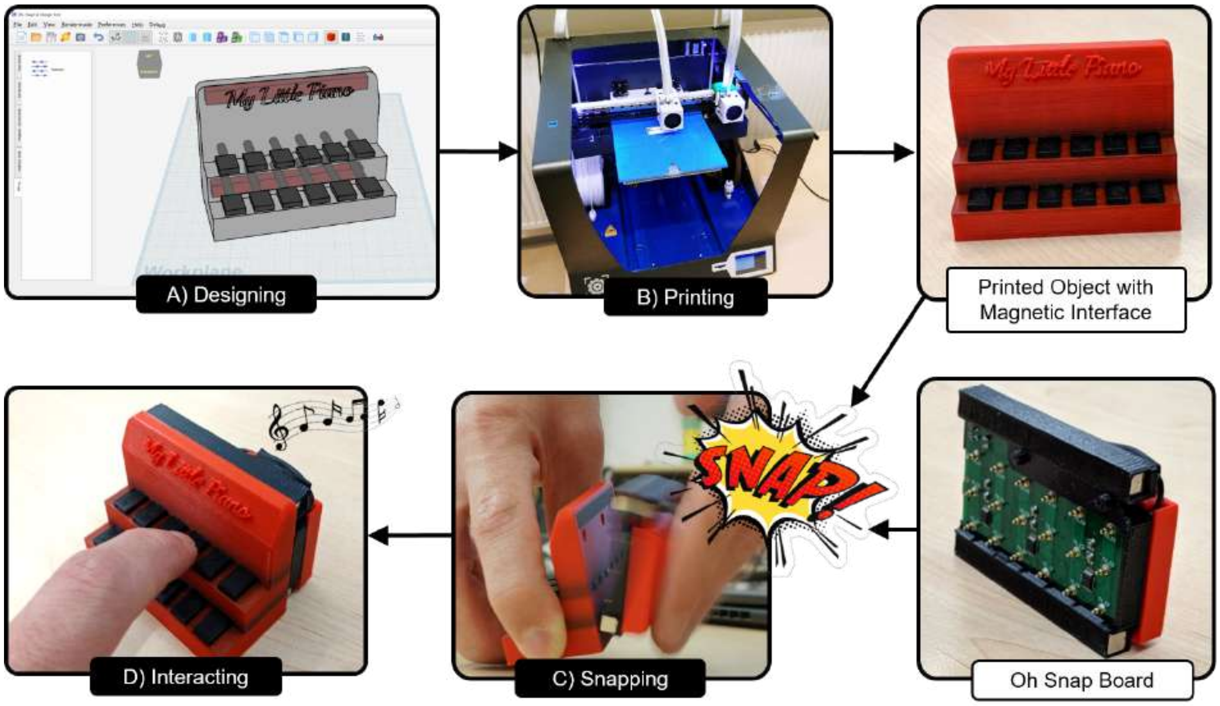

Figure 3: A user utilizes a dedicated tool to design the sensing structures and integrate the 3D-printed electronics component in a 3D object (A). After 3D printing (B), the printed object is magnetically attached to the *Oh, Snap!* board (C). Directly after snapping the board, the user can interact with the now interactive 3D-printed object (D).

fabrication pipeline that supports arbitrary sensing would require a complex design tool that is most probably unsuitable for non-expert users.

In the following, we detail on (1) the fabrication pipeline that enables users to create 3D-printed objects with embedded capacitive sensing structures and (2) a rapid prototyping board to magnetically connect the 3D-printed objects to conventional electronics.

4.1 Fabrication Pipeline

The first two steps in the fabrication pipeline concern the design and printing of objects with embedded capacitive sensing structures. The user then snaps a conventional electronic component to the printed object and starts interacting.

4.1.1 Designing. A graphical design tool enables users to equip a 3D model with the necessary structures without requiring expert knowledge in computer-aided design (see Figure 3A). As illustrated in Figure 4, a user performs the following steps:

(1) They loads a volumetric 3D model that is shown in a 3D view of the application.
(2) They then adds the required 3D-printed sensing structures to the 3D model. To that end, the user selects a custom-shaped subsurface either via a lasso tool (by clicking on the model's surface multiple times) or a free-hand pencil tool. The design tool automatically extrudes all created sensing structures in the normal direction of the surface and optionally submerges them under the surface.
(3) They places the 3D-printed component of the *Oh, Snap!* interface, available in the tool's sidebar, at an appropriate location in the 3D model, often the object's underside or back. To further ease this process, the tool alternatively offers to automatically find a correctly-sized and flat subsurface. The model of the 3D-printed component already includes conductive contacts for sensing pins, as well as the ferromagnetic and insulating part with correct dimensions. Hence, no additional work is required to ensure a proper fit after printing.
(4) When the user is finished, the design tool routes all necessary wires using A* that operates on a voxelized 3D model (as in previous work [36, 38]), because it knows the locations of sensing pins on the board and created capacitive sensors. This approach also avoids the collision of wires by keeping a pre-defined safety distance of voxels. Finally, the tool allows the user to export printer-ready 3D models for the insulating, conductive, and ferromagnetic parts via Boolean subtraction [24].

4.1.2 Printing. After the user has finished designing, they 3D prints the object using a commodity multi-material 3D printer (see Figure 3B). *Oh, Snap!* intentionally operates with affordable and consumer-level 3D printers to make it accessible to a wider audience.

4.1.3 Snapping & Interacting. After printing, the user magnetically attaches their conventional electronics component to the object

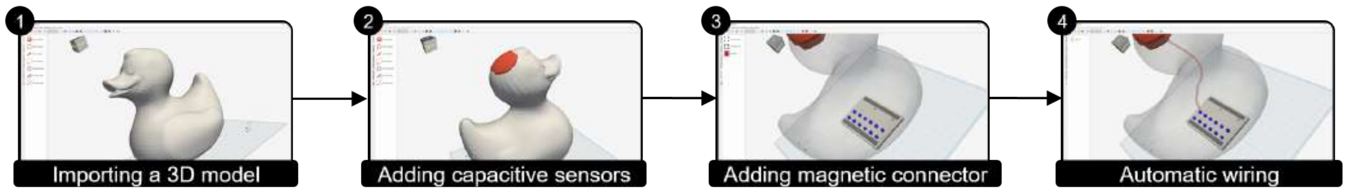

Figure 4: The *Oh, Snap!* fabrication pipeline consists of a design tool that enables non-expert users to (1) import a 3D-printable model, (2) add free-form capacitive sensors, and (3) the magnetic 3D-printed electronics component. After finishing the design, the tool also automatically wires the capacitive sensors to the nearest available sensing pin (4).

at the location of the 3D-printed electronics component (see Figure 3C). The conventional electronics component then can use the internal conductive structures of the 3D-printed object for sensing (see Figure 3D).

In general, the capabilities of the attached electronics depend on the specific use case and may vary depending on the sensing technology or a user's requirements. Following the ability of the design tool to generate conductive electrodes for capacitive sensing, we created an open board design that we present in the following. As it only contains standard components, this further eases the prototyping of 3D-printed objects featuring capacitive sensing.

4.2 Oh Snap Board

In the following, we contribute an open board design (see Figure 5) for capacitive sensing that enables users without expert knowledge in electronics to create a variety of different interactive 3D-printed objects.

A naive approach would be to use a touch screen with an adequate magnetic holding device. However, this only supports simple capacitive touch recognition, which is tuned to fingers. The board presented below, for example, also allows access to the raw data and features active shielding to counteract external interference.

4.2.1 Hardware Design. We use a custom-made PCB with small components to keep the underside, where the pogo-pins are located, free of soldering joints that might interfere with the attachment.

We have considered the following requirements for a viable prototyping board: its performance should suffice for pre-processing and small application logic and it should provide both Wi-Fi and Bluetooth, feature built-in touch sensors, and be of moderate power consumption, size and price. Therefore, we opted for the widely-known and used Espressif ESP32 microcontroller as it additionally offers a large community and many libraries. Besides the wireless communication, we included a micro USB port for cable-based power supply, adjusting the firmware or receiving sensor readings.

To facilitate easy deployment of the interactive object, we decided to include a lithium-ion battery as it is rechargeable, available in many sizes with different capacities, and very common in battery-driven embedded systems.

Despite the ESP32 features built-in capacitive sensing, we have added three TI FDC1004 capacitive sensing chips that are connected to the ESP32 using I2C multiplexers. Together, the three FDC1004 provide 12 sensing channels with an improved capacitive resolution compared to the ESP32 (up to 0.5 Femtofarad). Moreover, the three FDC1004 features six active shielding channels, i.e. to reduce environmental capacitive noise for high-precision measurements (e.g. [41]).

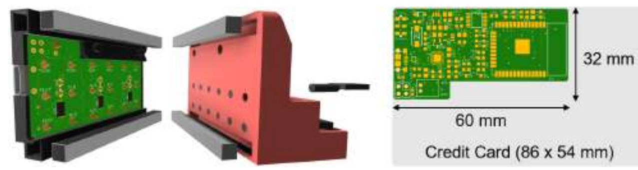

Figure 5: An exploded rendering of the *Oh, Snap!* board for capacitive sensing and an exemplary 3D-printed object (left) and a size comparison of the printed circuit board with a standard credit card.

The board features 19 pogo pins of which 18 are connected to the three FDC1004 chips (12 for capacitive sensing and 6 for active shielding), and one to the ground for passive shielding. Thereby, all available channels from the three FDC1004 plus the ground are usable.

4.2.2 Magnetic Adhesion Force. The magnets need to build up enough force to reliably attach the conventional electronics component to the 3D-printed object and at the same time ensure a good electrical connection. Besides the weight of the circuit board, the magnets must hold their weight, as well as the battery and the housing. In total, this amounts to about 60 g for our board. A factor to consider is the use of iron-based ferromagnetic filament which provides a weaker adhesion than standard metal.

To determine the required magnetic force, we conducted an informal test and found six neodymium N52 magnets (remanence of ~1.44 Tesla) each sized 20x5x5 mm to be sufficient to attach the board to the object. The ferromagnetic structure of the 3D-printed electronics component is printed in the same size as the magnets to maximize the contact area.

4.2.3 Prototyping Software Environment. The *Oh, Snap!* firmware runs a web server with a web-based user interface that serves as an interface for configuration, viewing raw sensor readings, and custom applications that may be uploaded by users. Thereby, simple applications can be directly run on the device, and *Oh, Snap!* can be used as a stand-alone system without the need for external hardware. The firmware either connects to a pre-defined WiFi or, if no WiFi is found, opens a new hotspot.

The firmware provides four ways to access the sensed capacitance data and interface with other applications: First, the data is transferred via a serial console available through the physical USB connection. Second, it is available via a WebSocket API over WiFi. Third, it can be accessed through a Bluetooth service. Fourth, the data is published via the MQTT protocol, a widely used networking protocol with easy programming access in a multitude of languages[1] Moreover, it seamlessly integrates with many smart home components that also use this protocol.

The board detects attachment of an interactive object with a 3D-printed electronic component due to a change in resting capacitance (i.e. adding conductive material results in a variation of capacitance).

Although all 12 sensing channels are capable of full-range capacitive sensing, one (or more) can be used to identify an object by shorting the sensing channel to the ground within the 3D-printed object and thereby reducing the sensed capacity to zero. That is, the ID of an object is decoded by examining whether an ID sensing channel is shorted (1) or not (0). After attachment or detachment, the board issues a respective event (e.g. *BoardConnected*) through the aforementioned data channels.

4.3 Fabrication Details

For our prototypes, we printed tri-material objects using conductive, ferromagnetic, and insulating materials with a standard multi-material FDM 3D printer (Prusa MK3 with Multi-Material Upgrade 2.0 for less than $ 1300), and commercially available printing materials.

The conductive structure consists of carbon-doped Proto-pasta Conductive PLA (cPLA) with a volume resistivity of $30 - 115\Omega cm$. The magnetic structure consists of non-conductive, iron-doped Proto-pasta Magnetic PLA (mPLA). We printed both cPLA and mPLA with a 0.4 mm thick nozzle at a temperature of 215 °C (speed 18 mm/s).

Both, the conductive and magnetic structure's infill density are important factors when fabricating *Oh, Snap!* objects as the amount of infill influences the electric current and magnetic force. To maximize conductivity and magnetic adhesion, we printed both structures with 100 % infill density for our prototypes. The force required for attachment can be adjusted accordingly by reducing the infill density of mPLA.

5 EVALUATION OF SNAPPING AND SUITABILITY FOR CAPACITIVE SENSING

The quality of the electrical connection for capacitive sensing is one of the most crucial factors for the operation, especially since the *Oh, Snap!* interface is intended for frequent reconnects. Therefore, we evaluated the quality and stability of the electric connection. In addition, we investigate the user experience of the attachment process and report on qualitative feedback.

5.1 Methodology

The main evaluation has investigated the following three objectives:

- **O1** Snapping establishes a usable electrical connection for capacitive sensing
- **O2** Connection quality is independent of the user performing the snapping and remains stable over multiple cycles

[1]see https://github.com/mqtt/mqtt.github.io/wiki/libraries

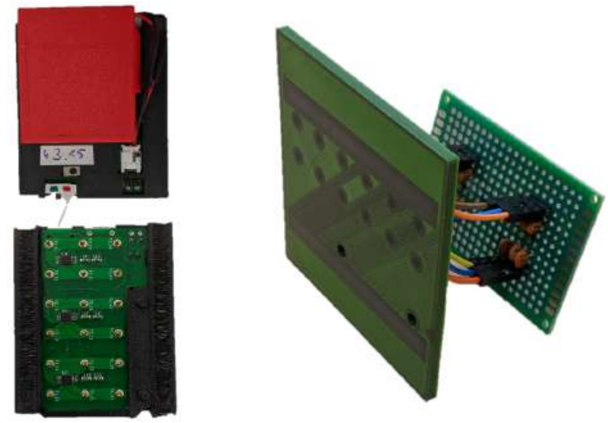

Figure 6: The prototyping board and the 3D-printed test object used for the study. Each sensing ping is connected to a ceramic capacitor (right).

- **O3** Users perceive snapping as easy and strong enough for frequent attachments

5.1.1 Setup & Task. While research frequently utilizes mechanical apparatuses to technically evaluate electrical properties (e.g. [10, 52]), we opted for an evaluation with 10 participants (7 identified as male and 3 as female, mean age 29.2, SD 4.16) to account for inter-subject variations in attaching the board. Participants received an introduction to the system before exploring it freely until they felt comfortable.

To assess the connection quality, we measured capacitance as it is closer to capacitive sensing than measuring contact resistance. To that end, we 3D printed a test object with a magnetic interface and equipped it with ceramic capacitors (each 100 pF with ± 5% tolerance) at each of the 12 sensing channels (see Figure 6). The capacitors' second pin was connected to ground on the board. We then measured the capacitance for each channel through the *Oh, Snap!* interface.

5.1.2 Procedure. Each participant had to disconnect and reconnect the board 10 times to the test object. After each connection, we sampled 100 raw capacitances (18 ms charge time), receiving a total of 10,000 measurements per sensing channel. For further analysis, we averaged the samples per trial.

The participants then explored how to attach the board to various realistic 3D-printed example objects (see Figure 7). Afterward, we conducted semi-structured interviews to examine the participants' experience with *Oh, Snap!* with regards to its mounting and robustness when connecting it to different 3D-printed objects.

5.2 Results

5.2.1 Quality of the Electrical Connection (O1). Given the capacitors' manufacturing tolerance of 100 pF ±5%, we expect the measurements to be between 95 pF and 105 pF. Generally, the mean capacitance for all trials ranges always between 95.6 pF and 104 pF and, hence, are fully within the capacitor tolerance levels. This is in line with the overall mean of 99.89 pF (SD=2.2 pF) across all sensing

Channel	SD	Range Δ	95 Abs. Percentile
0	0.020	[-0.087 , 0.037]	0.035
1	0.023	[-0.078 , 0.052]	0.050
2	0.039	[-0.214 , 0.067]	0.061
3	0.020	[-0.067 , 0.042]	0.040
4	0.019	[-0.094 , 0.040]	0.039
5	0.021	[-0.096 , 0.040]	0.042
6	0.022	[-0.079 , 0.047]	0.047
7	0.060	[-0.363 , 0.089]	0.087
8	0.029	[-0.132 , 0.060]	0.058
9	0.447	[-1.969 , 0.827]	1.004
10	0.596	[-4.961 , 0.574]	0.574
11	0.361	[-2.224 , 0.735]	0.698

Table 1: Summary of the standard deviation, range (maximal delta from mean) and the absolute delta 95-percentile for all channels. All values are relative to the channel mean and given in picofarad.

channels. As a result, we conclude that the snapping mechanism provides a usable electrical connection for capacitive sensing.

5.2.2 Independence of User and Multiple Cycles (O2). To investigate whether the connection quality is independent of the user, we compared the difference between the smallest and largest mean per participant. As it is only 0.42 pF, which is less than 0.5%, and thus also far below the 5% tolerance, we conclude that the connection quality is independent of the individual user.

To analyze the stability of the measurements over multiple snapping cycles, we normalized all measurements by the mean capacitance per participant to remove environmental effects. The average standard deviation across all measurements is 0.14 pF, indicating that multiple cycles do not substantially affect the connection. We report the standard deviation per sensing channel in Table 1.

Even for channel 10 with a standard deviation of 0.596 pF, the capacitance measured was off by only -4.96 pf from the respective mean value (103.9 pF) which is an error of less than 5%. For all other channels, the absolute error from the mean is below 0.1 pF in 95% of all cases, which is a relative error of less than 0.1%.

Since we observed very consistent measurements across participants and multiple attachment cycles, we conclude that the connection established by the *Oh, Snap!* concept can be repeatedly and reliably reproduced even across different users.

5.2.3 Snapping Experience (O3). In general, all participants found the magnetic snapping to be "easy" (P7), "good" (P2), and "simple" (P8). According to all participants, the adhesion felt "very strong" (P7) and "robust" (P3). P1, P5, P8, and P9 found it noteworthy how well the device pulls itself to the interface due to the magnets. When explicitly asked for alternatives, P1, P5, and P6 suggested clipping, but, along with all other participants, found magnetic adhesion to be the best solution. As all participants acknowledged sufficient and robust adhesion, we conclude that the users perceive snapping as easy and strong enough for frequent attachments.

P0, P1, and P5 suggested the development of an additional smaller version of the board with fewer pins, to support even smaller capacitive sensing objects. P1, P7, and P8 noted that the included battery is an "important factor" (P7) for successful integration in objects.

P0, P2, P3, P5, P8, and P9 further proposed to better use a fully closed device case with the pins and other electronics hidden away. This is in line with P0, P2, and P9, who feared to break something on the device as "it feels too lightweight" (P2). Both suggestions may be easily added to future iterations of the *Oh, Snap!* board.

6 EXAMPLE APPLICATIONS

To illustrate the broad applicability of the *Oh, Snap!* prototyping board for various types of interactions, we have created four interactive exemplary prototypes (also illustrated in Figure 7) that utilize capacitive sensing.

6.1 Gesture Control (Proximity)

Capacitive sensing can be used to detect interactions in the proximity of an object. Therefore, we have printed an example object (see Figure 7A) with four big conductive electrodes (2x2 cm) to detect different swipe gestures (e.g. from left to right or from top to bottom) performed over the object (in ~5-15 cm distance; printing time approx. 5h).

In our example implementation, the gesture control is installed, for example, in the interior of a car or on a bicycle. Once the board is connected to the 3D-printed object, the user can use swipe gestures to, for instance, control the music playback on the smartphone.

6.2 Smart Home Control & Piano (Touch)

The number of devices in smart homes is constantly increasing and so is the complexity of use. Therefore, this example uses the capabilities of 3D printing to (re-)produce complex three-dimensional miniature shapes representing individual devices in a user's smart home (printing time approx. 8h). By simply touching the printed miniature of a device, a user can, for instance, turn the respective device on or off or control other device functions.

For our prototype, we printed a smart home control (see Figure 7B) that resembles the shape of a TV, a lamp, and a speaker present in the user's smart home. Touching an individual device, for instance, turns it on or off. By increasing the complexity of the individualized design, also more complex user-specific functions can be triggered (e.g. touching the speaker and a miniature of the user's favorite artist could start the respective playlist of this artist).

In addition, we printed a piano using all 12 capacitive sensing channels (see Figure 3) that serves as one example how creatives (like musicians) can use *Oh, Snap!* as a basis to create individualized and novel instruments and frequently switch them easily on demand, for instanc, while improvising.

6.3 Key Rack (Object Presence)

This example illustrates the ability of *Oh, Snap!* to detect the presence or absence of conductive objects. As a demonstrator, we 3D-printed a key rack (see Figure 7C) specifically designed to detect keys via three electrodes behind each key suspension (printing time approx. 5h). In our example, the key rack differentiates between house, car, and mailbox keys. If a house resident grabs the car key, the garage opens automatically. If they grabs the house key, all

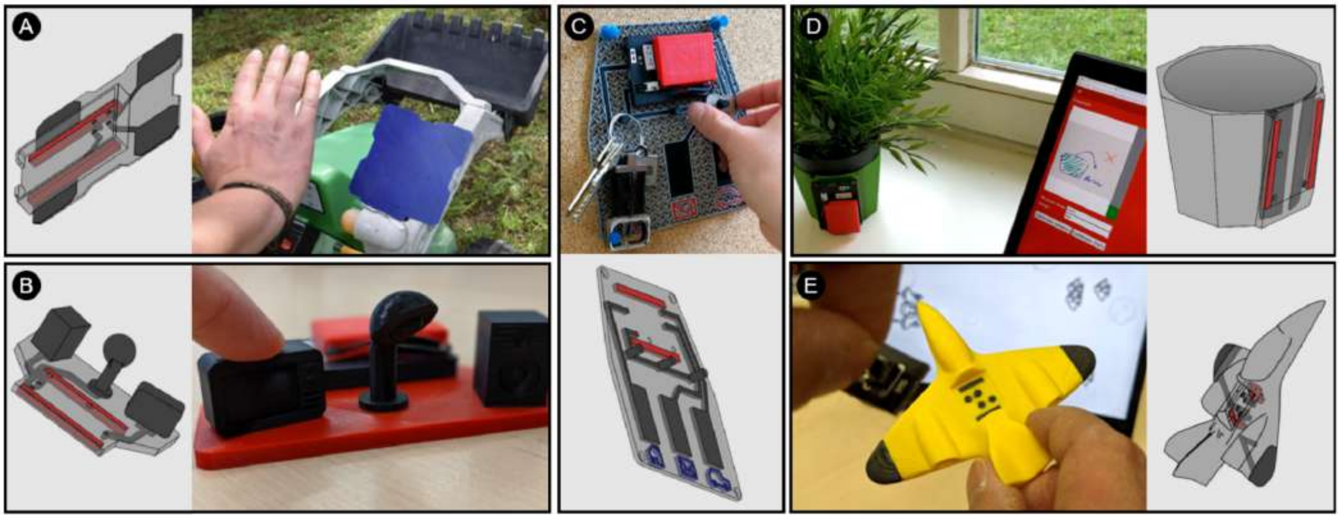

Figure 7: With *Oh, Snap!*, users can print custom interactive objects, for instance, for proximity gestures (A), controlling smart home devices (B), detecting the presence of keys on a key rack (C), water level measurements (D), or as a configurable game controller (E).

windows close, and the lights are turned off. When coming home and placing the house key again at the key rack, lights turn on again.

6.4 Flower Power (Liquid Level)

In this example, a 3D-printed flowerpot (printing time approx. 19h) senses whether a plant needs water by measuring the liquid level using capacitive sensing (see Figure 7D). In our implementation, a user received a notification when the level falls below a certain threshold and they should take care of the plant. Using *Oh, Snap!* each flower pot can be individually customized and printed according to the user's needs and the plant's requirements (e.g. varying threshold can be configured on the board's web interface).

6.5 Configurable Game Controller (External Hardware)

While this paper focuses on attaching sensing electronics at a single location, the *Oh, Snap!* interfacing concepts can also be used to attach different interfaces at multiple locations. As an example, we created a prototype of a configurable game controller (see Figure 7E) shaped like a plane that features the standard interface at the bottom but also a small interface at its top to quickly change between different physical input buttons (e.g., a pushbutton) used to fire.

While this paper focuses on attaching sensor electronics to a single location, *Oh, Snap!* can also be used to attach different interfaces to multiple locations. As an example, we printed a prototype of a configurable game controller in the shape of an airplane that, in addition to the standard interface on the bottom, also has a small interface on the top to quickly switch between different physical input buttons (e.g., a push button) used for firing.

7 DISCUSSION AND LIMITATIONS

While *Oh, Snap!* eases connecting conventional and 3D-printed objects, it currently has limitations that must be considered during fabrication and sensing. As follows, we discuss these limitations and also give an outlook on the potential of *Oh, Snap!* for the future of 3D-printed interactive objects.

7.1 Alternative Attaching Approaches

Clipping or plug-in connectors are possible alternative approaches of attaching electronics to a 3D-printed object. However, clips can wear off and the connectors also require additional force to ensure a proper connection. While plug-in connectors can be 3D printed in principle, they require tiny connector holes that are often not 3D printable in any orientation, which limits possible use cases. A further fastening approach is Velcro tape. However, it cannot be printed and most likely leads to a too large distance between the conventional and the 3d-printed electronics, because the pogo pins can only bridge a small millimeter distance.

In contrast, magnetic snapping operates independently from the printing orientation and requires no extra assembly effort for a robust and reliable connection. This fully printable solution inevitably leads to longer printing time at short sight, but this problem will most likely be solved by future printers.

7.2 Minimal Object and Board Size

An object must be able to accommodate at least the size of a microprocessor, auxiliary electronics, and a battery. Therefore, the minimal size for the casing and ESP32 (that includes WiFi and Bluetooth) including a small battery is 35 x 35 x 15 mm. However, board sizes can be further decreased by using smaller microcontrollers and chip package sizes.

Concerning possible object geometries and sizes, *Oh, Snap!* only requires a flat subsurface of at least the size of the minimal board.

The remaining object geometries can be as small, big, or complex as the respective 3D printer and the corresponding materials permit.

7.3 Printing Process

The conductivity of commercially available 3D printing materials does not yet compete with conventional materials for the production of conductive traces (e.g. silver or copper). Therefore, only simple circuits with low conductivity requirements can currently be integrated into 3D-printed objects. Nevertheless, capacitive sensors can detect a multitude of interactions, as we show with our example applications. Future 3D printing materials are most likely highly conductive, e.g. by deposition of conductive inks [31]. As a consequence, such 3D-printed objects allow even broader applicability of *Oh, Snap!* for connecting conventional with 3D-printed electronics.

A future ferromagnetic conductive filament would further reduce the required materials to two, since ferromagnetic and conductive structures are always electrically separated in the interface. Although we are not aware of such a material being commercially available, it could be made by manufacturers in the future by mixing iron and carbon particles with PLA. In addition, *Oh, Snap!* is also applicable with single-nozzle printers by using a filament splicer (such as Mosaic Palette[2]) or programmable filament [43].

7.4 Beyond Rapid Prototyping

We intent *Oh, Snap!* not as a replacement for other rapid prototyping techniques but an extension for later, higher-fidelity stages. We deliberately decided against evaluating the design process to keep focus on the fundamental aspects of the connection problem, often ignored by related research looking at the 3D-printed objects itself. As we first wanted to establish the required fundamentals, we see the investigation of the implication onto the design process as exciting and valuable future research.

Although inspired by rapid prototyping, *Oh, Snap!*'s easy and robust decoupling of expensive conventional hardware and low-cost 3D-printed objects is applicable in other domains where a non-permanent connection between both is beneficial. For instance, *Oh, Snap!* could also be:

(1) a mobile personal computing and interaction hub (e.g. integrated into today's smartphones) that quickly connects to 3D-printed interfaces that serve a specialized purpose (e.g. users personalize a shared tangible workspace by snapping the hub),
(2) or as a ubiquitous interface deployed in the world allowing to attach customized interactive objects to (e.g. blind people could easily connect customized haptic interfaces individually fabricated to their needs to improve accessibility).

7.5 Additional Interactions Beyond Capacitive Sensing

As stated in Section 1, research already has investigated many more exciting interaction possibilities, ranging from deformation input [1, 40] or sensing of liquid movements [39] to optical [2, 48] or auditory output [17]. While we already demonstrate the wide applicability of *Oh, Snap!* with a design tool and board for capacitive sensing, the *Oh, Snap!* interface may be beneficially applied to these approaches as well as they often require the tedious attachment of active electronics to the 3D-printed objects. However, the inclusion of additional sensing approaches still requires expert knowledge in conventional electronics as users would have to design and equip a custom-printed circuit board. Even though *Oh, Snap!* makes a first contribution by simplifying the attachment to 3D-printed objects, further research is required to support connections beyond capacitive sensing.

8 CONCLUSION

This paper has presented *Oh, Snap!*, a fabrication pipeline and interface concept that utilizes ferromagnetic and conductive 3D-printed structures to magnetically connect a 3D-printed object with conventional electronics. We further contribute a prototyping board that utilizes the interface concept for capacitive sensing, as this is a very frequently used approach for interactive 3D-printed objects. We illustrate the versatility of our approach through a set of example applications. An evaluation proves the viability of our approach for capacitive sensing and shows that snapping is perceived as easy and robust.

We are convinced that *Oh, Snap!* serves as a solid foundation for the community to connect conventional and 3D-printed electronics more easily and robustly without soldering or gluing. In general, the interface concept is not limited to capacitive sensing and may also enrich further interaction scenarios (e.g. for optical light guides [48]) that require a quick and robust connection of conventional and 3D-printed electronics.

9 3D MODELS AND SCHEMATICS

We will publish the 3D models, schematics, a list of all required electronic components, and the firmware described in this paper[3]. Further, we will provide the 3D models and implementations of the example applications. We are confident that this enables researchers and practitioners in the community to quickly use and adapt the contributions of *Oh, Snap!* for a simpler and more robust creation of 3D-printed interactive objects featuring a rich set of interactions.

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