A Series of Tubes: Adding Interactivity to 3D Prints with Hollow Chambers and Pipes

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ABSTRACT

3D printers offer extraordinary flexibilty in prototyping the shape and mechanical function of objects. However, in spite of recent work, a 3D printer's role in prototyping *interactivity* is still not clear. While macro-scale digital fabrication devices cannot manufacture electronics in-place, we propose a general technique for redirecting active components through the core and onto the surface of 3D printed interactive objects using a series of tubes. We describe the design space of tubes and hollow chambers for interaction design: there are a variety of types, topologies, and inserted media for tubes that can be leveraged to create diverse inputs and outputs. We present a technique and design tool for routing tubes of various topologies through the interior of 3D printed parts. Our design tool is integrated into a 3D model manipulation program. There are two distinct routing algorithms. One allows users to select begin and end points for tubes, then uses A* path routing and physics-based simulation to minimize the bending energy of routed paths. The second allows users to enter a description of paths to follow: for this we developed a novel neon sign routing algorithm and offer proof of several key traits. We present several totally tubular prototypes we created using this tool to show its flexibility and potential, as well as to explore new points in the tube design space.

Author Keywords

Prototyping; Fabrication; 3D Printing; Electronics; Hardware **VS: aw, let's keep it on one line. but what do we drop?**

ACM Classification Keywords

H.5.2 [User Interfaces (D.2.2, H.1.2, I.3.6)]: Prototyping.

INTRODUCTION

Redirection leads to reusable and iterable devices. Televisions have long been operating on this idea: before the recent switch to digital television signals, TV signals had remained unchanged since roughly the 1920s, and the only requirement to bigger and better viewing was an upgrade of the *endpoint itself*. A larger television does not require an upgrade of the underlying broadcast system. Similarly, the Internet, famously described by US Senator Ted Stephens (R-Alaska) as a "series of tubes", works on the principle of routing and distributing information to endpoints; there is no need to reduplicate information in multiple locations as long as it can be retrieved and manipulated by users at their laptops, tablets, mobile phones, or swarm devices.

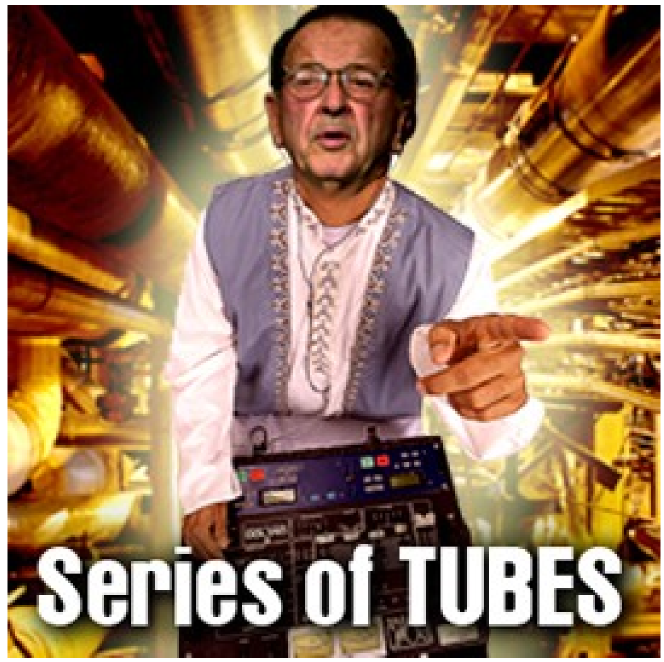

Figure 1. Here's a teaser figure of some cool stuff we did. Probably it should show one of our example objects, or we can make it really big (figure*) and show them all!

We propose the application of this idea, simple endpoints redirecting information to and from complex and localized systems, to user interface design. In particular, we believe that it lends itself to design for 3D printed devices. Since today's 3D printers cannot fabricate the electronics required to enable most devices, their place in designing interactivity has remained unclear. Typically, when electronics are integrated with 3D printed objects it is through a manual process, where the design of the object is tightly coupled to the form factor

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of the electronics. By using channels for redirection, a simple 3D printed object can be plugged in to a complex base structure to provide interactivity. This allows more rapid iteration on the device's look and feel, while preserving its functionality. **VS: I like this idea for the introduction much better, but the way to write it is not totally clear to me yet. suggestions welcome.**

Willis, et al., "envision a future world where interactive devices can be printed rather than assembled; a world where a device with active components is created as a single object, rather than a case enclosing circuit boards and individually assembled parts" [24]. This is a vision we eagerly share: 3D printers are capable of creating arbitrary geometries not feasible to manufacture using traditional processes, and makers and designers are underutilizing these capabilities.

In this paper, we propose a new technique in which interior hollow chambers and pipes are integrated into 3D printed devices to redirect interactive components from a central system to arbitrary points on a printed object's surface. Such channels introduce an entire design space of opportunities for adding interactivity to these objects. For example, copper material can fill the channels, to allow for standard electronic components to be easily integrated after the printout; air can be pumped through to create tactile output; or electroluminescent wire can be threaded through to create computer-controlled visual output.

Our work makes the following contributions to the field of interactive digital fabrication:

- We lay out a design space of tube-mediated interactive possibilities.
- We offer algorithms and techniques for routing tubes, as well as a design tool implementing them.
- We showcase a set of examples, enabled by our modeling tool and exploring new points in the design space.

THE DESIGN SPACE OF TUBES

We propose the use of tubes to redirect active components through the core and onto the surface of 3D printed interactive objects. By using different types and topologies of tubes and inserting different media into the completed tubes, a variety of inputs and outputs can be located at arbitrary points on the surface of a 3D print. We describe the design space of tubes, and then follow up with some of the input and output possibilities—both those that have been previously explored and those that are possible but remain unexplored.

Types of Tubes

TG: Maybe rename types to "openings"?

Tubes can come in four types: open, return, semi-closed, and fully enclosed. Each of these types offers distinct interaction capabilities (see Figure 2). Definitionally, in the following paragraphs we refer to a tube which is "open on the user side" to have its contents physically accessible to an interacting user at interaction time. This includes tubes which function as fountains, but it does not include tubes whose ends have been capped to keep water inside (whether this capping was done at print time, or later as a manual modification). Tubes whose contents are not physically accessible to the user are "closed on the user side". A tube which is "open on the system side" can have its contents manipulated by a machine, e.g., by resonating, pressurizing, or passing electricity through those contents. The system does not need to have physical access to the contents in order to manipulate them.

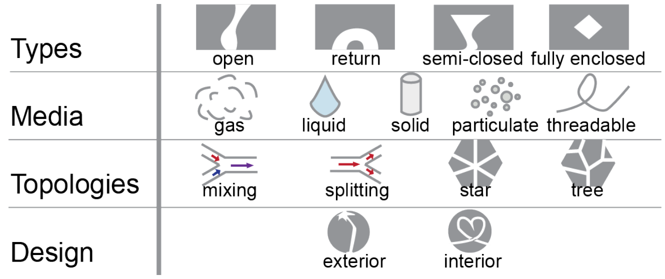

Figure 2. The design space of tubes. Tube types, media, topologies, and design are discussed more fully in the text.

Open tubes originate from the system side and connect the user side, with both ends of the tube open. This type of tube may be used to create, for example, capacitive sensors: an open tube filled with conductive paint can be connected to a sensing platform (e.g., Arduino) on the system side, while a user can touch the uncapped other end of the tube. Using Swept Frequency Capacitive Sensing [15] or other techniques, a user's touch of the open end can be sensed. An open tube can also be used for output, for example by creating in-air vortices as in [22].

A return tube originates at the system and returns back to it. By threading an electroluminescent (EL) wire through a clear return tube, a maker can create a custom piece of neon art. If a return tube passes very close to the surface of a 3D printed model, warm or cold water passed through the tube could be used for temperature-based haptic feedback.

Semi-closed tubes are open at the system end (for control of the enclosed medium) and closed at the user end. The closed interface is interesting when it fabricated from a mobile material: for example, a series of tubes terminated in thin rubber membranes on the user side can be actuated by an air pump to create haptic feedback, or a hinged cap which can be blown open by air pressure. Without a printer capable of fabricating flexible material, a maker could affix a balloon to an open tube's end to behave similarly; another possibility is to use semi-closed tubes as audio-generating resonance chambers.

A fully enclosed tube has no openings on either the system side or the user side. Fully enclosed tubes can be used as resonance chambers (e.g., for object identification), or as air bubbles (e.g., as used in [24] for internal display). **TG: used as a container for water or other particles that would otherwise fall out? VS: I re-worded above. please check.** Their physical design space is very limited, as any support material required to create their internal geometry cannot be accessed for removal.

Media in Tubes

Tubes can be filled with a variety of media to create different interface affordances and capabilities.

"Gas" comprises all compressible fluids. Use of fluid pressure inside tubes can create haptic feedback at semi-closed interfaces, or the gases can be used as carriers for scents or fog. As in [20], structures can be engineered to change in air pressure when manipulated correctly (e.g., a spiral that changes pressure when twisted, but not pressed), and thus fluid pressure can also be used as an input. **TG: I realize "fluid" pressure is technically correct, but might confuse readers, since this is the gas pararaph.**

Incompressible fluids ("liquids") can perform many of the same interface tasks as gases. One opportunity with liquids is to fill the interior of tubes with them and cap the ends. In addition, one can use driable conductive fluids, such as copper paint, to coat the interior of tubes and allow them to function as arbitrarily-shaped wires. This is especially helpful for the creation of a shared ground, or for creating single-wire capacitive interfaces amenable to sensing with SFCS [15].

TG: Again, this raises the question of how we are applying the design space - is it based on its properties when it is printed, or based on any post-print modifications **VS: re-worded above. I think we are basing it on status at "interaction time"** Tubes need not have hollow centers: in the case where routed tubes are filled with solid material—in particular, a solid material different from the model material—, interactions such as those in [24] are possible.

Particulates, either printed in-place or inserted, can be of varying densities. A single particle can be used for display. Sparse particles in a stream of fluid can provide haptic feedback. Dense particles in a semi-closed tube allow for jamming-based interactions at any point on the surface of an object [2].

Threadable inserted elements, such as electroluminescent (EL) wire or fiberoptic cables, are those that can be threaded through tubes post-printing. This allows overcoming limitations of printers: for example, a Printed Optics-style interface can be created on an inexpensive consumer-grade 3D printer using tubes and inserted fiber optic cable.

Tube Topologies

Tube network topologies enable different types of interactions.

Splitting or mixing tubes offer flexibility in output. If a maker wished to create a painting device, she might wish to have two system-side tubes feeding in primary-colored red and blue paints which mix in varying ratios, allowing their pigments to combine before purple exits from the device (see Figure 2). Splitting can also be useful, for example if our maker wants red paint output in two locations from her painting device, she could have one system-side tube, but split the tube into two (see Figure 2).**TG: How about multiple in/ multiple out (in contrast to branching/splitting which is single in multiple out)** **TG: This seciton should refer to the possibilities, not to what we actually did.**

Star and tree topologies are extensions of the splitting and mixing primitives. Using a star topology in which the tubes were filled with conductive paint, we created toys with several touch-sensitive areas, see Figure 8.

Design of Tubes

Tube designs may emphasize either their exterior features (connection points) or their interior paths. These two features lead to different kinds of interfaces. An example interface that focuses on the exterior connection points is the touch sensitive toy in Figure 8, where tubes must exit the toy at the eyes, ears, tail, etc. An interface focused on the internal path of the tube is the neon sign in Figure 13: output is based on the shape of the tube.

Dimensions of Tubes

VS: Reference those pages from Bjoern: http://ttb.com/recent-news/diagrams/ We can talk about wall thickness, tangent length, degree of bend, arg bend angle, inner and outer diameters, centerline radius, etc.

Inputs and Outputs

By crossing tube types, topologies, and inserted media, we create a space of possible inputs and outputs that can be tube-mediated. We offer a table (see Figure 3) containing these possibilities, referencing previous work on input/output techniques where appropriate, noting that many of these techniques have not been attempted using digital fabrication. We suggest new points in the design space that have been unexplored or not yet explored with digital fabrication.

Inputs

Tubes create opportunities for many types of input sensing across the surface of printed devices. We describe sensing touch, pressure, grasp, flexing, tapping, and manipulation of traditional electronic components. We recognize that there are likely more input sensing techniques, both existing and on the horizon, that are compatible with the use of tubes.

Touch sensing is enabled through tubes filled with conductive media. Traditional wires (threadable) may be used, but we have had success with conductive paint (liquid). Using conductive paint and Swept Frequency Capacitive Sensing (SFCS [15]), an interior star tube topology can enable single-wire touch- and grasp-sensing at any set of points on a printed object's surface (see Figure [**?**]). Simple capacitance measurements are possible using the same media, and custom-designed sensors like those created in Savage, et al.,'s Midas system are also possible [17].

Pressure can be sensed in multiple ways. Slyper, et al., in [20] contribute a set of semi-closed 3D printable primitives that respond to particular actions, like twisting or pushing, with changes in internal air pressure. These primitives can be attached as the terminus of any semi-closed tube; the user can manipulate the printed endpoint and the system can sense air pressure changes. Pressure can also be more simply sensed via capacitance using those techniques.

Grasp sensing can also be enabled using Wimmer's FlyEye technique [26]. This technique involves a pair of optical links

	Gas	Liquid	Solid	Particulate	Threadable
Visual	PneUIs, latex buttons, *smoke*	Splash Controller, *paint mixer*	printed optics	*embedded hourglass*	*faux neon sign, fiber optics*
Aural	*Helmholtz resonance*	*bubbling/ splashing*	*CNC maracas*		
Tactile/Haptic	PneUIs, *haptic textures*	Splash Controller, *warm/cold liquid*	*resonance for vibration*	Jamming UIs, *particle haptics*	Otherlab robots, *heat wire*
Olfactory/ Gustatory	*perfume mixing*	*cocktail mixing*			
Touch/ Pressure	latex buttons, Slyper armature	SFCS, *flowmeter, capacitance*	Jamming UIs	*traditional components*	
Other	Slyper robot armature	capacitance on wires		*traditional components*	

Figure 3. The design space of tube-based interactions. Existing systems are written in regular font. Those created with fabrication are in blue. In *red italic* are unexplored interactions creatable with custom-fabricated tubes.

at each point of interest: one of each pair is connected to an infrared (IR) LED and the other to a camera. When some object nears or touches a pair of cables, IR light from the LED is reflected back to the camera and the touched point appears as a bright spot. Follmer, et al.,'s Jamming User Interfaces [2] rely on dense particulates enclosed in a flexible volume, and can be sensed optically. These dense particulates can be printed in-place with desired characteristics (such as varying particle size or shape) using sacrificial support material, or added post-print. The optical links necessary for sensing with FlyEye or Jamming can be created either via clear solid cores as in [24] or via fiber optic cables threaded through hollow tubes (see Figure 11).

Some 3D printers, like our Objet Connex 260, can fabricate rubber-like materials. Much like Slyper, et al., in [21], we can sense flexing and bending of prints made on these machines. While Slyper, et al., created multi-level multi-stage silicone molds with embedded wires to build their sensors, by placing tubes in our rubberlike prints and inserting conductive media afterwards, we can perform the same flex sensing.

Tapping is another input possibility. Due to differential sound conductivity in different printed materials (in particular, the rubberlike Objet material compared to the hard Objet material **VS: presumably we should get or take some measurements of this and include it in the appendix?**), tubes of a greater conducting material can be embedded in a model of a lesser conducting material. A microphone or piezo placed at the system-side of these sound-conducting tubes can determine where the model was tapped and how it was tapped. Active acoustic sensing as described in Touch & Activate [11] is also possible; this technique would allow for particular areas of interest (connected to sound-conducting tubes) to be touch sensitive, while other areas (made of non-conducting material) are not sensed.

Sensing via traditional electronic components (e.g., potentiometers, alcohol gas sensors) can be accomplished by conductive inserted media. Components can be recessed into a print's surface, with their leads implanted into open tubes. By inserting liquid copper paint instead of threading traditional wires, all components in a model can share a ground line, and the paint's drying process obviates the use of solder or glue to affix the components in place (see Figure 10).

Outputs

While many input techniques require the use of conductive media inserted into tubes, output media are more varied. We describe potential tube-based outputs organized by the five senses: visual, aural, haptic, and olfactory/gustatory. In addition to outputs we mention explicitly, any outputs possible using traditional electronic components are possible as described above.

Visual outputs can be mediated by gases, liquids, solid, particulates, or threadables. EL wire can be threaded through custom paths to create neon signs, as in Figure 13. Colored liquids can be mixed and split before exiting an opaque device, or in a transparent device their mixing, splitting, and paths could be used for display. PneUIs [28] can be fabricated as single parts: the rubberlike material offered by our Objet is inflatable when thin (200% elongation at break), and a PneUI located at the terminus of a tube could be actuated by a system-side air pump (see Figure 9). Mechanical motion can be mediated through fluids (a light object which is partially contained in a tube or located at its end could be pushed by the fluid pressure of the tube) or threadables (e.g., muscle wire). Large particles trapped in tubes visible to the user can be used for, e.g., maze games (see Figure 12). Using techniques like those described by Harrison, et al., in [3] **VS: this paragraph seems terrible. I think all these paragraphs might seem terrible...**

Aural outputs can be created with gases. Zoran has successfully 3D printed a functional flute, which in essence is a long open open tube with semi-closed tubes coverable by keys [29]. Helmholz resonance (the phenomenon that creates noise when you blow into the top of a glass bottle, which is also how some musical instruments, like ocarinas, work) can be leveraged to create computer-controllable sound chambers. All that is necessary for this is an enclosed chamber with a tube connected to it via a narrow neck-point (see Figure 4). Passive sound amplification (like a phonograph horn) and sound redirection are also possible using tubes.

Figure 4. This box (a) contains an enclosed Helmholz resonator, seen in the cutaway view (b). This resonator creates a sound when air is blown through the tube at the top, because air compresses at the small neck joint between the chamber and the tube. VS: need to get a test print of this that actually works

Haptic outputs are possible through compressible and incompressible fluids. Fluids can actuate particulates and create programmable pliability (as discussed above and in [2]). Additionally, use of semi-closed tubes with rubberlike material as the caps allows for gases to actuate surface features (see Figure 9). Sodhi, et al., in [22] created free-air haptic feedback using controlled vortex generation: this technique could also be reproduced using a series of tubes. Iwata, et al., explored volumetric fluid-based interactions with programmatically inflatable balloons and an overhead projector in [6], and additionally haptic outputs can be used to increase ergonomics, as in the inflatable mouse by Kim, et al. [7].

Olfactory and *gustatory* outputs can be created through the mixing and splitting of tubes carrying scented or flavored fluids, respectively.

Identity

Tubes included in printed objects allow for their identification. While the tubes need not be visible (especially in the case of fully-enclosed tubes), their presence, location, network structure, and length change many properties of a printed object. This includes weight, acoustic resonance, and (if conductive material is present) capacitive signature.

VS: need to do a rewrite of this that doesn't necessarily focus so deeply on audio only. we can talk about these other non-visible measurements like weight and capacitive signature. I also need to actually get an intentional encoding test up and running... we are going to have to be clever about how we stimulate the resonance tubes, though. using a speaker won't really work: we have to agitate the air in the chambers, so we might need to use something like a reed (as in reed instruments).

Both identification by recall and intentional encoding are possible. As seen in [11], different objects have different acoustic signatures. Additionally, two objects that are visually identical but which have fully enclosed (or other types) of tubes on their interior can be distinguished acoustically. Thus we can recall an object's identity once its acoustic signature has been recorded.

We have also experimented with intentional encoding. Semi-closed tubes can function as resonance chambers: the first resonant frequency F_1 Hz of a semi-closed tube length L meters can be found by $F_1 = \frac{c}{4L}$ (where c is the speed of sound). All odd harmonics (i.e., $3 * F_1$, $5 * F_1$, $7 * F_1$, ...) of this frequency are also resonant frequencies of the tube. **VS: need to provide some guidelines for the number of IDs we can create in this way, and where in the sound spectrum they are. my sense is that this will depend highly upon the i/o sensitivities of the mic and speaker selected.**

An object's resonant frequency can be measured by attaching a speaker and microphone to it, sweeping frequencies with the speaker, and performing a Fourier transform on the resultant signal from the microphone. Peaks in the transformed data correspond to stronger returned impulses: the resonant frequencies of the object.

This is similar to work done by Willis, et al., in [25]. While their technique requires access a terahertz imaging tool, audio resonance identity encoding requires only a microphone and a speaker.

VS: in my experiments so far, it seems that the material printed does conduct sound fairly well, so this is feasible. I think we should get some equipment and do a small test, though, since I don't know how the resonance will change with the big hunk of plastic around the semi-open tube. hopefully discussing this with Alex soon.

RELATED WORK

While using a series of tubes can replicate the interaction techniques discussed (and more), our work's *contribution* is more generally related to two existing research areas: fabrication and routing.

Fabrication

Previous work has investigated the integration of interactivity into the fabrication process. [24] used light pipes, solid clear tubes, to create integrated displays: our work allows a superset of these capabilities, and Printed Optics is a part of our design space. Willis, et al., also did not offer a design tool or techniques for creating light pipes automatically. [16] investigated the use of computer vision to track interactions with physical mechanisms. Using tubes for redirection, it is possible to replicate these mechanically sensitive techniques (see Figure 11), however our work does not focus on computer vision alone. Slyper, et al., [20] 3D printed flexible robot armatures capable of sensing interaction via changes in air pressure. This technique is complementary to ours, as we allow for placing these interactive elements anywhere on an object's surface while they had to place them in locations accessible for electronics insertion.

Other research has attempted to bring traditional electronics to 3D prints, either on the surface or via interior channels. Sells, et al., in [19] create channels on the surface of a

3D printed object which are filled with a special computer-controlled syringe of liquid solder to create connections. Their focus is on creating self-replicating 3D printers, and their electronics are combined to traditional 2D routed circuitboards. Sarik, et al., [14] **VS: I never found a real paper of this. The Microsoft website has a "print" of it with TEI boilerplate, but I couldn't find it in the digital library. What's up with that?** and the Optomec company [12] both created techniques for taking an already-printed object and spraying conductive material onto its surface. In contrast, our technique can lead to more durable circuitry, since it is routed through the core of the object rather than on its surface. Navarette, et al., in [10] created a functioning GPS whose circuit routing extended into true 3D (as compared to the 2.5D boards created by stacking traditional 2D circuitboards). However, they created this one-off routing by hand and do not offer any general algorithms or techniques. In the area of robotics, softer-than-skin interactive surfaces have been created using tubed interfaces fabricated from silicone molds. [13] and [8] use microchannels filled with liquid metal for pressure or curvature sensing: the metal in the channels changes resistance as the channels are stretched. These techniques have not been used with fabrication, nor has a design tool to create such sensors been previously described.

Routing

Part of our contribution is in the algorithms and techniques used for routing tubes through 3D objects.

General-purpose routing for connecting 2D capacitive sensors to terminals is discussed in [17]. These techniques, based on circuitboard routing, are limited to planar and unfoldable shapes, and are intended for use on the surface of objects rather than through their cores.

Similar to our neon-sign routing algorithm, Wong presents a graph-based approach for generating continuous line illustrations from images [27]. Its approach of linking edges into a continuous line based on semi-Eulerization is similar to ours. However, we are not confined to the plane to avoid line-crossings, and we have additional freedom in creating invisible lines where none existed. This is possible for us thanks to *blocking out*[1]. Prior work used tours of nodes, rather than edges, and cast continuous line drawing as a traveling salesman problem [1]. Schweikardt, et al., also made a connection between electroluminescent wire and graph theory, though their contribution is orthogonal to ours: they provide a tangible construction kit with smart nodes for building physical graph examples in which edges are lit by EL wire [18].

Misc

BH: These may not belong in related work, but I'm just collecting them here.

- [23] - Strattman is the standard "text book" for neon lighting designers.

[1]In neon sign making, segments of a tube that should not appear illuminated are covered with opaque paint. This is called "blocking out". `http://en.wikipedia.org/wiki/Neon_sign`

A SERIES OF TUBES - A TOOL FOR TUBE DESIGN

We created a tool which makers can use to create tube-powered interfaces in arbitrary 3D models. This tool allows designers to brush over the surface of their model to select exterior connection points of their tubes (see Figure 6) or to import vector art describing the tubes' interior paths (see Figure 5). Once the user's selections are made, we create a complete routing using either the exterior connection point method (A*) or the interior path method (graph edge creation, Euler circuit generation). We thicken our routing and use a physics-based rod simulation to minimize bending energy of tubes. We also apply templates where appropriate (e.g., 3D cross-overs for tubes that intersect in the plane). The resultant routing is subtracted from the original mesh. The modified mesh can then be 3D printed.

Our tool is implemented as a part of Meshmixer, a consumer mesh editing tool, in C++.

Exterior Connection Points

To create tubes in which the location and shape of exterior connection points matters, we first allow users to select the connection points on the mesh's surface using a brush. Our tool then creates an initial shortest-path routing using A* to estimate the routed distance between points. This routing is used to create a rod; we run physics-based simulation steps on the rod to minimize its bending energy (and thereby minimize the bend radius of the tubes).

Figure 5. An example mesh with exterior connection points brushed (a), and the initial A* routing generated (b). Our physics-based, energy-minimizing rod/tube at rest (c) and after simulation (d).

Routing

Our basic first-pass routing algorithm uses the A* routing algorithm [5]. The path cost in our implementation is based only on shortest distance between the starting and ending points, without weighting for distance from the surface. We only permit the routing within the voxel grid of the mesh: i.e., the routing is not permitted to traverse through space outside the mesh itself.

Given this initial routing, we create a rod of slightly longer proportional length. The rod must be longer, as the A* routing can follow the mesh boundaries and the rod requires extra length to be pushed away from the mesh surface. While we do not have a theoretical basis for this proportional increase, **VS: yet. what might it be related to? we can test how much of the A* path is outside the model, and how much is inside; further we can consider the distance from the A* path that is outside the model to the surface. I think there's a good way to do this. It might even just mean iteratively changing the rod length until we get something reasonably short and also smooth. we can also return to the A* that I wrote which finds a routing through the mesh that respects its boundaries; this would get us closer to what we need for length in the first place.**, we have found 1.15 to be a reasonable multiplier in practice. A too-long rod is forced to kink and expand further than necessary inside the model, while a too-short rod must be stretched, leading to non-smooth bending.

Physical Simulation :

How does it actually work? **VS: Ryan?**

Bend Minimization

In order to force our simulated rods away from the surface of the mesh, we create "wind" pushing inward from the exterior of the mesh. This wind pushes the tube away from the surface.

Tubes with Multiple Endpoints

To allow designers to create tubes with multiple endpoints (like the star topologies in Figure 8), we ....???? **VS: create 0-size mesh points in the center of the object, to which we attach one end of every tube?**

Designing Interior Paths

A user can import a vector graphics file (such as SVG) describing the path she desires for her tubes. We create a graph based on this input data, then add edges to make it connected and semi-Eulerian. We create an Euler tour on the modified graph, and thicken the path to create tubes. 3D templates are used to resolve tube crossings in the plane.

The interior path routing problem is a version of the Chinese Postman Problem[2], in which we wish to traverse all edges of the graph described in the user's input with a single Euler circuit, much as a postman needs to walk along every road at least once to deliver mail. We call our relaxation the Spiderman Postman Problem: we allow the creation of non-existing paths (i.e., the postman may traverse buildings in addition to roads). If inputted path components are disconnected, we must create edges that connect them; additionally we can create new edges connecting odd-degree vertices

Figure 6. An input vector graphics file with the points which cannot be tubed as drawn highlighted in blue (a). The connected graph created by our software (b) and the resulting Euler circuit (c) permit creation of a novel neon sign (d).

rather than simply retracing existing edges. In the final artifact, all created edges will be blocked out by dark material so the inserted medium is not visible (see Figure 6).

We want a semi-Eulerian graph (i.e., we want a graph in which every vertex but two have even degree) so that the desired medium can be inserted, traverse every edge, and exit the graph at a different vertex. Let $G = (V, E_0)$ s.t. $\forall e \in E_0, weight(e) = 0, start \in V$ the start point $end \in V$ the end point. Let $e_{temp} = (start, end)$, $E' = E + e_{temp}$.

We need to connect disconnected subgraphs in G. Let $G_{dis} = \{G_1, G_2, ...G_n\} \in G$ s.t. $\cup\{G_i \in G_{dis}\} = G$ and $G_i \cap G_j = \{\} \forall G_i, G_j \in G_{dis}, i \neq j$ be disconnected subgraphs in G. Create $E_{conn} = \{e = (u, v), u \in G_i, degree(u)\%2 = 1, v \in G_j, degree(v)\%2 = 1 i \neq j, weight(e) = distance(u, v)\}$ be the set of all edges connecting odd-degree points in two distinct disconnected subgraphs. To keep only the most desirable edges in E_{conn}, contract each subgraph G_i to a single point u_i with the shortest outgoing edges to each other subgraph: $E_{conn} = \cup_{G_i \in G_{dis}}\{e = (u_i, v), v \in G_j$, s.t. $\forall E_{conn} \ni e_k = (u, v), u \in G_i, v \in G_j, weight(e_k) \geq weight(e)\}$. Sort E_{conn} s.t. $E_{conn} = \{e_1, e_2, ...e_n\}, weight(e_1) \leq weight(e_2) \leq \ldots \leq weight(e_n)$.

Let $E_{conn-min} = \{\}$. Beginning with e_1, add the first edge $e_i \in E_{conn}$ to $E_{conn-min}$. Then let $E_{dupe} = \{e = (u, v) \in E_{conn}$ s.t. u is reachable from v along edges $E' \cup E_{conn-min}$. Let $E_{conn} = E_{conn} \setminus E_{dupe}$. Repeat until $E_{conn} = \{\}$. Let $E' = E' \cup E_{conn-min}$.

[2]The CPP is also known as the route inspection problem: `http://en.wikipedia.org/wiki/Route_inspection_problem`

At this stage, we want an Eulerian graph: i.e., we need every vertex to be of even degree. Let $V_{odd} = \{v \in V$ s.t. $degree(v)\%2 = 1\}$. Create $E_{circuit} = V_{odd} \times V_{odd}$, s.t. $\forall e = (u, v) \in E_{circuit}, weight(e) = distance(u, v)$. Find minimum matching $E_{circuit-min} \subseteq E_{circuit}$. Let $E' = E \cup E_{circuit-min}$.

Now to remove our temporary edge and make the graph semi-Eulerian instead of Eulerian, let $E' = E' \setminus e_{temp}$.

VS: does the proof of this theorem belong in the paper, or in the appendix? we can push it back there if need be, although it's not super long.

Theorem 1. *$G' = (V, E')$ is a connected, semi-Eulerian graph for which $E \subseteq E'$.* **VS: why is there such a huge space after this paragraph?**

Proof. $E \subseteq E'$: we never remove edges from E in our algorithm. $\therefore E \subseteq E'$.

$G' = (V, E')$ is connected : if G' is not connected, $\exists G_i = (V_i, E_i) \subset G', u \in V_i, v \in V \setminus V_i$ s.t. u is not reachable from v. $G_i \notin G_{dis}$, because we create edges connecting $G_j, G_k \forall G_j, G_k \in G_{dis}$ and only remove an edge $e_{dupe} = (u, v)$ from E_{conn} once we determine that u is reachable from v along edges $E' \cup E_{conn-min}$. $\therefore G_i \notin G_{dis}$. This implies that G_i was not initially disconnected from G, because by definition G_{dis} is the set of all disconnected subgraphs of G. We cannot have disconnected G_i from G because $E \subseteq E'$. Thus, a contradiction. $\therefore G' = (V, E')$ is connected.

$G' = (V, E')$ is semi-Eulerian : Each edge e in our minimum weight matching connects a unique pair of vertices $v_i, v_j \in V_{odd}$ by the definition of minimum weight matching. Each edge $e = (v_i, v_j) \in E_{circuit-min}$ adds one to the degree of v_i and v_j, causing them to be of even degree. $|V_{odd}|\%2 = 0$ by the handshake lemma, $\therefore$ all edges can be paired. When we remove $e_{temp} = (start, end)$ from E', we cause those vertices, which were of even degree by the above process, to be of odd degree. Thus, all vertices except $start$ and end (which are of odd degree) are of even degree. $\therefore G'$ is semi-Eulerian. $\square$

We believe that a lower total weight matching is possible by connecting components and ensuring edge degree evenness together in a global process, however it this not crucial for our purposes.

Once we have a semi-Eulerian graph, we need to create an Euler tour. An Euler tour is a path that touches every edge once, beginning and ending at the two nodes of odd degree: in this case, those are the user-selected start and end nodes. We use a weighted modification of Fleury's algorithm[3] for this, where instead of randomly selecting from non-bridge paths at each node, we select the path which turns the least from the most recent path (i.e., we prefer to pass straight through a node, if possible). This minimizes turns in the final artifact, which eases support material removal and assembly.

[3] `http://en.wikipedia.org/wiki/Eulerian_path#Fleury.27s_algorithm`

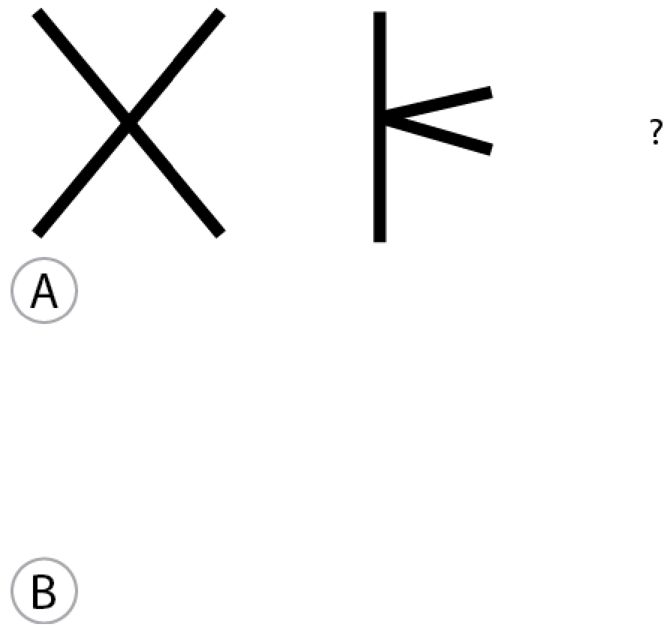

Figure 7. When edges intersect in the plane (a), we match them to the nearest of our several intersection templates (b) to create 3D paths that do not interfere with each other.

Edges that Intersect in the Plane

Once we have a tour, we must resolve tubes that intersect in the plane. Because we have a 3-dimensional canvas in which to work, we can push overlapping paths into the third dimension.

To detect intersecting edges, we **VS: I'm not sure what we do.**. We also consider edges at nodes with degree > 2, as these edges are considered to cross. When intersections have been detected, we match one of several templates to the affected edges (see Figure 7) using a nearest neighbors technique. Our templates are parameterized, so the templates can be modified to accommodate precise intersection characteristics.

Mesh Modification

How we actually cut stuff and make tubes happen. **VS: Ryan?** We have to actually respect whatever shapes people drew on the surface in the case of the exterior connection tubes (I mean, ideally, we would do a loft operation here).

Fabrication Techniques

VS: this section may not be at all important. I was thinking to use it to talk about different ways you can actually build the tubed things, and also constraints set down by the Makerbot vs. the Objet, but maybe that discussion is best made really short and moved to elsewhere

Printing

- different strategies with Objet (all print-in-place) and Makerbot (may need to add things like balloons afterwards). Ryan just got flexible material, we should see how stretchy it is...! We could also consider assembleable things that are easier to create using parts that clip together... probably out of scope.

Hand Tools
- post-fabrication modification is possible using hand tools. We can mark the surface to show where conduits are and how deep. I can also use this to test things before spending time printing them using a big ol' block o' plastic.

EXAMPLE OBJECTS

Totally tubular examples. We are making

Touch-sensitive Toys

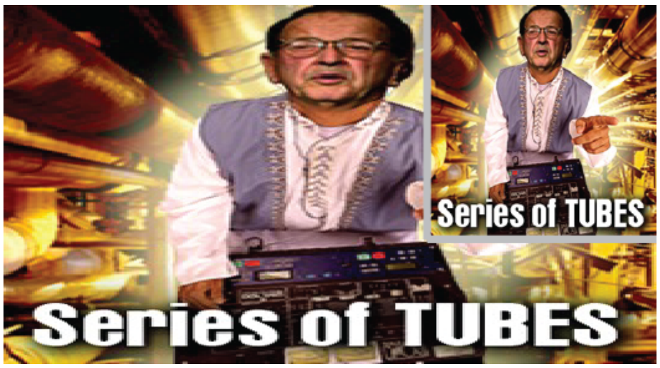

Figure 8. A touch-sensitive brain whose tubes are filled with conductive paint. Sensing is done on a single wire via SFCS. Inset shows the internal structure of the tubes generated by our design tool.

We created a set of touch-sensitive toys and a companion app, reminiscent of the boat application in [4]. The brain, rabbit, and boat each have several distinct touch points on their surfaces. These touch points are connected by an interior star topology of tubes filled with conductive copper paint, and touch sensing is performed via a single wire and SFCS (see Figure 8). We built a smart base which can distinguish between the toys and also determine which toy is mounted: since each toy and each gesture has a distinct capacitive signature, we use a simple classifier trained to detect both toy and gesture based on profile. These devices were all fabricated on a Makerbot Replicator 2.

Breathing Bunny

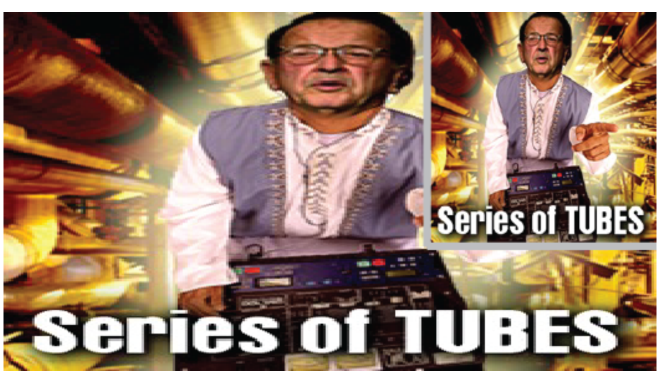

Figure 9. This rabbit has an open tube leading to its mouth and a semi-closed tube capped with flexible material in its back. When air is sucked in through the open tube, the back becomes stiff as though the rabbit has breathed in. Inset shows the interior structure.

We created a rabbit with a pair of tubes that can simulate breathing (see Figure 9). For this, we used a combination air/vacuum pump: one terminal creates a vacuum while the other creates positive pressure. Our rabbit has two tubes, one open tube exiting at its mouth and one semi-closed tube capped with rubberlike material in its abdomen. We connected one tube to each of our pump's terminals, and using a programmable power supply we can mimic a rabbit's breathing pattern. This example was printed on our Objet Connex 260. **VS: this paragraph is really unclear**

Custom Radio

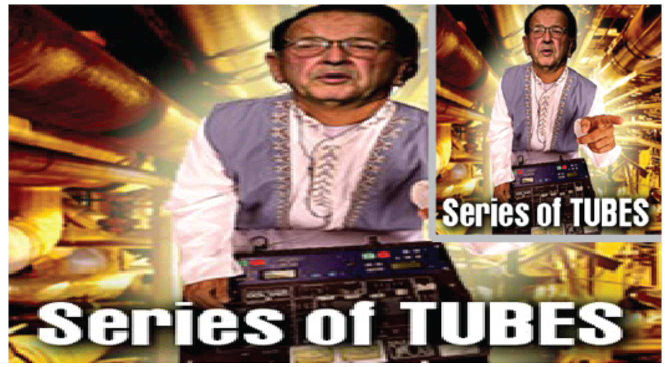

Figure 10. This radio is assembled from traditional electronic components connected by copper-filled tubes. The case was designed to allow the components to recess into it slightly. Inset shows the internal structure of the tubes generated by our design tool.

A custom radio built using tubes allows users to tune to different stations and listen in. This device uses a network of disconnected open tubes filled with conductive paint to connect traditional electronic components (two potentiometers, a speaker, and an LED) to a microcontroller. We hid the microcontroller and a battery-driven power supply in the base of the radio to make it portable. We fabricated this device on our Makerbot Replicator 2.

Presence-aware Pen Holder

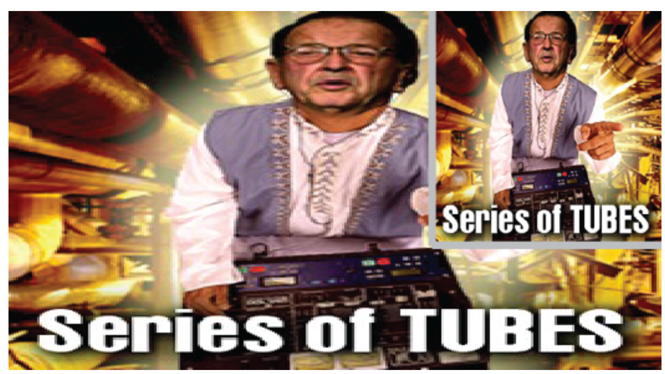

Figure 11. This pen holder uses the FlyEye technique to sense the presence or absence of an object in each of its tubes. Inset shows the internal structure of the tubes generated by our design tool.

Our presence-aware pen holder can distinguish which tool or tools a user has picked up (see Figure 11). Such information was used by [9] to determine which physical laser pointer a designer was using to interact with their interface. Our pen holder uses the FlyEye technique described by Wimmer in [26] and contains open tubes filled with fiber optic cables, two per pen chamber. One tube from each chamber leads to an infrared LED, and the other leads to a camera. When a pen is in its appointed place, light from the LED is reflected off its bottom and travels through the other optical fiber into the camera, where it registers as a bright point. A dark point on the camera region appears when a pen has been removed from its place, and the position of the point indicates which pen it is. This prototype was built by our Objet Connex 260.

Maze

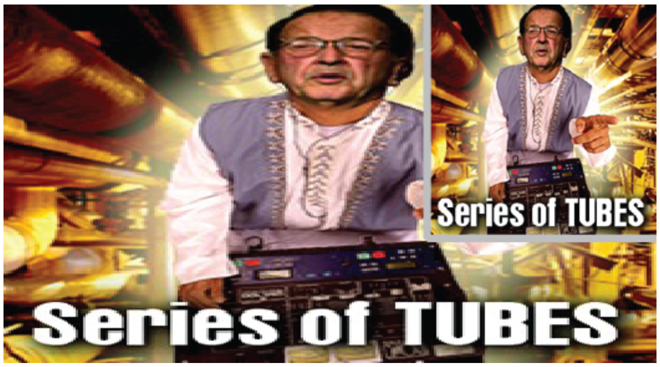

Figure 12. Our maze game has a large single particle trapped inside a fully enclosed tube. It offers hours of fun!

We created a maze game with a single particle trapped in a fully enclosed tube. To fabricate the tube, we created it in two halves that were fastened together via glue, due to limitations in our ability to remove support material otherwise. We created this prototype on our Makerbot Replicator 2.

Animated Neon Sign

Figure 13. A two-state animated neon sign designed using our tool (a)(b) VS: Tovi: we could use your PDF hax to make this animate in place :). (c) shows the SVG input files to create this sign, and (d) shows an isometric view of the tubes created by our tool.

Neon art, perhaps best known for its association with Las Vegas, is traditionally made from hand-formed glass tubes containing neon gas. The tubes light up when a current is passed through them. For this type of art, the path of the tubes is of crucial importance, as it determines how the sign will look. We designed a custom neon sign bearing the UIST logo and the waves of Hawaii. The piece features open tubes due to support-flushing constraints, however the tubes could also be semi-closed. They have been threaded with EL wire which is lit in sequence to create an animation. Our sign was fabricated on the Objet Connex 260.

LIMITATIONS AND FUTURE WORK

Tubes, while a powerful tool for directing interaction to arbitrary locations on an object's surface, have their shortcomings. Most obviously, their fundamental shortfall is that they cannot replace the active elements required for a functioning interactive device: they simply redirect sensing to different locations on an object's surface. All tubes need to, at some point, connect to a sensor, microcontroller, or pump.

Some media are difficult to insert in tubes, or may not be compatible with all types of tubes. Fluids in particular provide challenges. For example, the conductive paint we used in our designs can take multiple days to dry in tubes of sufficient length. Any liquid kept in tubes printed by the Objet can cause the exterior of the part to discolor due to seepage. Hobbyist machines do not guarantee watertightness of their prints, so leaking of water or air can occur.

The physical fabrication process also leads to some considerations. To print without support on a hobbyist machine, internal tubes cannot have overhangs of greater than $45°$. On the Objet, support-free prints cannot overhang more than $14°$. Removal of support from printed tubes can be troublesome, especially when their internal geometry and branching structures are complex.

Our design tool is not yet fully capable of realizing all possibilities in the design space of tubes. It lacks X and Y **VS: probably it will lack the network manipulation to make mixing or splitting tubes...?**. Additionally, as mentioned there are opportunities to improve the algorithm for neon sign routing, as ours does not guarantee a shortest-path routing. We hope to address this in future work.

VS: what other future work? miniaturization doesn't seem right, it's possible to use on mobile phones already with their on-board sensors (mic), maybe talking about shape-changing tubes? post-fabrication modification with drills? that doesn't sound very convincing.

CONCLUSION

While today's 3D printers are not yet able to fabricate active components in-place, we suggest that 3D printed interactive devices can be created with redirection of active input and output via tubes. In addition to describing the design space of tubes and connecting related works created through both traditional processes and rapid prototyping methods, we also presented a design tool for the creation of tubes inside arbitrary 3D models. We fabricated several example objects using this tool to explore new points in the design space.

We are heartened by our success: it opens new opportunities both for makers with consumer-grade 3D printers and research and industrial labs with higher-end machines. We are excited to release our tool into the wild and see what people will build.

Ten movies streaming across that, that Internet, and what happens to your own personal Internet? I just the other day got an Internet [that was] sent by my staff at 10 o'clock in the morning on Friday. I got it yesterday [Tuesday]. Why? Because it got tangled up with all these things going on the Internet commercially. [] They want to deliver vast amounts of information over the Internet. And again, the Internet is not something that you just dump something on. It's not a big truck. It's a series of tubes. And if you don't understand, those tubes can be filled and if they are filled, when you put your message in, it gets in line and it's going to be delayed by anyone that puts into that tube enormous amounts of material, enormous amounts of material.

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APPENDIX

INJECTION MEASUREMENTS

We injected the copper a distance of 1.16m (according to the spiral length calculator at http://www.giangrandi.ch/soft/spiral/spiral.shtml) in a spiral whose cross-section was a square of area $9mm^2$. I suspect that is about as far as we can go without using a vacuum at the end.

OBJET 260 CONNEX DIGITAL MATERIALS

Softer materials (concentration of $> 65\%$ Tango-series material) do not easily accept the copper paint (it cracks when bent and is easy to wash off). This may preclude flex sensors made of interior copper paint (conductive thread or other materials may be able to be used for some parts of this).

BEND RADIUS MEASUREMENTS

- EL wire diameter 2.3mm: minimum bend radius .35in = 8.89mm
- Water: uh. None?
- Muscle Wire: ?
- Fiber Optic Cable: ?

MATERIAL PROPERTIES

Name	Material	Resistance	Drying Time	Application Notes
CuPro-Cote Coating	Copper	2Ω/inch	O(1 day)	Syringe
Spectra 360 Electrode Gel	Liquid/Electrolytes	125kΩ/inch	O(hours)	Does not conduct dry
Wire Glue	Carbon/Graphite	23.6kΩ/inch	O(minutes)	Syringe, very runny
Bare Conductive Electric Paint	Carbon/Graphite	110Ω/inch	O(days)	Syringe
Homemade Conductive Paint	Carbon/Graphite	120Ω/inch	O(hours)	Too thick for syringe, apply externally with brush
Conductive Thread	Steel	1.8Ω/inch taut 2.5Ω/inch loose	N/A	Difficult to feed through turns
Solder Paste	Lead	2Ω/inch	N/A	Too thick for syringe, must bake to conduct