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 its optimality. 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

Makers, as well as professional designers, leverage 3D printers as tools for design work. A wide array of objects, ranging from bicycle helmets to jewelry to video game controllers, are now prototyped or even manufactured using these machines.

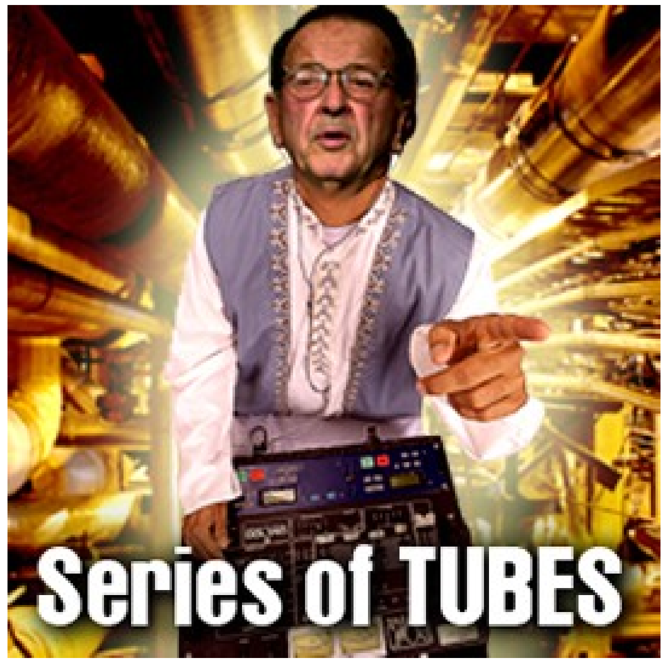

Figure 1. Here's a teaser figure of some cool stuff we did. Probably it should show one of our example objects, or we can make it really big (figure*) and show them all!

However, most devices fabricated by 3D printers are passive: accessible printers are not yet capable of creating integrated active systems.

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" [25]. This is a vision we eagerly share: 3D printers are capable of greating arbitrary geometries not feasible to manufacture using traditional processes, and we see these capabilities being underutilized by makers and designers. We see many opportunitities to increase the interactivity of 3D prints using today's printer technology.

Using specially modified printers or extra machinery, it is possible to create electronics on the surface of 3D prints [**?**] [20]. These techniques, however, require a high capital investment and technical expertise. In addition, they lack flexibility: the printed circuits must be routed in 2D to be created on the objects' manifold exteriors, and they can only be used to create electronic circuits. **VS: what?**

In addition to electronics, many other means of interactivity exist.

VS: Points to hit: there is more than electronics to worry about, like fluids and the organic haptic feedback they afford; tangible interfaces are important (do I have to say this every time??); assembly sucks

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 input and output types **VS: need clearer word than "types"** 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.

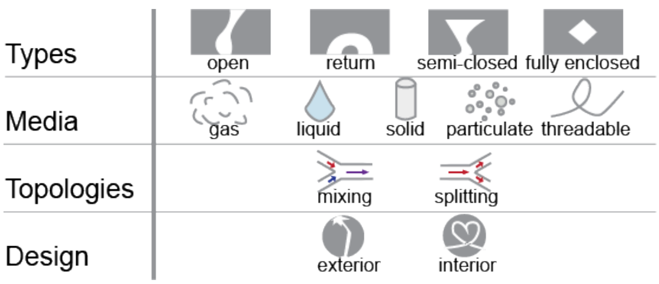

Figure 2. The design space of tubes. Tube types, media, topologies, and design are discussed more fully in the text.

Types of Tubes

Tubes can come in four types: open, return, semi-closed, and fully enclosed. Each of these types offers distinct interaction capabilities (see Figure 2).

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 [16] 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 [23].

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. We believe this closed interface is most interesting when it is 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. 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.

While possible to create, a tube which is open on the user side and closed on the system side is outside our focus is on computer-mediated interaction, and we therefore do not discuss these tubes.

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 [25] for internal display). 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 [21], 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.

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 [16].

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 [25] 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.

Topological variations

Tube topology enables 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).

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 a toy with several touch-sensitive areas, see Figure 8.

Features of Tubes

Tubes 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 12: output is based on the shape of the tube.

Inputs and Outputs

Interaction Techniques

These didn't get discussed yet.

- [8] - a display made up of many balloons that inflate and deflate to change the shape
- [9] - a basic mouse, but it inflates so you can store it and also use it more reasonably than a flat mouse
- [6] - hold a speaker in your hands, and air pressure changes make it feel like you're holidng a living, squirming thing

VS: this section includes related work. is that ok? it's in the table, and I think we should cover the related input techniques here rather than in the designated related work section (which I think is more suited to fabrication and routing stuff).

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 Capacitve Sensing (SFCS [16]), 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 [18].

Pressure can be sensed in multiple ways. Slyper, et al., in [21] contribute a set of semi-closed fabricatable primitives that respond to particular actions, like twisting or pushing, with changes in internal air pressure. **VS: that sentence is not clear** These primitives can be attached at 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 [27]. This technique involves a pair of optical links 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 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 [25] 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 [22], 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 [13] 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

	Gas	Liquid	Solid	Particulate	Threadable
Visual	PneUIs, latex buttons, *smoke display*	Splash Controllers, *paint mixer*	printed optics	*embedded hourglass*	*faux neon sign, fiber optics (see:light pipes)*
Aural	*Helmholtz resonance*	*bubbling/ splashing*		*CNC maracas*	
Tactile/Haptic	PneUIs, *haptic textures*	Splash Controllers, *warm/cold liquid*	*resonance for vibration*	Jamming UIs, *sparse particle haptic textures*	Otherlab robots, *high resistivity heat wire*
Olfactory/ Gustatory	*perfume mixing*	*cocktail mixing*			
Touch/ Pressure	latex buttons, Slyper robot armature	SFCS, *capacitance, flow meter*		Jamming UIs	capacitance on wires
Other	Slyper robot armature	*traditional components*			*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. Darker grey is output. Lighter grey is input. VS: I don't know what else might go in the blank spaces... looking for suggestions! Also, I'm not confident this breakdown is the most clear: for example, the "liquids" category includes the copper paint, which functions as wires ("threadables"), but takes the form of a liquid... and the general presentation of the table could probably be better in some way.

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 5).

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 12. 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 dispaly. PneUIs [30] 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 **??**). 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 [31]. 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 **??**). Passive sound amplification (like a phonograph horn) and sound redirection are also possible using tubes.

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 [23] created free-air haptic feedback using controlled vortex generation: this technique could also be reproduced using a series of tubes.

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, and length change the acoustic resonance properties of a printed object.

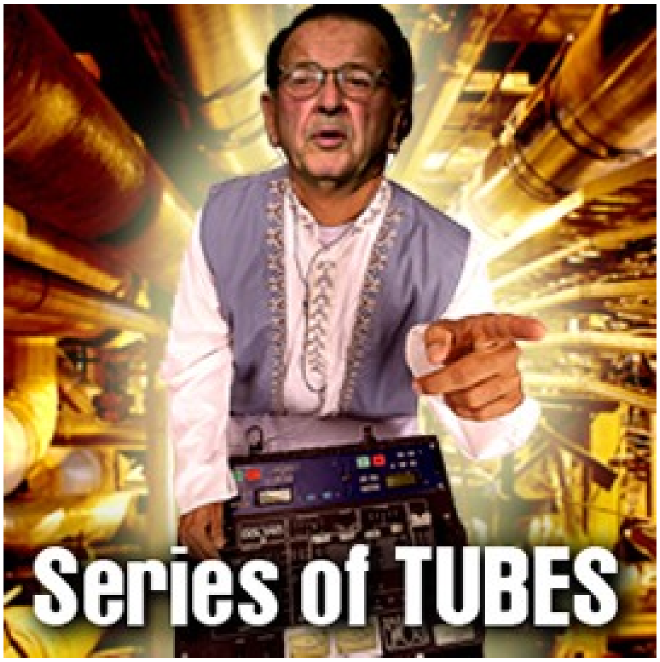

Figure 4. This sphere has a recessed space to hold a potentiometer. The potentiometer and the LEDs share a ground, seen by the translucent rendered view in (b).

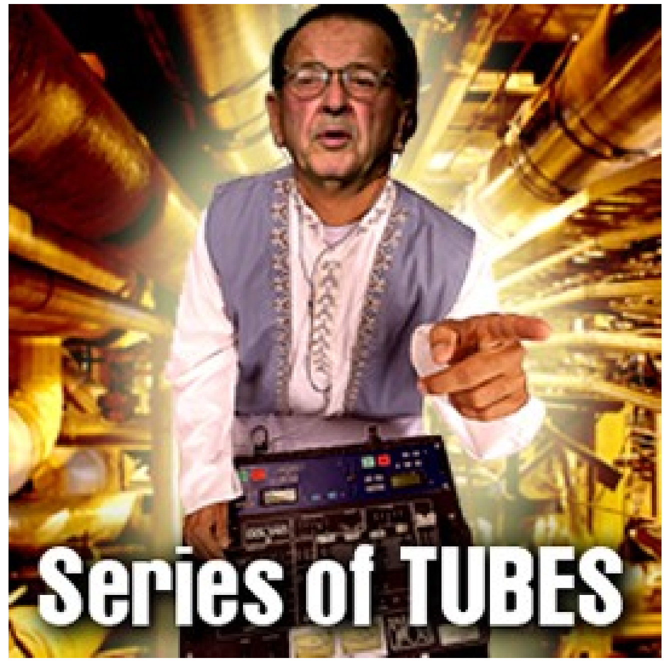

Figure 5. This box (a) contains an enclosed Helmholz resonator, seen in the cutaway view (b). This resonator creates a sound when air is blown through the tube at the top, because air compresses at the small neck joint between the chamber and the tube. VS: need to get a test print of this that actually works

Both identification by recall and intentional encoding are possible. As seen in [13], 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 distinguised 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 [26]. 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. [25] used light pipes, solid clear tubes, to create integrated displays. [17] investigated the use of computer vision to track interactions with physical mechanisms.

- [17] - Sauron. computer vision of mechanical components obviates electronics installation.
- [25] - Printed Optics. doing cool stuff with clear material (touch sensing and display)
- [21] - robots that are made of squishy stuff where air pressure changes are sensed. input components designed to react to different manipulations (pushing, squeezing, twisting, etc.)
- [12] - I'm a little unclear on what they did, but they fabbed something with a "3D circuitboard" that has a bypass that goes into 3D. they don't offer a routing algorithm or anything, though.

- [15] - this uses an airspray machine to add conductive paths to surface of 3D prints
- [**?**] - fancy machines that spray conductive film
- [20] - the RepRap people using a syringe of hot solder to squirt flat circuits into flat channels
- [7] - an instructable I followed to make my first batch of conductive paint

Routing

- [18] - Midas. routing in 2D to connect up capacitive sensors
- [14] - similar to injection of liquid metal, above
- [10] - inject liquid metal into really thin tubes in a soft substrate, sense stretching by changing resistance

Our neon routing algorithm is similar to that described by Wong, et al., in [28]. However, We are not confined to the plane to avoid line-crossings, and we also have additional freedom in creating lines where none existed. Because we can shield neon post-print with black tape or material (thus rendering it invisible), we don't have the same need to avoid drawing new line segments, and we are free to create much shorter paths. It's not quite a TSP

Interaction Techniques

- [16] - Touché. It's like Touché with sound, but without sound. SFCS.
- [3] - fabricate latex + acrylic buttons and pressurize with air
- [23] - air vortex generation in free space. air haptics.
- [30] - PneUIs, creating interfaces with pneumatics
- [22] - creating silicone bendy things with embedded electronics to sense flexing, stretching, etc., supported by those shapes.
- [8] - a display made up of many balloons that inflate and deflate to change the shape
- [13] - the Touché with sound paper from last year's UIST
- [2] - Jamming User Interfaces
- [9] - a basic mouse, but it inflates so you can store it and also use it more reasonably than a flat mouse
- [6] - hold a speaker in your hands, and air pressure changes make it feel like you're holidng a living, squirming thing

Misc

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

- [29] - Wong presents a graph-based approach for generating continuous line illustrations from images. It's approach of linking edges into a continuous line based on Semi-Eulerization is similar to ours. Prior work used tours of nodes, rather than edges, and cast continuous line drawing as a traveling salesman problem [1].
- [19] Schweikardt et al. also made a connection between electroluminescent wire and graph theory, though their contribution is orthogonal: they provide a tangible construction kit with smart nodes for building physical graph examples. Edges are lit up by EL wire.
- [24] - Strattman is the standard "text book" for neon lighting designers.
- In neon sign making, segments of a tube that should not appear illuminated are covered with opaque paint. This is called "blocking out"[1].

A SERIES OF TUBES

TOOL FOR TUBE DESIGN

We created a tool which novice designers can use to create tube-powered interfaces in arbitrary 3D models. This tool allows users to brush over the surface of their model to either select exterior connection points of their tubes (see Figure 7) or to author the tubes' interior paths (see Figure 6). 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). The resultant routing is subtracted from the user's mesh. The modified mesh can then be 3D printed.

Exterior Connection Points

our tool 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).

Routing

Focus on shape of points and location of points.

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.

Physical Simulation :

How does it actually work?

Bend Minimization

Collision detection

Designing Interior Paths

take into account bend radius of desired material - no need, we just do the minimum-bending path

(as the edges of the graph are the lines the user wishes to have lit)

This is a relaxed version of the Chinese Postman Problem[2], in which we wish to traverse all edges of the graph described in

[1] `http://en.wikipedia.org/wiki/Neon_sign`
[2] `http://en.wikipedia.org/wiki/Route_inspection_problem`

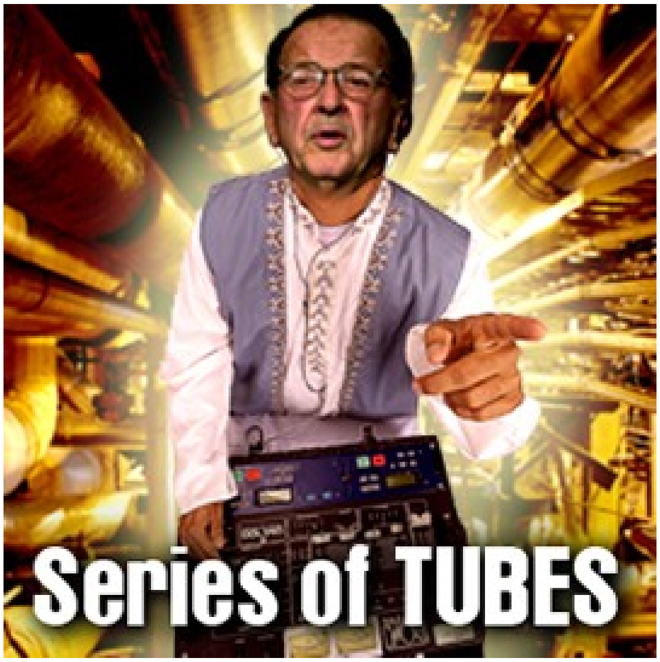

Figure 6. This figure has several sub-figures. a) shows a model with exterior connection points brushed. b) shows initial routing with A*. c) shows our physics-based, energy-minimizing rod/tube, d) shows the printed object with the tube (with something in it, copper paint presumably)

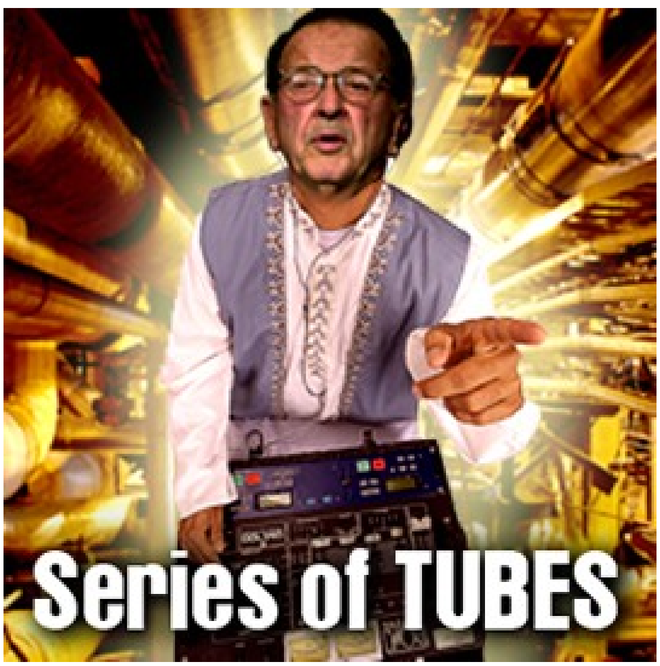

Figure 7. This figure has several sub-figures. a) shows an SVG file with some line art b) highlights the points which can't be tubed as drawn (if they are not connected, of odd degree, etc.). c) shows our connected graph, d) shows our routing e) shows a printed thing with that kind of tube filled with EL wire

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 edges to connect odd-degree vertices rather than simply retracing existing edges. In the final artifact, all created edges will be shielded by dark material so the inserted medium is not visible (see Figure 7).

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 $E_{conn} = \{e = (u,v), u \in G_i, v \in G_j, i \neq j, weight(e) = distance(u,v)\}$ be a set of edges. 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 $E' = E' \cup E_{conn-min}$.

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 $E' = E' \setminus e_{temp}$.

Theorem 1. *$G' = (V, E')$ is a connected, semi-Eulerian graph for which $E \subseteq E'$.*

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.

Mesh Modification

How we actually cut stuff and make tubes happen.

Fabrication Techniques

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 Toy

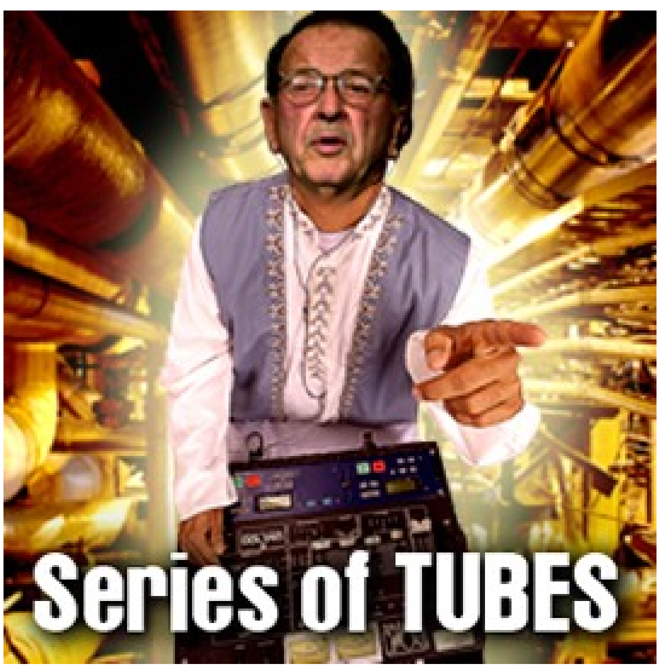

Figure 8. A touch-sensitive rabbit whose tubes are filled with conductive paint. Sensing is done on a single wire via SFCS. Inset shows the internal structure of the tubes generated by our design tool.

We created a touch-sensitive toy and an app that goes along with it, reminiscent of the boat application in [4]. This toy has an interior star topology where a single wire attached to an Arduino running an SFCS sketch splits to connect to sensors on the eyes, ears, tail, and nose. To accompany this toy, we built an app which prompts the user to find and touch certain parts of the animal (see Figure 8).

Braille Haptic Display

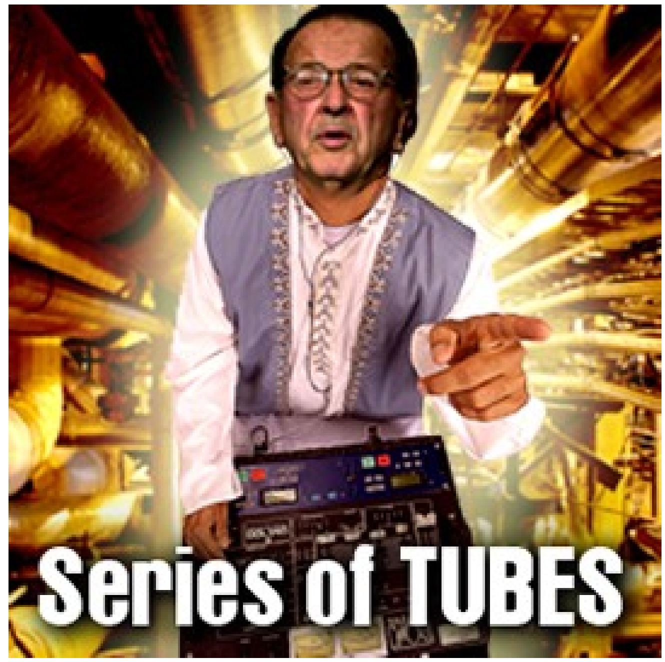

Figure 9. When air pressure is changed in the six tubes, their caps inflate or deflate. Through controlled actuation, we can create Braille letters. Inset shows the internal structure of the tubes generated by our design tool.

Using a 2×3 array of semi-closed tubes, we created a Braille output interface. The closed ends of the tubes are covered in a rubberlike material, while on the system side the tubes are attached to individually-controlled air pumps. These pumps can create positive or negative pressure in each tube, pushing the cap up or down and rendering a tactile Braille letter when used in concert (see Figure 9).

Custom Radio

A custom "radio" built using tubes allows users to tune to different stations and play sound files related to those stations. This device uses a network of disconnected open tubes filled with conductive paint to connect traditional electronic components (a potentiometer, a piezo, and an LED) to a microcontroller.

Presence-aware Pen Holder

Our presence-aware pen holder can distinguish which tool or tools a user has picked up (see Figure 11). Such information was used by [11] 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 [27] and contains open tubes filled with fiber optic cables,

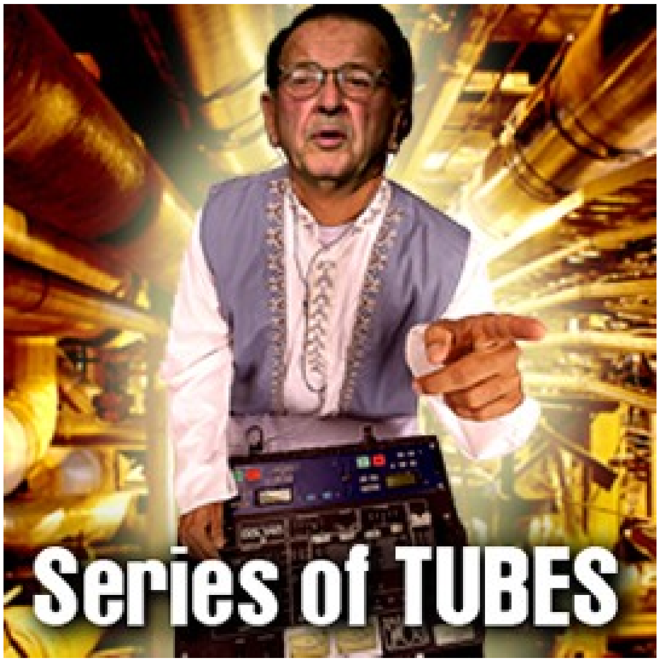

Figure 10. This radio is assembled from traditional electronic components connected by copper-filled tubes. The case was designed to allow the components to recess into it slightly. Inset shows the internal structure of the tubes generated by our design tool.

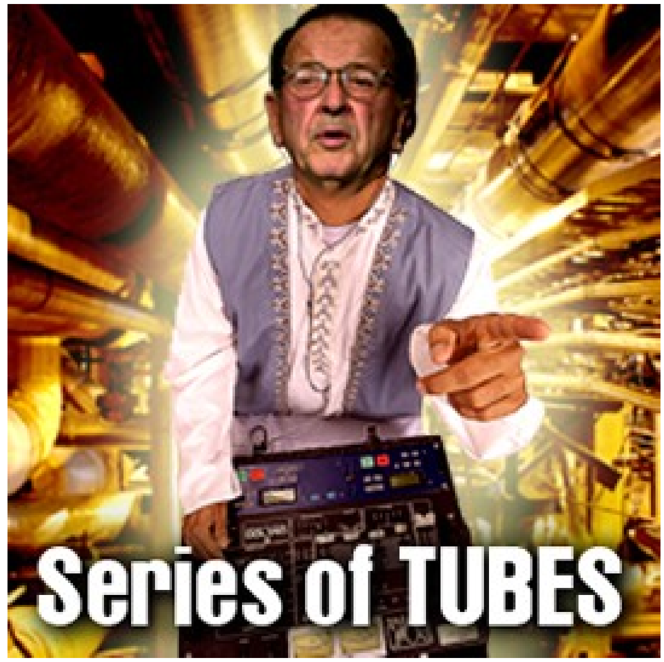

Figure 11. This pen holder (a) uses the FlyEye technique (b) to sense the presence or absence of an object in each of its tubes. Inset shows the internal structure of the tubes generated by our design tool.

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.

Animated Neon Sign

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 partial duplicate of a renowned piece of neon art from Seattle (or was it Portland?). 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.

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 complicated, 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...?**. 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

In conclusion, tubes are cool. You can do lots of things with them. There are different kinds and topologies of tubes. There are different things you can put in them. This is cool for makers and also people with really expensive machines.

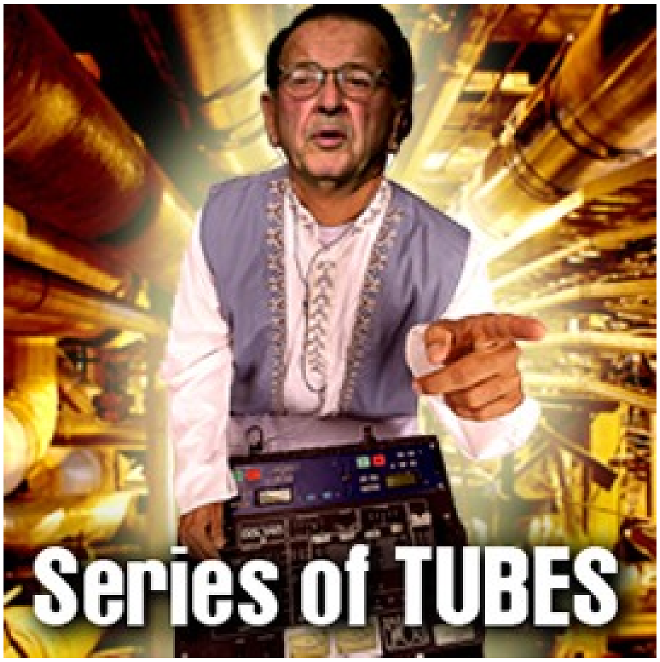

Figure 12. A neon sign (a) and its partial duplicate designed using our tool (b). (c) shows the selections we made to generate our tube structures. (d) shows the internal structure of the tubes generated by our design tool.

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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So long, and thanks for all the fish.

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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