Haptipedia

Accelerating Haptic Device Discovery to Support Interaction & Engineering Design

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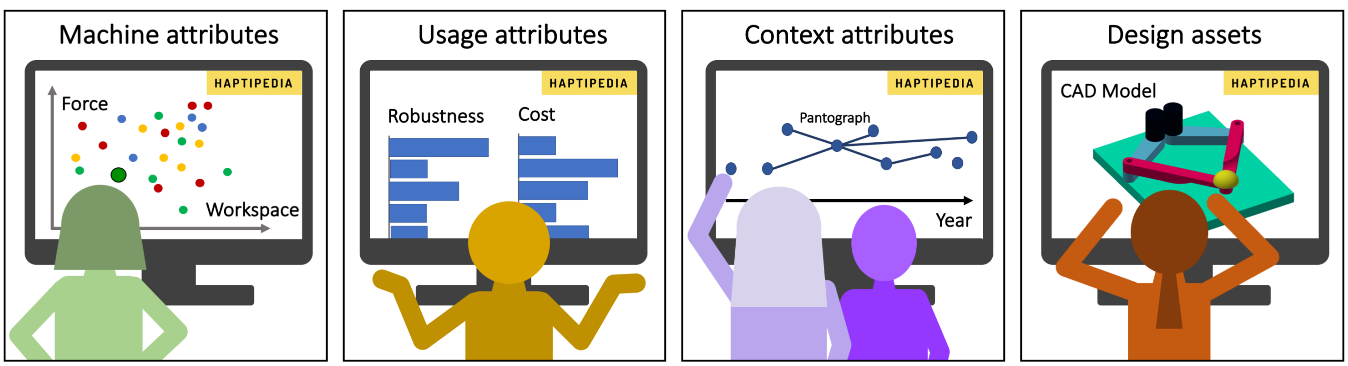

Figure 1: Designers with varying backgrounds and purposes care about different attributes when browsing a haptic device corpus.

ABSTRACT

Creating haptic experiences often entails inventing, modifying, or selecting specialized hardware. However, interaction designers are rarely engineers, and 30 years of haptic inventions are buried in a fragmented literature that describes devices mechanically rather than by potential purpose. We conceived of *Haptipedia* to unlock this trove of examples: *Haptipedia* presents a device corpus for exploration through metadata that matter to both device and interaction designers. It is a *taxonomy* of device attributes that go beyond physical description to capture potential utility, applied to a growing *database* of 105 grounded force-feedback devices, and accessed through a public *visualization* that links utility to morphology. *Haptipedia*'s design was driven by both systematic review of the haptic device literature and rich input from diverse haptic designers. We describe *Haptipedia*'s reception (including hopes it will redefine device reporting standards) and our plans for its sustainability through community participation.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **User interface management systems**; *Information visualization.*

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KEYWORDS

haptics; taxonomy; force-feedback technology; database; visualization; haptic design

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1 INTRODUCTION

Hundreds of haptic devices have been invented since 1992, intended for applications like surgery, education, and games. Each device delivers haptic sensations differently, crafting mechanical, electrical, and computational elements to address specific design priorities and compromises, fueled by both technical and human-centered insights. However, beyond haptic technology itself, developing effective touch *experiences* requires bridging ideas, hardware and interactions across interdisciplinary communities of practice. Rising engagement in virtual reality, maker culture, and physical computing has created the demand and capacity for such a bridge.

Despite surging interest in incorporating haptic feedback into a broad range of applications, most contemporary designers are largely unaware of the decades of haptic device design knowledge that exists. Reasons abound: the corpus is fragmented across disciplines (haptics, robotics, virtual reality, human-computer interaction) and described mainly by device mechanism and output, rather than interactions, use, and potential purpose. Non-engineers may find descriptions impenetrable, and even technically literate readers are challenged to leap from an engineering description to how a device feels or the ways its concepts can be reused.

Haptipedia provides a practical taxonomy, database, and visualization to efficiently navigate this fragmented corpus. By skimming the *Haptipedia* taxonomy for a few minutes, designers can easily learn about important haptic device attributes and their reporting prevalence in the literature. Through the visualization, both device and interaction designers can search and browse our database of 105 haptic devices, examine their design trade-offs, and repurpose them into novel devices and interactions.

To design *Haptipedia*, we asked: what taxonomy of attributes can best delineate haptic devices for both device and interaction designers? Academic papers and commercial device specifications report a dizzying array of engineering attributes, plus an inconsistent smattering of interaction descriptors (e.g., human body interface). Cataloguing all potential attributes is impractical and can undermine the most useful. What subset of engineering attributes is most informative? Which other attributes, missing from the literature, do users care about? Which missing attributes can be estimated by an expert device designer? Building such an attribute taxonomy demanded community engagement and systematic review of the literature by a team of experts.

Approach – We focused on grounded force-feedback (GFF) devices, as the earliest subset of haptic technology with rich device variation and considerable maturity in both research and commercial settings. From simple haptic knobs to robotic arms with a dozen degrees of freedom, GFF devices typically measure the user's motion and output force and/or torque in response. We iteratively developed a GFF taxonomy by reviewing attributes reported in the device literature, building a device database and visualization according to this taxonomy, and evaluating them with users. Device and interaction designers provided input on three major iterations of *Haptipedia*'s three components (*taxonomy*, *database*, and *visualization*) during haptic conference demonstrations, focus group sessions, and in-depth individual interviews. Specifically, we contribute:

- A *taxonomy* of GFF device attributes based on an analysis of the literature and user needs; it describes device mechanism and output, usage and interactions, and development context.
- A *database* of 105 GFF devices described according to the above taxonomy, plus purpose-created open-source 3D CAD models and device interaction videos for one third of the entries.
- An online *visualization* that facilitates database access, search, and device discovery.
- *Evaluation* of user interaction patterns with *Haptipedia*, its utility for supporting existing practices, and user questions and hopes about its process and future.

Community engagement and input from more than one hundred potential users were a crucial aspect of our taxonomy generation, and ongoing involvement is an integral part of our future plans. Thus, we describe development of the taxonomy and our data-entry tools in light of our future plans for scaling *Haptipedia* and evaluating its long-term community impact.

Finally, we show that the *Haptipedia* taxonomy provides a shared lexicon and the basis for future standards for various historically fragmented communities interested in haptics. It provides a targeted means to describe, evaluate, and generate ideas across disciplines [11, 12]: specifically, *Haptipedia* facilitates communication (descriptive power), prevents "reinventing the wheel" (evaluative power), and provides direction for future research (generative power - Section 8).

After reviewing related work (Section 2), we describe *Haptipedia*'s design and evaluation process (Section 3). Next, we detail our main contributions: our GFF taxonomy, database and visualization (Sections 4-6). We present our evaluation results, discuss them, and conclude in Sections 7-9.

2 RELATED WORK

Obstacles to 'Design Thinking' for Hapticians

To make haptic design accessible, researchers have attempted to establish haptic design as a field, connect it to the design thinking framework [17], and support it with effective tools. Schneider *et al.* compared and contrasted haptic design activities to the established design thinking methodology and practices [32, 38]. They noted that while haptic design benefits from an iterative process similar to that in other design fields, it also requires unique tools for ideating and designing in both hardware and software.

A specific and crucial obstacle is the difficulty of exploring the space of design possibilities [32]. Design exploration can be facilitated with maker kits and browsing tools. In haptics, some researchers have developed hardware kits and guidelines for this purpose. SimpleHaptics by Moussette *et al.* is a canonical example, adapting the then-emerging 3D fabrication and maker movements to facilitate rapid sketching with haptic hardware [34, 35]. More recently, projects like WoodenHaptics [23] and Haply [24] have provided haptic novices with open-source, customizable starting points for design exploration; however, these few examples cannot span the almost infinite space of historical device invention.

Galleries and browsing tools showcase a design space through examples and thus provide another means of design exploration. In haptics, a few galleries and resources exist for this purpose. VibViz allows users to explore and search through a library of 120 vibration examples [39]. Culbertson *et al.* provide a library of 100 haptic textures that can be incorporated into virtual environments [20]. On the hardware side, device designers can use online collections provided by companies such as IEEE GlobalSpec and McMaster-Carr to select hardware components (e.g., motors, sensors) for their projects [5, 6]. These galleries, however, are not specific to haptic hardware and more importantly are largely inaccessible to those new to the field.

Haptipedia showcases a large number of haptic hardware designs to facilitate design thinking processes for both novice and expert device and interaction designers.

Reviews of Haptic Devices and Attributes

Review papers and surveys of haptic technology and hardware are an additional resource for learning about haptic hardware. These review papers categorize haptic devices into technology subsets and highlight important attributes and performance metrics for each haptic technology subset.

These reviews tend to categorize haptic technology according to whether they target the user's kinesthetic or tactile sense [26, 29]. Hannaford and Okamura further categorize haptic devices into grounded devices, which are connected to a stable surface (e.g., the floor or desktop), and ungrounded devices (e.g., exoskeletons, wearables), which are mounted directly to the operator's body [26]. We adopted this practical slicing of the hardware space in choosing our scope.

GFF devices can be compared through a myriad of attributes and metrics. For the early stage of haptics research, Hayward *et al.* proposed numerous attributes for describing a GFF device's performance, including its degrees of freedom (DoF), workspace size, peak force, and resolution [27]. Recently, Samur compiled a list of metrics for measuring physical and psychophysical performance of a haptic device [37]. Yet, the majority of these attributes are missing from the corpus due to a lack of standards. Interaction design and usage attributes of haptic devices are rarely acknowledged in the earlier reviews and remain uncharacterized to date. Finally, a typical review captures just a subset of the relevant attributes, leaving designers with the need to read (at least) dozens of papers or books to learn about GFF devices.

We used the existing review papers to collect an initial list of mechanism and performance attributes for our taxonomy, further refining and complementing them with interaction and context aspects through user input and an in-depth literature review.

Taxonomies and their Visualization in Other Fields

Biological taxonomies have historically been a common scientific way for categorizing and understanding the rich variety of species and diseases [25, 36]. Although less common, computing and HCI researchers have also developed taxonomies of selected user interfaces and technologies, e.g., [21, 22].

Types of taxonomies – Traditionally taxonomies categorize items statically according to a handful of attributes. More recently, interactive interfaces and visualizations have enabled larger taxonomies that capture the richness of a design space by categorizing and showcasing items along a large number of attributes. The Information Visualization (InfoViz) literature has several examples categorizing the range of InfoViz techniques and interfaces [15, 19]. Similarly, our *Haptipedia* taxonomy characterizes devices according to a large number of attributes and facilitates flexible use of the taxonomy and the database through an interactive visualization.

Relatedly, the InfoViz community has developed interactive visualized systematic reviews, which enable users to browse and search prior work in a field by adjusting attribute ranges such as time [10, 30, 31, 40]. These interactive

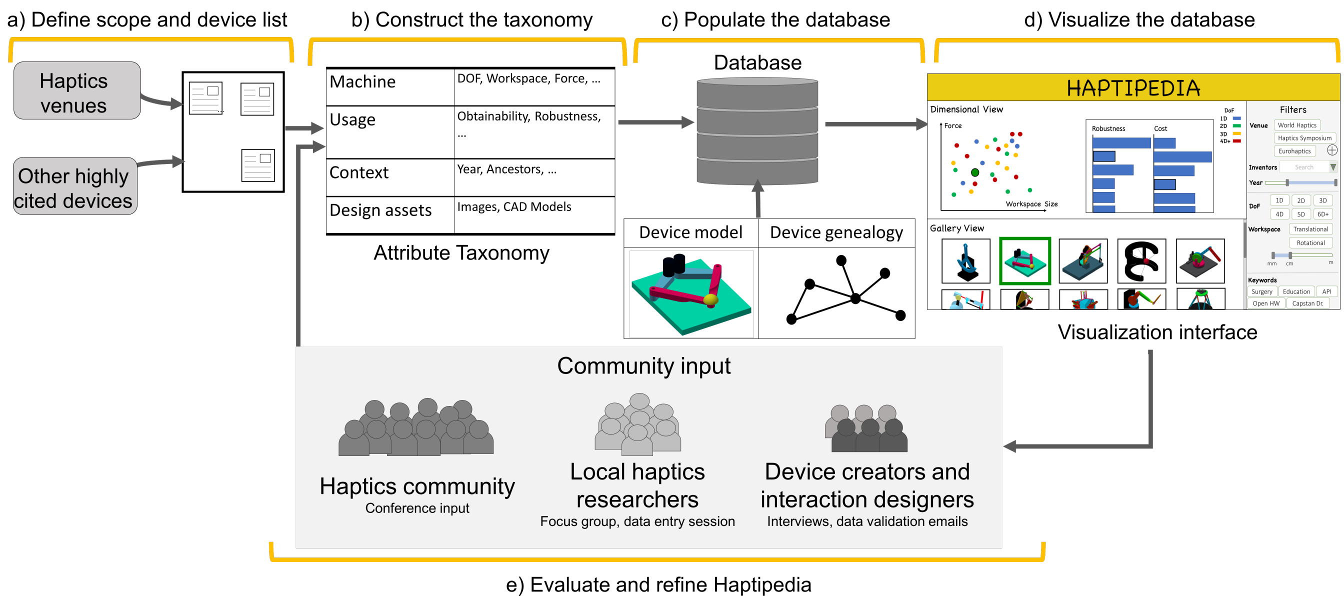


Figure 2: Our process for designing and evaluating the *Haptipedia* database and visualization.

reviews are commonly applied to the InfoViz literature itself to provide design galleries of various techniques developed by InfoViz researchers. Yet, they may or may not provide a taxonomoy of these visualizations.

Process for developing taxonomies – Taxonomies are often developed through an in-depth analysis of the examples in a design space. In InfoViz and HCI, the examples are typically described in academic publications, and therefore taxonomy generation involves systematic review of the literature [15, 16, 19]. Here, the taxonomy attributes are mainly the result of a researcher's analytic process in examining the corpus.

While we used this approach, we realized that the haptic device literature is biased toward an engineering view. Thus, we sought expert designer input on haptic devices and their attributes to complete our taxonomy creation.

3 *HAPTIPEDIA* DESIGN & EVALUATION PROCESS

Our iterative process for creating *Haptipedia* comprised five main stages (Figure 2).

a) Define scope and device list

We identified two main sources for our investigation. Source 1 is drawn from a systematic search of all papers published in the IEEE Transactions on Haptics (2008–2017) [9] or the three principal haptics conferences: Haptics Symposium (ASME 1992–2000, IEEE 2002–2016) [1, 2], Eurohaptics 2010–2016 [3], and IEEE World Haptics Conference 2005–2017 [7]. Source 2 is an expert-selected set of widely used and cited published and/or commercial mechanisms, such as the Pantograph [28] and Phantom [33]. Together, these two sources balance database richness and coverage with manageable size.

We started by labeling all articles in Source 1 as within or outside scope by reviewing their title and abstract (n = 215[1] out of 2812). In parallel, we selected highly cited academic and commercial devices (Source 2) based on citation patterns in Source 1 and our historical knowledge of major developments in the field (n = 52). Finally, we went through the articles and data sheets for this device list and selected 105 devices whose documentation reported at least DoF, workspace size, and peak force/torque (the three most reported GFF machine attributes).

b) Construct the taxonomy

Our taxonomy evolved in the number and definition of included attributes as well as their structure. The evolution process was highly intertwined with our database population and *Haptipedia* evaluation. Our initial taxonomy was a flat list of 22 attributes that authors reported for the first 33 device papers meeting our in/exclusion criteria.

Next steps used all available channels: more device papers, designer interviews, review papers, and affinity diagramming. For usage attributes (e.g., robustness), our team brainstormed initial definitions for these attributes, which were often less tangible, and later validated them with users. Furthermore, we proposed and refined categories based on

[1]n denotes the number of within scope papers.

Table 1: Summary of our evaluations and participant backgrounds. While our interviewees had a mixed range of design backgrounds, P1-5 were mainly interaction designers (denoted as Pi_{IxD}) and P6-P11 were mainly device designers (Pi_{DevD}).

Early in the design process: Conference demonstrations to get large-scale input
IEEE Haptics Symposium 2018 - 20 attendees interacted with and provided feedback on *Haptipedia* during a two-hour session
Eurohaptics 2018 - 60 attendees provided feedback during a 1.5-hour demo session.
Middle of the design process: Focus groups with local haptic researchers
Two local focus group sessions with 7 and 15 haptics researchers who discussed the taxonomy and visualization. Each session lasted 1 hour.
Data-entry session with 18 haptics researchers who provided input on our data-entry form for one hour after entering device information into *Haptipedia*.
Final stage of design: In-depth interviews with 11 device and interaction designers
P 1_{IxD} - MSc in Computer Science with interaction design background. P1 described using a 2-DoF GFF device to design an application for STEM education.
P 2_{IxD} - Bachelor's in Electrical Engineering and PhD in Computer Science. P2 described designing GFF applications for STEM education.
P 3_{IxD} - Bachelor's and Master's in Biomedical Engineering, PhD in Robotics and Computer Science. P3 described using a 6-DoF GFF device to study human-robot collaboration but has no experience as a device designer.
P 4_{IxD} - PhD in Computer Science. P4 has mainly worked as a multisensory interaction designer in academia and briefly in industry. P4 described his recent experience in developing a 4-DoF GFF device and application for visually-impaired users.
P 5_{IxD} - Bachelor's in Control Engineering and PhD in Mechanical Engineering. P5 has experience both as a device and interaction designer and described designing an application for surgical training using a 3-DoF GFF device.
P 6_{DevD} - Bachelor's in Mechanical Engineering and Master's in Applied Dynamics. P6 has experience in building devices and APIs and described developing an open-source GFF device.
P 7_{DevD} - Master's in Electrical Engineering, PhD in Mechanical Engineering. P7 has built several open-source 1-DoF and 2-DoF GFF devices.
P 8_{DevD} - PhD in Mechanical Engineering. P8 described developing 1-DoF and 3-DoF GFF devices.
P 9_{DevD} - Master's in Mechanical Engineering and Robotics, PhD in Haptics. P9 described developing a 6-DoF GFF device.
P 10_{DevD} - PhD in Computer Science and design. P10 described learning about GFF engineering and has developed two GFF devices.
P 11_{DevD} - Bacherlor's in Engineering, Master's in Computer Science, and PhD in Robotics. P11 is the CEO of a GFF device company.

potential utility for our use cases, e.g., we identified the "selecting and integrating" category based on how our participants described device selection and integration. We then iteratively found and proposed more attributes within these categories, also culling some. Our final taxonomy is composed of 62 attributes organized in a four-level hierarchy and grouped into the three categories of machine, usage, and context attributes (Table 2).

c) Populate the database and build device assets

A mechanical engineer and an interaction designer in our team read through each device document, extracted and verified entries, and discussed disagreements with the team. We used off-the-shelf tools (GROBID and PDFFigures [8, 18]) to extract text, images, and references from the device documentation and to derive the interconnections among device documents (cross-citations and shared authors).

Device asset construction – We found that including images and animated 3D CAD models of devices captured in videos dramatically increased the value of browsing and searching for users. The above-mentioned team mechanical engineer created CAD models and videos for 30+ devices in our database by closely examining the structure of the devices, visiting other research labs to make precise measurements of their haptic devices (when possible), and animating the models to show the device movement in the video (2–10 hours per device).

Data entry and verification with haptic community – To test our data-entry tools for a future crowd-sourcing step, we organized a session in which 18 local hapticians entered data for 25 total devices over the course of two hours and then provided feedback on our data-entry form for an additional hour. We reviewed and added these entries to the database. Then, we revised the data-entry form based on this feedback and sent entries for 14 haptic devices to their five creators who verified and revised the entries but reported no confusions or additional attributes for our taxonomy.

d) Visualize the database

We iteratively designed a set of interlinked visualizations based on the salient attributes in our growing taxonomy. The two initial *Haptipedia* prototypes were Tableau visualizations [4] with 33 and 45 devices respectively. The third prototype was developed in javascript [13], included device images, enabled filtering across visualizations, and was used in our interviews. Our final *Haptipedia* visualization was developed in javascript [13]; it features new views (e.g., Gallery view) as well as revised versions of the previous visualizations (e.g., Workspace size).

e) Evaluate and refine *Haptipedia*

We iteratively evaluated *Haptipedia* to identify important attributes for our taxonomy and database, devise effective visualization interactions, and assess user reactions (Table 1).

Data collection – Early in our process, we collected broad input from the haptics community through conference demonstrations. Specifically, we demonstrated our first Tableau prototypes at the 2018 IEEE Haptics Symposium and EuroHaptics conferences. Approximately 20 and 60 attendees, respectively, interacted with *Haptipedia* and provided feedback verbally and on sticky notes.

We conducted focus group sessions with local haptics researchers at mid-to-late design stages. We organized two focus group sessions, with 7 GFF device designers and 15 haptics researchers (6 shared with the first session) respectively, to identify gaps and usability issues with *Haptipedia* and obtain feedback on our 3D device models. In each session, the participants formed small teams to discuss *Haptipedia* device attributes and visualizations (40 min) and ended by sharing their thoughts with everyone in the session (15 min).

Finally, we refined and validated our taxonomy and tools with in-depth interviews with device and interaction designers. Two researchers interviewed 11 haptics designers (2 females) with prior experience in making GFF devices or interactions. We recruited our participants to have a range of backgrounds (Table 1) with roughly half of them focused on interaction design (n = 5) and the other half on GFF engineering.

In a one-hour interview, the participants summarized their educational and work experience, described a previous project in which they used or designed a GFF device, and interacted with the *Haptipedia* prototype to find haptic devices for their previous projects. We audio-recorded their verbalizations and screen-recorded their interactions with the prototype.

Data analysis – We compiled the results using thematic analysis [14]. Notes from conference and focus group sessions were discussed and summarized into: 1) requested devices and attributes, 2) reactions and comments, and 3) usability issues of the prototypes. Three researchers separately coded the interview audio transcriptions and used discussions, memo-writing, and axial coding to develop the initial themes [14]. In a final analysis, we reviewed the focus group and conference feedback again and refined the themes accordingly.

4 FINAL ATTRIBUTE TAXONOMY

Table 2 categorizes and describes our taxonomy of GFF device attributes according to: 1) machine attributes, 2) usage attributes, and 3) context attributes.

We present the percentage of interaction and device designers who requested each attribute in our interviews, as well as the percentage of devices for which that attribute is available in the corpus (reported or estimated). The most requested (≥50% by device or interaction designers) and informative (≥70% available in the corpus) are highlighted in green and include attributes from all three categories.

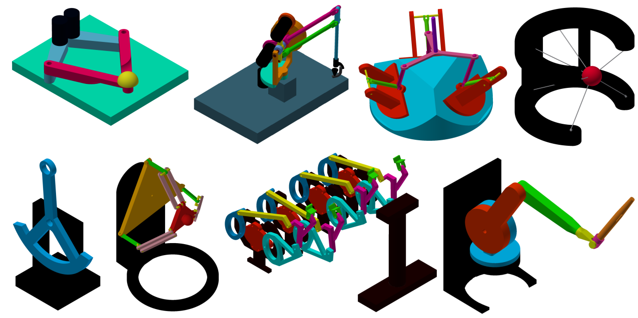


Figure 3: The *Haptipedia* database includes our newly-made 3D CAD models for one third of the devices.

5 HAPTIPEDIA DATABASE

Our database presently consists of 105 GFF devices, including 74 research prototypes and 31 commercial devices released between 1992 and 2017. For each device, we include:

- **Device attributes -** Values of the taxonomy attributes for each device are extracted from its documentation. Estimated attributes were tagged in the database and missing ones were left blank. Our team defined the seven attribute ratings (e.g., fabricability) and rated the devices accordingly. A device's interconnections are recorded in four lists of device IDs, denoting its reported ancestors plus devices in our database that are cited by, citing, or have shared authors with this device.
- **Design assets -** We provide our created-for-*Haptipedia* open-source 3D CAD models and videos for 30+ devices, to show device mechanism and movement and encourage design reuse (Figure 3). Images and videos from the inventors are also linked in the database and visualization.
- **Annotator metadata -** For each device, we provide information on who entered the data (e.g., inventor, seller, user) and their confidence in the reported data.

Our database is accompanied by an online form where users can enter information about a new device[2].

6 *HAPTIPEDIA* VISUALIZATION

Haptipedia.org hosts our interlinked visualizations for accessing the database and is built around our main taxonomy categories (Figure 4). It is composed of the following features:

[2]Visit http://haptipedia.org/pages/get-involved/ for a link to our data-entry form

Table 2: The *Haptipedia* taxonomy is composed of the device's machine, usage, and context attributes. For each category, we show the sub-attributes along the columns. The first two numbers indicate the percentages of interaction designers (IxD) and device designers (DevD) who, in our interviews, utilized or requested information on that attribute. The third number denotes the percentage of devices for which the attribute could be derived from the device documentation. For nested attributes, the parent attribute shows the maximum value of all subattributes. We highlight the most requested (≥50% of interaction or device designers) and informative (≥70% available in the corpus) attributes in green.

Machine attributes include engineering specification of the device mechanism and its output. While both device and interaction designers can be interested in these attributes, device designers focus more on performance details. Physical features, motion range, and mechanism attributes can typically be derived from the device documentation, yet detailed performance parameters are missing and hard to estimate. No standard exists for reporting any of these attributes.

			IxD	DevD	Corpus
Physical features	Mass		20	0	18
	Size		60	50	69
		Width			69
		Depth			69
		Height			68
Motion range	DoF axis types		20	67	100
	Input/Output DoF		60	83	100
		User-reachable DoF			100
		Sensed DoF			100
		Actuated DoF			100
	Motion types		60	50	100
		Translational			100
		Rotational			100
		Grasping			100
		Other			100
	Workspace size		80	100	97
		Translational size			97
		Rotational size			96
		Other			96
Mechanism	Number of links		0	0	83
	Number of actuators		20	0	84
	Sensor types		0	0	99
	Actuator types		0	50	100
	Link types		0	33	100
	Control paradigm		40	0	99
	Mechanism structure		0	33	100
Performance	Force/torque		60	100	85
		Peak force			85
		Continuous force			49
		Resolution	20	83	16
	Spatial resolution		20	67	57
	Friction		0	33	43
	Stiffness		40	50	54
	Inertia		0	33	35
	Other		20	67	20

Usage attributes highlight the needs of interaction designers who are searching for a device for a novel experiment or application. While there are no agreed-upon terms for describing these attributes and they are not explicitly reported by the creators, a haptics expert can estimate the majority of them based on existing device documentation. Our team discussed definitions for the "selecting and integrating" attributes and refined them with the studies.

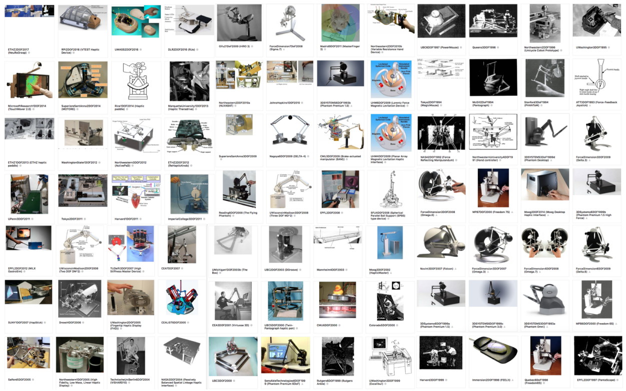
		IxD	DevD	Corpus
Interactions and applications	Anticipated applications	20	33	100
	Body part interface	20	0	100
	End-effector shape	0	0	100
	Interaction paradigm	20	0	<10
	Virtual environments	40	17	<10
Selecting and integrating	Device type	100	50	100
	Patent status	40	50	68
	Operating system	0	0	69
	Programming language(s)	20	17	61
	API(s)	60	67	48
	Hardware requirements	20	33	50
	Obtainability	100	50	100
	Fabricability	20	50	100
	Ease of programming	80	17	100
	Robustness	40	100	100
	Portability	60	50	100
	Repairability	0	50	100
	Cost	80	83	100

Context attributes provide historical context about the device in the larger ecosystem of people, organizations, and research problems. All this metadata can be extracted from the device documentation.

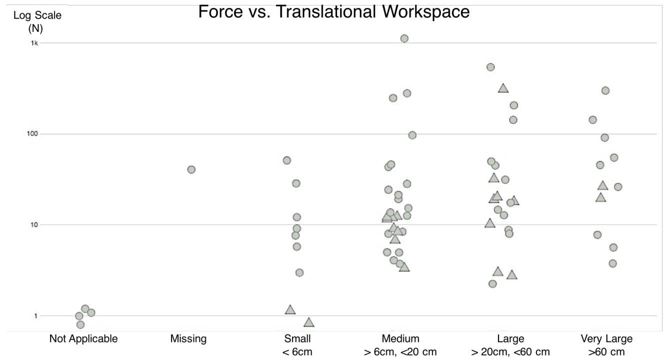
		IxD	DevD	Corpus
Metadata	Device ID	0	0	100
	Device name	60	0	80
	Release year	0	50	100
	Organization(s)	0	0	100
	Country(ies)	0	0	100
	Inventors	20	17	100
	Documentation	80	67	100
	Number of citations	40	0	100
	Novelty	20	0	100
Geneology	Ancestors	20	0	49
	Citations	20	0	100
	Shared authors	0	0	100

(1) **Gallery visualization** enables browsing all devices in a list using their device images and names.

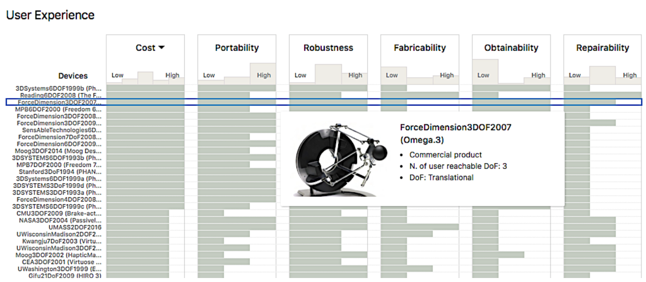
(2) **Publications visualization** shows the invention context via a timeline of all the devices and their interconnections (device ancestors, citations, and shared authors). By hovering over a device mark in the timeline,



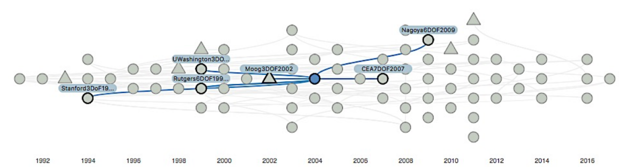
(a) Gallery visualization lets users browse all the devices using their images and names.



(b) Device Output visualization plots force and workspace for all the devices.



(c) User Experience visualization shows the seven rated usage attributes of all the devices in a bar chart.



(d) Publications visualization depicts the development context and interconnections between all the devices in the database.

Figure 4: Four of the visualizations in *Haptipedia* that provide access to (a) design assets, (b) machine attributes, (c) usage attributes, and (d) development context of the devices in our database.

the marks for relevant devices are connected through lines.

(3) **Workspace size visualization** includes three plots of the translational and rotational motion range for all the devices.
(4) **Device output visualization** shows two plots of device peak force and torque vs. their workspace size.
(5) **User experience visualization** presents the most important usage attributes (e.g., robustness). Users can see bar charts of the devices (each in a single row) against their seven rated usage attributes (across the columns).
(6) **Device summary page** shows all information available on a device (e.g., extracted attributes, images, paper abstract) and allows users to view and download our device CAD models and videos.
(7) **Comparison page** summarizes all attributes of the bookmarked devices side by side for decision making.
(8) **FAQ and Get Involved pages** address questions around using and contributing to *Haptipedia* and understanding its design process.
(9) **Filter panel** allows users to search the database according to the most informative taxonomy attributes (highlighted in Table 2). An "Advanced" button lets users customize and expand the list of visible filters.
(10) **Searching and bookmarking widgets** allow users to find devices by device or inventor name and bookmark them for future comparison.

7 RESULTS OF FORMATIVE EVALUATION

Here, we summarize findings from our thematic analysis of designer interviews (section 3) via three relevant questions.

Q1. How do users browse and search with *Haptipedia*'s taxonomy and visualization?

The participants' interactions with *Haptipedia* followed two overall phases: 1) getting a feel for the data and 2) selecting a few relevant devices. These phases were sometimes iterative and intertwined but were distinct in their goals.

Getting a feel for the data – In the first phase, the participants wanted to get a sense of the range of devices and the meaning of available device attributes, and to form an opinion about the database quality and their strategy for phase

2. Our participants took various strategies (and switched between them) to get a feel for the data. $P2_{IxD}$, $P6_{DevD}$, and $P10_{DevD}$ browsed the devices, hovered over them for pop-up information and images, and applied different filter combinations to see their impact. $P6_{DevD}$: *"I'm kinda browsing... trying to see what I can find out here."* While browsing, they frequently asked about the definition of attributes and our data source. Some used a device they already knew as a reference for exploring the database. $P4_{IxD}$ searched for a specific device and tried to find similar devices and their descendants over the years. $P4-5_{IxD}$, and $P6_{DevD}$ used a reference device to guess our attribute definitions and translated them to their project requirements (e.g., robustness). The device name was especially useful for finding a familiar device as a reference. While getting a feel for the data, participants formed an opinion about the database quality, the correctness of the content and definitions, and voiced their agreement or doubts: ($P9_{DevD}$: *"I use commercial devices. There are probably some commercial devices that aren't very robust."*).

Selecting a few relevant devices – The participants adopted a selection strategy based on the previous phase: some mainly selected devices as they browsed the database, while others applied filtering to get to a relatively small subset for further examination. In both cases, they were concerned with missing interesting devices. In the first case, they resolved this by looking through all the devices, while in the second case, they filtered according to the most important project requirements and used loose filter ranges. DoF, workspace size, and commercial availability were the most commonly used filters. When a desired attribute was not available for filtering, the participants set a loose proxy filer and browsed through the resulting device subset. Making the final selections involved removing devices from the subset based on implicit criteria they had in mind. When the set was reduced to 1-3 devices, the participants wanted to see and compare all (or selected) device attributes in one place and identify the reference documents (e.g., publication or data sheet) to check for further details.

Device images informed both the exploration and selection phases. The participants used images to form a first impression about a device ($P3_{IxD}$, $P7_{DevD}$, $P10_{DevD}$), find similar devices ($P4_{IxD}$), confirm if a device is familiar ($P3_{IxD}$, $P6_{DevD}$), guess its mechanism ($P6_{DevD}$, $P8_{DevD}$, $P10_{DevD}$) or interaction attributes ($P3-4_{IxD}$, $P6-7_{DevD}$, $P10_{DevD}$), and estimate its size and aesthetics ($P3_{IxD}$, $P10_{DevD}$). The provided design assets were important for understanding device output capabilities; $P4_{IxD}$ and $P6_{DevD}$ suggested using 3D models and animations for an effective representation of DoF and workspace size.

Q2. What device and interaction design practices can *Haptipedia* support?

New devices and applications are commonly the result of adapting existing devices that are familiar to device and interaction designers. Building and adapting existing haptic devices was common among our interviewees and helped them prototype an idea ($P1-2_{IxD}$, $P4_{IxD}$) or learn about engineering details before developing a new device ($P4_{IxD}$, $P6-8_{DevD}$, $P10-11_{DevD}$). However, all the interviewees described adapting devices they had heard of in the past and rarely explored other options. $P4_{IxD}$ wanted to brainstorm various device solutions to a design problem but eventually chose one based on familiarity: *"We were brainstorming and we couldn't think of many things... then the PI [Principal Investigator] came in and said what was that thingy you're working on... that's how we came up with the idea."* Similarly, for $P3_{IxD}$ availability of a device in the lab sparked the idea for a research project.

Examining device attributes and their trade-offs as a whole is an integral part of ideating and selecting haptic devices. The participants mentioned various goals for using a database like *Haptipedia*: 1) identifying a device gap ($P11_{DevD}$), 2) comparing their device performance to other devices ($P9_{DevD}$, $P11_{DevD}$), 3) finding design variations to improve a prototype ($P4_{IxD}$), 4) searching for a device to buy or fabricate ($P3-5_{IxD}$), and 5) keeping track of the technology ($P4_{IxD}$, $P6_{DevD}$). Here, the aggregation of device attributes in one interface helped them identify design tradeoffs and get an overall sense of the device.

Some device attributes are inherently in conflict; thus designers need to trade off between them when building or selecting a device ($P2-5_{IxD}$, $P6-7_{DevD}$). A notable trade-off was device cost and obtainability vs. quality of its haptic output. For our participants, cost usually received priority over quality of haptic feedback. Also for interaction designers, the hardware and software requirements of the device (electronics and APIs) were sometimes prioritized over haptic quality. $P4_{IxD}$ noted that these trade-offs may change depending on the stage and goals of the project (prototyping vs. refining, and researching vs. deploying to users).

On the other hand, some device attributes (such as the quality of haptic feedback) are hard to quantify. Our participants defined this particular metric as the hands-on-feel of the device and used various proxies for it, including: 1) values of a set of machine attributes such as peak force, force resolution, and workspace ($P6_{DevD}$), 2) user study results and range of virtual environments that were built with the device ($P6-7_{DevD}$), 3) relationship to a reference device, e.g., better than the Sensable Phantom Omni ($P10_{DevD}$), or 4) tacit knowledge about their mechanical structures. $P5_{IxD}$:

"We wanted [the device] to be quite stiff. [A] delta platform [a specific mechanical structure] works quite well for that."

Haptipedia's aggregated visualized taxonomy helped users examine these trade-offs and overall qualities for their goals.

Q3. What questions, concerns, and hopes does *Haptipedia* raise?

Our participants (conference attendees, focus group participants, and interviewees) were excited about the idea of *Haptipedia*, inquired about our process, and hoped for improved performance metrics and standardization in the field.

Trusting the database: questions about the process and contributor role – Many quickly noted the challenge of compiling a quality database for haptics and were curious about the accuracy of the data. Our interview participants used various strategies to test the data quality before trusting it. Seeing familiar devices helped them gain trust. $P2_{IxD}$: *"I wanna see if it includes all the stuff that I'm thinking of... to make sure that this is a good library."* $P3_{IxD}$ and $P4_{IxD}$ checked values assigned to a familiar device to verify database accuracy. When information about a device did not match their anticipations, the participants doubted the database. $P3_{IxD}$: *"Is [the] Phantom a research prototype?"*

Relatedly, the participants were curious about our data sources and their role in the process. $P9_{DevD}$: *"Did you choose the robustness or did you ask the designer? Or did you ask twenty subjects to test for the robustness?"* $P11_{DevD}$, a senior haptic engineer from the industry, wondered how he/she can correct inaccuracies about his/her devices and emphasized the need for data verification: *"For me, if I see that I have the possibility to [directly] edit the data in a tool, I won't trust the tool anymore ... it's important that this is moderated."* In our local data-entry session, one researcher wondered if and how his/her data would be verified and entered in the database. Others wanted a way to signify their confidence in the estimated values so that their data could be possibly reviewed by an expert.

The *Haptipedia* "FAQ" and "Get involved" pages describe our process and contributor roles.

Hopes for improved metrics and standardization – Several of our interviewees noted the lack of standards in the field and hoped that the *Haptipedia* taxonomy can provide metrics and protocols for device characterization. $P7_{DevD}$:*"In all the papers they just tell you ... I built it, and it works ... what does that mean?"*

The solution, however, was not straightforward. $P7_{DevD}$: *"I don't really know what to do... there's not a specific standard in haptics."* $P6_{DevD}$ suggested defining protocols for replicating device output values. $P10_{DevD}$ and a local researcher offered to work with us for measuring attributes of devices they had in their labs, while $P6_{DevD}$ and $P11_{DevD}$ suggested collecting user ratings of the devices: $P6_{DevD}$: *"What would be cool is if people start filling them out and ... maybe you can have a Yelp for devices."*.

A large collection of devices specified according to one taxonomy raises opportunities for defining and testing standards that are compatible with haptic device variety.

8 DISCUSSION

Utility of the Taxonomy, Database, and Visualization

We discuss *Haptipedia*'s capabilities and potential use in terms of three criteria outlined by Beaudouin-Lafon: a taxonomy's *descriptive*, *evaluative*, and *generative* power [11, 12].

Descriptive power – The *Haptipedia* taxonomy provides a framework and lexicon for describing various aspects of GFF devices. Our team, local haptics experts, and remote device creators were able to code 105 devices using this lexicon. Also, the taxonomy provided a means of analyzing attribute reporting trends in haptics and summarizing designer needs.

Evaluative power – Users can examine merit and novelty of a device compared to existing major haptic inventions. The database and visualization highlight unique devices along various dimensions (e.g., force, fabricability). Our evaluation results suggest that our taxonomy and visualization let users assess device trade-offs and overall hands-on feel, and select relevant devices from a large corpus. If scaled, the tool and corpus can help device engineers and reviewers to claim and evaluate novelty of a new device against historic inventions.

Generative power – Our taxonomy and visualization can inform design of future haptic devices and design tools. Finding a gap in the literature is one obvious usage scenario for *Haptipedia*. In addition, our taxonomy includes information on device ancestors and interconnections, thereby providing novices with concrete examples of developing a novel mechanism based on an existing one. A good example is the development of various pantograph configurations based on Hayward *et al.*'s design in 1994. We aim to further evaluate the generative power of *Haptipedia* in future studies with novice and expert haptic designers.

Informing other technology subsets – This paper will facilitate future taxonomy creation by providing a process and an exemplar taxonomy. In particular, other haptic technology subsets such as exoskeletons or surface haptic displays could be catalogued by a similar process. Furthermore, many attributes are re-usable: the high-level categories (machine, usage, context) and most of our usage and context attributes apply to all device types. Many machine attributes will also apply for closely related haptic device categories (e.g., body-grounded and wearable force-feedback devices), whereas new attributes will be needed to capture salient properties of other types of devices. A comparison of the resulting haptic device taxonomies could, in turn, provide great insights on these technologies and their cross-pollination. Non-haptic technologies such as head-mounted, augmented, or virtual reality displays may also benefit from designer-focused taxonomies and interactive libraries.

Ongoing and Future Plans

Evaluating long-term impact on the community – The main motivation for designing *Haptipedia* was to close the gap between various design communities and inspire novel devices and interactions. We plan to assess the extent to which *Haptipedia* achieves this goal by conducting large-scale longitudinal studies across the haptics, robotics, and HCI communities.

Scaling Haptipedia through community-sourcing and automation – While a static snapshot of the field can have a long-lasting impact on inspiring new designs, a living library would be an invaluable resource. In our next step, we are inviting the haptics and HCI communities to contribute to the database, and we are investigating the use of natural language processing (NLP) techniques to infer attributes from device documentation. Regardless of how these developments impact *Haptipedia*'s use by its communities, we believe these automation and expert-sourcing efforts can inform future haptics and HCI studies.

Developing haptic standards – The lack of standards is frustrating for designers, reviewers, and the community as a whole. Our taxonomy provides a list of the most informative attributes for describing a GFF device to an interdisciplinary audience and can be an initial roadmap for devising haptic standards. Measurement of some attributes is straightforward, but we need to develop and reinforce standards for reporting. For example, currently researchers report an inconsistent subset of user-reachable, sensed, and actuated DoF for a device. For some other attributes, a standard definition or measurement procedure may still be open for research or discussion (e.g., stiffness). One solution is to invite authors of future papers to detail their measurement procedure as a design asset for reviewers and readers, and for publication venues to support or even require this. As an alternative, our team is currently researching objective means of measuring such attributes based on the device models and/or standardized direct measurements of device examples.

9 CONCLUSION

We presented *Haptipedia*, an online taxonomy, database, and visualization of 105 haptic devices that aims to reduce the gap between device and interaction designers across disciplines. Results of our evaluations support the utility of *Haptipedia*, inform its visualization features and device attributes, and highlight the community's concerns and hopes. Our preliminary experiments with automatic and community-based scaling of the database have been promising, and thus we plan to focus our future efforts on these avenues. Further, we hope to extend our evaluations to assess *Haptipedia*'s utility and impact in haptics and the larger designer community over time. Eventually, we hope that *Haptipedia* can inspire new inventions, improve the field's standards, and encourage other community resources for engineers and designers.

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