Giving Form to the Voices of Lay-Citizens: An Intelligent, Robotic, Civic Monument

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ABSTRACT

In an increasingly digital society, it seems only apt that lay citizens be afforded interactive systems in civic, public spaces to give form to their thoughts and desires as a collective of individual voices. While civic monuments are largely static, petrified representations of the past, sponsored by institutions and political authorities, our *Monumental-IT* is an open-source, physical-digital (robotic) environment reconfigurable in real-time by lay citizens. We elaborate a process for generating and evaluating design alternatives for this large-scale, physical-intelligent artifact. As computation becomes ubiquitous in our everyday environments, the case of Monumental-IT serves as a guide for designing large-scale tangible artifacts for the public domain. Monumental-IT represents a promising future for the TEI community with respect to ubiquitous computing environments for public places, sentient, human-physical-digital interaction, and "robots for citizens."

Author Keywords

Design, architecture, robotics, monuments, human factors.

ACM Classification Keywords

H.1.2 User/Machine Systems–Human factors, H.5.2 User Interfaces–User-centered design, J.5 Arts and Humanities–Architecture.

General Terms

Design.

INTRODUCTION

Increasingly, computation is becoming embedded into the very fabric of our everyday, built environments at large-scale, impacting the ways in which we interact with each other and the things around us. This paper elaborates an iterative design process for Monumental-IT, a citizen-configurable, robotic monument (figure 1). We elaborate the generation of alternative design concepts for Monumental-IT, the basis for their evaluation, and the critical process of selecting a final design. The mixed methods employed here, both human-centered and "creative," promise to guide designers in designing intelligent, physical artifacts of room-scale or larger. Such artifacts promise to cultivate new ways for people to interact with each and their physical and digital surroundings. It should be evident that the realization of such an intelligent artifact at full-scale and *in-situ* is a costly and complex enterprise that we hope to undertake; but this ambition must begin, *as does the monument-designer's work*, with a *to-scale prototype* that sufficiently captures the complexity of the full-scale implementation.

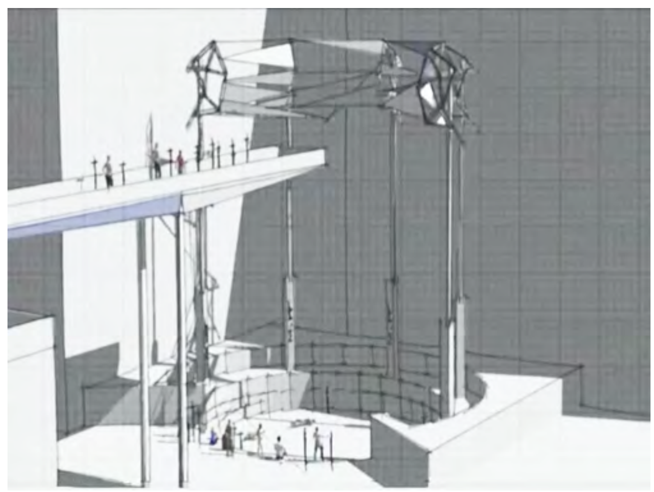

Figure 1. A drawing of Monumental-IT as a final design.

MONUMENTAL-IT, DEFINED

Monumental-IT is an open, reconfigurable, and interactive monument designed to give form, color, sound and movement to users' feeling about a specified human event. The intelligent monument is comprised primarily of five tall masts terminated by actuated, hinged linkages; the movements of these scissor-like linkages reconfigure canopies of fabric tethered above the visitors (figures 1, 7 and 8). Microphones distributed across the physical site of the monument (figures 3 and 8) invite users to annunciate what they feel in response to a specified human event; this audio input then is "read" by the system for its emotive value, and translated by the system into a multi-modal, dynamic expression of sentiment. As well as the inputs offered by users locally, Monumental-IT affords remote users to access the *Monumental-IT website* and express their sentiments by way of responses (radio buttons) to a series of questions found there. The input of remote users is actuated in the monument during those periods that are void of local user input (dead spaces). We designed the core of the monument to be transportable: the masts, linkages and canopies that comprise Monumental-IT can be dismounted, moved, and reinstalled into a ground infrastructure prepared specifically for the local context. This infrastructure may be as elaborated or as fleeting and temporary as local contexts dictate. The Monumental-IT design team would encourage local communities to consider the re-purposing of this local infrastructure, should the monument not be planned as a long-standing addition to the public domain.

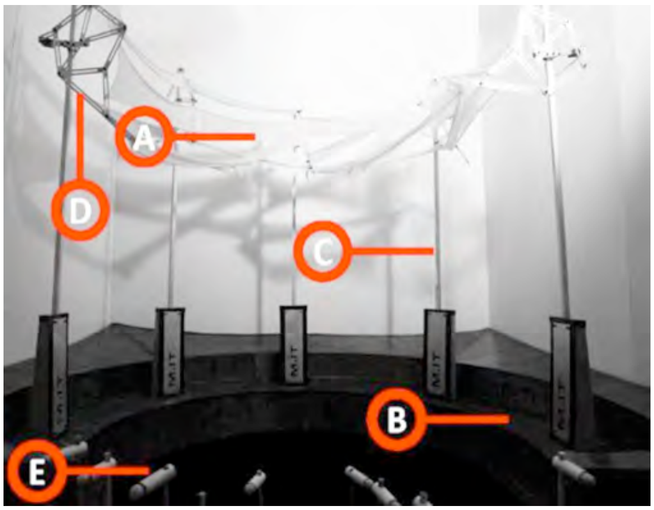

Figure 2. To-scale, physical prototype of Monumental-IT identifying its key components (A = compliant canopy, B = mast base, C = mast, D = linkage assembly, E = microphone).

For our test bed, we selected historic Charleston, South Carolina [USA] in proximity to the old Slave Mart, where tourists and other individuals passing by the site could communicate their feelings. Effectively, this intelligent civic monument makes visible, at large-scale, the sentiments of human beings – individual citizens – about a profound human event which, in our test case, is the history of slavery marked by the historic Slave Mart building, now a museum dedicated to this event. Implemented elsewhere, the transportable artifact is organized and re-tuned as a monument referencing the localized socio-cultural context.

PROCESS OF DESIGN: SIX STAGES

In developing a computational-physical artifact of this scale and complexity, a human-centered "iterative design process" is critical [3],[12],[13],[15],[17].

The iterative design process for Monumental-IT follows these six steps: (1) *defining targeted users in the form of personas* which cultivate for the design team an understanding of intended users, and the aspects of the design alternatives these users might appreciate or not; (2) *generating and describing numerous alternative design concepts*; (3) *subjecting the alternative designs to a conceptual screening process* to arrive at the design(s) which promise to be engaging, feasible, and usable, and that fulfill the broader philosophical and conceptual aims of the research; (4) *engaging in the concept resolution of fundamental components* (e.g. the physical structure and its mechanics) of the envisioned design artifact that need focused study prior to furthering any single design alternative in a holistic manner; (5) *prototyping the selected design(s)* by employing low and high-fidelity prototyping materials and embedding sensors and actuators; and (6) *designing/establishing system behaviors*. By the sixth-stage in the process of design, a final, to-scale prototype has been identified as the concrete basis for realizing a full-scale, *in-situ* artifact.

Our design chronology, in brief: we sketched more than 30 conceptual visions for M-IT; from this field of 30 visions we cultivated twelve alternatives; we compared the twelve alternatives, representing their strengths and weaknesses according to conceptual-design criteria; we selected the best two alternatives to physically prototype at 1:6 scale; and we subsequently evaluated the two physical prototypes with "experts" and "real users" towards selecting one design for intensive design development. The outcome of our iterative design process – the final to-scale, functioning prototype – is presented in figures 1-4 and 8.

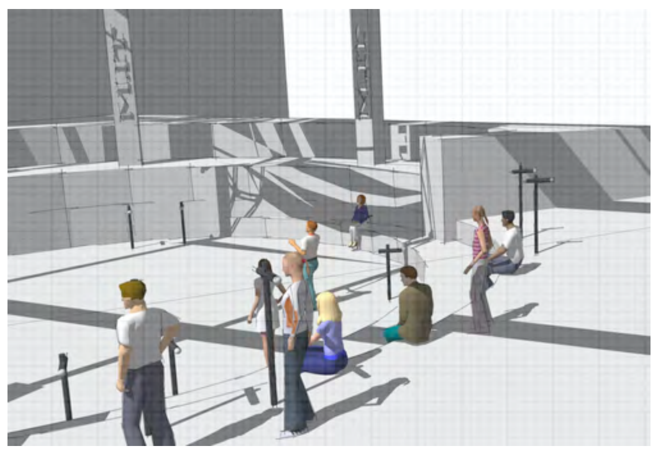

Figure 3. Visitors at the microphones of Monumental-IT.

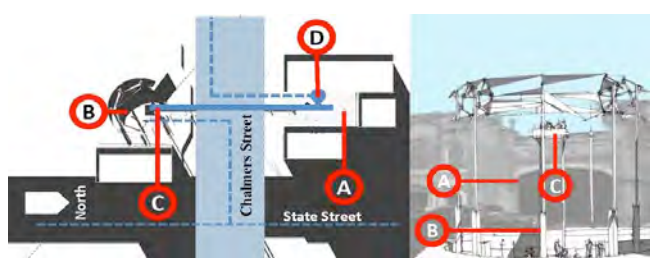

Figure 4. Monumental-IT in its test-bed, Charleston.

1. "Personas": Towards Understanding Targeted Users

"Personas" are fictional user-profiles representing envisioned user groups, conceived by the design team to assess alternative design concepts. These "user archetype(s)…guide decisions about product features, interactions, and even visual design [7]. For Monumental-IT, we employed two personas: 24-year-old **Megan** and 54-year-old **George**. Our intent in designing Monumental-IT is for the monument to engage and accommodate all users, inclusively; the two "personas" introduced here made tangible to the design team probable user groups towards our realization of a usable, attractive and useful system. We envisioned the behavior and attitudes of Megan and George upon discovering and interacting with Monumental-IT; and from this fictive enactment, the two personas guided the basis of our concept generation – "an approximate description of the form, behavior and working principles" [18] of this intelligent monument.

2. Generation and Description of Alternative Designs

The main formal problem in designing Monumental-IT was the configurability of its physical, dynamic structure, especially given that there exist few examples of dynamic structures in the history of architectural design, let alone, the design of monuments [19].

Our research team propagated more than thirty design sketches for the monument, narrowed down to twelve designs (see Table 1) based on team deliberations, again envisioning Megan and George as representative users. To simplify the concept selection phase, we assigned each of the twelve design alternative a descriptive title in accordance with its external features: Rotating Tube (A), Fan Leaves (B), Waving Strips (C), Solid and Void (D), Flower Leaves (E), Rotating Gears (F), Spider Arms (H), The Mesh (I), Hydraulic Plates (J), Strip Wall (K), Skin Wall (L), and Skeleton and Skin (M).

Following the identification and naming of the twelve design alternatives, the team described each one according to its underlying form, kinematics and working principle. Given the limited space here, Table 2 provides these descriptions for design alternatives K, L and M to offer a sense of this stage of our iterative design process.

3. Concept Screening

We employed Ulrich and Eppinger's procedure of *concept screening* [18] for concept selection. In *concept screening*, "rough initial concepts are evaluated relative to a common reference concept using the *screening matrix*," [18]. The reference concept we selected for our comparison is the "Muscle Body" by the Hyperbody Research Group of TU Delft [16]. We selected the Muscle Body for the following reasons: (1) The Muscle Body is an interactive installation at room-scale employing sensing and actuating technologies as would Monumental-IT; (2) The Muscle Body is designed for a public space for public use; (3) The Muscle Body is well known by the design team; and (4) The Muscle Body shares the fundamental characteristics of openness and re-configurability that we envision for Monumental-IT.

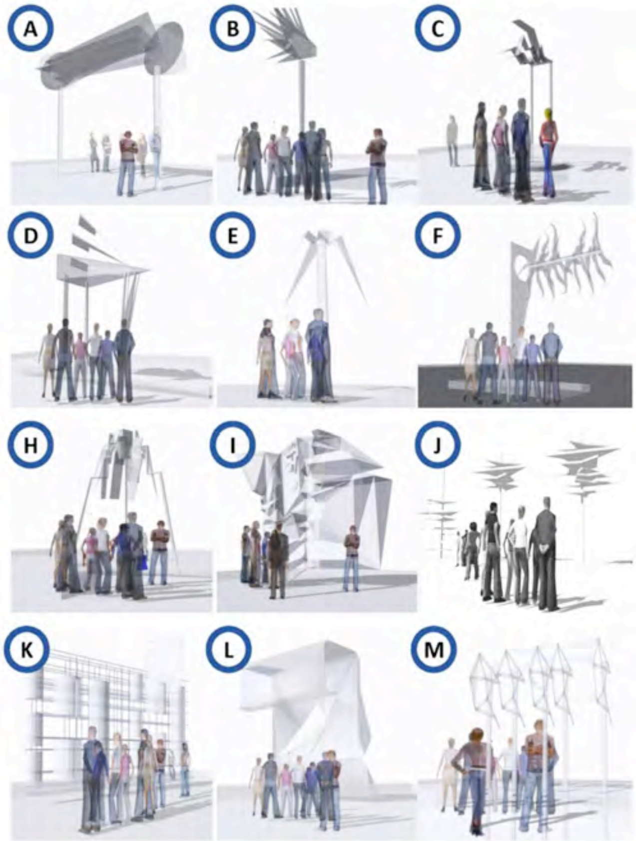

Table 1. Twelve alternative design concepts

Concept K: ***Strip Wall***

Form: A mesh structure of vertical, solid, metal elements which expand and shrink, much like a heart beating inside a skeleton.

Underlying Kinematics: Horizontal Motion

Working Principle: Shape memory alloys comprising the solid elements are actuated using pulleys and motors, expanding and shrinking horizontally, opening and closing the mesh.

Concept L: ***Skin Wall***

Form: A Z-shaped structure covered with a fabric skin expands and contracts, much like living skin on a static body.

Underlying Kinematics: Horizontal and vertical motion

Working Principle: The fabric skin is actuated using pulleys and strings attached to motors, moving in tandem with the skeleton beneath it.

Concept M: ***Skeleton and Skin***

Form: Elastic, fabric canopies deform as their 5 skeletal armatures of 12 hinged members rotate.

Underlying Kinematics: Horizontal and vertical motion

Working Principle: The closed-loop chains are actuated by servo motors, forming different configurations by changing motor speeds, rotational angles, and directions of rotation.

Table 2. Concept descriptions for designs K, L and M: Form, Underlying Kinematics, and Working Principles.

In *concept screening*, we prepared the *selection matrix*, employing design criteria and human-centered design criteria that follow the philosophical and conceptual foundations of this research, as well the lessons learned from our previous design research in interactive physical environments [9], [10], [11] and related work informing it, as considered by us in [9]. These criteria are identified as follows: *openness* (the extent to which the design availed itself to personal interpretation), *configurability* (the extent to which the design accommodated changes in form), *structural stability* (a major problem in designing kinetic structures), *aesthetics* (to what extent were the design qualities drawing the interest of users), *technological viability* (whether the suggested technology was apt and feasible for its design application), *legibility* (the extent to which users were likely to perceive apparent meaning in the design, and *impressionability* (the extent to which the design might make an impression on users after they engaged it). In the concept-screening matrix, the previous twelve concepts have been listed at the top of the table, and the criteria are listed on the left-hand side. The concepts are rated against the reference concept (The Muscle Body) using the following code: (+) for "better than," (0) for "same as," and (-) for "worse than," in order to identify particular concepts for further consideration (Table 3).

After calculating the sum of the *better than*, *same as*, and *worse than* attributes, a net ranking score was calculated by subtracting the "*worse than*" from the "*better than*" ratings. "Those concepts with more pluses and fewer minuses are ranked higher" [15]. The selected concepts were L: *Skin Wall* and M: *Skeleton and Skin*, both of which were considered further via low-fidelity prototypes at 1:6 scale for testing user interaction and usability.

4. Concept Resolution

Before developing physical, working prototypes of the design alternatives, L: *Skin Wall* and M: *Skeleton and Skin*, several aspects of the intelligent-monument concept required resolution, most importantly: (1.) the selection of hardware dedicated to actuating the robotic components of the monument; (2.) the manner of mapping the audio inputs (human vocal effects) to human emotion; and (3.) the manner of mapping human emotion to the colored lighting that we envisioned to be integral to the monument.

As for the first aspect to resolve, it was relatively straightforward to determine which hardware was most apt to actuate the robotic components of the monument. The research team selected continuous rotation servomotors for actuating both alternatives L and M, considering the formal character of these two designs, their anticipated range of behaviors, an economy of means, and overall system robustness, given the application.

The second aspect to resolve was how the intelligent monument maps an audio input (a human vocal effect), captured by its microphone, to a distinct human emotion.

Concepts

	Selection Criteria	A Rotating Tube	B Fan Leaves	C Waving Strips	D Solid & Void	E Flower Leaves	F Rotating Gears	G Muscle Body	H Spider Arms	I The Mesh	J Hydraulic Plates	K Strip Wall	L Skin Wall	M Skeleton & Skin
Design	Openness	-	-	0	-	0	0	0	+	+	+	0	0	+
	Configur-ability	-	+	+	-	+	0	0	+	0	-	0	0	0
	Structural Stability	+	-	-	+	-	+	0	-	+	+	+	+	+
	Aesthetics	-	0	0	0	-	0	0	0	0	-	0	0	0
	Techno. Viability	0	0	0	0	-	0	0	-	0	+	-	+	0
HCI	Legibility	-	-	+	+	0	0	0	+	-	0	+	0	+
	Impressio n-ability	+	+	0	0	+	+	0	+	-	-	+	+	+
Sum	Sum +'s	2	2	2	2	2	2	0	4	2	3	3	3	4
	Sum 0'S	1	2	4	3	2	5	7	2	3	1	3	5	3
	Sum -'s	4	3	1	2	3	0	0	2	2	3	1	0	0
Rank	Net Score	-2	-1	+1	0	-1	+2	0	+2	0	0	+2	+3	+4
	Rank (1=highes t)	7	6	4	5	6	3	5	3	5	5	3	2	1
	Continue? No/Yes	N	N	N	N	N	N	N	N	N	N	N	Y	Y

Table 3. *Concept-Screening Matrix*. Muscle Body (dark shading) is the comparison case. Designs L and M (light shading) were selected for further investigation

Clearly, the speech recognition system of Monumental-IT needed to be capable of differentiating distinct vocal emotions offered by each visitor via the microphone; but this aspect of concept resolution was a little more involved than was the specification of hardware for actuation. Towards resolving this mapping problem, we drew from research on vocal effects in natural and synthetic speech. While for robotic applications, Gibilisco [5] categorizes vocal effects to just three frequency ranges or "formants" (f1 for frequencies less than 1000Hz, f2 for ranges from 1600Hz to 2000Hz, and f3 which ranges from 2600Hz to 3000Hz); Murray [14] expands the vocal effects to seven categories (frequency, intensity, pitch, rate, quality, change in pitch, and articulation). For Monumental-IT, we found a a more apt middle-ground in Breazeal's characterization [5] of vocal effects (for social robotics applications) in terms of frequency and intensity. Focusing on only frequency and intensity to characterize vocal effects, and employing Murray's attribution of these effects to the four emotions – Fear, Anger Sadness and Happiness – we arrived at the following conceptual resolution for vocal effects employed in Monumental-IT (Table 4):

	Fear	**Anger**	**Sadness**	**Happiness**
Frequency	Very Much Higher	Very Much Higher	Slightly Lower	Much Higher
Intensity	Normal	Higher	Lower	Higher

Table 4. Vocal effects mapped to four human emotions

The third aspect to resolve was to determine how distinct emotions might be mapped to the colored lighting that we envisioned as integral to the monument. While the team was fairy confident in resolving the concept of vocal inputs just considered, we recognized "no general validity" in previous research efforts to associate color and emotion [2], [6],[8]. With no evidence to inform this aspect of concept resolution, the design team reasoned to tentatively assign the "vibrant" color red to anger, the "cold" blue to fear, "multi-colors" red, yellow, green, and blue to represent happiness, and white to represent sadness. In our iterative process of design, we tested our assumptions of color and emotion by means of surveying participants, who were asked to ascribe the four distinct emotions to images showing the color coding just described, superimposed onto the physical prototypes in the way the team envision they might be experienced. The results of the survey are presented later in this paper.

There were other aspects of Monumental-IT that were part of our concept resolution phase of design; what we offer here are three key aspects of the design that demanded resolution, and how we resolved them. What is clear and important to note from this and the previous stages of our design process so far considered, is that some design decisions were, for the team, more practical, some design decisions were evidenced-base, some design decisions were aesthetic, informed by design precedent, brainstorming and creative play, and some design decisions (e.g. our emotions-color mapping) were reasoned yet mostly subjective in those cases when the team could find little or no evidence for informing the design process. Recognizing these mixed circumstances endemic to complex design problems like this one, the design team took utmost care to address each design challenge of the iterative design process, employing whatever means to best inform the developing design of Monumental-IT.

5. Physical Prototyping

Prototypes of design alternatives L: *Skin Wall* and M: *Skeleton and Skin* were realized largely with digital fabrication tools in paper, cardboard, metal, wood, plastic and fabric as 1:6 scale models embedded with motors and lighting (figure 5). These physical, functioning prototypes were subjected to human-centered design methods to evaluate the usability of each design, to understand its different components, and to study robot actuation. Specifically, we employed heuristic evaluations involving "experts" in the domain fields of usability, electrical and computer engineering, and architecture; we also employed usability surveys. The aim of these investigations was to identify one of the two design alternatives for focused design development, and to better understand the potential of Monumental-IT as an intelligent, digital-physical, large-scale built environment.

The first prototype of design "L" was 60 cm wide and 80cm high made of corrugated cardboard sheets and Lycra fabric. The skin was actuated using nylon strings anchored at different points of the fabric at 15cm intervals. The strings were attached to three servomotors controlled by an Arduino microcontroller, programmed in Arduino [1].

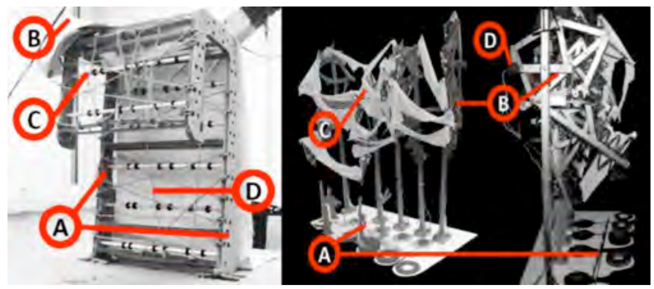

Figure 5. First prototypes: alternatives L and M.

Initial testing of "L" suggested that the various physical configurations afforded by the design were not adequately distinguishable to represent distinct emotional states. Also, it became evident that variable weather conditions, namely wind direction and speed, would significantly alter the behavior and legibility of "L".

The first prototype of design "M", at the same 1:6 scale as that for "L", was comprised of the key components identified earlier: microphones to capture users' speech; closed-loop, kinematic chain structures (hinged links) actuated by servo motors; elastic fabrics (skins) attached to the chain structure; LEDs, and Arduino microcontrollers, programmed in Arduino. At first, the chain structures were fabricated using plastic tubes (figure 6 – left); but we discovered that the tubes obstructed a clear path of rotation. Evidently, the linkage-hinge mechanical system of "M" required further investigation. Consequently, a second version was realized using corrugated cardboard which allowed for unobstructed rotation (see figure 6 – center). This second version served the purpose of allowing the team to study the behavior of the moving monument – the key intent of this earliest phase of prototyping; however, and as we half-anticipated, the cardboard structure was only adequate for the earliest phase of investigation, as the joints between linkages were not capable of supporting the dynamic loads of the moving assembly, and the friction caused by the joints hindered rotation.

In initial testing of the two prototypes, the various physical configurations afforded by the design "M" promised to be, more so than "L", sufficiently distinguishable to represent the distinct emotional states intended. As well, it became evident that 'M" would be less likely impacted by variable weather conditions as compared to "L". While these findings were not clearly evident from the design drawings (3D models) of "L" and "M" when explored across the twelve alternatives, the physical scale models of "L" and "M" availed to the team the dynamic, reconfigurable physicality of the two alternative designs, enabling us to arrive at the conclusion to exclude concept "L" from further study, and to focus our attentions on refining design "M".

The hinged linkages of "M", however, demanded further study. The next iterative prototype of "M" was consequently made using wood linkages joined by hinges of bolts and nuts. This iteration presented further challenges: the rotation of the mechanical system was retarded due to frictional force of the hinge assembly and its heaviness. We improved rotational speed through the implementation of smaller bolts and lighter materials (aluminum) for the linkages. These mechanical changes also served to overcome another critical challenge: the embedding of the motors compromised the structural integrity of the overall monument, particularly as the structural loading is dynamic. It was evident that the momentum of the moving structure affected the connections of the structural posts (masts) with the bases. To further improve the behavior of the prototype, the post-to-base connection was strengthened.

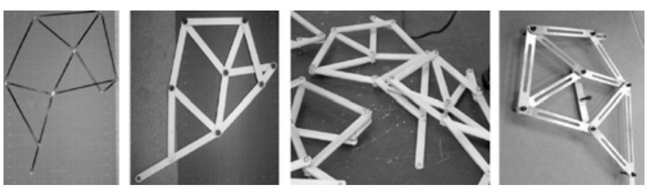

Figure 6. Linkage designs in (L to R): plastic tube, cardboard, wood and (ultimately) laser-cut aluminum.

6. Designing/Establishing System Behaviors

By this point in the design process, we had identified a single design selected from a range of alternatives, we had adequately resolved its structural and mechanical systems for the purpose of prototyping at 1:6 scale that began to capture a semblance of the full-scale implementation, and we had resolved some number of key concepts (e.g. colored-lighting and vocal mapping to emotion). To further the design, the team established a combination of lighting and movement behaviors for each of the four emotions the monument was intended to exhibit. The strategy for displaying color has already been considered here. The strategy for the monument's movements, its "choreography," was initially developed through lab discussions. Both color and movement were iteratively designed and evaluated by user studies as described below.

As initially designed, the four modes can be described as follows (see prototype in figure 7):

"Fear" mode (i.e. the "blue configuration"), in which the blue LEDs turn on, and the hinged links atop masts 1, 3 and 5 actuate, alternatively, at very slow speed, one-quarter rotation of the kinematic loop;

"Angry" mode (i.e. the "red configuration"), in which the red LEDs turn on, and all the hinged links (atop masts 1-5) actuate together, at full speed;

"Happy" mode (i.e. the "multi-color configuration"), in which the different LED colors randomly turn off and on, while the hinged links actuate, in succession (1-2-3-4-5), at normal speed; and,

"Sad" mode (i.e. the "white configuration"), in which all LEDs turn off, and the structural elements actuate in succession (1-2-3-4-5), in full rotations of the kinematic loops, at slow speed.

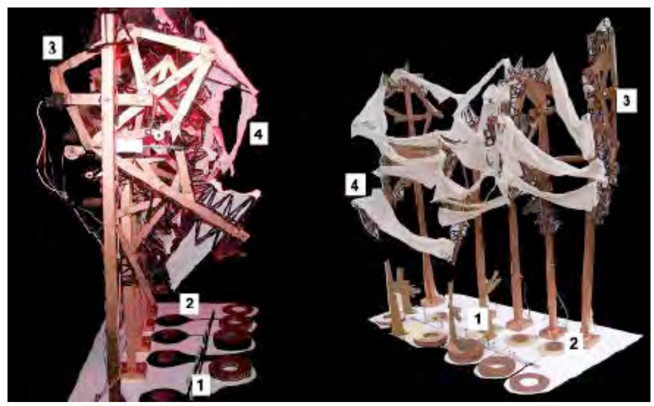

Figure 7. Images of prototype "M" as initially designed.

EVALUATION OF EARLY PROTOTYPE AND ANALYSIS

Working from prototype "M" described above, heuristic evaluations and usability evaluation techniques were employed for further design development and evaluation of Monumental-IT. All evaluations were performed in our lab with user consent and IRB approval.

Participating in the heuristic evaluation were five "experts" from the domain fields of usability, electrical and computer engineering, and architecture. On a survey form created by the team, experts identified problems with and made recommendations for each stage of engagement with the monument, from the first sighting the monument to leaving its physical site; the experts were then asked to rate the severity of each problem identified, using Nielsen's five Severity Rating Scale [15]: (0) no usability problem, (1) cosmetic, (2) minor, (3) major, or (4) catastrophic problem. The average severity ratings for usability problems were used to identify priorities for improving the design of Monumental-IT. From the completed heuristic evaluation forms, the research team collated, summarized and prepared a complete set of usability problems identified by the experts identified (Table 5). Following the heuristic evaluations, sixteen users (from the larger university community – students and faculty) were presented with the prototype performing the four modes in succession. Users were then asked to complete a survey aimed at providing feedback about the monument's design as presented in the prototype, particularly with respect to verifying our mapping of programmed mode (color, form and movement) to emotion.

We found that our modes, as initially designed, did not map well to the intended modes of "emotion" modes (table 6). Participants mapped: the blue configuration to sadness (rather than to fear); the white configuration to happiness (rather than sadness); and the multi-color configuration equally to sadness and fear (rather than happiness). The red configuration did, however, map well to "angry" as initially designed. Informed by these outcomes, the team re-mapped the configurations (or "modes") to emotions, accordingly.

Heuristic(s) Violated	Descriptions	Severity Ratings
Visibility of System Status	How do users know that the monument is waiting for their inputs?	2.6
	The users need priming to start getting involved.	2.2
	The skin doesn't offer much: it doesn't create an environment.	1.6
Aesthetic and Minimalist Design	Users don't know what to do next after speaking to the microphones or stepping on the footsteps	2.2
	The speaker and the footsteps are not integrated in the design of the monument.	3
	There is no need for an acoustic beep to indicate formal physical cue.	2.2
User Control and Freedom	The users do not know if the system accepts their voices or not.	2.2
	Do people need to reset a button after speaking to the microphones?	1
	The skin doesn't offer much: it doesn't create an environment.	2
Differentiate Monumental-IT's Configurations	The skin doesn't offer much: it doesn't create an environment.	1.6

Table 5. Usability Problems identified and rated following the Heuristic Evaluations of "Experts"

The survey included, as well, a qualitative component. To the question, "*How would you describe Monumental-IT in one sentence?*" for instance, some revealing responses included: "making history interactive," "evolving and changing humans' identities in a way of representation," and "making history interactive." Overall, users reported a very positive attitude for and appreciation of our developing prototype and, more broadly, our concept of a citizen-reconfigurable monument.

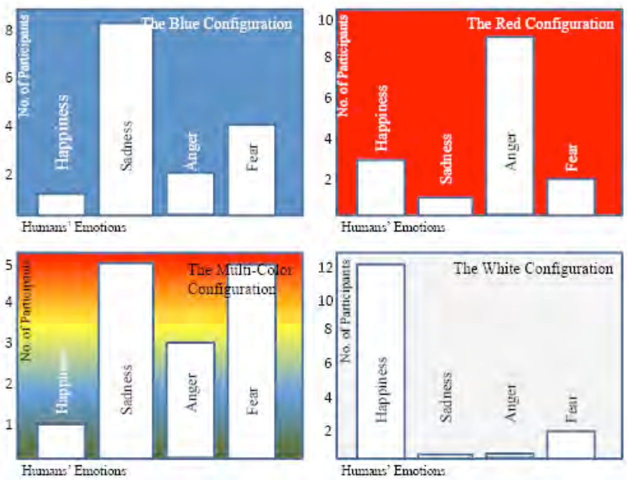

Table 6. Numbers of users (y-axis) mapping a given modes to one of the four emotions.

CONCLUSION

We presented our iterative design and evaluation processes for a digital-physical monument that is literally shaped by public engagement. Monumental-IT represents a promising future for the TEI community with respect to ubiquitous computing environments for public places, sentient, human-physical-digital interaction, and "robots for citizens."

For any design activity, generating and evaluating design alternatives, and ultimately selecting one or more for further refinement, is a complex undertaking that has no single, agreed-upon methodology. When the design activity is focused on developing intelligent digital-physical artifacts at the scale of a room or larger, the undertaking can become daunting. We explored such an undertaking, tracing the design evolution of a citizen-reconfigurable monument that invites people to engage and share, to ponder and interpret collective human history, locally and remotely. Our early design processes included, on one hand, design advances that were well-informed by User-Centered Design (UCD) approaches involving users throughout the design and development process [3],[12],[13],[15]; on the other hand were our design advances shaped by the research team through regular discussion, brainstorming, creative play, and debating activities that drew from a multitude of inspirations.

After the successive stages of design presented here, the team proceeded with further design developments of the prototype, informed by the learned lessons above as well as the same mix of methods. The final scale prototype, functional in key respects, is presented in figures 1-4 and 8. To emphasize again, the realization of this artifact as a full-scale, physical-robotic monument, *in-situ*, is a costly and complex enterprise that we hope to undertake; but such an ambition must begin as a functional, to-scale prototype that sufficiently captures the complexity of the full-scale realization. While this is not the way of working in the TEI and robotics communities (where 1:1 scale is the rule), it is the workspace of architects, landscape architects, urban designers and planners working at large-scale: the new frontier of ubiquitous and tangible computing and HRI. The aforementioned computing and environmental design communities have much to learn from one another as they converge to shape a realm that is, at once, physical, digital, technological and social.

Our elaboration of the successive stages of designing the functional to-scale prototype is intended to inspire and guide interdisciplinary design teams (like ours), undertaking the inevitable challenges of designing room-scaled or larger intelligent, physical-digital (robotic) environments. It might be said that the process of design elaborated here shares much in common with monuments themselves, as the techno-cultural products of history.

Figure 8. Moving linkages and fabric canopies of the final prototype (top); Detail of final prototype (bottom).

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