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From passive to active forms

Abstract

Based on the continuous increase in functionality of interactive prod-ucts, tangible user interfaces are coming up. We will address one important de-sign challenge: how to design the feedback of the internal state of the interac-tive product in a natural way. Although already several solutions are possible, we will introduce a new approach via smart materials. With smart materials the feedback of tangible I/O devices can move from passive to active forms. Based on a general concept of active forms we will demonstrate and discuss the state of the art of using smart materials to explore a new design space for feedback in human computer interaction.

1. Introduction

Nowadays, developing a new product or service means being creative and taking risks to explore new opportunities provided by upcoming technologies. But before any particular semantic could be mapped to a new syntactical form, we have to explore this syntactical design space first. Combining all kinds of new materials and advanced technology is part of the established engineering research agenda. Given new syntac-tical interesting combinations the next step is investigating possible meaningful map-pings of functionality (i.e. semantics) to these new forms. This is part of the research agenda of industrial design. But at the end to launch a successful product or service on the market these new combinations of form (i.e. syntax) and functionality or con-tent (i.e. semantics) have to be embedded in the behavioural interaction pattern of the customers (i.e. pragmatics).

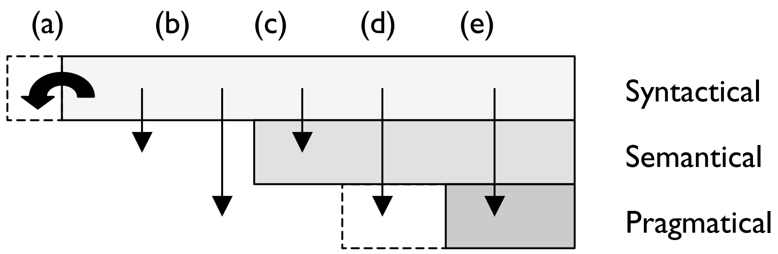

Figure 1. The 3 different levels of a product development process: from syntax to pragmatics.

We assume that functionality or content (i.e. semantic) can *not* exist without a prede-termined form (i.e. syntax). Although this assumption is debatable, we still think it is quite useful for the following discussion. We can distinguish six different situations to explore each level (i.e. syntactic, semantic, pragmatic) and to investigate the map-pings between them (see Figure 1, (a) … (f)). In situation (a) we *only* explore the syntactical level and try to find stabile or at least interesting combinations of new materials and/or electronics. The difference between situation (b) and (d) is that (b) is a *useless* mapping and (d) is a *useful* mapping of semantic to a new form. Usability testing can help to distinguish between both situations [16]. In situation (c) a company wants to introduce a new product or service on the market (i.e. pragmatic) and fails due to an inappropriate mapping between syntax and semantic. In situation (e) such kind of 'failure' can be repaired by intensive marketing and advertisement to extend the scope of the pragmatically level. Only situation (f) guarantees without extra effort a successful introduction of a new product or service on the market. User centered design increases the chance for achieving (f) [24]. In this paper we describe our pre-liminary results somewhere between situation (a), (b) or (d).

1.1 Exploring the design space

Looking back in history we can identify three major design styles: (a) mechanical style, (b) electronic style, and (c) mechatronic style (see Figure 2). At begin of the industrial revolution dedicated forms for a particular set of functionality was intro-duced and widely used (e.g., typewriter device). For each function a dedicated set of hardware controls was designed; the function-form mapping was almost 1:1. The internal state of the interactive device was perceivable in a limited, fixed and prede-termined form-function-state space. We call this period the *mechanical design style*.

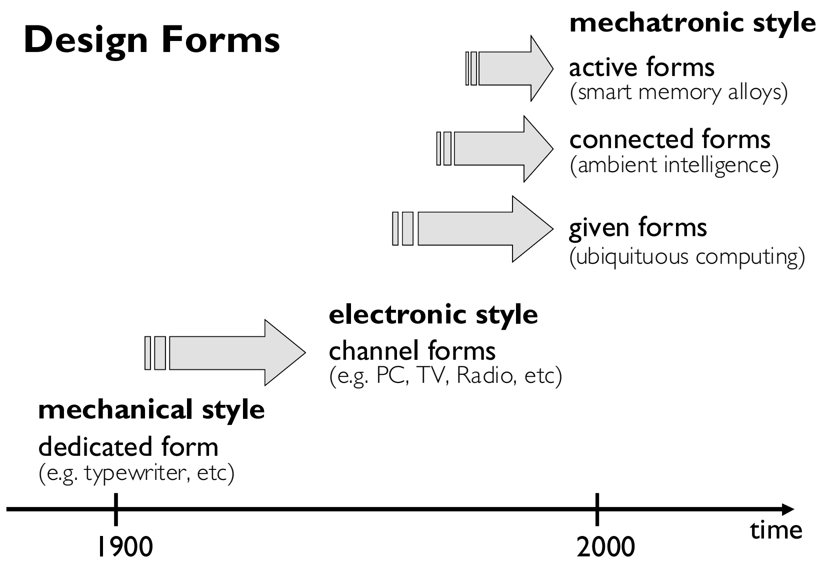

Figure 2. Historical overview of the major design forms and allocated styles (see [15]).

With growing functionality the mechanical style reached its limits. Above a particular threshold of functionality the new electronic style had to be introduced to overcome the limitations of the mechanical style. Most of the new functionality disappeared into the device itself and could only be accessed via a generic set of input controls (e.g., key pad, game console, mouse, remote control, etc.). The function-form mapping between hardware controls and embedded functionality was now 1:many. This lead directly to the concept of modes. A mode determines temporarily the actual semantic of the limited and fixed set of hardware controls. The complexity of the functionality had to be separated from the form in which this functionality or content was embed-ded. The form of the overall container turned into a *channel* and was mainly perceiv-able via the graphical form changes on a display (e.g., graphical user interfaces for PCs). We call this period the *electronic style*.

The latest development is called the *mechatronic style* in which we can distinguish three kind of forms: (a) given forms enhanced with additional functionality (e.g. ubiquitous computing), (b) connected forms of channel devices (e.g., ambient intelli-gence), and (c) most recently active forms (e.g., smart material). In the rest of this paper we will focus particularly on these active forms.

1.2 Smart materials as a new design option[1]

One new type of material is called 'smart material' [5]. With this type of material new applications can be realized: e.g., smart tennis racquet, smart dragonfly, the magic teaspoon, etc. A definition of 'smart materials' is still not set. However, words as *active* or *intelligent* are often used and smart materials are often grouped as material systems with unique properties. A good general description for smart materials is "materials that respond with a change in shape upon application of externally applied driving forces" [1]. This response in change of shape can be used to convert the en-ergy that is applied into desired motion or action [30]. Because this paper focuses on changes of shape of materials, following definitions and background regarding stress and strain terminology might be helpful.

Stress: The external forces (pull, push, shear, twist or bend) applied to a compo-nent result in stresses within the material. A stress is a measure of the force in a component relative to the cross-sectional area over which the force is applied. Stress is measured in force per unit area, for example, N/m^2 (Pascal, Pa). $\sigma_t = F_t / A$ where σ_t is the stress, F_t is the force, A is the area, and the subscript t denotes that the force and stress are in tension.

Strain: Strain is a measure of deformation (either elastic or permanent). Hence, strain in a wire denoted as ε, may be written as $\varepsilon = \delta / L$. Where L is the original length of the wire and δ is the change in length that occurs when the wire is pulled by weight F.

In terms of stress and strain, Hooke's Law may be written as $\sigma = E\varepsilon$ where E is a constant of proportionality referred to as Young's modulus or the elastic modulus. The Young's modulus is constant of proportionality referred to as Young's modulus or the elastic modulus. Young's modulus is analogous to a spring constant that it is a measure of the relative elastic stiffness of a material [14]. The Young's modulus is the degree of elasticity and is the range for which ratio of stress to strain over the range for which this ratio is constant, i.e. up to the yield point. It is a measure of force that is required to deform the film by a given amount and is therefore a measure of the in-trinsic stiffness of a film [2].

Yield strength: Design stresses must be lower then the yield strength to ensure that a part does not fail by plastic deformation. Shear strength may be estimated from the yield strength.

Shear strength: Strength of a material is stress at which a shear-loaded member will fail [14].

1.2.1 Shape Memory Alloys (SMA)

Description: Upon motion application on e.g. Nitinol wire in a system, using a force (stress, with a bias) to get Nitinol after the detwinning phase and in plastic deforma-tion and thus elongated (strained). When a small current is applied through the wire, the temperature of the wire is increased due to electronic resistance. As the tempera-ture reaches austenite phase temperature, the wire contracts at a limiting upper tem-perature to the form stress-induced, which is powerful enough to lift up 4 to 5 times it's own weight. The reaction speed depends on the diameter of the wire and usually takes a fraction of a second. Higher temperatures will cause non-elastic formation and irreversibly destroys the wire. When the current is switched off, the wire cools down and depending on the wires' diameter the heat lost by convection. This will cause the wire to expand within seconds, hence straining the wire with a bias force. Within conditioned parameters the wire can contract and expand 4 to 5% for over a million times [32].

Application: SMAs can be used as semi-finished material in bars, rods, wires and strips. Several successful products have been marketed, such as scald protection in shower valves, air conditioner air flow control mechanism, and actuators to improve automatic transmission shifting and reducing pollution emissions in automobiles, and in medical devices.

Technical facts: Because Nitinol has being developed and used since the early 1970's, it is commercially available and it has proven to be the best SMA. Flexinol has been used to produce MuscleWires which has the following physical properties [32]. Density: 6.45 g/cm3. Melting temperature: 1300°C. Minimum bend radius: 50x it's diameter. Maximum recovery force: about 600MPa (= 106 N/m2). Recommended recovery force: 1/3 maximum recovery force (200MPa). Recommended bias force: 1/10 – 1/20 maximum recovery force (30-60MPa). Maximum recovery ratio: 8%, up to a few cycles. Recommended recovery/deformation ratio: 3 – 5%, for maximum wire life. Breaking strength: 10x maximum recovery force, expect deformation of 15-30% before breakage. Young's *Modules:* Enduring strain varies greatly. Low temp around 28 Gigapascal (comparable to lead), High temp: 75 GPa (comparable to alu-minum). Poisson's Ratio: How much narrows when pulled at each end (shrinkage under stress) This ratio varies widely; for Nitinol about 0.33 (same as aluminum). Magnetic fields: Nitinol is virtually non magnetic. Activation start – finish tempera-ture: 68 – 78°C. Relaxation start – finish temperature: 52 – 42°C. Resistivity: austen-ite approx. 100 Ohm/cm, martensite 70 Ohm/cm [17].

1.2.2 Electro Active Ceramic (EAC)

Description: Commercially most widely used piezoelectric ceramic is PZT, Lead-Zirconate-Titanate. Piezoelectric polymers (semi-crystalline polyvinylidene fluoride, PVDF) are usable under high temperature. Piezoelectric polymers and ceramics con-vert mechanical stress or strain into proportionate electrical energy. They also respond mechanically by expanding or contracting when a voltage is applied. Piezoelectric polymer and ceramic films also have pyroelectric properties, that is, they produce electric energy in response to heat. Piezoelectric polymers and ceramics are associ-ated with a low noise and inherent damping that makes them very effective receivers as well as broadband transmitters for high frequencies tasks [3]. There is however a big difference in properties between the piezoelectric polymers and the single crystals or ceramics such as high temperature [7].

Application: All 'watch beepers' are piezoceramic audio transducers, most battery operated smoke detector alarms, fish finders, some cigarette lighters, microphones, sonar headphones, many gas grill igniters. Micro actuators and manipulators for opti-cal, robotic, biomedical, electronic, and process engineering; small, lightweight, low power, solid-state actuators for aerospace and battery powered devices [21]. Com-mercial available as a thin bag filled with rows of piezoelectric material to make it flexible. They only have to be connected and can be used instantly, used as transducer or sensing device [10].

Technical facts: Density: 7800 kg/m3 Commercially available as small strips in va-riety of width (few inches), height, and thickness (µm-mm). More technical properties can be found in reference [21].

1.2.3 Ion-exchange Polymer Metal Composites (IPMC)

Description: Small strips of IPMC used as bio-mimetic (= mimicking biological system) sensors and actuators. These strips react very closely to the applied low volt-age, which results in bending that makes the material remarkably accurate and repeat-able [30]. They can be placed in the electrostriction group because of the electro-chemical nature of the actuation of this material. Used as a sensor, large displacement can be measured when sensing the output voltage occurs when mechanical bending the sample [31]. Because the principle of IPMC strips relies on movement of ionic charges to achieve displacement, solvency must exist, but they can operate in dry air when kept moisten.

Application: Used in robotics as grippers, tactile sensors, propulsion, and locomo-tion. In other fields e.g. stirrers, pick-and-place manipulators, diverters, pumps, rotary actuators, and relay switches. Commercial available as MuscleSheets, even though it completely exists of soft electro-active plastic [31].

Technical facts: IPMC materials are light and their response time is high, they have unique characteristics including low density, high toughness, large strain and inherent vibration damping. IPMC can work under low-temperature, wet and hazardous envi-ronments. MuscleSheets are low voltage powered, have a high response time and are capable to move 10 to 50 times their own (light-) weight. They can be used as sensors because they give a voltage as output when bend mechanically. The essence of the underlying iono-elastic response of such materials is due to Colombic electro-dynamic charge interaction amongst a dispersed phase of metallic particles that are charged either positively or negatively, mobile phase of cat ion such a hydrogen ions H+ (protons) or Li+, Hydroxyl anions OH-, and a fixed anionic phase such as an assembly of sulfonates SO3- elastically attached to the backbone of the polymer net-work macromolecules. The mathematical model is analogous to classical Euler-Bernoulli's beam theory modified to accommodate a non-homogeneous distributed electrically induced moment due to the presence of a non-homogeneous electric field in an electric material [30].

1.2.4 Terfinol-D

Description: This material is applied in a system to replace high frequency actuators and is placed in the field of magneto-strictive actuators. It supposes to be accurate in positioning of mechanical loads, accurate in force and speed and exceed solid-state actuator technology [12]. "A properly magnetically biased magneto-strictive actuator will operate at the frequency of the input current. A pre-stress system will optimize output and efficiency. The most important design consideration is careful engineering of the 'magnetic circuit'. The magnetic circuit consists of the solenoid coil to provide the oscillating field, permanent magnets for bias, and careful selection and shaping of the other parts through which the magnetic field passes.

A good magnetic circuit ensures the highest magnetic flux density in the Terfenol-D, and very uniform mag-netic flux in all phases of the actuator operating cycle" [12].

Application: In machinery used as tool positioning and control and as combustion engines fuel injectors; for hydraulics the replacement for pumps and valves and in aerospace for precise positioning [12].

Technical facts: Because they can be customized, all the equipment actuators have specific properties. Check the website for the latest details [12].

2 What are Active Forms?

It appeared to be quite difficult to define all relevant dimensions for a complete and coherent framework for *all* possible active forms [29]. To begin with we will there-fore discuss some relevant aspects and characteristics. First, we constrain the scope to objects with a physical form on a macro scale. Second, these objects should have an inherent dynamical complexity which enfold in the behaviors of these particular ob-jects. The functionality embedded in these objects determines their internal and be-havioral complexity. Third, we are focusing on objects on a macro scale which can be used in an interaction with a human user. These interactive objects should be able to express their actual internal state via perceivable form changes on the surface. Before we discuss these kinds of objects we will introduce already existing examples, al-though not satisfying all above mentioned requirements.

2.1 Active forms in nature

Active forms are quite common in nature. One of the best know example is water which changes the form according to temperature (i.e. solid=ice, fluid=water, gase-ous=cloud, see Figure 3). These three major forms of water (the three aggregate states) express clearly the internal state space on the surface. The transitions between these three different forms are fully reversible. Living organisms (e.g. humans) changes normally their form related to their age. These form changes are almost irre-versible. A mix between reversible and irreversible form changes are used by plants (e.g. trees). Trees change their appearance within the season cycle (the reversible part), but also along the lifespan (the irreversible part).

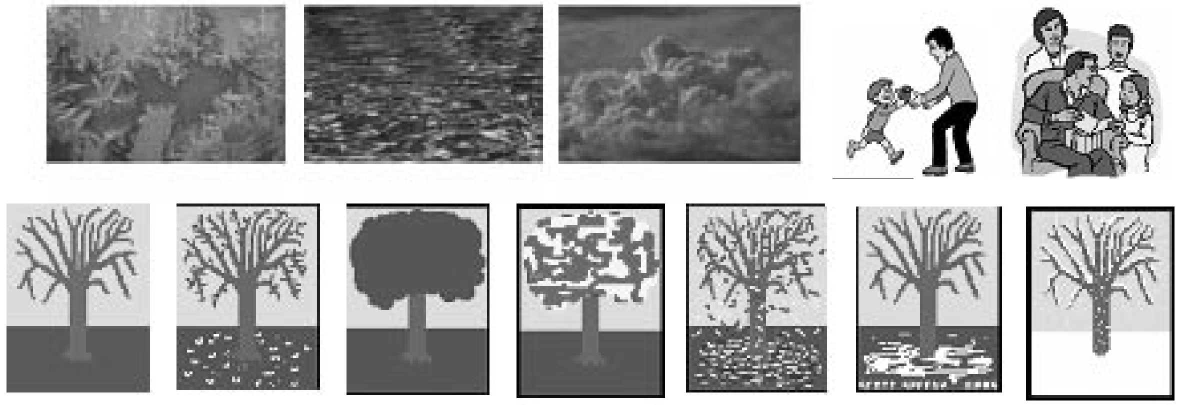

Figure 3. Three examples taken from nature: (a) left above the three reversible aggregate states of water, (b) right above the irreversible growth of humans, and (c) line below the [ir]reversible changes of a tree through out the seasons. (Pictures are taken from different internet sources)

2.2 Artificial active forms

One of the most popular artificial active forms is given as robots (e.g. humanoids). Of course there are many others objects as well that have similar characteristics (e.g. products for transportation, consumer products, etc) [11]. But among all these other options humanoid (and pet) robots have an exceptional position to be probably the most promising future input devices to provide access to intelligent environments [28] [34]. Human-robot interaction in daily life will be part of next generation interface concepts.

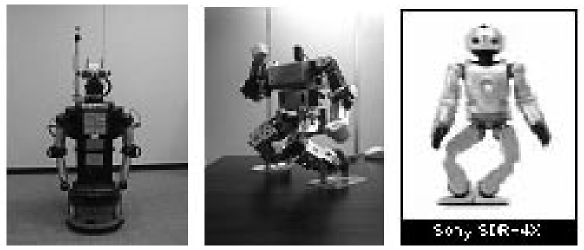

Figure 4. Examples of robots: (a) Robovie [20], (b) Tai-Chi robot [33], (c) Sony SDR-4X

One of the major limitations of this kind of active forms is their fixed physical ap-pearance. Although the internal state space transformed to motions can be unlimited, still the elements on the surface are static, only their positions in the 3D space are changing. Ongoing research is addressing the design challenge of giving humanoid robots a human-like face. This kind of design challenge is the primary target for our concept of active forms. The face should change according the intended non-verbal expressions. All know solutions are using so far elastic artificial skin controlled by hidden and embedded mechanical actuators [19]. What, if the surface could change by itself?

3 Active Forms as a New Way for Feedback

If we want to design a self changing surface of an interactive object we need material which can change their form by itself. This was our primary motivation to start ex-ploring the syntactical design space with smart material. So far we could identify the following three options.

Micro-Electro-Mechanical Systems (MEMS) are the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of nano-fabrication technology. Although it is the system that is smart, this construction technique is very promising for the future [6]. For large batch production in comparison with Integrated Circuit's, MEMS are cheap.

Ferromagnetic Shape Memory Alloys (SMA): This material delivers high actuation and heavy-duty strain. The use for environmental interaction this material can be appropriate [4].

Shape Memory Polymers with SMA [8] based properties improved with particu-larly easy shaping, high shape stability, adjustable transition temperature, and, very large strain [22].

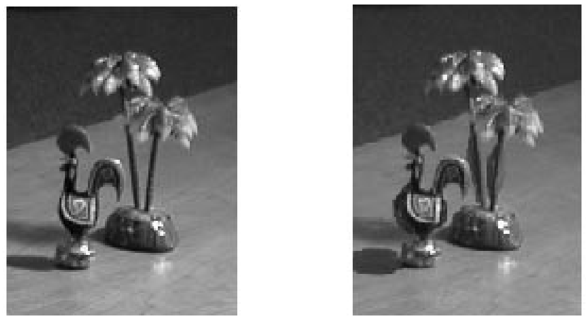

Figure 5. Input controls for access the multimedia content in an intelligent home environment. Left picture shows the unloaded state (adopted from [18]), right picture the loaded state.

We applied Nitinol as one SMA to the following design problem. Given a tangible, RFID tagged interaction prop [18] which is wireless connected to a multimedia database to get access to a particular subset of stored content (e.g., the picture set of the last holidays), how does the user know whether the prop is loaded or not [25].

Of course there is a quite simple and straight forward solution, attach a LED to the prop. If the LED is switched on then the prop is linked and loaded, otherwise not. But, how natural would it be if the shape of the prop would carry this information: 'slim body' for being unloaded state, 'fat body' for being loaded (see Figure 5)!

4 Conclusion

To build new tangible interaction devices, peripherals or autonomic robotics, smart materials could be used replacing classical motors operating on static forms. A great advantage is space reduction and material specific movement, which allows a system to respond naturally. Advantage of particular smart materials is their output response on mechanical deformation, which has the potential to create simple but advanced feedback signals without sophisticated electronics.

SMA: For the relative ease of use of SMAs with their worldwide availability, this material is suitable for the use in robotic application thus for the use of user-system interaction, most probably as feedback channel, used as actuator replacing a motor [9]. Using strain to move or set motion into a system would be the basic mechanism.

IPMC: MuscleSheets strips can be cut any size but the real advantage of this mate-rial is their bending capabilities of approximately 90 degrees. A disadvantage can be its difficulties to operate in aquatic or wet surroundings [13] [17].

Finally, we could open an entirely new syntactical design space, at least on the syn-tactical level for providing users with natural feedback [27] about the hidden internal state space of interactive products operated by complex functionality.

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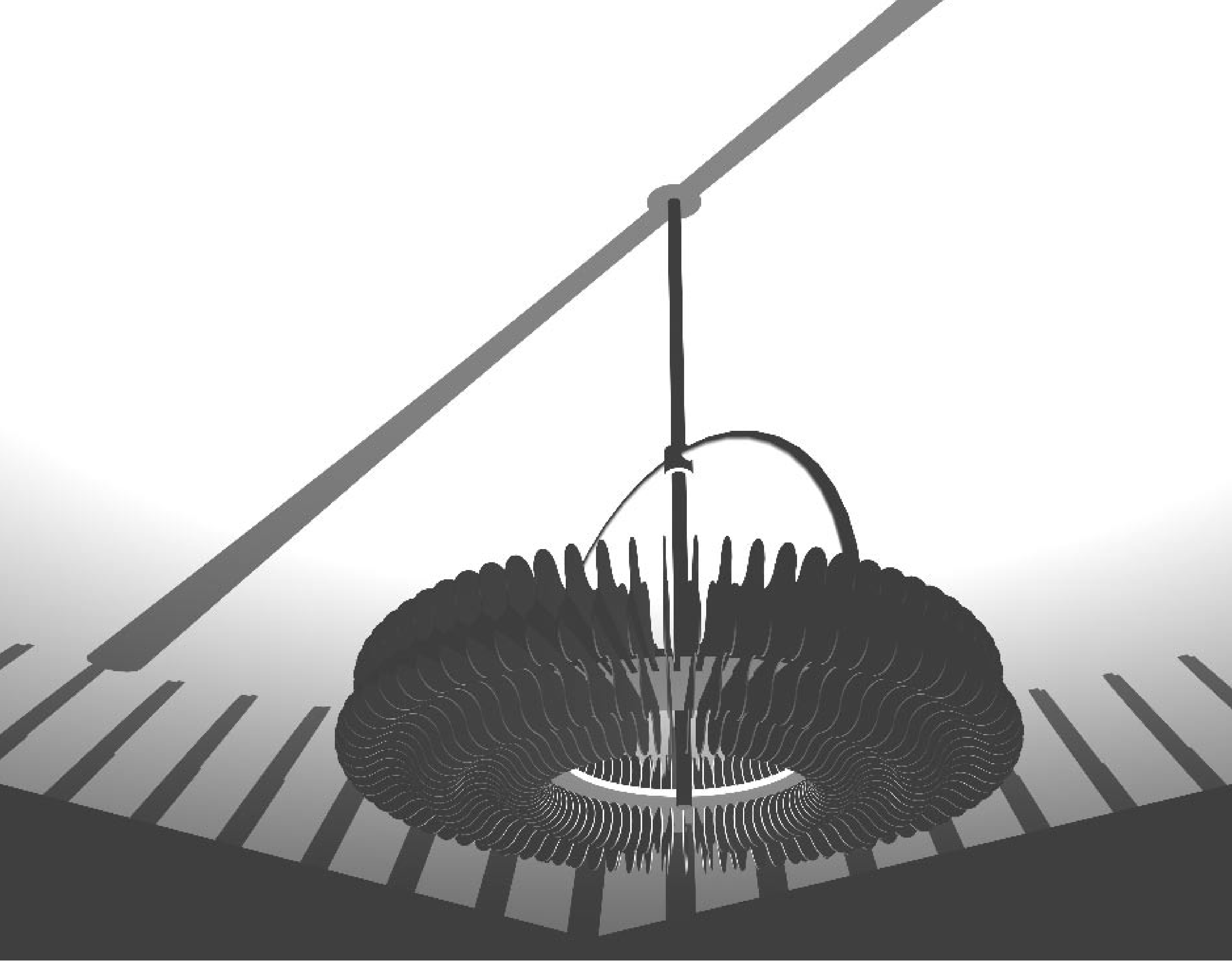

Design and semantics of form and movement

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