ABSTRACT
This paper outlines the design, prototyping and construction process of a dynamically morphing, spatially adaptable wedding hall/event space. The documentation highlights a number of valuable real-world lessons of building a real computer-controlled kinetic architectural environment that must be permanent, safe and extremely robust to failure. The project also draws upon many fields of knowledge outside of architecture including mechanical engineering, computer science, digital projection, tensile design and acoustics. The design of the kinetics itself incorporates aspects from windsurfing, rock-climbing, sailing and traditional industrial automation. In this paper we outline the conceptual design, design development, prototyping, control system and final construction. We also discuss the affordances and limitations of digital fabrication with respect the fabric design and fabrication. With an understanding of many student project that explore similar adaptable architectural scenarios we, hope that this paper can help to bridge the gap between what is animated and prototyped at an Arduino scale, with the realities of both physics and computer control at a real-world scale.
MOTIVATIONS

Arguably, the most innovative designs utilizing kinetics arise from unique situational use, and it is this use that is a driving force in the changing and evolving patterns of human interaction with the built environment. The motivation for this project relates to dynamically changing spatial layouts that address desires to have rapid changes within the context of how a wedding ceremony is carried out, as well as the need to adapt the space for other events such as a marketplace or corporate product launch. There is great potential for dynamic architecture that arises from understanding what a space is currently doing and how it can aid in promoting or accommodating a specific change. Such spatial optimization is defined as a kinetic environment which can, from a practical standpoint, serve as a means for adjusting spatial configurations based on changing stimuli and programmatic considerations. Optimization scenarios are considered both physically and organizationally for the development of a system that has the ability to accommodate spatial adaptability. William Zuk states in his classic book Kinetic Architecture (1970) that “our present task is to unfreeze architecture, to make it a fluid, vibrating, changeable backdrop for the varied and constantly changing modes of life. An expanding, contracting, pulsating, changing architecture would reflect life as it is today and therefore be part of it.” Kostas Terzidis explains that “deformation, juxtaposition, superimposition, absence, disturbance, and repetition are just a few of the techniques used by architects to express virtual motion and change.” He clarifies the polarity that while the form and structure of the average building suggests stability, steadiness, sturdiness and immobility, the introduction of motion may suggest agility, unpredictability or uncertainty and may also suggest change, anticipation and liveliness. The integration of motion into the built environment, and the impact of such results upon the aesthetics, design and performance of buildings, may be of great importance to the field of architecture. “While the aesthetic value of virtual motion may always be a source of inspiration, its physical implementation in buildings and structures may challenge the very nature of what architecture really is.”

In architecture, the notion of kinetics implies relationships of cause and effect. A number of things typically happen to architecture to which it must adapt. Zuk argues that a solution is to design a space that can meet any functional demand. To be able to design such a space requires an exploration of the dynamics, flexibility and adaptability of the architectural environment. One way to begin exploring the dynamics is through rethinking architecture beyond conventional static and single-function spatial design. Emphasis is on the dynamic configuration of physical space with respect to constantly changing needs. The implications of such kinetic architecture touch upon building performance on one hand and aesthetic phenomenology on the other.

CONCEPTUAL DESIGN

Initially, the project began as an exercise to create a space which could very quickly change to accommodate a variety of layouts and scenarios that are inherent within the context of a wedding. The notion quickly arose that the building would have the capability to quite literally physically encourage hundreds of people to move around the space.

PERISTALSIS APPLIED TO ADAPTABLE SPACE

The concept was developed in the context of a weeklong design study whereby natural analogies were studied and the concept of peristalsis (a series of wave-like muscle contractions that moves food to different processing stations in the digestive tract) were brought to the fore which implied that a “soft” architecture would be developed within the rigid confines of the existing warehouse building. The concept was then diagrammed as to how it could accommodate a number of spatial scenarios that came about through attending several weddings and understanding the sequencing of space throughout the ceremony. It was also required that the space could be opened up to be as large as possible for other events that might occur within the space and that there would be a stage at one end of the building and an open garden at the other. In effect, the space had to have absolute three-dimensional flexibility.

RENDERING DESIGN INTENT

Once it was decided that the dynamic part of the building would be made of fabric a number of conceptual renderings were developed as a means of communicating to the client the aesthetic capabilities of the approach. There were many obvious advantages to using fabric including projection, lighting and the economics involved in having a mechanistically simple approach.
Adaptable Scenarios: Diagrams applied to sequential programmatic scenarios (Fox, Lin 2013)

Exterior Rendering (Fox, Lin 2013)

Interior Rendering (Fox, Lin 2013)

Physical Model: Small-scale physical model of fabric (Fox, Lin 2013)

Small-scale prototype model: Physical model actuated with servo motors (Fox, Lin 2013)
DESIGN DEVELOPMENT
Although typical digital modeling was initially used as a means to develop the design relative to the scale and context it was quickly discovered that physical modeling was necessary to understand the physical properties of fabric that is kinetic. Animations were later used to simulate various types of possible movement. Neither approach was for communication to the client but they were necessary to understand and develop the kinetics of the design.

PHYSICAL MODELING OF ACTUATED FABRIC
Numerous physical models were created at various scales using fabric that had relative proportional stretch properties to what would be used in the project. Although it was very early on, a specific type of four-way stretch fabric was chosen at this time which provided a valuable design constraint. Various schemes were approached as to how the fabric would be attached and it was decided that a series of vertical and horizontal ribs would be used. At the scale of the model, however, it was impossible to approach the physics of the weight of the fabric as it might sag. Assumptions were made at this time as to what would be possible regarding the placement of ribs within the fabric. The working models simulated the three-dimensional capabilities of the fabric by means of a sine-wave, but did not include the base movement.

ANIMATION AS SIMULATION NOT VISUALIZATION
Although the physical models served their intent of clarifying an understanding of the ribbed approach and the limits of the fabric stretch, it was difficult to program many complex scenarios of spatial adaptability in a short time. For this reason a series of animations were developed that could demonstrate the possibilities based on the earlier physical models. The animations were developed as a means of simulation and not visualization, whereby the physics were constrained to the specific properties of the fabric.

SYSTEM DEFINITION
At this point computational models reconciled the fabric system with the structure of the building. The ribs were put at a forty-five degree orientation relative to the structure of the building. Attachment points were schematically developed.

MOTORS AND CONNECTIONS
This It was decided at this point to use a total of fifty-five motors with each rib having seven motors (five on the rib itself and two on the floor). The two ends of the system would be fixed and mounted to rolled steel tubing.
Of the five motors on each rib, three would be clustered on one side and two on the other each up near the top of the building. The two floor motors would sit under the floor itself. Pulleys would also have to be used for the top three attachment points. In order to have the lines to the motors clear the fabric in a fully extended position.

**FABRIC PERFORMANCE**

The decision to have the ribs at forty-five degrees added an unforeseen magnitude of difficulty to the project in the way that the fabric would perform. Several critical design decisions were made prior to the fabrication of the entire fabric that were dependent upon the performance at unique states of motion.
FABRIC AND BASE CONNECTIONS

When a fabric section is unrolled with this geometry of an arch at forty-five degrees it creates a curvature that was not possible to create with the ribs. The unrolled fabric curvature was therefore approximated to a straight line at forty-five degrees. A full-scale mock-up of two rib sections was created at this point to understand the stretch properties at full-scale and to make adjustments to the spacing of the ribs or a pre-stretching of the fabric. Pre-stretching meant that the fabric would be cut smaller than the dimension of the un-stretched fabric so that when it is installed it would not sag between the ribs.

FABRIC AND BASE CONNECTIONS

Two major connections were developed and tested at this time. The connection point to the fabric was a simple knot held by a ball and was developed so as not to “pinch” the fabric. This became a standardized detail at every instance. The floor connections were much more challenging, as the ribs needed to “telescope” at the base and change their length by up to three meters on each side without losing strength, and they also needed to move in a line along the floor while having free rotation. Numerous designs and prototypes were developed for this detail and in the end a fixed screw-drive was used in the floor that was connected to a base for windsurfing boards. The rib was allowed to telescope on this moving joint which anchored the fabric.

FABRIC FABRICATION

There were two major issues regarding the fabrication of the fabric. The first was the aforementioned curvature created when unrolling the geometry and the second was the fact that when the diameter of the rib increases the line of the base in the track moves at a different angle than that of the track. In preparation of sewing the full fabric we had to make several compromises based on the client’s desire to have the fabric perform optimally well at the most open position. In other words there could not be sagging or creasing of the fabric when fully expanded. Due to this requirement it was calculated that the un-stretched fabric should be sewn at 68 degrees so that when it is in the fully stretched position and the base attachments are near the outside of the building, they would hit the point on the track at forty-five degrees relative to the structure of the building (Figure 17). We also calculated a 10 per cent pre-stretch of the fabric in the horizontal (long) dimension and added three meters of extra fabric on the short dimension for the telescoping base connection.
ACTUATION AND CONTROL SYSTEM

Two types of motors were used because of the different torque and speed requirements, and custom software was developed to choreograph the overall motion.

MOTORS, ATTACHMENTS AND STRUCTURE

The motors used were NEMA 42 high torque hybrid stepper motors with 6 amps peak current per phase and a peak line pull of about 300 pounds each. For the two motors that were used to pull the points near the center of the arch, a 5-1 worm gearbox and larger sized pulley was used. The geared motors used a larger pulley to approximate the speed of the non-geared motors. The non-geared motors had a peak line pull of about 150 pounds with smaller pulley. The drivers were separately powered by 220VAC, 4 amps.

The motor/spool combinations pulled at a max speed up to 0.5 meters per second, but were operated around 25 cm per second to reduce the load. The available motor torque decreases with speed, so selection of gearing and spool size was important. The spools had to match the capability of the motors in that a small spool could pull the line with significant force, but only very slowly, while a larger spool might require the motor to move slowly to avoid running out of torque and slipping. Some solutions to these issues could be handled from a standpoint of hardware and some could be handled with software. For instance the torque issue mentioned above could be handled by the software telling the motors to ramp up and ramp down along their path, lessening the peak loads caused at acceleration and deceleration.

COMPUTATIONAL CONTROL

The software allows the operator to define the range of motion, maximum speed and acceleration for each motor, and then choreograph the motors as a percentage of full range. Once each motor is initialized, the interface of a simple set of slider bars allow for easy manipulation of the variables. The software allows the track motors to turn about 600 rotations at high speed, while the geared motors turn only fifty rotations at modest speed and the non-geared spooling motors turn only about twenty rotations. Each driver circuit board controls six motors. All eight driver circuit boards share a single serial data channel.

The command format includes a two-number address to select which circuit board and which motor on the circuit board will respond to the command. Commands may be sent to all motors at the same with a global command. All commands expect units of ticks, except velocity and acceleration commands which are ticks per second and ticks per second squared. The number of ticks
per revolution is set with switches on the power driver mounted next to the motor. Floor motors were be set to 200 ticks per rotation while the overhead motors were set to either 1600 or 3200 ticks per revolution.

SPECIFICATIONS
As this was a very unusual architectural endeavor, a set of sub-specifications was created within the building specifications which were further broken down into assemblies. The specifications will not be further described here but a list of the assemblies follows:

01. FABRICS
02. PRIMARY RIB ASSEMBLY
03. SECONDARY RIB ASSEMBLY
04. MOTORIZED LEG ASSEMBLY
05. FLOOR TRACK ASSEMBLY
06. PULLEY ASSEMBLY
07. BUILDING STRUCTURE RECONCILIATION
08. MOTOR ASSEMBLY – 1
09. MOTOR ASSEMBLY – 2
10. CENTRAL CONTROL ASSEMBLY
11. MISCELLANEOUS PARTS

FULL-SCALE MOCK-UP CONSTRUCTION
A full-scale mock-up of the entire system was then created with the intent of re-using as many parts as possible and identifying as many issues as possible. The mock-up ran concurrent with the other aspects related to the general construction of the building. The mock-up construction took several weeks and numerous aspects were tested and refined relative to the performance of the fabric and the motor control.

LESSONS LEARNED AND SAFETY CONSIDERATIONS
A number of issues were identified in the mock-up that had to be remedied. The major decision was that the long horizontal ribs would be eliminated from the design. This was an aesthetic decision made by the client which had positive effects on the performance of the system as a whole. The most important decision was that no “slipping” of the motors could be allowed. Although the geared motors in position 3 and 5 could not slip, the other motors would slip if their maximum torque was passed, causing
them to release the cable from the spool and need to be reset. It was decided that the structure could never fall below the minimum “rest” position and safety chains were installed on the top three motors of each rib. Also it was decided that although safety cables were employed at position 4, a brief power outage could also cause the motors to release, and so UPS devices should be used on each motor as a backup power source.

Additional decisions included the scaling of the spools from 2.5 cm to 1 cm and using “line” rather than steel cables on most of the motors. Spectra rope, which is ultra-high molecular weight polyethylene (UHMWPE) fibers that yield very high strength and are cut resistant, with much greater flexibility and one-tenth the weight of steel, was specified. Although the geared motors will have steel cables for safety reasons, it was found that the steel cables are much more problematic in terms of the connections and wear over time. The only major issues with the fabric is that it could be pre-stretched a bit more to 15 per cent in order to reduce sagging between the ribs and although the poles at the base were bending, this was an issue which could be resolved by adjusting the pulley point locations in the ceiling.

**FINAL CONSTRUCTION AND CONCLUSIONS**

The final construction included many smaller aesthetic considerations and was coordinated with projection mapping onto the fabric, acoustic design and general event lighting. A person was hired and trained to operate the system and fine-tune it over time as well as identify and remedy unforeseen hardware issues with regards to the operation of the system.

In general a project such as this is much more difficult than creating static architecture primarily due to the lack of such multi-disciplinary precedent. The path will certainly get easier through understanding the lessons learned by such built projects and the capabilities of the environments they can produce. The project described in this paper begins to map out a world where we have a wealth of potential for motion, a world in which spaces and objects can move and transform to facilitate numerous changing situations, ranging from the contextual and environmental to the programmatic. Our capabilities for using kinetics in architecture today can be extended far beyond what has previously been possible. Advancement, however, will only be accomplished when kinetic structures are addressed not primarily or singularly, but as an integral component of a larger architectural system.
MICHAEL FOX is a founding partner of FoxLin. He is also author of the book *Interactive Architecture* by Princeton Architectural Press and the upcoming book *IA: Pioneering and Adaptable World*. He currently serves as the president of ACADIA. Fox founded the Kinetic Design Group at MIT as a sponsored research group to investigate interactive architecture. His practice, teaching and research are centered on interactive architecture. Fox has lectured internationally on the subject matter of interactive, behavioral and kinetic architecture. He has won numerous awards in architectural ideas competitions and his masters’ thesis at MIT received the outstanding thesis award for his work on computation and design processes. Fox’s work has been featured in numerous international periodicals and books, and has been exhibited worldwide, most recently at the 2013 Venice Biennale. His work has been funded by NASA, the Annenberg Foundation, the Graham Foundation and others. Fox is an Associate Professor of Architecture at Cal Poly Pomona and has taught on the subject matter of interactive, behavioral and kinetic architecture at MIT, The Hong Polytechnic University, the Art Center College of Design in Pasadena and Southern California Institute of Architecture (SCI-ARC) in Los Angeles as well as numerous international workshops.

**IMAGE CREDITS**

Figure 1–31. Fox, Michael (2013) Eco29 Project: Israel.
Figure 32–35. Shemish, Eran (2013) Eco29 Project: Israel.