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EMBEDDED ARCHITECTURE
ADA, DRIVEN BY HUMANS, POWERED BY AI

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Introduction

Named after the polymath, mathematician, first computer programmer, and early innovator of the computer age, Ada Lovelace, Ada is a collaborative project by Jenny Sabin Studio for the Artists in Residence Program at Microsoft Research, 2018-2019. The first architectural pavilion project to incorporate AI, Ada is a lightweight knitted pavilion structure designed with Microsoft Research which embodies performance, material innovation, human-centred adaptive architecture and emerging technologies, including artificial intelligence and affective computing. An external rigid experimental shell structure assembled from a compressive network of 895 unique 3D-printed nylon nodes and fibreglass rods holds Ada's form in continuous tension. Working with researchers and engineers at Microsoft Research, Ada is driven by individual and collective sentiment data collected and housed within the Microsoft Research Building 99. A network of sensors and cameras located throughout the building offer multiple opportunities for visitors and participants to engage, interact with, and drive the project. The data include facial patterns, voice tones and sound that are processed by AI algorithms and correlated with sentiment. Three scales of responsive and gradated lighting, including a network of addressable LEDs, a custom fibre optic central tensegrity cone, and five external PAR lights respond in real time to continuous streams of sentiment data. These data are correlated with colours, spatial zones within the project, and responsive materials.

An important aim of the project was to expand and inspire human engagement. While artificial intelligence powers the project through the precise narrowing and statistical averaging of data collected from individual and collective facial patterns and voice tones, the architecture of Ada augments emotion through aesthetic experience, thereby opening the range of possible human emotional engagement. In turn, the project opens new pathways for fundamental research on the use of AI to correlate connections between human sentiment and local environment. Ada will be used as a platform for researchers to test their data and machine learning algorithms at Microsoft Research.

Suspended from three points and hovering above the ground floor of the atrium, Ada is a socially and environmentally responsive structure that is interactive and transformative. This environment offers spaces for

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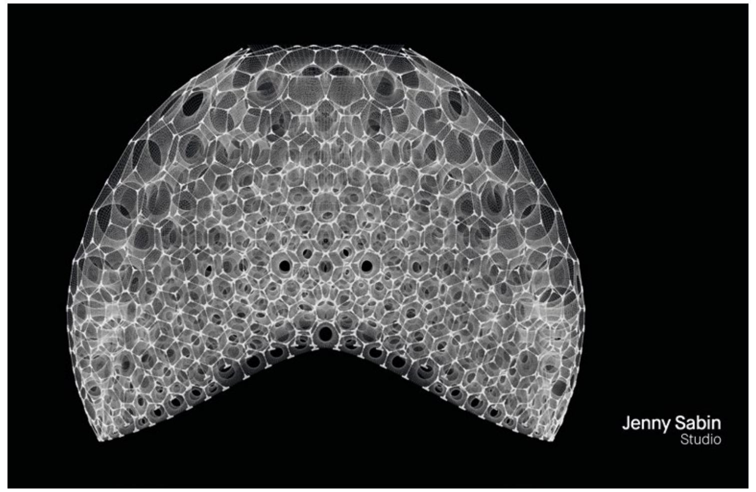

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curiosity and wonder, individual and collective exchange, and rigorous research experimentation as the pavilion filters light, casts dynamic shadows, and changes in response to participants' input.

Background

The history of modern computing may be traced back to an uncanny meeting between two disparate inventions that were simultaneously emerging: the punch cards that mechanised the Jacquard loom through stored memory, and Babbage's steam-driven calculator, the Analytical Engine. Credited with being one of the first computer programmers, Ada Lovelace intuited the revolutionary impact that Jacquard's punch cards would bring to Babbage's computer, launching the precursors of modern-day scientific computing. As Lovelace stated, 'The Analytical Engine weaves algebraic patterns, just as the Jacquard loom weaves flowers and leaves' (Lovelace, 1843). In this project, the textile as an information-mediating surface architecture builds upon this history with forward-looking integration of artificial intelligence and affective computing. In the last decade, knitting and high-tech fabric structures have been explored for their responsive and versatile material behaviour in architecture (Sabin et al., 2018). For example, Active Textile Tailoring is a new project at the Self-Assembly Lab where they are exploring changes in fibre shape and structure in response to heat and moisture for custom fit. In parallel, affective computing has found itself embedded in prototypical architectures at the scale of the human body as wearables in fashion. Behnaz Farahi's recent work embeds human sentiment as data into responsive fibre systems (Farahi, 2018). Many data-driven responsive projects are now incorporating data as an active and evolving overlay of spatial information. For example, Jason Kelly Johnson of Future Cities Labs employs techniques to inscribe and translate data collected from local sites and environmental analysis, such as ambient sound, into materials and spatial fields, creating novel configurations and lighting effects (Johnson and Gategno, 2018). Asif Khan's MegaFaces installation for the Sochi Winter Olympics also integrates light and image to generate a responsive façade of visitors' faces scanned and updated every 20 seconds (Frearson, 2014). Drawing synergies with this body of international research, Ada builds upon 13 years of design development at the intersection of knitted textiles, bio-inspired design, computation, and architecture.

Methods

Generative Design and Structural Analysis

The design of Ada commenced with a series of collaborative conversations between Jenny Sabin and Microsoft Research on topics spanning artificial intelligence, adaptive and embedded architecture, affective computing and personalised space. Initial design studies were later informed by a 3D-scanned model of Microsoft Building 99, the location for Microsoft Research in Redmond, Washington where the installation would ultimately be housed. This approach allowed for precision modelling within a detailed and accurate representation of the site. A series of ellipsoidal and spherical 3D models were generated in Rhinoceros as an iterative study that primarily considered the overall form of Ada in relation to lines of sight, opportunities for interaction, circulation paths, and material and structural qualities. These initial studies would ultimately inspire the form of the exoskeleton as a concave shape that lifts along the short axis at the bottom to allow inhabitants to enter the space underneath. The polygon grid structure that makes up this surface was generated using parametric computational tools developed as Grasshopper definitions that are based on graph theory. The process of form-finding was based on particle spring systems and implemented via Rhinoceros, Grasshopper and plugin Kangaroo developed by Daniel Piker. The NURBS surfaces were discretised into the mesh network M_0 with defined grid spacing and grid shape based on the final digital knitting fabrication process. Nodes of the mesh triangular faces are considered as particles connected by edges which are calculated as elastic springs. We input mechanical properties of the knit fabric by assigning axial stiffness and a damping coefficient to each edge of M_0. The form found mesh M_1 is then generated from the node coordinates and their connectivity. From mesh M_1, we used the dual graph method to reconstruct a new mesh representation M_2 which is tessellated by polygonal cells and cones.

The size and density of the cells in this network were manipulated according to the geometry of the exoskeleton, specifically the angles of curvature in the concave form. Once generated, the exterior cells were pulled inward to create an inner surface with an adjacent polygon grid that has a soft materiality and reciprocal structural behaviour. The cells on both the exoskeleton and inner surface were filled with either circular panels or conical forms that connect the two surfaces which are referred to as windows and cones respectively.

The structural concept of Ada builds upon previous work by Jenny Sabin Studio, with engineering design by Arup, where structures display the balance of tensile and compressive forces as a means for generating lightweight

1. The first architectural pavilion project to incorporate AI, Ada is a lightweight knitted pavilion structure composed of digitally knit responsive and data-driven tubular and cellular components held in continuous tension via a 3D printed semi-rigid exoskeleton shell. Photo: Jake Knapp for Microsoft.

2. Ada, designed and built by Jenny Sabin Studio for Microsoft Research Artist in Residence Programme 2018–2019, fills an airy 3-storey corner in building 99 on Microsoft's Redmond, Washington campus. Ada translates data into colour and light. Photo: John Brecher for Microsoft.

3. Generative study of Ada with form-found fabric structure and exoskeleton. Lines of sight, opportunities for interaction, site conditions, circulation paths, and material and structural qualities are considered as primary design constraints. Courtesy Jenny Sabin Studio.

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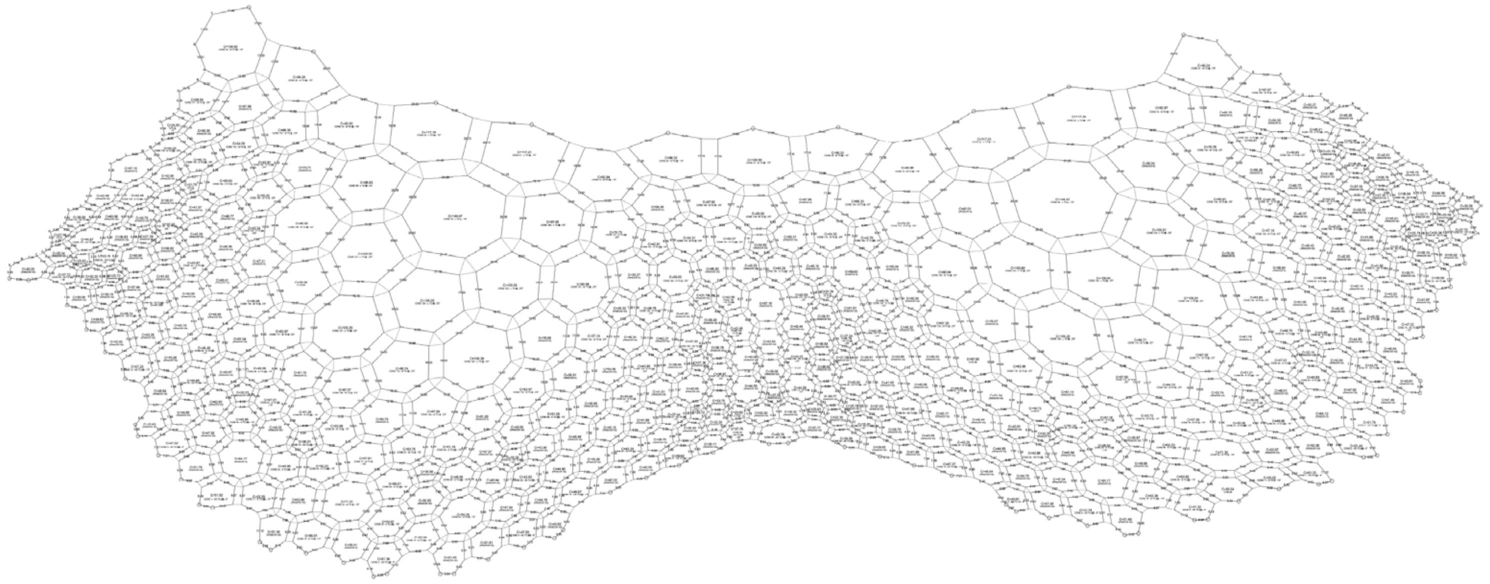
4. Jenny Sabin and her team installing the knit fabric structure to the exoskeleton. The size and density of the cells in this network were manipulated according to the geometry of the exoskeleton, specifically the angles of curvature in the concave form. Precise tolerances between the transfer of the forces in the tension net and the compressive outer 3D printed nodal shell, were simulated and incorporated as variable parameters in the digital fabrication process such as a stretch factor. Photo: John Brecher for Microsoft.



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and expressive forms. The generative question for the design was how to create a convex surface (an ovaloid) of knitted tensile elements. Early in the process, we identified that a compressive, shell-like structure was required to achieve this form, and developed the idea for a hexagonal mesh, grid shell structure. In order to achieve this, we developed the concept of a lightweight three-dimensional cable truss or, more accurately, a cable-stiffened hybrid grid shell consisting of an outer compressive layer (the grid shell) and an inner tensile layer (a 'cable net' of nylon webbing), connected together by tension elements (the digitally knitted 'cones'). The pretension in the webbing net applies a uniform load to the grid shell which stabilises it against deformation that would lead to elastic buckling. The capacity and stability of the structure was confirmed via explicit finite element analysis, accounting for non-linear geometric effects using the analysis software Oasys GSA.

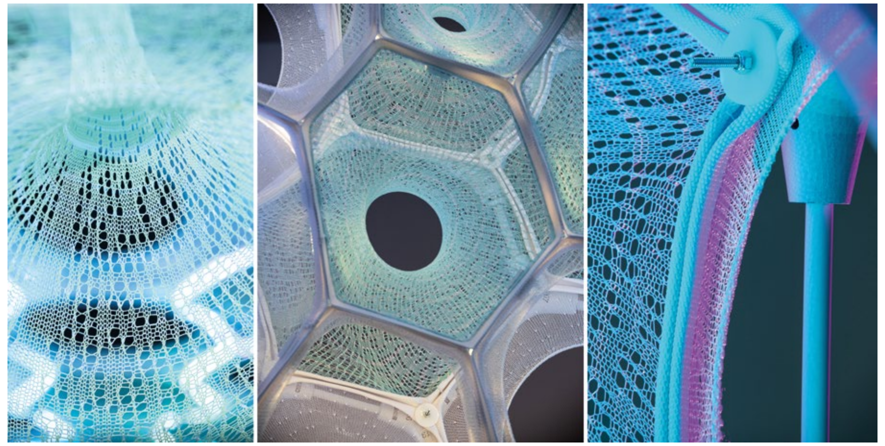
When the net form-finding process was complete, each cell and cone received a unique ID that followed each component through the entire fabrication and production process. The circumference of each of the cells when slack and when fully elastically prestressed was entered into an excel spreadsheet to aid in knit fabrication planning. The knit materials include a high-tech responsive yarn and a white fire retardant 'fill' yarn called Drake. The photoluminescent fibres emit light after the absorption of electromagnetic radiation from, for instance, the sun or UV lights. This causes the light emission or glowing effect across the fabric structures.

The free edge of the hybrid grid shell was stiffened using a custom-fabricated aluminium edge ring that also serves to transfer tensile and compressive reactions between the webbing net and outer exoskeleton. Over the flattest part of the shell edge, the ring splits into two pieces which creates a more expressive separation between the tensile and compressive surfaces, but also results in a stiffer element to resist out-of-plane buckling at this location with low inherent geometric stiffness. Working in conjunction with the exoskeleton, the upper and lower metal rings were designed to establish terminal conditions. This provided both structural stability and weight, and a framework for establishing key points of attachment for the exoskeleton at the top and bottom of the installation.

3D-printed Nylon Nodes and Exoskeleton

The complex composition of cellular units that aggregate to make up the exterior surface of Ada required an exoskeleton that can synchronously define both the shape of each cell and the overall geometric form. This network contains an irregular combination of convex polygons that have between four and seven edges. We were interested in further exploring the use of pultruded fibreglass rods that had been used in previous work for the grid shell members; using them as bending-stiff struts rather than an active-bending spline. While the structure

5. Sewing pattern drawing for inner net surface showing distribution of 'cones' and 'cells'. The tension elements or 'cones' connect the inner surface to the outer surface, behaving as springs. Courtesy Jenny Sabin Studio.



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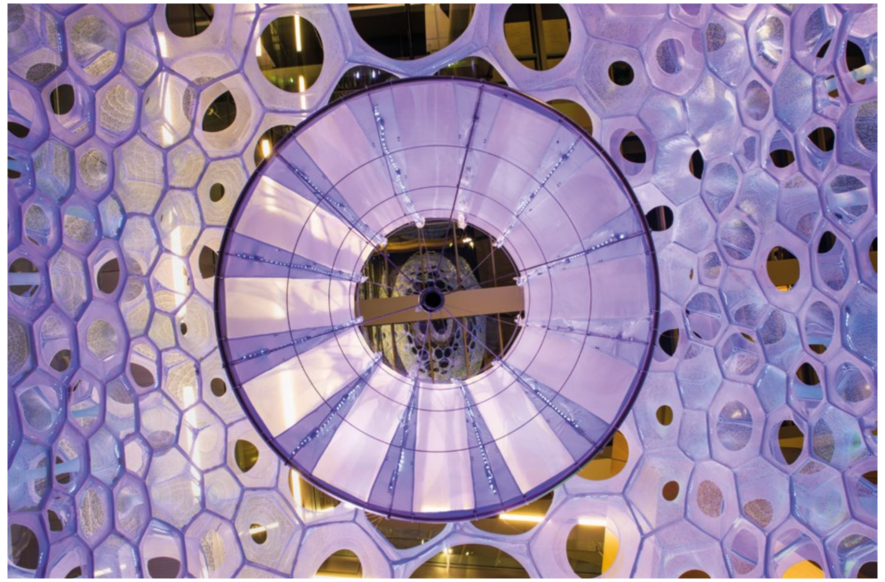

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6. Material details of Ada. (left) Responsive photoluminescent yarns activated by 3-tiered lighting system driven by real-time sentiment data collection; (middle) detail of responsive interior knit surface connected by the 'cone' tension elements to the 3D-printed exoskeleton. The primary tension forces are taken through the nylon webbing. The LED network nests in the fold of the webbing between the two surfaces; (right) connection detail of the knitted fabric surface to a 3D-printed node in the exoskeleton. Photos: Jake Knapp for Microsoft.

7. Tensegrity cone with embedded fibre optics. Situated at the centre of Ada, the tensegrity cone is an independent structure that was designed to showcase additional innovations in AI-driven responsive materials and interactive lighting technology. Seven programable LED strips run the vertical length of the cone to connect a series of diodes directly to bundles of fibre optic strands within the custom-designed and fabricated fabric sleeve. Photo: John Brecher for Microsoft.

is 4-way symmetrical, there are 895 nodes due to the variable patterning and size gradient of the mesh. For this reason, mass-customisation via 3D printing was an obvious fabrication choice. A node typology was developed by generating a tubular end fitting around each of the three rods coming into a node and then meshing together. In order to allow for the assembly of the structure, a number of the nodes were split along the mid-surface and clamped together using stainless steel cable ties. Each node was required to transfer compression and flexure between all the rods coming into it. Interference fits, aided by the pre-compression in the shell, created these positive connections between the nodes and rods without use of adhesive. Several materials were considered for these nodes, including PLA, ABS, and nylon. After mechanical testing, according to ASTM D638-14 standard methodologies on an Instron 5900 Series Universal Testing Instrument, Multi-Jet Fusion (MJF) printing in nylon was determined to have the most appropriate performance characteristics for handling the significant bending forces created by the rods at each node. MJF by GoProto is a new technology that heat-fuses parts at the voxel (volumetric-pixel) level, resulting in rapidly manufactured parts with both superior finishes and mechanical strength.

Central Tensegrity Cone

The central tensegrity cone is a cable net forming a simple hyperboloid of one sheet stretched between a pair of circular rings. The system is pretensioned by means of a central flying strut and radial cables connecting the mast ends to the rings and resulting in an extraordinarily lightweight armature for the custom fibre optic fabric skin. The central tensegrity cone comprises a finely tuned steel structure wrapped in a semi-transparent fabric that is embedded with fibre optics. The sleeve contains panels of the fibre optic fabric that were designed to conform to the dimensions of the interior tensegrity cone and sewn and finished together with alternating strips of elastic material. A zipper that runs the vertical height of the cone is also sewn into the fabric as a means of joining the two ends of the sleeve. Seven programmable LED strips run the vertical length of the cone to connect a series of diodes directly to bundles of fibre optic strands within the fabric sleeve. Light from these diodes is transmitted across the strands and is visible through a subtle glow of the fibres and bright emissions through curated breaks in the surface of the fibres.

Brain Ring Hardware

Ada's Brain Ring is a bespoke yet simple assembly of laser-cut stainless-steel parts with strategic voids for ventilation and channels for wiring. It accommodates

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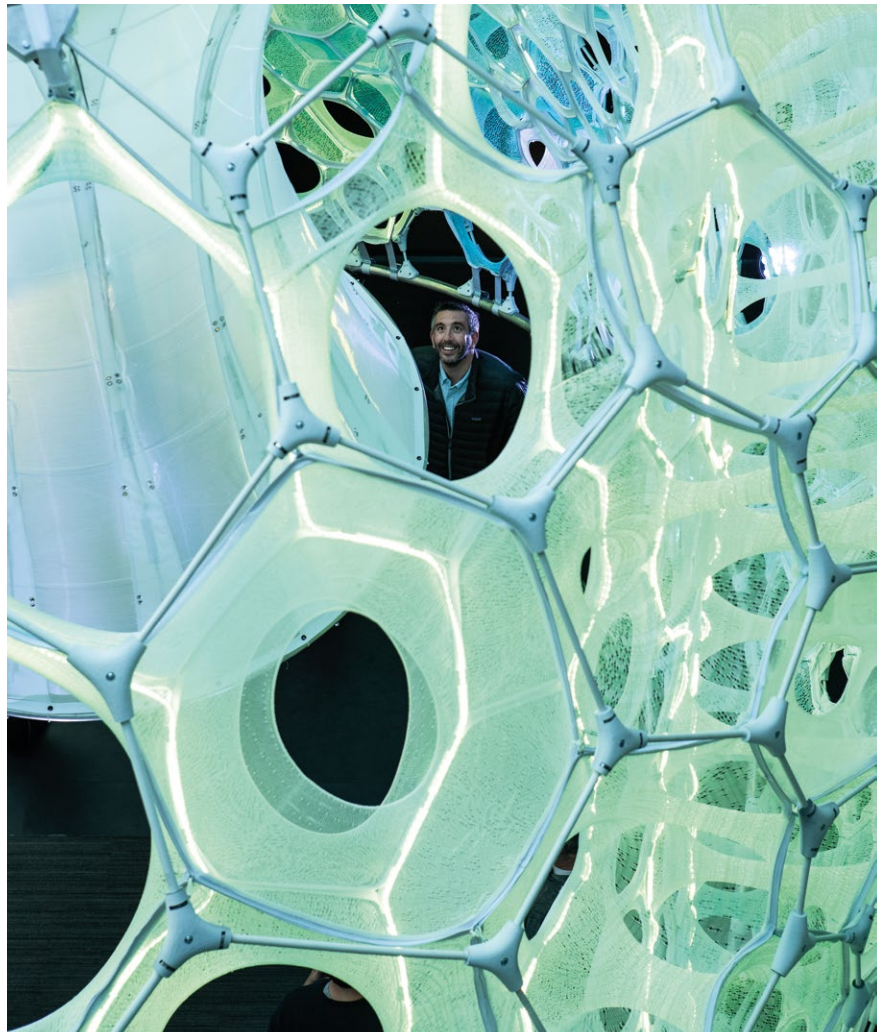

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all of the electronics and networking hardware used to process, display and spatialise sentiment data read from an on-site PC. It discretises the data into streams depending on spatial, contextual conditions. The brain ring contains Raspberry Pi 3B+ microcontrollers, custom PCBs (printed circuit boards) for PWM (pulse width modulation) addressable LED control, Ubiquiti 10X Ethernet Switches, power supplies, and ethernet and power cables. Working collaboratively, Jenny Sabin Studio and Microsoft Research designed and programmed the software architecture for two programs which allow Ada to interface with human sentiment in her environment: a program running on the on-site PC, and a program running on each Raspberry Pi in the Brain Ring.

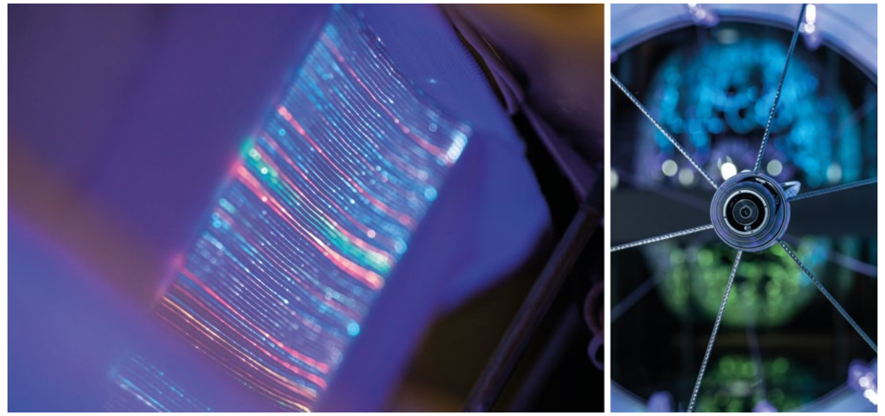
PC & Raspberry Pi Software

The PC software continually queries data from the network of MSR cameras which analyse user facial expressions. These expressions are classified using Microsoft researcher Daniel McDuff's platform, which drives Ada. McDuff works at the intersection of psychology and computer science to design hardware and algorithms for sensing human behaviour at scale in order to build technologies to improve human experience and daily life. AI algorithms turn this data into numeric gradients of sentiment which are then passed to the PC in the form of probabilities, each representing the program's certainty that a given expression is being observed. Expression data is cross-referenced by the programs to check for patterns such as:

1. Global average of all sentiment values
2. Local averages of sentiment in close physical/spatial proximity within Ada's site
3. Sentiment values with global maximum probability
4. Sentiment values with local maximum probability in close physical/spatial proximity within

Ada's site

A table of colour values represented as three-component vectors (red, green, blue) was designed to correspond to real-world facial expressions and voice tones. Colour vector transformations are applied through a series of functions which augment or inter-relate spatial zones based on [1]-[4] above. Finally, colour vectors are transmitted to their respective spatial zones on Ada's exoskeleton and knit structure through a local network connecting Raspberry Pis to the external PC, and through a PC-DMX interface to Elation SIXPAR PAR lights. When data are received, the program instantiates a specified number of LED pixel-objects, passing a colour vector to each one as its colour attribute. The pixels are illuminated through a series of animation frames which update each pixel's colour attribute. The animation occurs at an interval of 3 seconds,



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8. Embedded system diagram highlighting sentiment-to-colour translation. Courtesy Jenny Sabin Studio.

9. View from above, participant interacting with Ada through the central camera. Photo by Jake Knapp for Microsoft.

10. (left) Illumination of the optical fibres embedded in the central tensegrity cone; (right) interactive camera located at the bottom of the central tensegrity cone. Photos by John Brecher for Microsoft.

with 100 frames per second. Lighting software and hardware systems work in tandem to continually update the display colour of the LED network, which uses addressable LED strips in lengths varying from 1.26m to 6.46m. Strips are partitioned into zones on Ada's overall form, each corresponding to a camera located in Ada's site. A single 360-degree camera is housed on the interior of Ada at the centre of the tensegrity cone. This acts as a cycloptic eye through which inhabitants can experience a direct and personal interaction with Ada from within. Strips are connected to data and power through Ada's Brain Ring. Ada's three-tiered lighting system – PAR lights, LEDs, photoluminescent fibres, and fibre optics – provides critical and emergent experiential effects in relationship to human behaviour in Ada's context.

Results and Discussion

Generative Design, Exoskeleton, and Tensegrity Cone

The final digitally-fabricated result of a generative design process within a 3D-modelling environment is dependent on an accurate representation of physical and material conditions. As discussed, a physics engine was developed in Grasshopper to simulate the built form of all non-rigid elements (knit surfaces, nylon webbing systems, etc.) under accurate force conditions. Traditional techniques and machinery require that 3D forms in the Rhinoceros space must be projected, flattened, or unwrapped into a legible 2D representation. For complex geometries and double curvature there is an inherent approximation that is necessary in order to make this translation possible, and this carries a variable level of inaccuracy due to the challenge of simulating the physical material behaviour and elasticity. Additionally, standardisation of elements was desirable for easier fabrication and assembly which encouraged dimensional rounding in order to maximise homogeneity. Often these errors in translation and rounding were either absorbed into a stretch factor associated with non-rigid materials or accounted for within established tolerances.

The exoskeleton, in co-action with several other key elements in the project, is a major contributor to the structural infrastructure of Ada. Moreover, these characteristics added an interactive haptic feature to Ada that would shake, ripple and bounce when touched and pushed by inhabitants.

Fabric Structure and Base/Upper Ring

Due to the high level of precision needed for the key attachment points, fabrication techniques of three-dimensional freeform aluminium tube-bending allowed for variable radius profiles to be produced in the base ring. The fabric structure was produced using four distinct cones lengths of 20.3cm, 30.5cm, 48.7cm, and 61cm with the assumption that the inherent elasticity of the knit fibre in each cone would be able to accommodate the 182 unique lengths that composed the entire network of cones within the canopy.

Conclusion

Ada builds upon 13 years of collaborative work and innovation across architecture and science, where projects embrace and are informed by technology, non-standard and bio-steered concepts, and the hidden spatial structures within data. These projects have the capacity to facilitate and reveal human expression and emotion in the built environment (Sabin et al., 2018). Through ten built projects commencing with the myThread pavilion in 2012 and, most recently, with Lumen for MoMA and MoMA PS1 YAP 2017, Jenny Sabin and her team have explored generative design and digital fabrication in knit and woven structures through multi-sensory responsive environments. Drawing synergies with current work at the intersection of data-driven cyber-physical assemblies, digitally knit structures, and textile architecture, Ada celebrates, integrates, and materialises AI, affective computing, responsivity, and material performance as can also be seen in work by Ahlquist, CITA, Farahi, Johnson, Khan, and Scott.

However, in contrast to these projects, Ada breaks new ground in scale, in the intricacy of embedded systems, and fine-scale design and manipulation of fibre material, resulting in the first architectural pavilion structure to be driven by human sentiment data in real time and powered by artificial intelligence. This platform would not have been possible without the unique collaboration with Microsoft Research. Unlike the pioneering work of Mark Sagar, such as his BabyX project that seeks to humanise

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AI through 'more symbiotic relationships between humans and machines', Ada does not appear lifelike (Vance, 2017). Instead, Ada offers subtle and abstract interactions with humans through space, material and form to augment and expand our emotional range in a specific context – an office environment – which, in turn, affects the probable sentiment data being collected as new information. The spaces and environments that we inhabit influence and partially shape who we are and how we are feeling.

Through the integration of responsive materials and emerging technologies including artificial intelligence, Ada offers an interface for personalising architecture, to make it more human and reflexive. At the same time, Ada expands human emotional engagement through beauty and materiality. Ada has the capacity to promote and, hopefully, increase wellbeing through direct engagement with the architecture that we inhabit and encounter.

Ada's form, software functionality, and relationship to its physical and social context inform one another as a result of a rigorous design process in which materials, data and light are programmed. Installation challenges, due to variable tolerances and the precise transfer of forces across the complex structural system of Ada, present productive areas to refine for future projects. The introduction of fibre optics and finer scale manipulation and programming of a 3-tiered lighting system also present important leaps and openings for future permanent projects featuring embedded architectural systems. Finally, Ada opens up dialogue around important and pressing issues concerning personal data acquisition and privacy as well as justifiable concerns with AI. Ada is a project that celebrates AI, an architecture that is 'happy to see you' and 'smiles back at you'.

11. Ada, view from above with reflection in glazed surface. Ada incorporates responsive digitally-knit textiles as an information mediating surface architecture to materialise human sentiment data captured live and processed through artificial intelligence algorithms and affective computing. Photo by John Brecher for Microsoft.

Acknowledgments and Credits

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