How to Integrate Soft Robots into Built Environment?

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Abstract

In the current times with the world context focussed on trying to incorporate hybridity into various industries. There is a certain research gap between architecture and soft robotics where inflatable architecture has been implemented and architectural robotics has also been implemented but a combination of pneumatic robotics has not been explored much. In this aim, my thesis explores the possibility of integrating using Soft robotics leading to the symbiosis of digital and physical. The research can describe what a possible scenario of living and working with robots could look like within spontaneous environments and architectural actors that optimize and enhance experiences.

Introduction

Human beings have always associated buildings with being something static, rigid and on many occasions nothing more than a shelter. My thesis aims to redefine this assumption of buildings and highlight them as something plastic that interacts and is aware of.

"The future of Architecture will be soft and hairy"
- Salvador Dali to Le Corbusier

With the current trajectory of humankind's technological development, Connectivity to surroundings is becoming a necessary convenience. Be it using IOT, Bluetooth or buying products of the same brand to set up a home ecosystem, all our lives have an invisible overlay of digital connectivities that form a complex adaptive system[1] of digital and physical interfaces. Such systems can adapt using tools such as artificial intelligence and not requiring the intervention of a specialist to maintain the interdependencies of the system. Distributed adaptive robotic systems in architecture can support an environment that can continually negotiate conditions with the users' and their surroundings with a very high spatial resolution.[2]

The Intersection of robotics and spatial design explores a new tangent in architecture where the relationship between the human and space is constantly challenged and enhanced using sensors, active and responsive materials and ambient intelligence.[3] The design represents an ever-changing living environment where human social behaviour not necessarily with space dictates the plasticity of the environment. The soft robots have been used as a means to highlight and explore how spaces could react to humans on a material scale.

[1] Chan, S., & Gell-Mann, M. (2001). 1 Complex Adaptive Systems.
[2] Decker, M. (n.d.). *Soft Robotics and Emergent Materials in Architecture*. 8.
[3] Parlac, V. (2019). *Architecture and its (non)permeable boundaries*. 9.

1. Soft Robotics

1.1 Introduction

Usually, robotic systems consist of raw exposed machine components that have a very mechanical and rough exterior and work as an assembly of parts. Integrating robots into human environments requires special attention and establishing a safe space for direct machine-human interaction is essential. Soft Robotics offers a more human-friendly approach to human-robot interaction. The materials used to manufacture soft robots are inspired by nature itself and their soft nature leads to a reduction in the risk factor of human injury around automated machines. Soft robotics use developments in material sciences and bioinspiration for the creation of a new generation of robotics. [4]

Traditionally Pneumatic architecture has focussed on creating habitable envelopes that separated surrounding environments from the occupants. This led to a certain large scale being associated with pneumatic structures in architecture. Combining current technology with Pneumatics as a tool for transition between environment and architecture has the potential to be an adaptive architectural space that exists in symbiosis with its environment.[5]

Conventionally in architecture we assume the building and the spatial boundaries are the same, in the sense that the spatial envelope that separates the interior from the exterior is also the physical boundary. However, “In physics, the boundary is a place of action where different energy fields transition into one another. Boundaries, therefore, could be thought of as active regions rather than surfaces of delineation” (Addington and Schodek, 2005, 6)

[4] Decker, M. (n.d.). *Soft Robotics and Emergent Materials in Architecture*. 8.
[5] Melendez, F., Gannon, M., Jacobson-Weaver, Z., & Toulkeridou, V. (2014). *ADAPTIVE PNEUMATIC FRAMEWORKS*. 8.

“Soft robots are compliant mechanisms consisting of soft components and actuated by fluids.”

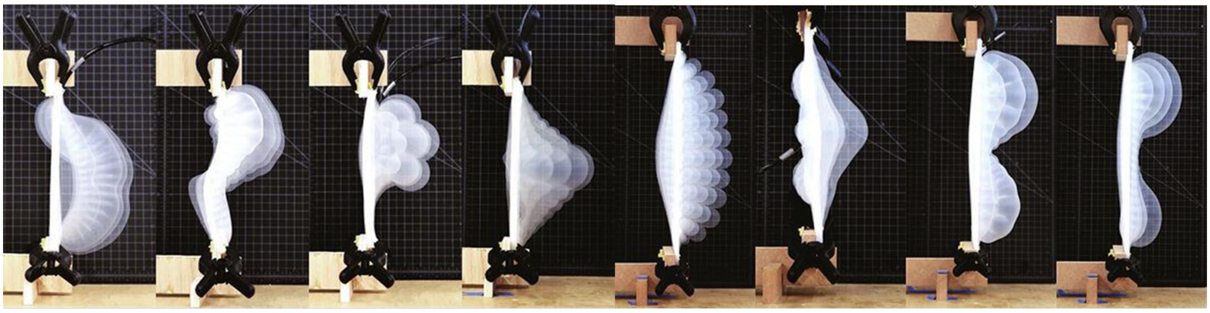

Fig.1

1.2 Precedents

Muscle NSA

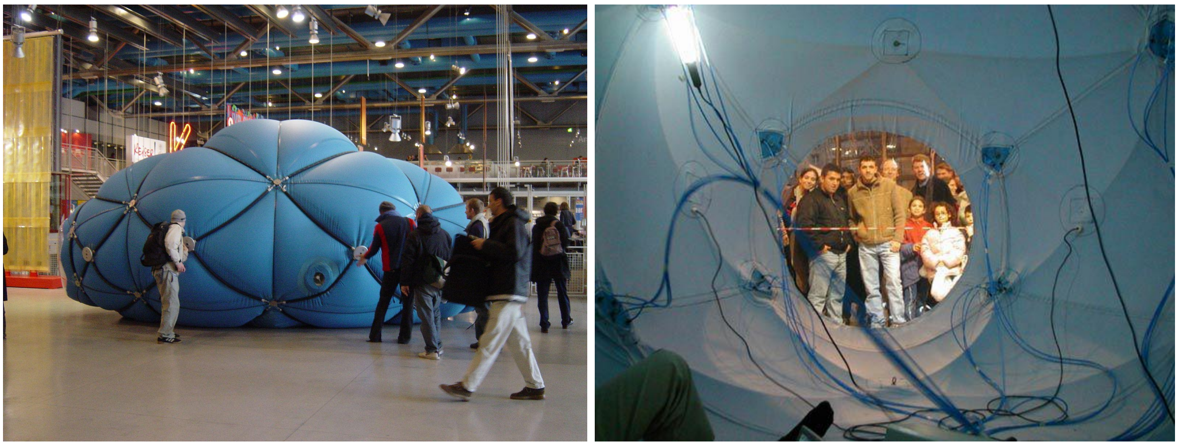

Fig.2A & 2B

The NSA Muscle was a part of the Non-Standard Architecture Exhibition at Centre Pompidou in 2003. It was a programmable building that could reconfigure itself based on environmental conditions and crowd movements. The soft volume is enveloped by seventy-two tensile actuating components. When the actuated components contract similar to an organic muscle, displacing the connecting nodes thus altering the volume. The movements of the structure are executed through the connecting muscles which behave as a flock. The coordination of the muscles is organised such that the change is performed through co-operation and varying the air pressure of the muscles. The movements possible are twisting, bending, hopping and rotating. The prototype is in a constant state of calculations, transforming real-time based on the input values from the surroundings.

A collection of sensors generate a field around the prototype which enables public interaction with the prototype. The body senses the change and movement of its surroundings and responds with various configurations, which change the physical shape of the dynamic structure.[6]

[6] http://www.hyperbody.nl/research/projects/muscle-nsa/index.html

Swarmscape

Fig.3

Swarmscape is a Hyperbody project designed as an interactive, intelligent and floating landscape. The project was designed to manage huge crowds of the future World Expo at a candidate city of Rotterdam in 2025. It addresses the problem of lack of public infrastructure in cities and offers a unique solution. Swarmscape addresses a solution to provide new infrastructure over the water without any robust and large construction.

The project has a modular system approach to soft robotics, and there are two sizes of modules. The larger module is used to provide the floating space of the landscape and the smaller one is used for crossing over the river. The modules work on a swarming algorithm where real-time input informs the modules to move towards the crowded attractor points. Each module also was independently capable of reacting to different amounts of people.

The interactivity of the landscape was enabled through LED lighting and bending the larger corner modules upwards. Swarmscape is an attempt to implement soft pneumatic systems at an urban scale. The small module is designed with a hull that allows it to travel through the water quickly and the sides are designed for connecting other modules. The big module consists of a core and several smaller inflatables around it which can bend upwards. The core is responsible for regulating the bending by receiving and sending data to the triangles. It also has a motor that allows the module to move and communicate with other modules, The data for processing is received from pressure sensors distributed throughout the module, which also serve as an energy source. This data is used to inform the pumps responsible for the inflation of the air chambers.[7]

[7] http://ex25.hyperbody.nl/index.php/Msc1G2:Group

Works of Chico Macmurtrie

Fig.4

Chrysalis was a live interactive environment installation from the collection of Inflatable Architectures by Chico MacMurtrie / Amorphic Robot Works.
The prototype contains 100 interconnected high tensile fabric tubes that form when fully inflated, a 40 foot long, 26 foot wide and 16-foot high immersive architectural space that can reform into various crystal-like configurations.

A servo-controlled computer system controls the network of tubes which is divided into 16 live sections using compressed air. The installation responds in real-time to crowd movement by opening up portals within the structure upon sensing approach. The installation also works on pre-recorded sequences that control the amount of air entering and leaving the fabric tubes, resembling a muscle and bone framework. The structure is capable of expanding and retracting, lifting and lowering, and collapsing movements.[8]

The installation provides a transformative experience as a person moves from the outside to the inside. The scale of the structure relative to the human is used to engage and completely engulf the audience, responding to every movement.

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[8] http://amorphicrobotworks.org/chrysalis

2. Research Methodology

The research by design was used as a strategy for integration of the soft robots into architectural space. Different instances of spaces were studied for possible deformations using various principles of soft robots such as creating bending, folding motion or locomotion using variable air pressure sequences. Those individual cases were used as a catalogue of behaviours to understand the deformations of the soft robots, this has been demonstrated in Section 2.1. A connected layout of volumes was be achieved by distributing them across the enclosed site creating a certain experience of circulation. This layout was to be integrated with a uniform connected system of soft robots, to transform the interventions into a singular organism-like hybrid structure that functions as one huge network.

During the research phase, various forms of geometry were tested to evaluate their behaviour and spatial relevance. Initially, individual spaces were modelled and geometric qualities such as scale and organic or rigid forms were explored as shown in Fig.5A and 5B.

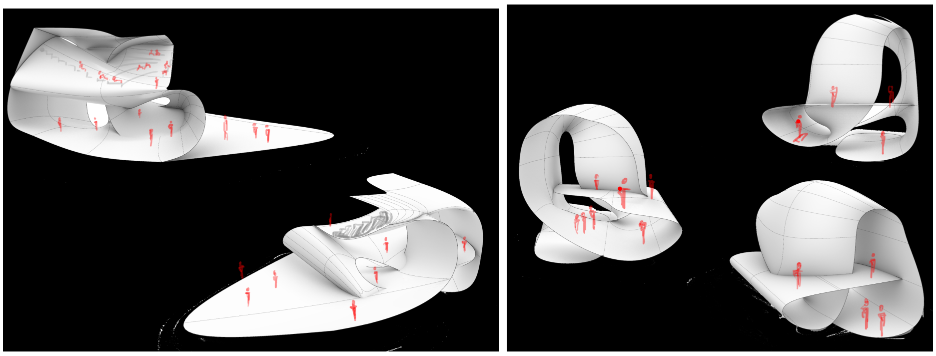

Fig.5A & 5B

The above geometries modelled on rhino were evaluated based on visual connectivity within the volumes and the possible movement of people.

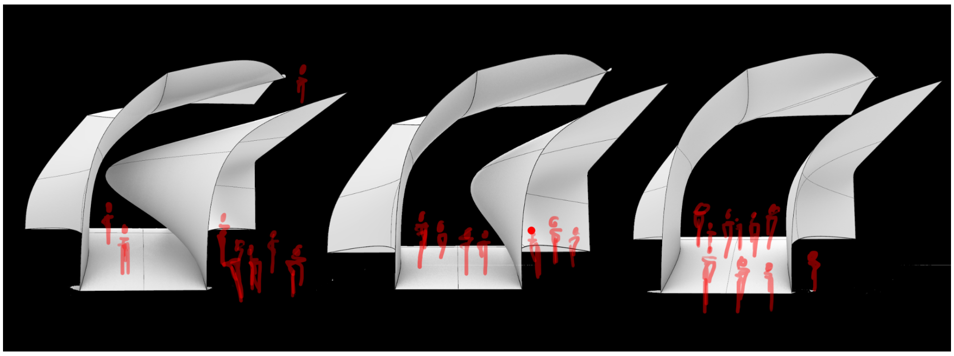

Fig.6

A similar language of design was further explored, but with a reconfigurable aspect in mind to evaluate how the changing space would impact the flow of the people and the visual quality of the space. This form language was then translated onto the scale of the site as seen in Fig.7.

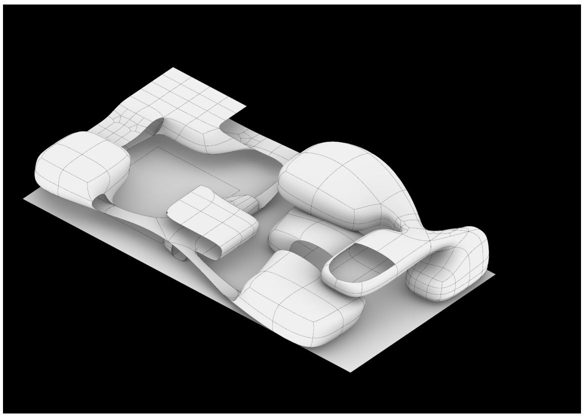

Fig.7

The conclusion drawn from the above design process was that there was a need for a more hierarchical approach to the integration of soft robots. This hierarchy helped establish a relation between the static forms and the structure of the soft robot itself. For the final design, a Voronoi system was adapted on all three scales: Micro, Meso and Macro.

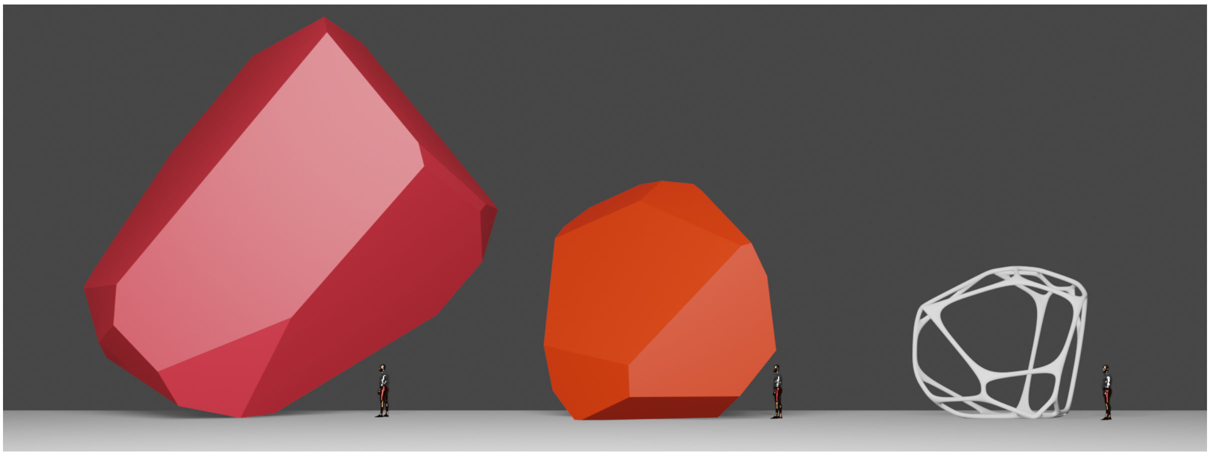

Fig.8

These scales refer to the three levels the design was addressed at. On the macro scale, the design addresses the urban context and the existing building which results in clusters of Voronoi cells. The meso-scale addresses each function as an independent voronoi cell. The macro-scale refers to the integration of the soft robot inside the function volume. The soft robot structure is also derived from the voronoi logic for a consistent language of the design.

The Voronoi Logic helped in consolidating the design language through all scales thus forming a cohesive design. Parameters of scale and mobility are used as a parameter to inform and drive the computational workflow.

2.1 Speculative Studies

The speculative studies are a series of possible spatial interventions and expected outcomes of actuating the soft robotic components.

Study 1: Uniform Actuation in one plane leads to the formation of a landscape.

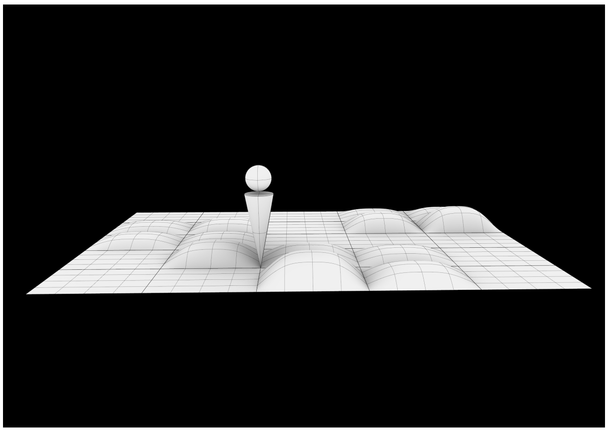

Fig.9

Study 2: Non - Uniform Actuation in one plane leads to bending of walls.

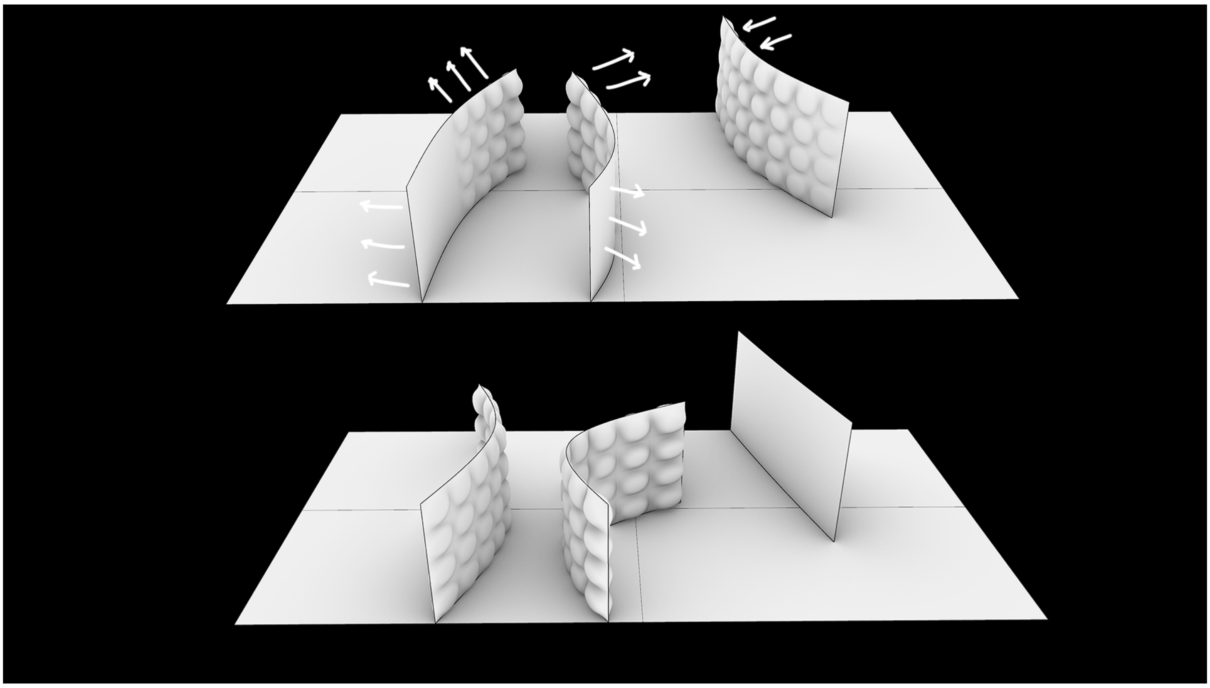

Fig.10

Study 3: Actuation within enclosed spaces to morph in architectural features such as dome and creating an interactive volume.

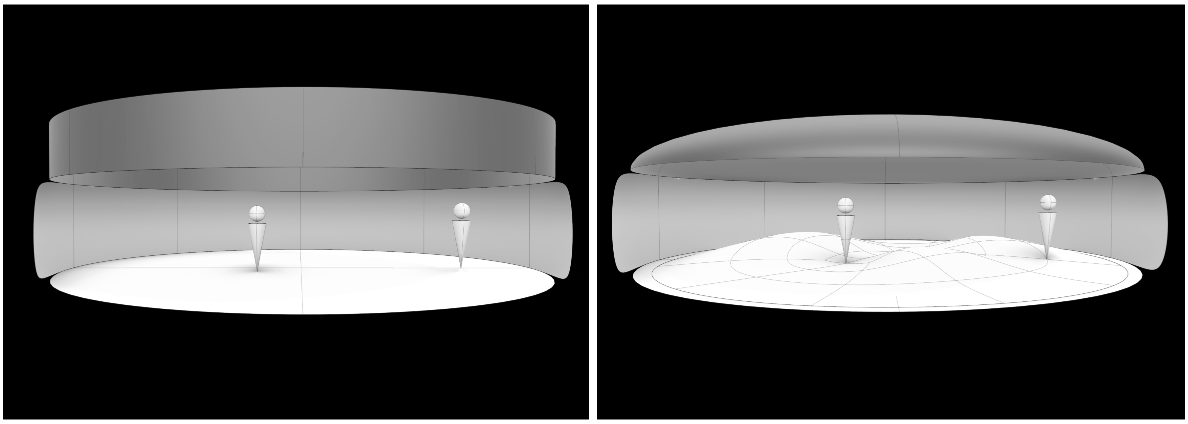

Fig.11A &11B

Study 4: Actuating with slender elements. While the movement is restricted to bending, more combinations are possible due to its more responsive plural form.

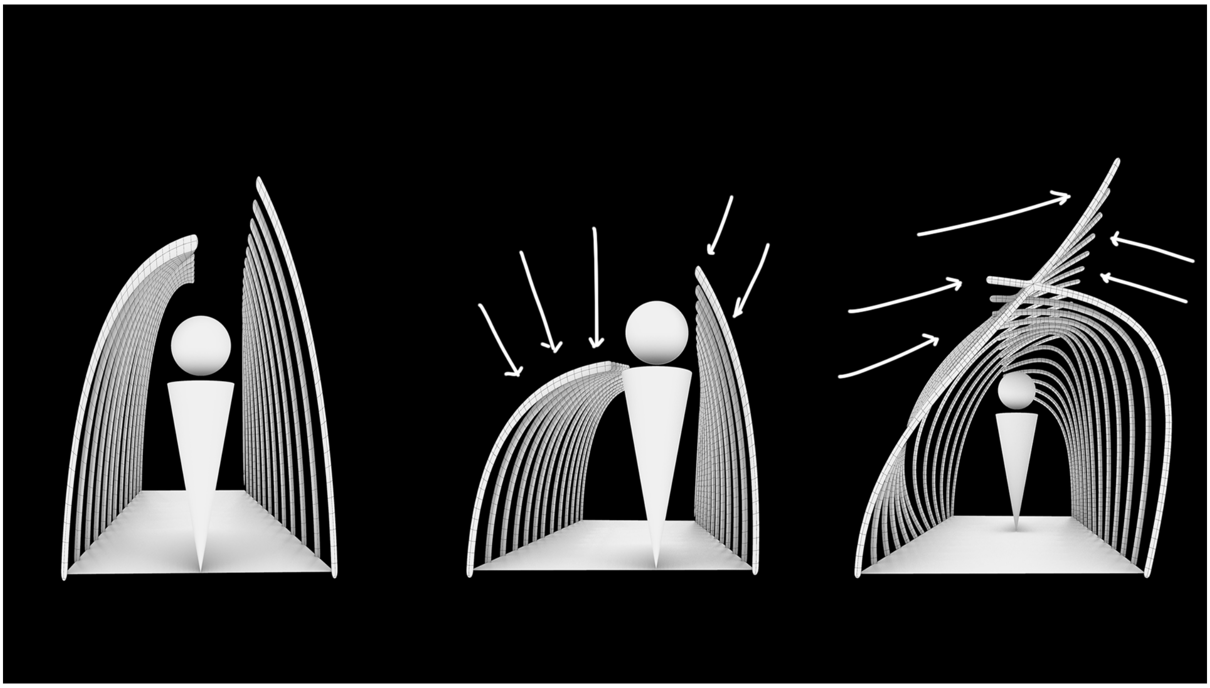

Fig.12

Study 5: Forming a 3D Grid structure that can deform. This can control crowd flow and movement based on openings. This design has limited capacity to affect the volume of space but controls visual connectivity between two volumes.

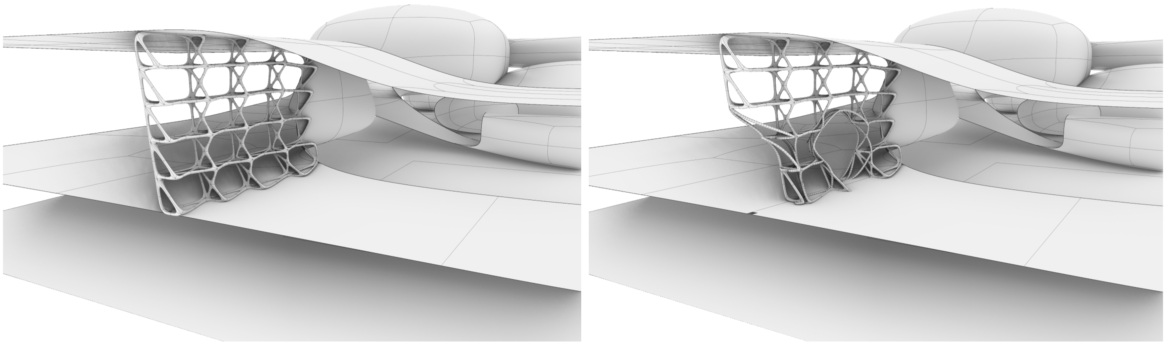

Fig.13A & 13B

Study 6: Implementing the Grid as a 2D and 3D part of volumes. In Fig.14A the grid in its 2D form is implemented as a roof structure to control light conditions of the space. In Fig.14B, The grid has a more 3-dimensional integration, controlling the size of the corridor based on crowd flow, allowing for increased interactivity due to many moving elements.

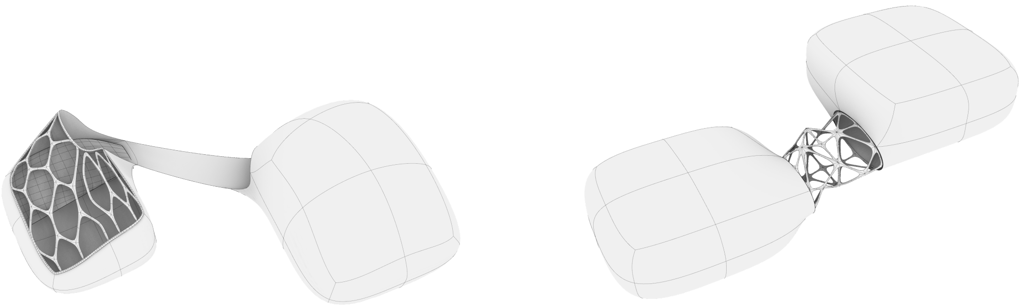

Fig.14A & 14B

Study 7: Integrating a volumetric space that can deform into the structure. This also adds an element of porosity.

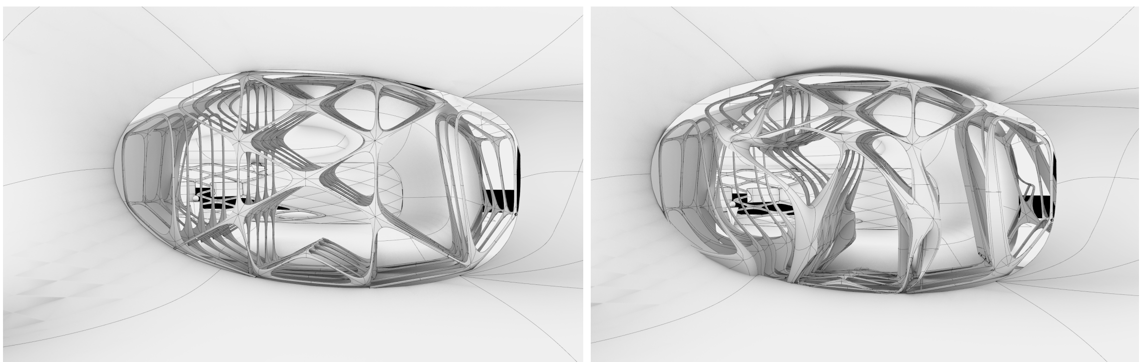

Fig.15A & 15B

2.2 Industry Application and Context

Within the domain of Architectural construction, information can be divided as user information, environmental information and structural information[9]. A soft robotic assembly has been derived from an amalgamation of the second and third type of information. Environmental information relies on the use of sensors
, and robotic assembly is performed as an outcome of the sensor data that has been computationally processed. In the project this is implemented using infrared sensors which are connected to microprocessors (Raspberry pi pico) that process the data. The data is then analysed and the next pose of the soft robot is determined and new air pressure levels are sent to the air pressure sensors in the soft robots.

In the architecture industry currently, examples of autonomous inhabitable robotic architecture are scarce. This is not only due to the scale and cost of these responsive autonomous systems, but also resolving the interaction between these autonomous robots and humans in an uncontrolled environment.[10]

The industry is currently evolving to integrate automated components and robotic production and operation that can respond in real-time to user needs. This approach can be seen in the manufacturing process of ICD/ITKE Research Pavilion 2016-17. [11]
The construction of the pavilion explored a collaborative set-up between multiple machines such as a custom-built UAV that communicated with two stationary industrial robots for the manufacturing process.
The aforementioned case studies such as NSA Muscle also highlight the integration of sensors and actuators into the built environment and their real-time response mechanisms to human interaction.

The potential of soft robotics yet remains to be explored but for smaller temporary interventions it might be easier to experiment and understand how it can be further developed for large scale integration with respect to state of the art of technology.

2.3 Design Approach

[9] Tibbits, S. (2011). *A Model for Intelligence of Large-scale Self-assembly*. 8.
[10] Kilian, A. (2018). *The Flexing Room Architectural Robot. An actuated active-bending robotic structure using human feedback*.

[11]https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/icd-itke-research-pavilion-2016-17/

In the context of this thesis, the soft robots are integrated using various instances to show how they can be used based on the level of interaction they have with the user.

Direct Interaction:

The soft robot setup responds directly with the user based on the user's movements and allow for spaces to be formed around a group of people.
This subsystem is responsible for tracking the human in real-time tracking of the people inside the building. The primary difference between direct and indirect interaction is that there is only one input from the user's movement or facial expression for direct interaction.

Indirect Interaction:

Indirect Interaction is an output of the ambient intelligence of the space. The use case for this comprises of controlling lighting and enhancing the acoustics of the room. These interactions don't react with the user immediately, but process environmental conditions as input.

The advantage of using a voronoi logic is that it works on all the scales of human, function and building. The voronoi cells 3- Dimensional logic helps in addressing human scale in a 3D environment where even the smallest voronoi cell can accommodate one human to pass. This helps reduce and remove redundancies and uninhabitable spaces in the design.

3. Computational Approach

3.1 Scripting

The computational logic was divided into four systems.

1. **Generating the Geometry with respect to functions**

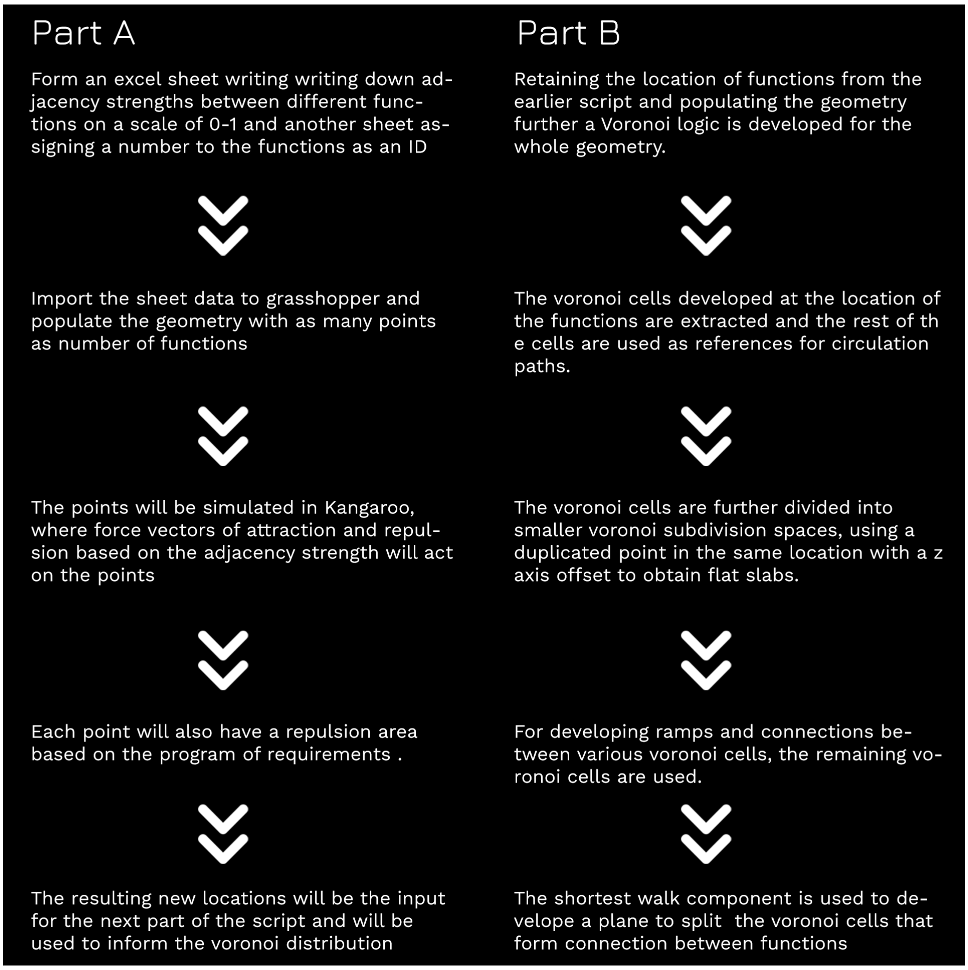

Fig.16

The site is populated with random points which represent various functions. These points are then acted upon by forces of attraction and repulsion based on an excel sheet that has the adjacency logic for each function. The strength of attraction or repulsion was also manually graded on a scale of 1-10 this number is used in the script as a multiplication factor for the attraction/repulsion force. The script is then simulated in Kangaroo to generate the new informed locations of these functions.

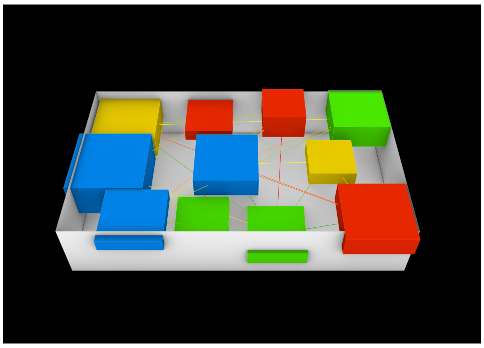

Fig.17

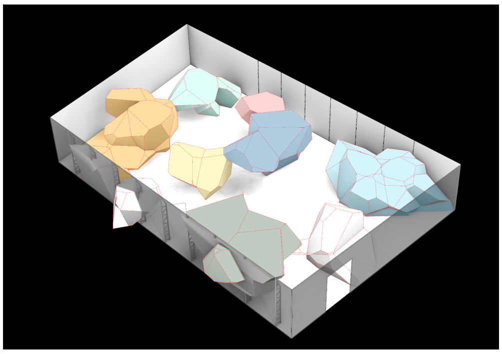

Fig.18

The Voronoi geometry was then generated based on a hybrid method that involved a manual selection of Voronoi cells to be retained at the point locations derived from the kangaroo simulation result.

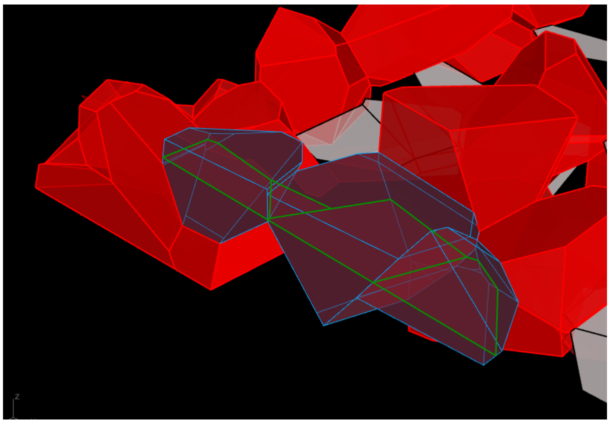

Fig.19

The functions are based on a voronoi logic which has been derived from a Delaunay triangulation diagram since the points used as input for the voronoi are vertices of Delaunay triangulation. Since the Voronoi diagram gives the edge lines of each volume, the Delaunay triangulation is used to derive the connecting lines between all the functions. This Delauney diagram is used as a reference guide curve for the connection between two functions. The Delaunay diagram is used as an input into the shortest walk component. The adjacent cells that are not used for the main functions are manually selected as connections between two functions and a ramp is derived from those cells using a shortest walk curve which forms a plane that splits the cells to obtain the ramp's face borders.

2. Creating the Soft Robot Voronoi

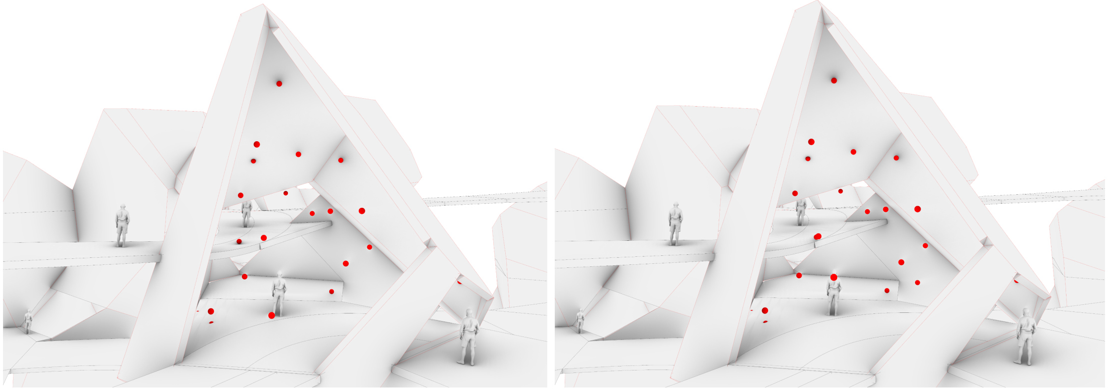

Fig.20A & 20B

For the soft robot Voronoi to be generated, the circulation paths and slabs had to be decided first. These circulation areas were then used to inform a point cloud distribution within the Voronoi cells. This informed point cloud resulted in the soft robot line diagram such that apertures were big enough for a human to pass.

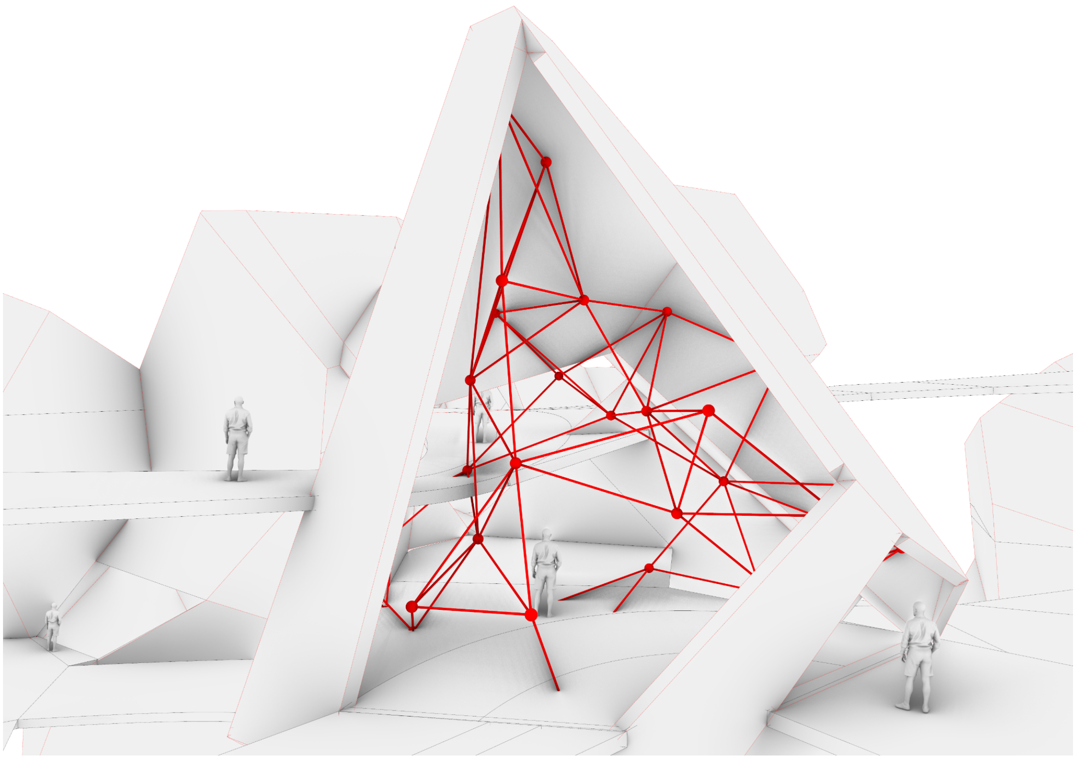

Fig.21

3. Structural Analysis

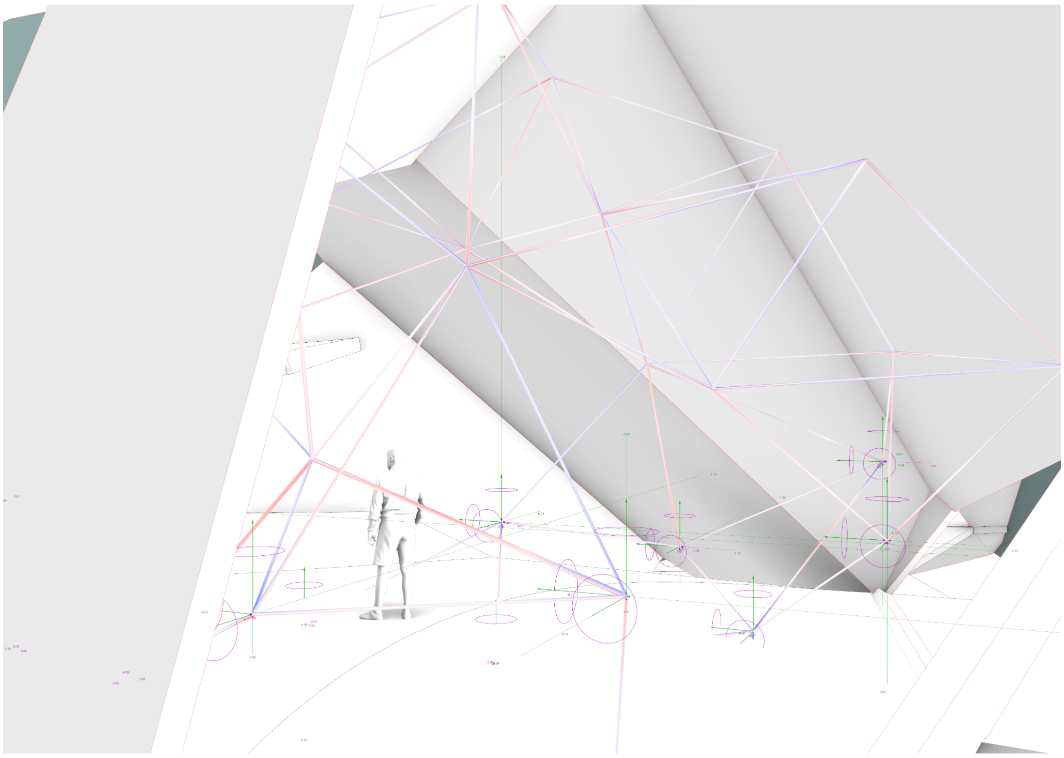

Fig.22

This line diagram of the soft robot was then structurally analysed to understand which members were being utilised. The members were then sorted out into tension, compression and redundant members based on the colours generated by the baked mesh from the structural analysis model. This information was used to identify static members from the setup which serves as structural members and also the dynamic members, whose movements will not compromise the structural stability of the system.

4. Setting up the dynamic system

The information from the structural analysis was then used as an input for setting up the interaction element of the script. Kangaroo plugin in Grasshopper was used to achieve this simulation. The whole soft robot setup was established as a rigid body system with a certain strength value. The beams that were identified as active tension and compression members were anchored to their positions. The endpoints from the dynamic members were extracted, and a force vector was applied to them for every movement of the user. This force vector was a function of the users' distance from that member, which would be calculated using infrared proximity sensors and data received from the wearables.

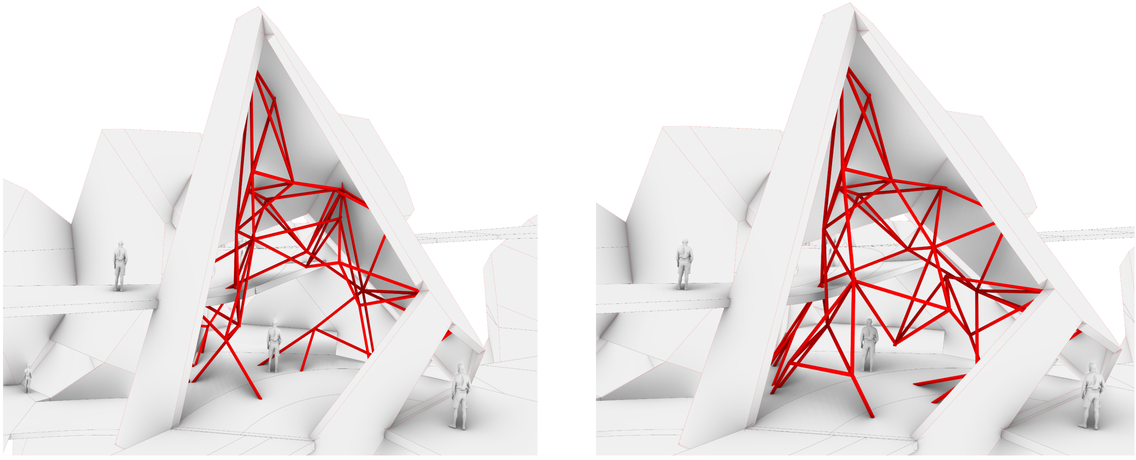

Fig.23A & 23B

3.2 Implementing Artificial Intelligence and Machine Learning

Since this project experiments with testing boundaries of incorporating autonomous robots in our environments. It is extremely necessary to have an extremely sophisticated software backend capable of processing various outputs from the robot.

Enhancing Acoustics

Fig.24

Reference for the AI Software: https://github.com/jramcast/mgr-app

The acoustic enhancing use case speculates the possibilities of optimizing live performances in real-time. The system is set up such that every time there is a live performance the sensors analyse the sound and detect which genre it is. This output is then cross-referenced against a data landscape generated through machine learning, where various configurations of the soft robots are designated for different genres. The closest one to the output from the AI software is selected and that movement is executed by the soft robots.

Responding to Body movement and emotions

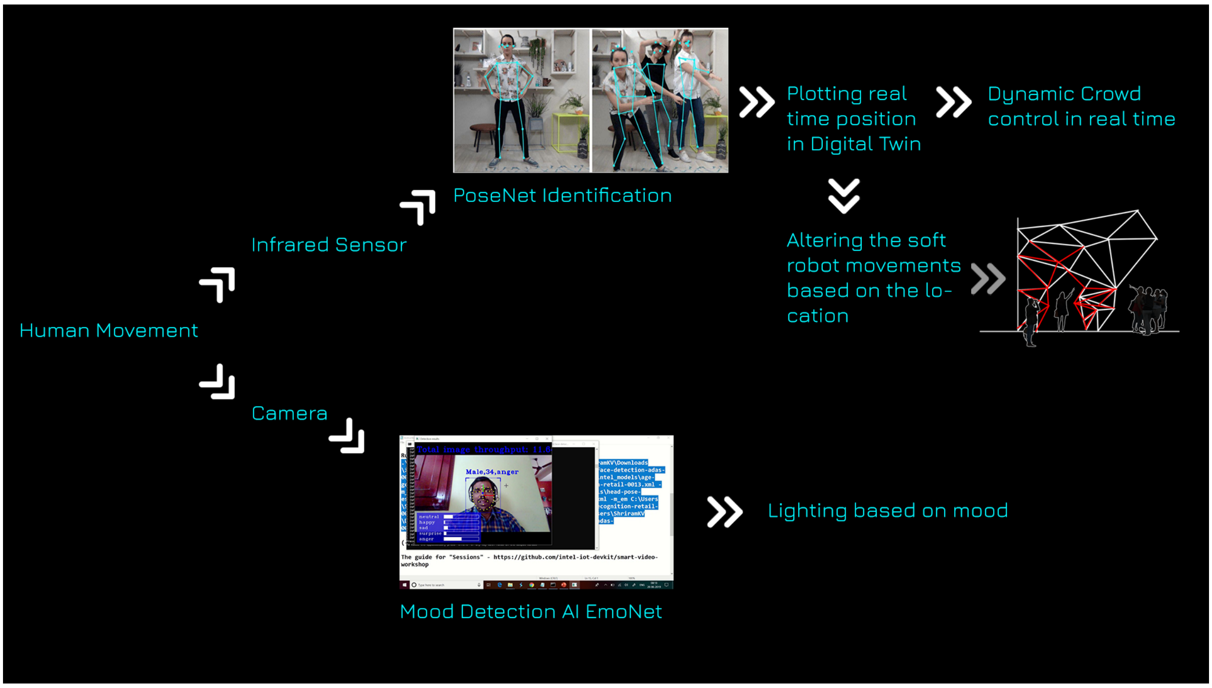

Fig.25

Reference: https://ml5js.org/reference/api-PoseNet/ & https://sites.google.com/colorado.edu/emonet/

This workflow analyses the human movement for direct and indirect interaction. The human movement is captured and analysed by both the infrared sensor and the cameras. This movement is then analysed by Google AI's PoseNet framework which identifies the gestures. These inputs are then reflected in a digital twin which is a virtual model of the entire space. Once a person's location is identified, their position is plotted in the digital twin this helps with identifying the number of people in a certain area. If the person is in close proximity to the soft robot, the processing unit that controls the pressure in the soft robot will start a feedback loop of interaction between that particular human's movements and the spatial changes in that area based on the simulations run in the digital twin.

3.3 Digital Twin

The workflow is driven by real-time data inputs through pressure sensors and wearable sensors on the user's body to accurately map the positions of the people in a virtually constructed 3D model of the space.

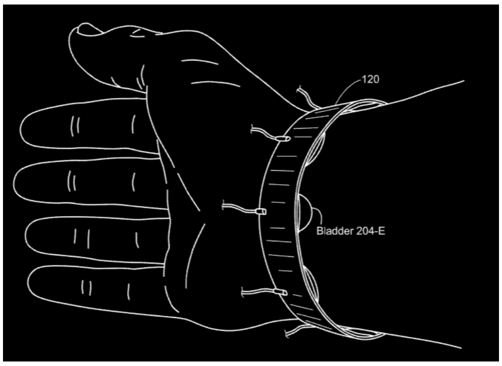

Fig.26

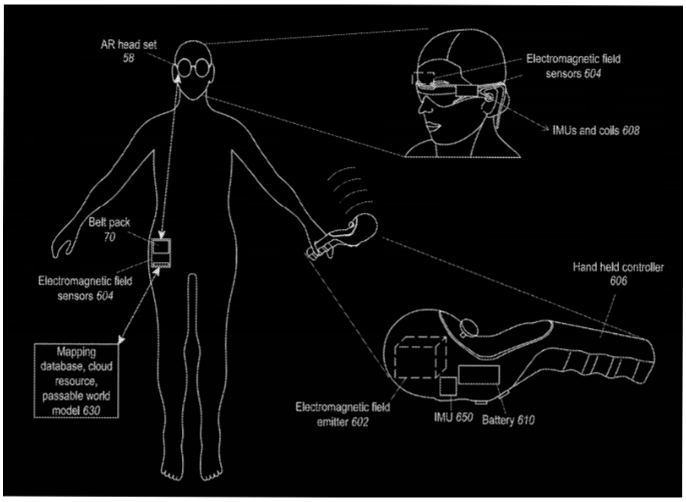

Fig.27

Reference: https://patent.nweon.com/12683 (Fig.26)
Reference: https://patent.nweon.com/10616 (Fig.27)

The digital twin is a virtual model of the physical environment which in this case is the inside of the building. This model will serve as a real-time counterpart to the soft robot setup, constantly updating itself based on sensor input. The digital twin will have the real-time positions of the soft robots and the humans as they move across the structure. Once the digital twin receives the data, it processes it to determine the next pose or movement of the robots. The digital twin will test all the possible poses and scenarios and select the most appropriate one based on factors such as safety, proximity and predicted movement of the users.

The advantage of the digital twin is to ensure the safety of the robotic system's movement through predictive analysis. While introducing a very small latency, the digital twin will be able to execute the movement of the robot first in a virtual environment to check for potential collisions with itself or the environment including the humans and then perform the action once it has deemed safe.

4. Materialization

4.1 References

Flexing Room - Axel Killian

Fig.29

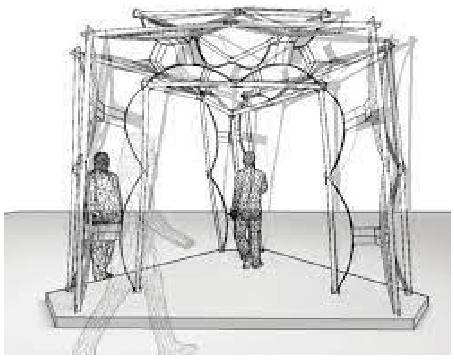

Fig.30

The flexing room is an experiment to explore the potential application of human-scale architectural robotics in a human environment. It's an actively bending skeleton frame that is actuated using pneumatics. The test setup established a feedback loop between receiving the sensor data in the computer and sending values for air pressure settings.
[12]

The structure responds to the sensor input data of human count by transforming into various positions through actuation. The materialization strategy involved setting up a custom pressure sensor in each actuator to regulate the air pressure and verify the contraction length in the pneumatic muscle. A Kinect sensor was used to track and quantify human presence within the set-up.

Each actuator was incorporated with a custom-designed pressure control unit that was controlled through an Arduino. Pressure sensor and power transistors in a custom housing.

[12] Kilian, A. (2018). *The Flexing Room Architectural Robot. An actuated active-bending robotic structure using human feedback.*

Muscle Tower II - Hyperbody

Fig.31 Fig.32

Reference:http://archtctr2.0.viernulvier.nl/sensory_enhanced_bamboostic/Sensory%20enhanced%20Bamboostic.htm

The tower was a part of series of explorations done by the research group Hyperbody, TU Delft. The interactive structure responded to its environment through bending and rotation behaviours. It was conceptualised as an interactive billboard that would use dynamic behaviours to attract the attention of people.

The structure was made up of a network of aluminium rods that were connected to each other in a flexible manner and to pneumatic muscles through hollow spherical nodes. The tower used Fluidic Muscle type (MAS) from Festo. These muscles contracted to up to 20% of their initial length when pneumatically actuated thus acting as a force on the nodes of the tower.

The stacking allowed the tower for a higher degree of movement and the truss-like frame enabled bending and twisting deformations without the tower toppling over. Motion sensors were used to map the spatial coordinates of the people around it which created a sensing field that was used as an input to make the tower deform with respect to that person.[13]

[13] Oosterhuis, K., & Biloria, N. (2008). Interactions with Proactive Architectural Spaces: The Muscle Projects. *Commun. ACM*, *51*(6), 70–78. https://doi.org/10.1145/1349026.1349041

4.2 Sensor and Actuator Integration

Since the project is heavily reliant on sensors and actuators, there is a huge influx of hardware required for the project (Fig.33). For detection of human movements, any type of small camera has to be installed in multiple locations in the building and on the soft robot itself. This is also be accompanied by motion sensors which would be used to detect proximity. For acoustics, an acoustic sensor would be used at each of the exhibition halls to provide real-time input to the soft robots.

For pneumatic actuation, a pressure sensor and a differential pressure valve unit is required for each member of the soft robot. These are then attached to the air pump which works based on input from the computer that is processing the sensor input data and determining the next configuration of the soft robot.

Raspberry Pi Pico	Microprocessor
Centralised Server unit	Data processing
Pressure Sensors	Inflation/Deflation
Network Cameras	Emotion/Movement Capture
AI compute server	Image Processing
Infrared Sensor	Proximity data collection
Differential pressure valve unit	Maintaining the pressure
Air Pump	Pumping air into the system
Acoustic Sensor	Acoustic data collection

Fig.33

5. Conclusion

This research presents a method of integrating soft robotics in architecture that could be developed further to explore the potential of interactive robotics in Architecture. With the current change in times and the uncontrolled influx of technology into our lives, this project offers a way to control all the data that we as humans create just by our movements and use it to inform spaces that we habit.

The design process uses various computational tools that set-up the soft robot geometry inside the virtual 3D space. This workflow allows for simulations governed by a set of rules making it possible to predict behaviour under ideal conditions. The design method also has a hybrid process where computation is not a linear workflow but often informed by manual decisions taken from the output of the previously computed result.

This technology can be further developed as a modular assembly-disassembly system that can be applied on sites where the situation is changing actively such as stations and music festivals. The technology can also be integrated with other mediums such as elastic fabric and light fixtures to create spatial experiences. The benefit of the soft materiality of the robots also allows it to be used in locations such as pre-schools to monitor children safely.

The merit of this technology lies in its ability to be used at varying scales, as something completely embedded in a structure or something more temporary. Since the project also involves gathering a lot of personal data from the visitors, the technology does pose an ethical aspect that needs to be clearly defined. Giving users the choice to select the amount of data they wish to share in terms of selecting between different wearables which enable interaction with the space will help the users feel more secure and also engaged with the space.

This approach to soft robots also helps as a new means of data collection to understand how humans move and behave in close proximity to robots. The function of the site as a new media art exhibition integrated with soft robots also give us more specific data on how people react to art and the space.

The materiality of the soft robot still requires further resolution to ensure working on an architectural scale. The primary challenge of this technology is ensuring an efficient closed-loop system of airflow while minimizing the amount of cable wiring and tubes required. The potential of soft robots in design is still in its infancy but many of its applications could be relevant now such as crowd control. With the introduction of wearables and sensors into the environment the project tries to establish a mutually aware relationship between the human and space where the feedback loop is constantly active.