ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

MODULAR KINETIC SYSTEM PROPOSAL WITH RESPONSIVE DESIGN APPROACH FOR ACOUSTIC PANELING SYSTEMS

M.Sc. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

TEPKİSEL TASARIM YAKLAŞIMI İLE MODÜLER KİNETİK AKUSTİK PANEL SİSTEMİ ÖNERİSİ

YÜKSEK LİSANS TEZİ

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Suat Batuhan ESİRGER, a M.Sc. student of İTU Graduate School student ID 523171009, successfully defended the thesis entitled "MODULAR KINETIC SYSTEM PROPOSAL WITH RESPONSIVE DESIGN APPROACH FOR ACOUSTIC PANELING SYSTEMS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family and beloved cat,

FOREWORD

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February 2022 Suat Batuhan ESİRGER
(Architect)

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ABBREVIATIONS

ANC	**:** Active Noise Control
FDM	**:** Fused Deposition Modeling
PETG	**:** Polyethylene Terephthalate Glycol
PLA	**:** Polylactic Acid
PNC	**:** Passive Noise Control
PU Foam	**:** Polyurethane
ROS	**:** Responsive Open Space
SM	**:** Servo Motor
SSV	**:** Sound Sensor Value

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MODULAR KINETIC SYSTEM PROPOSAL WITH RESPONSIVE DESIGN APPROACH FOR ACOUSTIC PANELING SYSTEMS

SUMMARY

The regular needs of people are dynamic as they had never been before, thanks to the rapid increase in technological developments. Architectural components are also affected by this dynamism with the integration of new computer and communication technologies into daily life. As a consequence, research and development on interactive and adaptive building elements became a rising trend in the architectural community. Moreover, in today's architecture, the computational approach has become a tool for designing intelligent spaces, rather than being a tool for designing ordinary spaces. Due to this trend, using algorithms, computations, and intelligent systems in designed environments became essential, considering that it is playing an undeniable role in the interactivity of a space.

The most common reflection of interactivity on architecture is the "responsive" design approach. In today's world, there is a good quantity of building elements that are intelligent enough to respond to changing heat, sound, light, and humidity levels. Among them, exterior surface components are commonly subject to heat and light control. On the other hand, interior components are more related to sound-related inputs such as noise control and acoustic comfort.

Auditory input is already a key element during the daily interactions of living beings, as it warns of impending danger. Followed by survival instincts, acoustic comfort becomes essential for both physical and mental health. Studies show that there is a significant amount of association between acoustical comfort and the well-being of living beings. Prolonged and repeated exposure to poor acoustic comfort, especially an uncontrolled noise environment, can cause anxiety, headaches, and many more stress-related health conditions. Therefore, it is a must-consider topic in both natural and man-made environments. However, we encounter acoustic discomfort often, and in its most common form called "noise". It is also a fact that as much as the noise causes health issues, aimlessly and excessively quiet acoustic conditions can lead to a feeling of detachment, considering the lack of background sound might cause disassociation from the related environment, leading to mental health problems in the following term. The conventional approach to deal with this problem is to add static, non-adaptive, sound-absorbing, or scattering materials to problematic space. Since there is multidimensional dynamism in space, design requirements should consult for the noise levels of various scenarios that can occur throughout the day, especially for multifunctional places.

This thesis focuses on the research and development of sound-absorbing responsive panels as indoor system solutions.

The research question of this thesis is if it is possible to improve the acoustical comfort of indoor spaces which has dynamic noise profiles, based on the help of sound-

absorbing adaptive modules. The findings of this research show that there is a potential for improvement for the indoor solutions related to acoustical performance.

In this context, a modular and interactive surface pattern, which balances the indoor sound performance and strengthens the bond between the user and the space with its visual interaction, has been studied by transforming the environmental sound pressure levels into action. In addition to that, the study concludes with prototype manufacturing processes of the components. For this purpose, the proposed panels are physically produced in 1x1m dimensions with an electro-mechanical exterior and sound-absorbing interior. The modules' controller mechanism consists of an Arduino Board, actuators, and sound level sensors. Arduino serves as a processor, reading the value from the sound intensity sensor and calculating the motion in order to control the actuators. Actuators change the openness of front plates and regulate the sound waves passing to the absorber located behind the system. Therefore, the system manages to control the amount of sound that will be absorbed or scattered with the help of these front panels. Iris diaphragm leaves are 3D printed with PETG material. Gears, structural elements, and exterior surfaces are manufactured with 3D printing technologies. Lifespan and after-use-disposal factors are considered key subjects for the sustainability of the modular system. Thus, the exterior material is a biodegradable plastic, and PETG that is used in the diaphragm leaves is recyclable. Underneath that, acoustic foam is applied as the sound-absorbing material, which is also biodegradable.

The aforementioned system reacts to the environmental auditory inputs, both performatively and visually. The dynamism of structure and reactions for various sound levels are evaluated with digital simulations. Thus, the system differs from existing responsive architectural components in that it focuses on both the performance and the visualization of sound. As a result of this research, the Adaptive Kinetic Module proposal has been evaluated as a performative acoustic comfort enhancer, with a visual representation of environmental noise.

The purpose and scope of the thesis are discussed in the introduction chapter.

The second chapter is focused on existing acoustic concepts in the context of responsive architecture. It uncovers building acoustics terminology as well as the effects of sound level and quality on human health following with responsive precedents in literature. The chapter presents design requirements, sound absorption solutions, and production processes of case studies. They are evaluated according to the materials used and the methods preferred.

In the third chapter, a proposed responsive module has been introduced. Production methods and the processes from material selection to physical implementation are explained and evaluated in this chapter. The final system decisions are explained, test results of panels and findings from the system's real-world performance are discussed.

For the final chapter, as a result of simulations, the Responsive Kinetic Module proposal was evaluated, and its future potentials, as well as development possibilities, were discussed. Mass production details, visual satisfaction issues, and health-related aspects of the system are discussed as unfolding development possibilities.

TEPKİSEL TASARIM YAKLAŞIMI İLE MODÜLER KİNETİK AKUSTİK PANEL SİSTEMİ ÖNERİSİ

ÖZET

Günümüzde insanların gündelik ihtiyaçları, teknolojik gelişmelerdeki hızlı artış sayesinde hiç olmadığı kadar dinamik hale gelmiştir. Yeni bilişim ve iletişim teknolojilerinin günlük yaşama entegrasyonu ile mimari bileşenler de bu dinamizmden etkilenmektedir. Sonuç olarak, etkileşimli ve uyarlanabilir yapı elemanları üzerine araştırma ve geliştirme, mimarlık camiasında yükselen bir trend haline gelmiştir. Ayrıca, mimari tasarımda ele alınan bilişim, sadece bir mekan tasarlama aracı değil, aynı zamanda bir mekanları akıllandırma ve değişen ihtiyaçlara adaptasyonunu sağlayan bir tasarım aracıdır. Dolayısıyla, bu tür mimari ortamlara entegre edilecek akıllı sistemler ve algoritmalar, bir mekanın dinamizmi ve etkileşiminde önemli bir rol oynamaktadır.

Etkileşimin, mimariye en yaygın yansıması “tepkisel” tasarım yaklaşımıdır. Günümüz dünyasında, değişen ısı, ses, ışık ve nem seviyelerine cevap verebilecek kadar akıllı olan çok sayıda yapı elemanı bulunmaktadır. Bunların arasında, dış yüzey bileşenleri, genellikle ısı ve ışık kontrolü sağlamaktadır. Öte yandan, iç bileşenler daha çok gürültü kontrolü ve akustik konfor gibi sesle ilgili girdilerle çalışmaktadır.

İşitsel girdi, yaklaşan tehlikeye karşı uyardığı için canlıların günlük etkileşimleri sırasında kilit bir unsurdur. Hayatta kalma içgüdülerini takip eden akustik konfor, hem fiziksel hem de zihinsel sağlık konularında önemli bir yer arz etmektedir. Bununla birlikte akustik ile hastanelerdeki nüfusun refahı arasındaki ilişki bir çok çalışmada ortaya konmuştur. Kanıtlar göstermektedir ki, işitsel koşulların, iyileşme sürecine yardımcı olmak veya kaygı veya stresle ilgili koşullara neden olmak gibi hasta sağlığında önemli bir rol oynamaktadır. Bu nedenle işitsel girdi, hem doğal hem de insan yapımı ortamlarda dikkate alınması gereken bir konudur. Ancak akustik rahatsızlıkla sıklıkla karşılaşmaktayız ve en yaygın şekli “gürültü” olarak adlandırılmaktadır. Gürültünün sağlık sorunlarına neden olduğu kadar, amaçsız ve aşırı sessiz akustik koşulların da kopukluk hissine yol açabileceği, uzun dönemde akıl sağlığı sorunlarına sebep olabileceği bilinmektedir. Bu sorunla başa çıkmak için geleneksel yaklaşım, sorunlu alana statik, uyarlanmayan, ses emici veya saçıcı malzemeler eklemektir. Günümüz mekanlarında, çok boyutlu bir dinamizm olduğundan, özellikle çok işlevli mekanlar için gün boyunca oluşabilecek çeşitli senaryoların gürültü seviyelerine yönelik gereksinimleri karşılayacak tasarım elemanlarına başvurulmalıdır.

Bu araştırmada, iç mekan akustik konfor çözümü olarak, ses emici uyarlanabilir panellerin araştırılması ve geliştirilmesine odaklanmaktadır. Bu tez çalışmasının araştırma konusu, ses profili dinamik olan iç mekanlardaki akustik konforu, kinetik ses yutucu mekanizmalar aracılığıyla iyileştirme sorusudur. Yapılan çalışmalardan elde edilen bulgular doğrultusunda bu konforun kinetik sistemlere dayalı olarak artırılması potansiyeli olduğu ortaya konmuştur.

Bu kapsamda, ortam ses basınç seviyeleri harekete dönüştürülerek, iç mekan ses performansını dengeleyen ve görsel etkileşimi ile kullanıcı ile mekan arasındaki bağı güçlendiren modüler ve etkileşimli bir yüzey deseni çalışılmıştır. Buna ek olarak, çalışma, bahsedilen bileşenlerin prototip üretim süreçlerini içermektedir. Bu amaçla önerilen paneller, fiziksel olarak yaklaşık 1x1m boyutlarında, elektro-mekanik dış ve iç ses yutucu olarak üretilmektedir.

Modüllerin kontrol mekanizmasını, bir Arduino Nano kartı, aktüatörler ve ses seviyesi sensörlerinden oluşturur. Arduino Nano, aktüatörleri kontrol etmek için ses şiddeti sensöründen değeri okuyan ve hareketi hesaplayan bir mikroişlemci görevi görür. Aktüatörler, ön plakaların açıklığını değiştirerek sistemin arkasında bulunan yutucuya geçen ses dalgalarını düzenler. Bu nedenle sistem bu ön paneller yardımıyla emilecek veya saçılacak ses miktarını kontrol etmeyi başarmaktadır. İris diyafram yaprakları PETG malzemesi ile 3B basılır. Dişliler, yapı elemanları ve dış yüzeyler katmanlı üretim tekniklerinden olan üç boyutlu baskı teknolojileri ile üretilmektedir. Modüler sistemin sürdürülebilirliği için kullanım ömrü ve kullanım sonrası atık faktörleri kilit noktalar olarak kabul edilir. Bu göz önünde bulundurularak, dış malzeme biyolojik olarak parçalanabilen bir biyoplastik olup, diyafram yapraklarında kullanılan PETG malzemesi geri dönüştürülebilir. Bunların arkasında bulunan, ses emici malzeme olarak da, biyolojik olarak parçalanabilen akustik köpük kullanılmaktadır

Yukarıda bahsedilen sistem, çevresel işitsel girdilere hem performatif hem de görsel olarak tepki verir. Yapının dinamizmi ve çeşitli ses seviyelerine yönelik tepkiler dijital simülasyonlarla değerlendirilir. Bu nedenle sistem, sesin hem performansına hem de görselleştirilmesine odaklanması bakımından mevcut tepkisel mimari bileşenlerden farklıdır. Bu araştırmanın sonucunda, Adaptif Kinetik Modül önerisi, çevresel gürültünün görsel bir temsili ile performatif bir akustik konfor arttırıcı olarak değerlendirilmiştir.

Tezin amacı ve kapsamı giriş bölümünde tartışılmıştır. Bu araştırma kapsamında iç mekan akustik konforunun, ses profilinin değişkenlik gösterdiği mekanlarda iyileştirilmesi üzerine, adaptif ve tepkisel ses yutucu panellerin etkilerinin araştırılması yapılmıştır. Bu kapsamda önerilen bu tepkisel adaptif panelin, fiziksel prototipinin, yeni nesil üretim teknolojileri ile üretilmesi ve denenmesi ele alınmıştır.

İkinci bölüm, tepkisel mimari bağlamında mevcut akustik kavramlara odaklanmaktadır. Bina akustiği terminolojisinin yanı sıra ses seviyesi ve kalitesinin insan sağlığı üzerindeki etkilerini literatürdeki tepkisel emsallerle birlikte ortaya çıkarmaktadır. Bu bölümde, tasarım gereksinimleri, ses yutma çözümleri ve örnek olay incelemelerinin üretim süreçleri sunulmaktadır. Bahsedilen çalışmalar, kullanılan malzemelere ve tercih edilen yöntemlere göre değerlendirilmektedirler.

Üçüncü bölümde, önerilen bir tepkisel modül tanıtılmıştır. Üretim yöntemleri ve malzeme seçiminden fiziksel uygulamaya kadar olan süreçler bu bölümde açıklanmakta ve değerlendirilmektedir. Sistemin üretiminde ağırlıklı olarak katmanlı üretim tekniklerinden olan üç boyutlu yazıcılar kullanılmıştır. Üretim yönteminin bu şekilde belirlenmesinin tasarıma yansıması olmuş, sistemin tasarımında özellikle toleranslar ve de formlar, üç boyutlu yazıcıların kabiliyetleri dahilinde optimize edilmiştir. Bu tasarım yaklaşımı, sistemin dünya üzerindeki diğer FDM tipi yazıcılar ile üretilebilmesini, dolayısıyla üretimin tekrarlanabilirliğini sağlamaktadır.

Sistem, dört ana bölümden oluşmaktadır, bunlar dışarıdan içeriye doğru; yansıtıcılık görevi gören ön paneller, ses geçirgenliğini belirleyen adaptif diyafram yaprakları, bu yaprakların hareketini kontrol eden elektromekanik sistem ve en arkada bulunan ses yutucu yüzeyden oluşmaktadır. Kısaca sistem, yansıtıcı bir yüzey olarak görev alan ana modül yüzeyinin üzerinde açılmış dairesel boşlukların, diyafram benzeri bir mekanizma ile açıklığının kontrol edilmesinden, bu sayede arkadaki ses yutucu malzemeye ulaşan ses dalgalarının regüle edilmesiyle, gürültü kontrolünün sağlanması prensibiyle çalışmaktadır. Sistemin tepkiselliğini sağlamak adına geliştirici kartları ve ses girdisini ölçmek için ses sensörleri kullanılmıştır. Ölçülen bu ses verileri, mikrokontrolcü tarafından işlenerek motor hareketine çevrilmekte ve bu da sistemin ses geçirgenliğini modifiye etmektedir. Bu bölümün sonunda, nihai sistem kararları açıklanmakta, panellerin test sonuçları ve sistemin gerçek dünya performansından elde edilen bulgular tartışılmaktadır.

Son bölümde ise simülasyonlar sonucunda Tepkisel Kinetik Modül önerisi değerlendirilmiş ve gelecekteki potansiyelleri ile geliştirme olanakları tartışılmıştır. Bilgisayar modellemesi olarak Rhinoceros programının Grasshopper eklentisindeki parametrik tasarım algoritmaları kullanılarak, farklı akustik durum senaryoları için, sistemin tepkisi simüle edilmiştir. Kullanılan üretim teknikleri itibariyle karşılaşılan avantaj ve dezavantajlar ele alınmış, ölçeklenebilirlik ve erişilebilirlik kalemleri ile tekrarlanabilirlik konuları incelenmiştir.

Seri üretim detayları, görsel tatmin sorunları ve sistemin sağlıkla ilgili yönleri, ortaya çıkan geliştirme olanakları ele alınmıştır.

1. INTRODUCTION

Societies have created and evolved living spaces in need of shelter through interaction with nature for centuries. The living spaces that started in caves in the early ages consisted of solids and voids to meet the needs of society. In this context, the concept of surface in architecture has been an important part of the building that makes up the main living space and enables the definition of closed space. With the development of technology, different methods and construction techniques that evolve the design have begun to emerge.

Thanks to the widespread use of computers and the internet in the 1980s, transformations began in every field, and societies began to connect to each other by establishing a strong network with information and communication technologies. Architectural building elements, which have been static and fixed for centuries, now have a different format in today’s dynamic environment (Ebru, 2007). Thus, in order to describe these new components and systems, they are involved in, definitions such as adaptive, kinetic, responsive, and dynamic architecture have emerged. Adaptive-Responsive architecture is the reinterpretation of architectural components so that they can be modified to meet different phases, functions, and conditions in an environment. Initial proposals for this approach were in the late 1990s when electronics and mechanics were incorporated into building envelopes to manage energy consumption (Gür, 2018). Nevertheless, today's adaptive-responsive feature has the potential for much more than building envelopes; it can appear as operable and mobile elements attached or embedded on vertical or horizontal dividers.

In this context, it has been an important research and development area in architecture that static building elements can change, move and interact. They can adapt to the environment and increase the effect of interaction, providing a relationship in which the senses are also involved. In the light of these descriptions, this thesis study is constructed on the topic of acoustic indoor wall paneling systems that can actively transform and interact with the environment, focused on acoustic comfort and based on environmental factors. The panels instantly react to the noise that may occur in interior spaces such as office rooms where the acoustic need and noise threshold varies for different situations at different times of the day. They also interact with the user visually by depicting the noise as the modules transform.

The kinetic system modules and the interior wall in which they are integrated are primarily modeled with Rhinoceros software. Environmental sound pressure data was measured with sound sensors and converted into digital data, and these data were converted into pre-programmed motor movements by processing with Arduino Nano microcontroller. Thus, the opening of the system is adapted to the ambient noise level. User feedback was used to determine how much noise levels were reduced and whether they met the comfort conditions. As a result of the analyses, a kinetic cover with a sound barrier feature was formed across the wall surface. The mechanism of the system components has a flexible structure that can be programmed according to different interactive elements. If it is developed according to more than one environmental factor, it is possible to provide very high building performance thanks to this structure. It is envisaged that the system will enable more effective and widespread application areas by increasing interdisciplinary work.

1.1 Purpose of Thesis

The purpose of this thesis is to investigate, understand and develop responsive architectural components.

The most important reason for working on the sound-oriented adaptive surface in the interior is that the interiors could find less space in the research and study areas for walls that interact with sound data. In addition, this study aims to optimize acoustic comfort and increase the indoor acoustic performance of the building. The sound interactive wall is designed to act as a sound absorber against high sound pressure and to reflect the sound otherwise. In addition, it is aimed to strengthen the connection between the people in the building and the architectural surface through visual interaction, with the transformation of sound into movement.

1.2 Scope

The spatial scope of the study is a shared office space with varying acoustic needs throughout the day. Sound simulations and real-world tests were conducted for dynamic noise range detection in an office building in Kasımpaşa in an area of 20 sqm.

At the application scale, it has been studied within the scope of computational, fast, and customizable production.

1.3 Method

The method of this thesis study follows as the review of current literature, production of a prototype, and evaluation of the product according to design criteria. In this thesis, prototyping and testing out possible scenarios has been used as a research method

The environmental interactions of adaptive facades are examined through examples that can be accessed in the literature, and their changes or transformations according to the situations and factors they adapt to, and types of movement are examined. Then, the way the modules of the proposed adaptive interior surface system come together and the kinetic system mechanism is described together with the manufacturing process.

The method of manufacturing the prototype of this system is based on computer-controlled additive manufacturing techniques, for this instance 3-dimensional printing with the Fused Deposition Method. This approach has also been compared to other conventional manufacturing methods. such as laser cutting of sheet materials in a CNC Laser cutter.

2. ACOUSTIC CONCEPTS FOR RESPONSIVE ARCHITECTURE

Interactive Space is defined by Bongers (2002) as the environment in which people live and establish mutual relations. In addition, it interacts with users in it in real-time, able to sense human activities, responding simultaneously visually, audibly, or in motion. At this point, the concept of "Hybrid Wall", which can be considered as a new type of wall, emerges.

As Zellner (1999) emphasized, architecture belonging to the digital age is now transforming, determining its own limits and adapting to an increasingly flexible world. Bongers (2002) also supports this idea by saying that next-generation structures will be more lively structures that can change, speak, move with the help of new dynamic materials such as light, sound, moving elements, and computer programs.

Oosterhuis (1996) sees the next step of architecture as moving architecture and states that it will become a game played by the users of architecture, that the space will react to our presence, that it will start talking and exchanging information with its user. In general terms, this architecture, which is defined as mobile architecture, is also defined as architecture that can be created and controlled with the data it receives from the environment (Sherbini and Krawczyk, 2004). This chapter is intended to draw a general framework of acoustic terminology as well as responsive architectural examples with knowledge of the material, which could engage intelligence, interactivity, and transformability with design.

2.1 Building Acoustics

The legibility of speech is of great importance in places such as educational buildings and office environments (Jablonska, 2021). In their studies, Kuri and Perez (2022) emphasize that most of the educational buildings where acoustic comfort is a must, continue to be designed and built the same as the technologies of decades ago despite the remarkable innovations in the area of architectural and construction elements. As a result, negative impacts occur in acoustic scope in buildings containing educational, investigative, and administrative functions.

There are three main categories in acoustics to understand; material properties, problems, and strategies (Figure 2.1). Sound absorption, reflection, or transmission of sounds are the acoustical characteristics that may be found in all building materials (Figure 2.2).

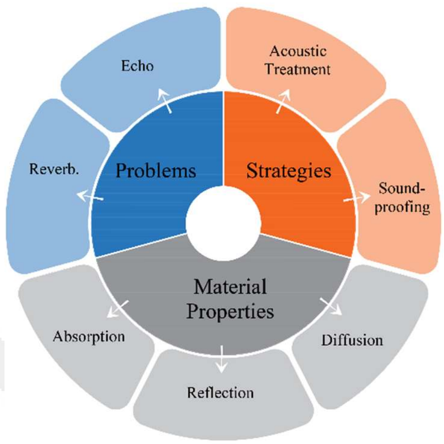

Figure 2.1 : Elements of Building Acoustics.

The echo and reverberation values in a room are increased when sounds are reflected. However, when rooms are properly treated, echo and reverberation are minimized. Sound absorption and diffusion by soundproofing and acoustic treatment are two strategies for treating these problematic interiors. The most effective treatment models incorporate these together (May, 2021). Soundproofing refers to less noise and is commonly used in studios as well as near major roadways, schools, and construction sites. On the other hand, acoustic treatment provides better sound by improving the sound quality within an environment. Understanding the physical causes of sound transmission is required in order to design wall constructions with effective sound insulation. Airborne sound insulation is applied to establish the acoustical quality of rooms (Hongisto, 2000).

As a result of the analyzes found in the study of Liu et al. (2021), it is seen that the problems related to the current acoustic environment design are primarily divided into two main issues. The comprehension of architects is insufficient to handle itsacoustic design's problem's inherent constraints, as architects' approach to public requirements and preferences and demands. However, it is the architect’s responsibility to correct the situation.

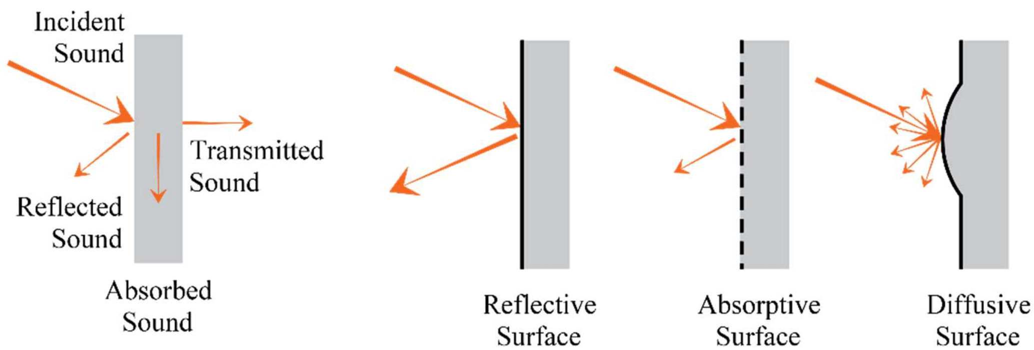

Figure 2.2 : Type of Sounds and Surfaces.

Noise pollution has a significant effect on the environment, health, and the economy today. The public's knowledge of sound's impact on the human body is expanding, resulting in an increase in the number of documents aimed at reducing general noise, reverberation noise, and ensuring proper speech intelligibility (Trocka-Leszczynska & Jablonska, 2021). Individual sound exposure is also an area of research in order to understand the effects of human mobilities on sound exposure in relation with psychological health (Kou et al., 2021). Noise control, in general, comprises both active and passive management. Vasina et al. state those management types under the names of Active Noise Control (ANC) and Passive Noise Control (PNC) (2020). Low-frequency noise is effectively mitigated by ANC systems that do not employ noise-absorbing materials. Passive noise reduction devices that employ sound-absorbing materials, on the other hand, are quite big, costly, and useless at low frequencies. Low frequencies are affected because the absorber thickness is inadequate in comparison to the acoustic wavelength. As a result, PNC devices are only effective for high-frequency noise. Porous materials are commonly used to decrease unwanted noise. New types of appropriate sound-absorbing materials are being developed on an ongoing basis. There are multiple examples of 3D printed architectural-acoustical elements among literature studies. In comparison to traditional manufacturing processes, 3D printing allows for the production of sound-absorbing materials with superior open-pore structures (Vasina et al., 2020). Gao and Hou (2018) proposed a 3D printed metamaterial composed of micro helix structures through polylactic acid. They achieved different absorption coefficients in the results of their experiments and thus formed a material structure with high sound absorbing characteristics. Another 3D printing-based example is the spherically perforated bio-degradable material from

Sailesh et al (2022). The impact of spherical openings and their sequencing on the acoustic properties of a 3D printed bio-degradable material is examined in their study. Aslan and Turan (2020) developed an innovative gypsum-based sound absorber by using 3D printing technology.

2.2 Responsive Precedents in Literature

Architectural and industrial developments simultaneously respond to and represent the society in which we live. The systems designed by architects are creative solutions for the critical and comprehensive evaluation of needs. This is made possible by a range of cognitive and manufacturing capabilities; primarily, the ability to develop and produce an adaptive product (Whalley, 2014).

Since the same terms are frequently used with different interpretations, it is vital to compare and discuss work in this domain using widely accepted definitions of adaptivity and self-adaptive systems (Petrovska et al., 2022).

The growing focus on building performance, as well as the accompanying digital simulation technologies, are radically changing aspirations for building design and operations. The growing interest in building performance as a design paradigm is due to the rise of ecology as a primary socioeconomic concern, as well as recent advances in cultural principles and technologies. At that point, Kolarevic (2003) states performative architecture as a "meta-narrative" with universal goals that are dependent on specific performance-related characteristics of each project.

Meagher (2015) examines 2 types of responsiveness in architecture; one is engaged with the changing environment, while the other is involved with the behaviors and interests of the building's occupants.

Analysts estimate that towns and residences will become more occupied with sensors capable of regulating consumption and enriching the life quality of the residents. Various studies have been conducted to discover how parametric forms and structures would react to various external variable situations, according to the diffusion of these systems. Turco et al. (2017) mention “Smart Buildings” and “Smart Structures” by exemplifying that architectural elements such as panels can be operated by several tiny electric motors that are controlled by a web of sensors detecting the ambient illumination and air temperature. One of the main difficulties in architecture is ensuring comfort in lighting, thermal, and acoustic assets. Smart adaptable surfaces, in this sense, offer an effective solution to today's modern requirements for more environmental and efficient buildings (Andreozzi et al., 2016). Sound performance is important in the experience of space. According to Reindhardt et al. (2012), the acoustic qualities of a place have a substantial impact on the experience of its users. This is especially relevant when the acoustics of the place are inextricably linked to the programs envisioned for it. Reindhart (2018) highlights scientific research into robotic prototypes that investigate the acoustic impacts of complex architectural geometries, with a focus on macro and micro-geometric surfaces that can be exploited to increase acoustic performance through scattering.

The research of Spaeth and Menges (2011) describes a performance-oriented design navigator tool that works on generating spatial concepts based on acoustic factors. The design explorer is a genetic evolutionary system that evaluates rooms based on auditory and morphological features. The study provides the design concept, concentrating on geometry synthesis, material property assignment, evaluation criterion implementation, and a description of essential acoustic criteria (Spaeth & Menges, 2011).

Similarly, The Responsive Open Space (ROS) project of Gau et al (2012). is a performative environment that incorporates audio-visual arrangement in response to human interaction. They define their project as "experiencing diverse segments of a space-sensitive soundscape and its visual representation through interaction with one other" (Gau et al., 2012). The physical design is envisioned as a hanging information cloud from the ceiling.

Buildings and sound interact constantly, sparking new solutions, forming creative structures, and becoming both factors and subjects (Jablonska et al., 2015). Precedents that are examined in this section are selected to their scope of indoor acoustical comfort-enhancing, sound defining, sound visualizing properties. The result products range from architectural office projects to workshop outcomes of computational design organizations. It has also been a key factor that all of the examples include physical fabrication processes. All examples have at least one key feature which is addressed in the research.

2.2.1 Resonant chamber origami architectural acoustic panels - RVTR

Resonant Chamber is an indoor acoustic solution by a paneling system designed by RVTR. The project incorporates the techniques of origami in order to transform the acoustic composition of the space.

The panels are made of a combination of solid bamboo inserts, pointillated porous expanded polypropylene, and electroacoustic panels (Figure 2.3). As a result, the final system as a whole has both reflective and absorptive characteristics. The components can dynamically adjust their shape to expose or hide these surfaces, accordingly altering acoustic conditions.

The electrical basis of panels contains a group of sensors and controls for actuation and amplification of distributed mode loudspeakers (DML) (Figure 2.4). When vibrations are introduced using an electroacoustic exciter, sound is both reflected and created by the panels. To predictably arrange panels into optimal acoustic options, computational modeling was used. Inputs including optimal reverberation period and directional data were used to develop variations. This allows optimization of the displacement and positioning of the panels' tessellated surface (Filippetti, 2012).

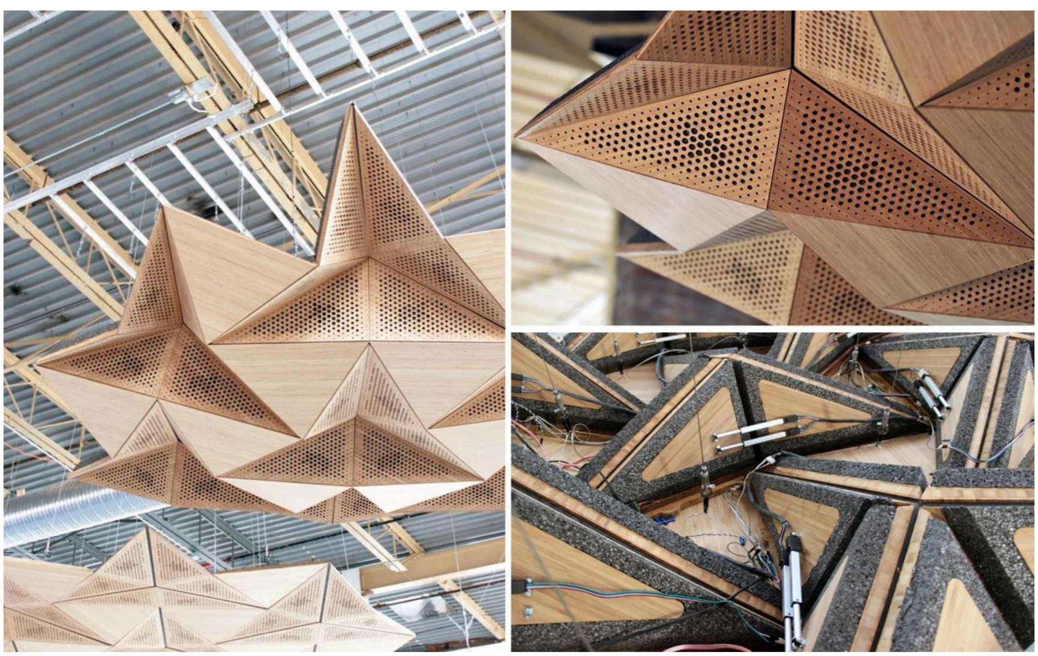

Figure 2.3 : (1) Installation view, (2) Closer view of acoustic panels, (3) Closer view of circuitry (© RVTR).

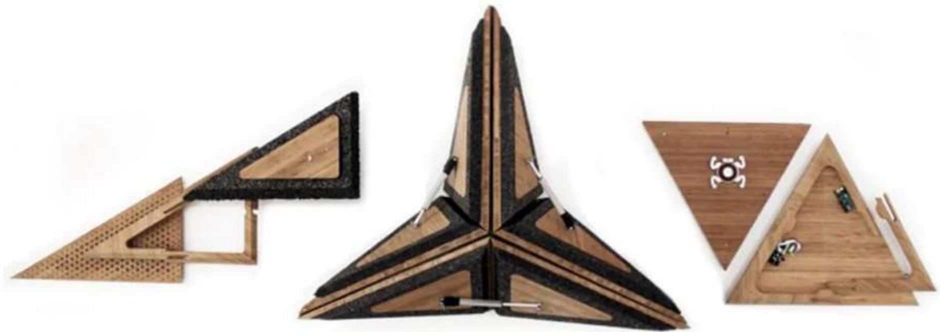

Figure 2.4 : (1) Porous expanded polypropylene panel, (2) view of a single 'unit', (3) base structural components (© RVTR).

2.2.2 Manta acoustically responsive sculpture - Smartgeometry 2012

Zackery Belanger, Guillermo Bernal, Seth Edwards, and Eric Ameres designed their acoustically reactive suspended sculpture project Manta as part of the Smart geometry 2012 workshop. The multidisciplinary project demonstrates a fusion of architecture, fabrication, interactive technology, and research under the concept of acoustics. The body consists of CNC machined panels and connectors comprised of high-density polyethylene (Figure 2.5). Bending stiffness and triangulation were shape-determining factors.

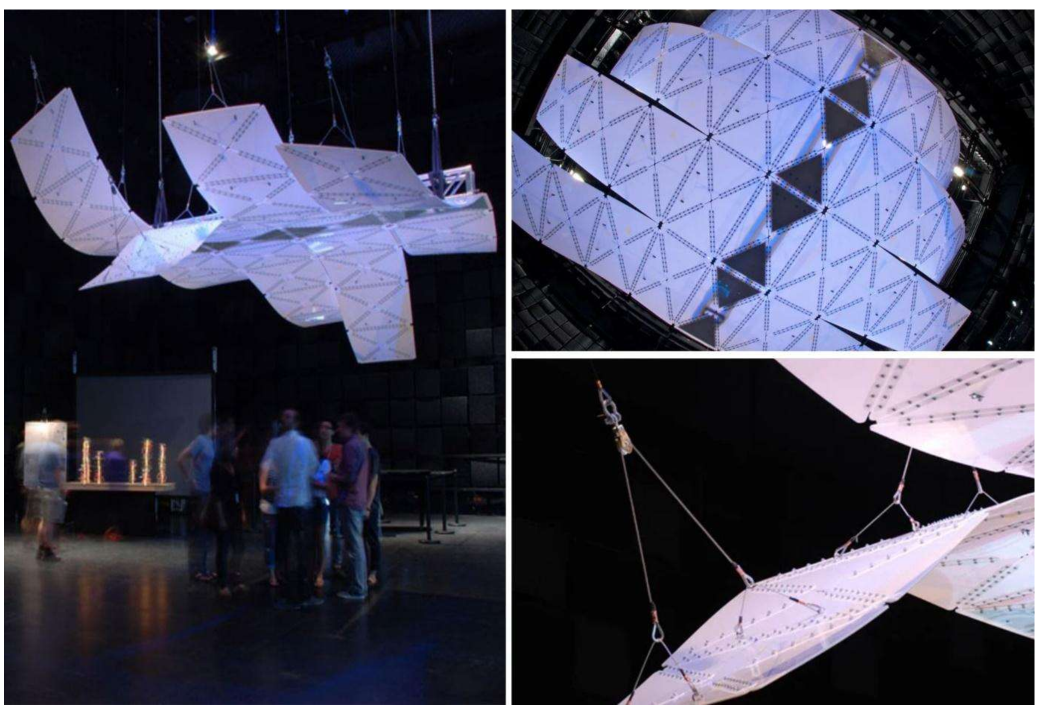

Figure 2.5 : The kinetic sculpture and detailed view of moving arms (© M. Leo Villardi).

Attributed to the impact of the person standing right beneath the structure, the sculpture slowly moves. The goal was to produce a surface that responds to multi-modal input such as sound, stereoscopic vision, multi-touch, and brainwaves by changing its form and therefore acoustic nature (Figure 2.6).

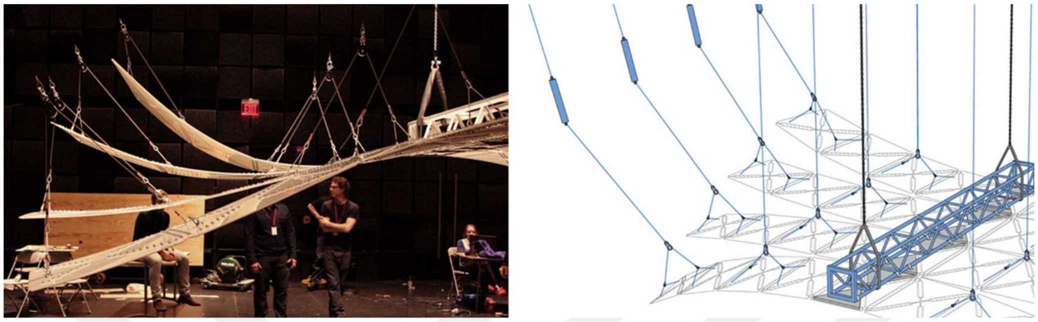

Figure 2.6 : Installation and a detailed perspective picturing the piece's supportive backbone structure. (© M. Leo Villardi).

The project differs from prevalent adaptive acoustic treatments by its approach of progressing acoustic systems beyond specific parts. Manta investigates flexibility and adaptability in the surface itself and provides the corrective treatment.

2.2.3 The hyperboloid responsive acoustic surface - Smartgeometry 2011

The diffuse soundscape discovered within Antonio Gaudi's Sagrada Familia inspired the Smartgeometry 2011 workshop. The soundscape of the basilica lacks the echoes and extended reverberations found in other venues that are made of acoustically reflecting materials such as stone. As a result, the Responsive Acoustic Surfaces project sought fresh insights into the relationship between geometry and sound in the realm of sound scattering.

The theory was that the Sagrada Familia's hyperboloids scattered the sound, limiting audible reverberation. The acoustic characteristics of hyperboloids were investigated using a mix of 1:1 prototypes, 1:10 3D printers, and computer simulations. As a result of research, the hyperboloid wall produced far less audible reverberation than a flat plaster wall. This finding implies that acoustic engineers may manage reverberation not just by reflecting or absorbing sound, but also by constructing geometric patterns that scatter sound (Figure 2.7).

Figure 2.7 : The physical model of Hyperboloid Responsive Acoustic Surface (Burry et al., 2011).

A unique hyperboloid brick was prepared in such a way that it could be assembled in multiple sets to form a semi-circular fragment (Figure 2.8). A duplicate wall of equal size was built from smooth plaster and used as a control for the sound tests. The general geometry of both was a semi-circular fragment. Since sound coming from the acoustic focus is reflected back to the source, any difference in the reflected sound between two walls is immediately perceptible by someone standing in the center of the semi-circle.

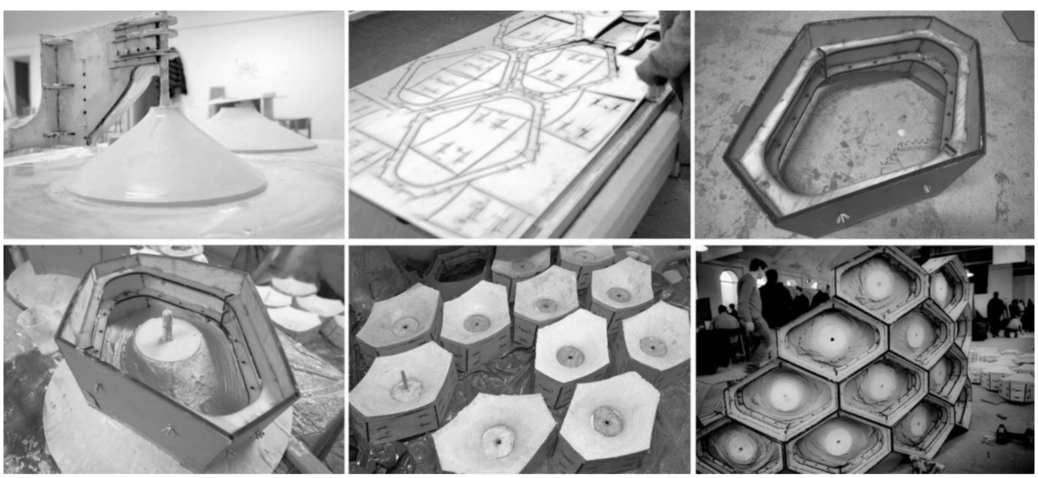

Figure 2.8 : Mould, laser cutting of frame, frame, frame on mold, selection of bricks, assembled wall (Burry et al., 2011).

It is found to be noticeable different acoustic qualities between the smooth and the hyperboloid walls. Hyperboloid produces no perceptible echo, while smooth wall generates a discernible echo. It is explained with the incident sound that is reflected by the hyperboloid geometry in different directions and only a part of the sound returns to the focus point.

As a result of the research, distinct acoustic properties were found related to two different surfaces. Speaking while standing in the acoustic focus of the smooth plaster wall produces a detectable echo, which seems magnified in relation to the fact that the cylindrical shape focuses the reflected sound back to the focal point. On the other hand, speaking from the same location in front of the hyperboloid wall creates no audible echo since the incident sound is reflected in numerous directions by the hyperboloid geometry, and only a fraction of the sound returns to the focus point. The cylindirical shape of the prototype is an approach that is frequently focused on in acoustic studies (Cairoli, 2021a)(Cairoli, 2021b) (Cairoli, 2020). These impressions are consistent with the acoustic measurements of the 1:10 prototypes and the sound scattering visualizations (Figure 2.9).

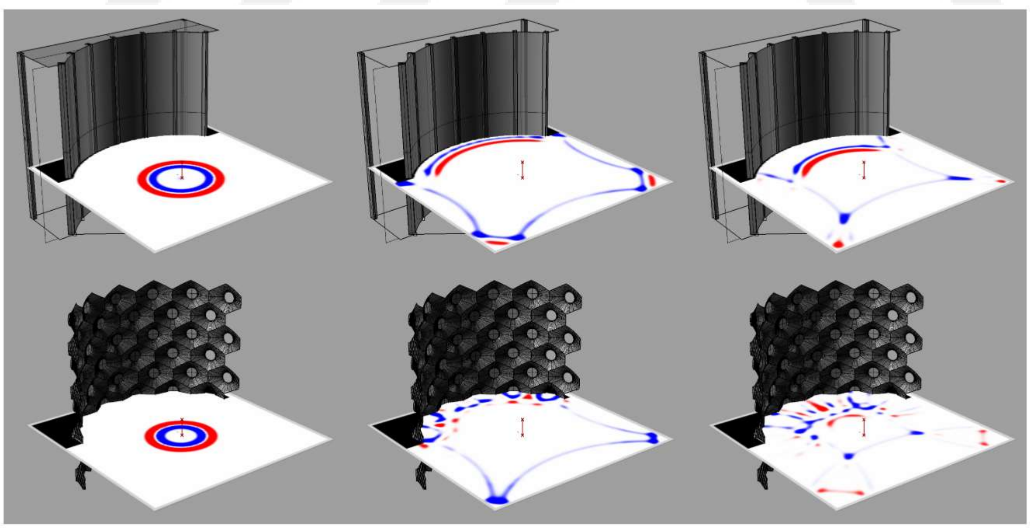

Figure 2.9 : Visualization of Scattering from the smooth wall compared to hyperboloid wall (Burry et al., 2011).

2.2.4 The Distortion 2 Project - CITA, Akustikmiljo, Krydsrum, Acoustica

The Distortion 2 Project is a responsive acoustic surface that was created, manufactured, and tested based on the idea of an auditory experience in open-plan settings. The study shows how, through the specification of geometry and material, a surface can respond to acoustic performance criteria. The surface was created to produce unique auditory effects and the design was simulated using acoustic analysis software Odeon as well as a custom integrated acoustic software.

The study illustrates a way for creating space and sound-defining surfaces. It also introduces the idea of acoustic subspace and proposes new parameters for defining it. The acoustic subspaces were created by defining the material, the amount of enclosure of the wall, and the form of the panels (Figure 2.10).

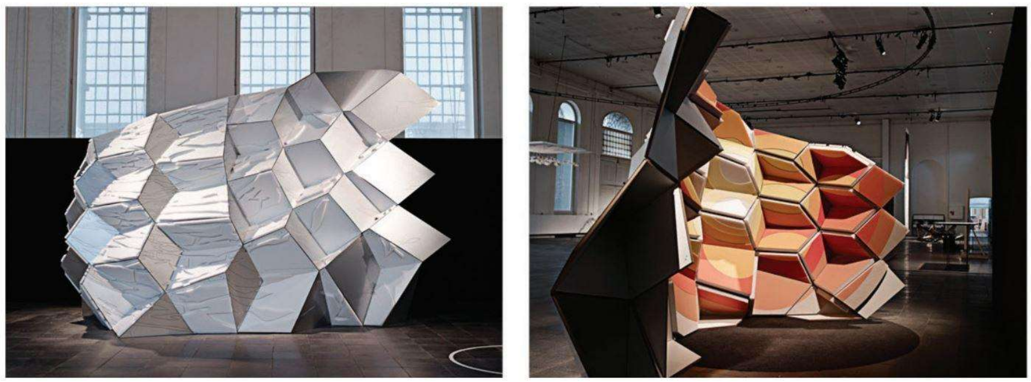

Figure 2.10 : The Distortion 2 Project.

The structure is a continuous, single-layer folded-plate system. This allows the distribution of the structural loads through the surfaces and along the folded seams across three dimensions. In addition to that, different tessellation patterns can achieve different spatial effects, structural conditions, and sonic effects (Moussavi, 2009). The tessellated folded plate components scatter the sound in different directions (Figure 2.11)

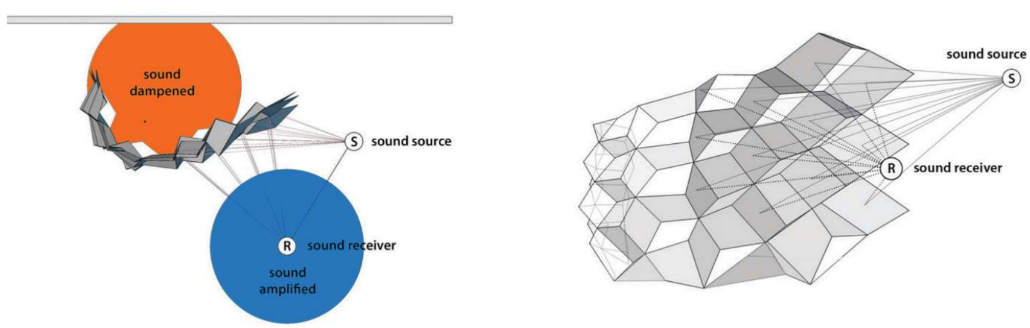

Figure 2.11 : The representation of the acoustic concept.

Table 2.1 shows the intersections and divergences of the Modular Kinetic System Proposal with selected examples from the literature. While the examples generally contain both acoustic and visual transformation, there is also an example that does not create visual action due to its static design. However, the proposal in the thesis study can be mentioned among the extensive examples in the literature, providing both acoustic and visual transformation.

All of the systems in the examples have direct or indirect reflective and absorbing properties either by material selection or by their mobility. The system proposed in the thesis study has both reflective and absorbent properties at the same time thanks to both the material selection and the movement element.

Table 2.1 : Comparison table of Modular Kinetic System Proposal and examples found in the literature.

	Resonant Chamber Origami Architectural Acoustic Panels	**Manta Acoustically Responsive Sculpture**	**The Hyperboloid Responsive Acoustic Surface**	**The Distortion 2 Project**	**Modular Kinetic System Proposal**
Function	● Acoustic transformation ● Sound visualization	● Acoustic transformation ● Sound visualization	● Acoustic transformation	● Acoustic transformation ● Sound visualization	● Acoustic transformation ● Sound visualization
Acoustic Characteristics	● Reflective ● Absorptive	● Reflective ● Absorptive	● Reflective ● Absorptive	● Reflective ● Absorptive	● Reflective ● Absorptive
Location	● Indoor - Ceiling	● Indoor - Ceiling	● Indoor – Wall	● Indoor - Wall	● Indoor - Wall
Shape Defining Concept	● Origami	● Triangulation	● Hyperboloids	● Tetragons	● Hexagons
State	● Kinetic	● Kinetic	● Static	● Static	● Kinetic
Modularity	● Modular	● Modular	● Modular	● Modular	● Modular
Material	● Bamboo ● EPP ● Electroacoustics	● HDPE	● Plaster	● Fibrefloat	● Biodegradable Plastic
Fabrication Method	● Milling	● CNC Routing	● 3D printing ● Laser Cutting ● Plaster Moulding	● Laser cutting ● Knife cutting ● CNC routing ● Metal bending	● 3D printing
Add-ons	● Sensors ● Controls	● Connectors	● None	● None	● Sensors ● Controls

The items with the greatest variation among the headings in the table are seen as shape-defining concepts and material choices. Concepts related to form are diversified as origami, triangulation, hyperboloid, and tetragon, and in the thesis study, the hexagon was studied. While the materials are diversified such as Bamboo, EPP, HDPE, Plaster, and Fiberfloat, the Modular Kinetic System Proposal presented in the thesis uses biodegradable plastic. In addition to that, it is seen from the table that CNC, Laser, and 3D printers are frequently used in fabrication methods. While static samples do not have electromechanical attachments on them, the Resonant Chamber and Manta projects are equipped with sensors, connectors, and control elements. Similarly, the thesis proposal, which is a kinetic system, is equipped with sensors and controls in order to react instantly to ambient sounds.

3. A MODULAR KINETIC SYSTEM ACOUSTIC PANELING

The scenario of the office environment was selected as the indoor location of the problem. The workflow of the system within the area was presented in Figure 3.1.

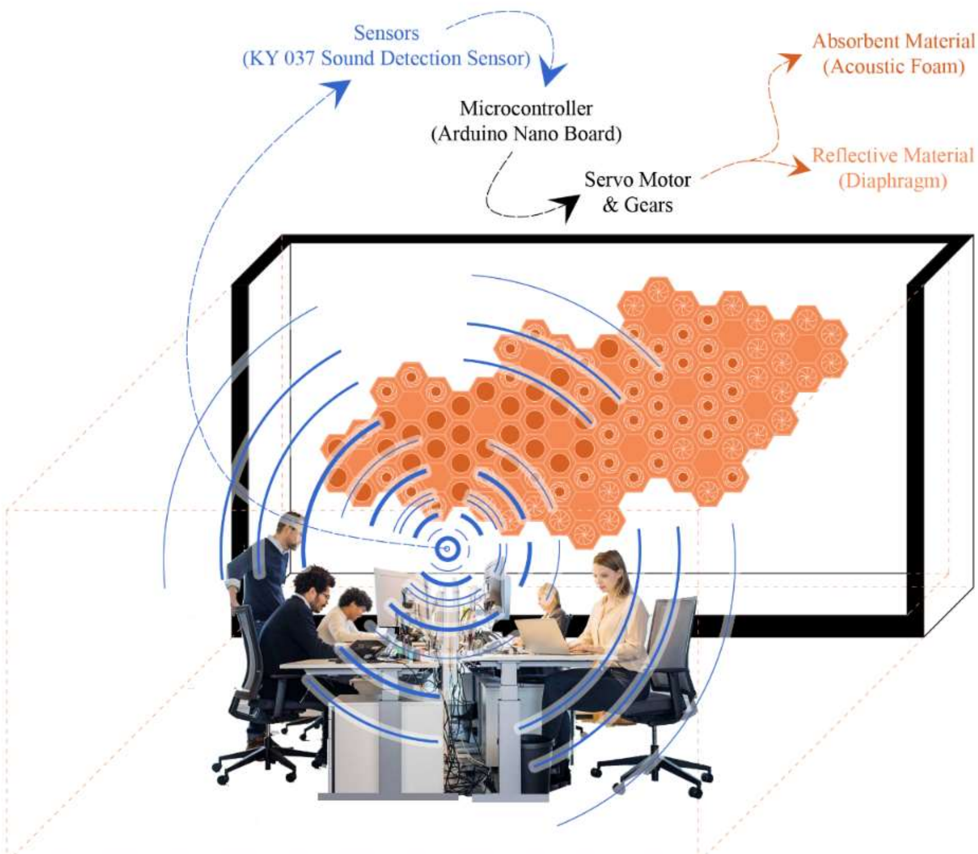

Figure 3.1 : Responsive Environment.

3.1 System Components

System components are presented in Figure 3.2. In the next sections, further explanations were made.

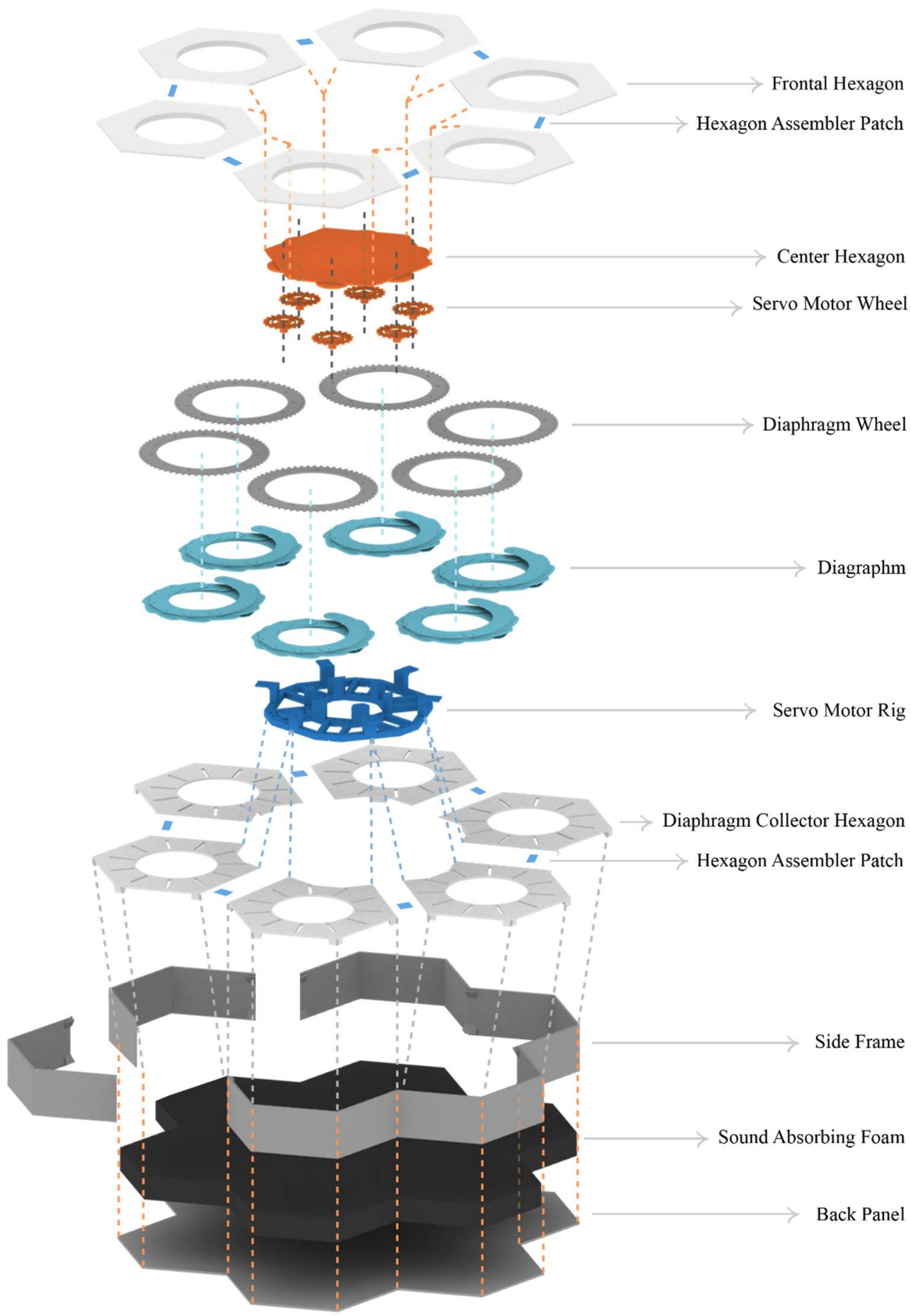

Figure 3.2 : Exploded axonometric system components view of responsive acoustic module proposal.

The module consists of seven hexagons, one located in the center, and the other six are adjacent to each edge of the central hexagon. Dimensions of each hexagon are the same, for the sake of stackability.

For the prototype, every hexagon has a diameter of 21 cm. The diaphragm holes are centered in the hexagons and they have a diameter of 11 cm. The module itself has a width of 56 cm and a height of 54 cm. In order to house the electromechanics and the sound-absorbing material, the modules have a thickness of 13 cm (Figure 3.3). The modules have been modeled with parametric design in mind, thus, all of the modules can be scaled up depending on the environmental needs. This being said, the dimensions of the module are limited within the capabilities of the manufacturing tools capabilities, in this case, the build volume of the 3D printer.

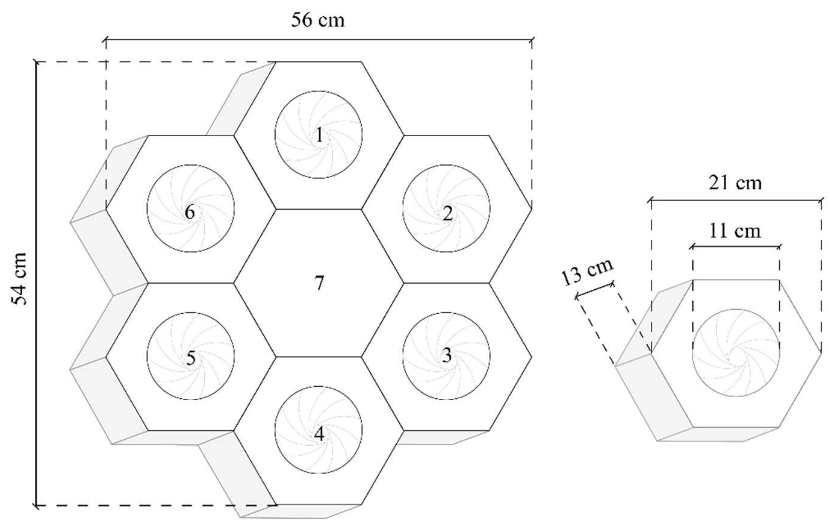

Figure 3.3 : Dimensions of the prototype.

The modularity of the units includes both design, manufacture, and usage scenarios. This aspect of the research can be examined in 3 different topics which are scalability, stackability, and connectivity. For the scalability aspect, as mentioned before, thanks to the parametric design of the modules, modeling software allows the parts to scale up while keeping crucial connection dimensions for the off-the-shelf parts and electronics. Another future goal of this research is to adapt the 3D model parts to the openSCAD platform, in order to increase the accessibility and ease the model modifying process.

Other than the module scale, there is application scalability. The number of modules can be defined according to spatial needs. The stackability aspect comes into play at this point. Each has been designed to have magnet connections on the sides. These magnets allow the modules to connect to each other, not just physically but also transmit power and signal between modules. For each side, there are 3 magnets, which correspond to the positive electrical line, the ground line, and the signal line. This magnet contact method allows tool-less assembly and connection on site. Other than the centralized control, this allows to power all modules from one electrical line, this way, connecting only one of the modules to the electrical grid is sufficient to power all the adjacent modules (Figure 3.4).

Figure 3.4 : Render of a group of responsive acoustic modules in an office environment.

This hive-like connection allows unified control across modules, and in future developments, it can be connected to the internet to collect acoustic metrics and also allows the modules to be controlled with internet-connected devices

Because each module has its load-bearing structure, modules can be stacked on top of each other. This allows the modules to be used as a wall, for separating spaces while providing acoustic insulation.

3.1.1 Frontal hexagonal piece

Frontal hexagons are the pieces of the system that faces the user. The main shape has been decided to be a hexagon, to minimize the reflective area and maximize the diaphragm holes in order to have the maximized sound absorption if needed. The diaphragm hole/hexagon surface ratio is also crucial to have enough space for the diaphragm leaves to retract. All of these parameters were kept in mind while determining the dimensions of the frontal hexagon as well as the print size of the 3D printers that the modules are manufactured (Figure 3.5). Due to the nature of 3D printing, panels are optimized to be printed front-face facing to the build plate to have a smooth surface finish. Details will be given about this process in the manufacturing process section.

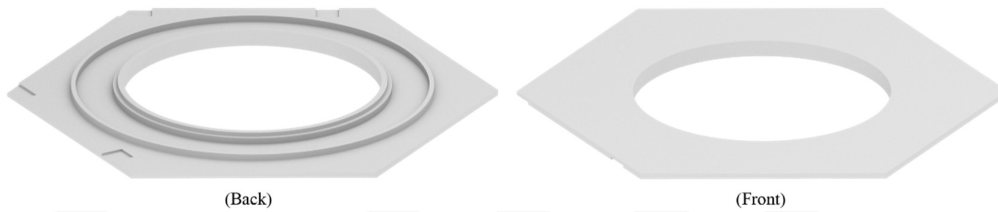

Figure 3.5 : Back and front views from a unit of the frontal hexagon.

Another key part of the Front Hexagon is the rail of the diaphragm wheel. The purpose of the rail is to house and guide the wheel while it turns to move the leaves. The rail keeps the wheel centered while the first and the secondary ring minimizes the touched surface, in order to keep the surface friction between the diaphragm wheel and the front hexagon. In addition to that, the rail and the rings are lightly sanded and then coated with lacquer during the after-print process which will also be detailed in the manufacturing process section.

For ease of alignment, cavities are added to the adjacent panels. While in the assembly process, panels are aligned using these cavities. For added stability, hexagon assembler patches are fixed in these cavities with a cyanoacrylate adhesive. This method both eases the assembly process by acting as a guide and adds rigidity to the panel joints. (Figure 3.6). A similar method is used while fixing the frontal hexagons to the central hexagon with the help of servo rig legs, which will be detailed in the next part.

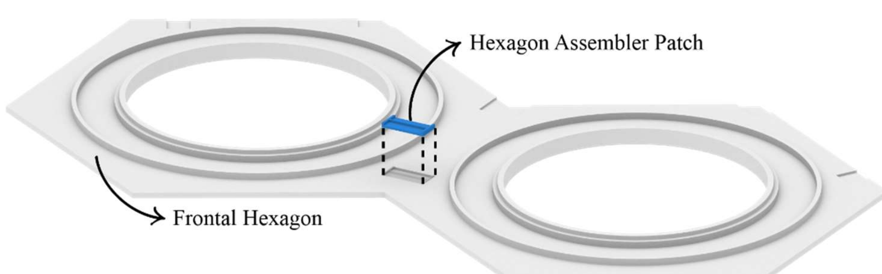

Figure 3.6 : Assembly of two frontal hexagons.

3.1.2 Central hexagonal piece

The central hexagon is the middle part of the module. It connects front hexagon panels, holds servo gears, and houses the electronics, such as servos and a microcontroller.

Due to the hexagonal shape, six servo gear fixers are placed on the six edges of the panel (Figure 3.7). Similar to the rail of the diaphragm wheel, it has 2 rings in order to minimize surface to surface friction. Cylindrical extrusion in the middle of each gear fixer goes in freely into the servo gears, in order to keep them aligned and give the gears a fixed center of rotation. These gears are screwed to the servo heads prior to being attached to the cylinders.

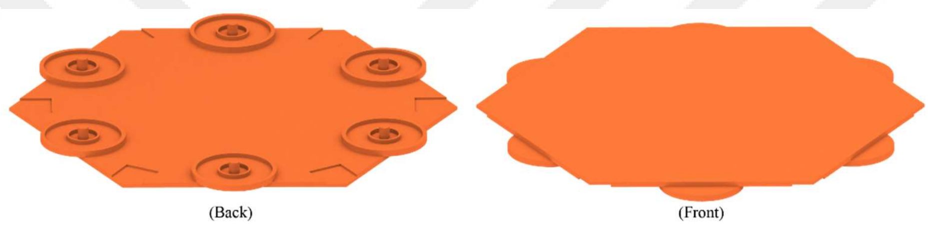

Figure 3.7 : Back and front views of a central hexagon.

There are also corresponding cavities on each side of the center hexagon for the servo legs in order to align and fix the front hexagon panels. Legs are fixed in the cavities using the plastic welding method for them to uniformly bind the panels and the legs.

Asides from connecting the front hexagons together, the main function of the central hexagon is to house electronics and a kinematics system, which consists of a microcontroller, servos, and gears with the help of the servo rig. Due to the needed space that is occupied by servos and gears, the central hexagon serves as a service space for the electromechanical components.

The flat front surface of the panel can behave as a sound-reflecting surface as is, due to material selection and surface geometry. However, this surface area is open to possibilities for sound scattering and sound-absorbing material and or geometry experiments. Adding different shaped panels is considered for future research developments.

3.1.3 Servo motor wheels and diaphragm wheels

The servos are the main actuators for the whole system. In order to increase the range of motion on the diaphragm, the translation rate of the movement has been optimized. This is achieved by increasing the radius of the servo gear. (Figure 3.8).

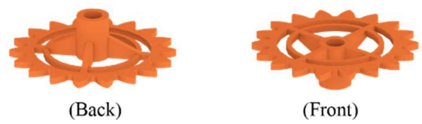

Figure 3.8 : Back and front views of a servo motor wheel.

Gear models are generated in Rhinoceros with the help of the Grasshopper plugin. These calculations ensure that gears are compatible and in sync. It is also another benefit of the CAD process that, the range of motion can be simulated prior to any physical manufacturing thus, lowering the research costs while saving time.

After setting the gear ratio for both servo gear and diaphragm wheel, appropriate fixing geometry has been added to the servo gears. To reduce weight, material usage, and surface friction, gears are designed around a light carcass, while allowing it to be screwed into the servo head, with the help of a metric 2 bolt. The bolt hole doubles as a guide, which is then put on top of the cylindrical extrusions on the central hexagon. The diaphragm wheel is also generated in the Grasshopper. It has eleven holes, in 4mm diameter, which is used to secure one of the ends of the diaphragm leaves (Figure 3.9).

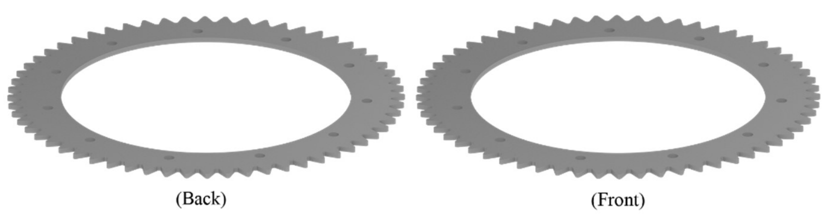

Figure 3.9 : Back and front views of a diaphragm wheel.

The diaphragm wheel goes on top of the front hexagon wheel, which rotates freely on a predetermined axis. To reduce friction between the ring surface and the wheel, both parts are sanded down prior to installation (Figure 3.10).

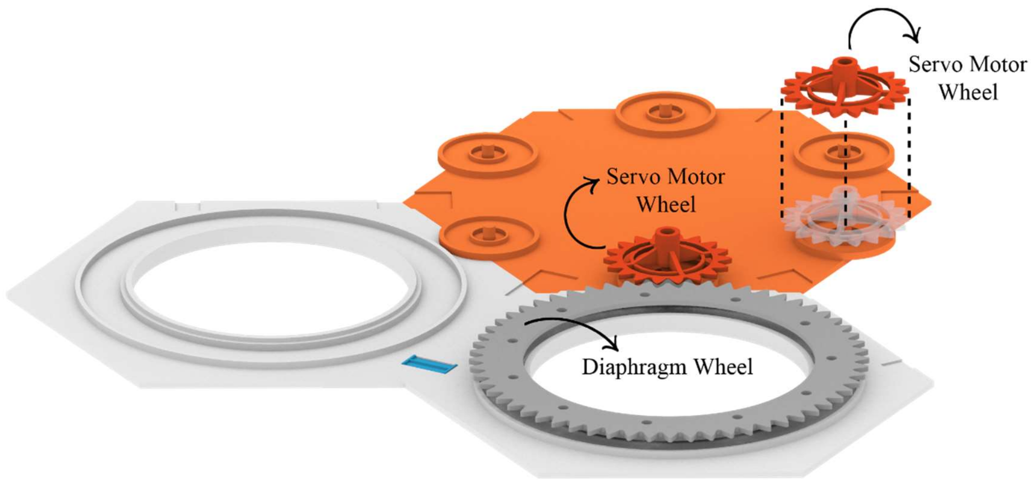

Figure 3.10 : Assembly of servo motor wheel and diaphragm wheel.

Before assembly, servos are zeroed to maximize the range of motion. Leaves are set in a normally open position so when and if the system is powered down, it will have the maximum noise-absorbing level.

3.1.4 Servo motor rig

As mentioned before, the whole kinematic system is based on servo movement, so placement and the fixation of the servos have crucial importance. In order to achieve a reliable installation, a custom servo holder is designed in Sketchup.

Existing measurements of the servos were taken by calipers and then recreated in a CAD environment. With the help of this digital representation, a fitting servo holder has been designed digitally (Figure 3.11). Arraying the said servo holder, based on the center of the center hexagon, a servo rig is created.

For ease of access and maintenance to the servos, motors are screwed onto the servo rig, using metric 3 bolts and nuts. This allows repairing or swapping the servos if needed.

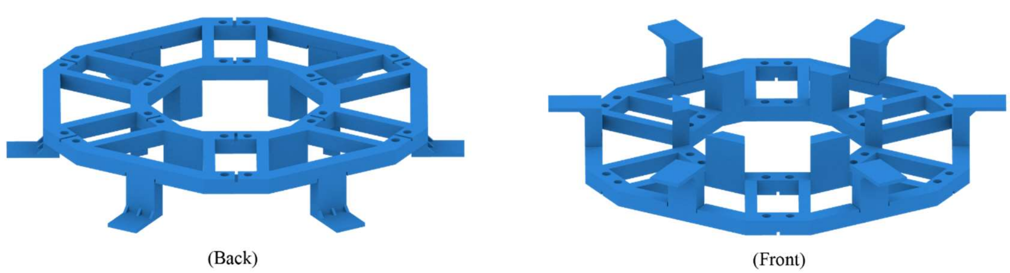

Figure 3.11 : Back and front views of servo motor rig.

After the installation of gears and motors, the servo rig is placed on the central hexagon (Figure 3.12).

The alignment cavities on the central hexagon ensure that the rig is in the right place. After the alignment, the rig is fixed on the plate with superglue and plastic friction welding technique.

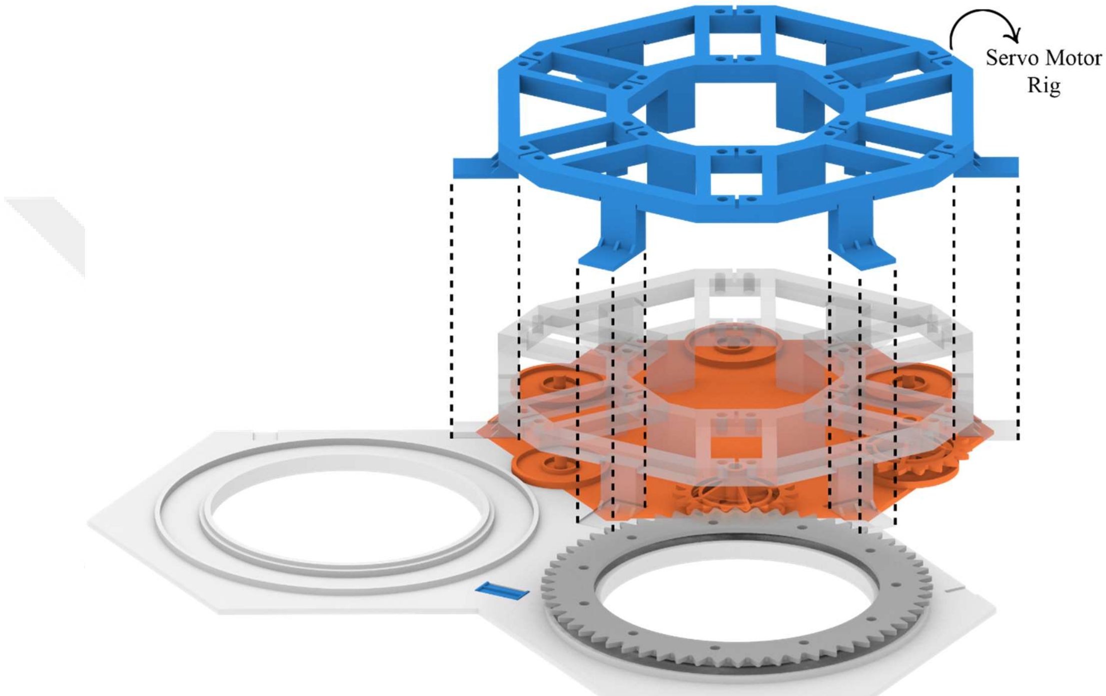

Figure 3.12 : Assembly of a servo motor rig.

3.1.5 Diaphragm and diaphragm collector hexagonal piece

Diaphragm leaves are the parts that block the sound waves from passing through to the sound-absorbing back panel. The angle and position of the leaves determine the gap of the diaphragm hole (Figure 3.13).

To optimize the production of these leaves, in early experiments, they were cut from 0.5mm sheet PETG material. Initial trials showed that PETG when in form of extruded sheet material, lacks the rigidity needed in this application. When applied pressure, instead of doing the desired motion, leaves were subjected to torsion and jammed the system, because the material was twisted instead of turning from the rotational axis.

After these experiments, it was decided to try 3D printing the leaves with PETG material, which is in 3d printing filament form.

Due to the nature of additive manufacturing, different directional layer overlay helps with the rigidity of the leaves, with this added benefit, the leaf design was modified to be fabricated by a 3D printer. To minimize the material, 3D printing time, and post-processing time, leaves were designed to be printed flat on the print bed.

Figure 3.13 : Back and front views of a diaphragm leaf.

Leaves both rotate and move, according to the guides set by the diaphragm collector hexagon. This mechanical design and choice of 3D printing technology presented a design challenge because leaves should have been able to connect to the upper and lower disks. This design challenge has been overcome in the post-processing section, by fixing a piece of 3D printer filament to one of the ends of the leaves, while 3D printing the other extrusion.

While modeling this revised leaf design, a hole in 3mm diameter has been added to the design at the opposite end of the extrusion. This was done in order to ease the process of attaching and fixating the 3D printer filament to the leaves. In order to achieve desired diaphragm leaf movement, collector hexagon modules were designed (Figure 3.14).

The extrusion on the leaves, is positioned in the slots of the collector hexagon, allows them to move only in a predetermined path while allowing them to rotate freely on the extrusion axis.

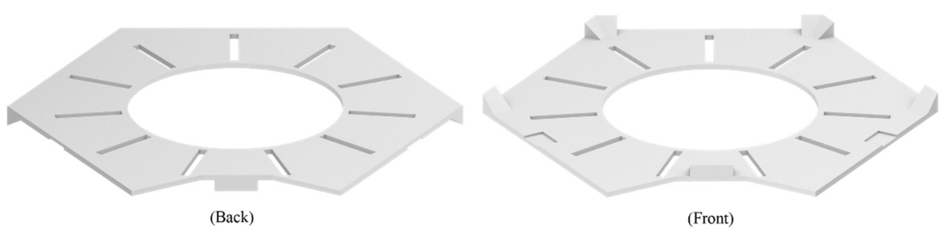

Figure 3.14 : Back and front views of a diaphragm collector hexagon.

Pyramid-like extrusions are added to the edges of the hexagon plate, considering the installment process. Added surface area increases the stability of joint detail, whether it is superglued or friction welded. It also helps to align side panels parallel to the edges of the collector hexagon. Similar to the front panels, cavities are added to the diaphragm collector hexagon, which helps the aligning process of the panels (Figure 3.15). Adding a hexagon assembler patch to the said cavities enables the systems to have added stability, durability, and rigidity to the whole electro-mechanical system.

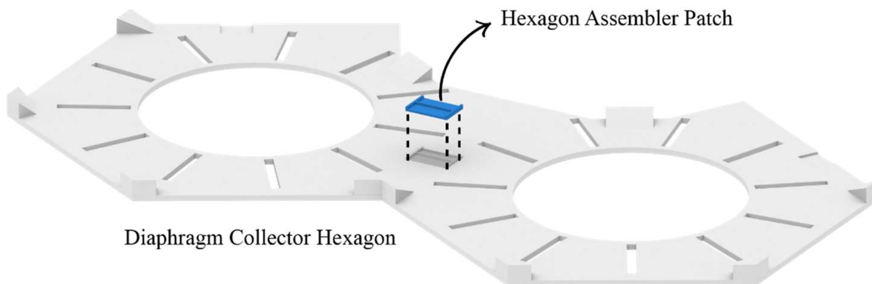

Figure 3.15 : Assembly of two diaphragm collector hexagons.

Diaphragm leaves are assembled between the diaphragm wheel and the diaphragm collector hexagon (Figure 3.16). Extrusions on both ends of the leaves are carefully placed into the corresponding holes. 3D printed, washer-like pieces are 3D printed before the assembly and post-processed, hole diameters are rebored and surfaces are sanded down, for ease of installment. These 3D printed washers are placed upon the extrusions after placing them thru the holes, then heat-welded into the extrusions.

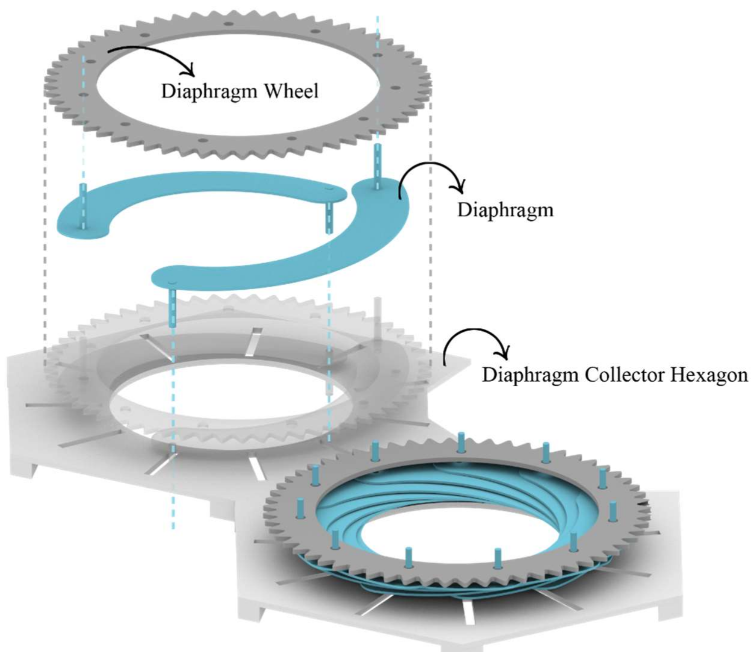

Figure 3.16 : Assembly of two diaphragm leaves.

3.1.6 Sound absorbing foam and back panel

Polyurethane foam sound-absorbing material is used for this research as the sound-absorbing material. Pyramid-shaped generic acoustic foam panels are placed in the back of the electromechanical system. This foam also works as a noise absorber for the sound generated from the servo, gear, and leaf movement (Figure 3.17).

Laser-cut acrylic panels are used as the back panel of the system. This way, the system is more like an all in one-panel solution rather than a DIY research project.

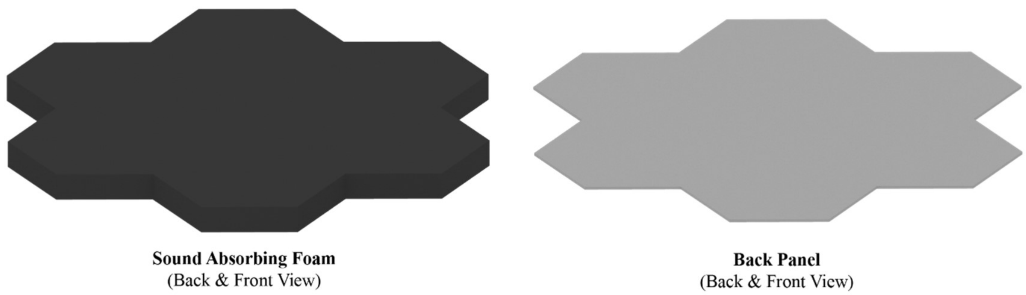

Figure 3.17 : Sound absorbing foam and back panel.

3.1.7 Side frame

Side frame parts are designed to keep the layered kinematics systems in place. These parts are the only ones that have been 3d printed with support structures, because of the overhangs on the assembly teeth (Figure 3.18).

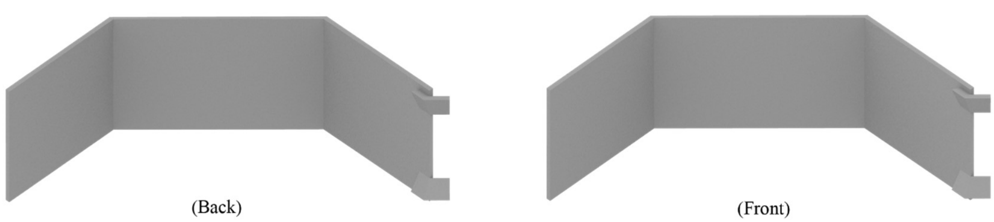

Figure 3.18 : Back and front views from side frame.

3.1.8 Sensors

Sound level measuring Arduino compatible sensors are used in this research, in order to measure the environmental noise as data, for Arduino to process and react accordingly. The KY-037 sensor has the capabilities of giving both analog and digital outputs (Figure 3.19). The digital output option works as a two-state switch. Users can define a sound threshold by using the blue potentiometer, an adjustable resistance, as a numerical value. The sensor reads electric signals from its piezo microphone and processes this value, then compares it with the potentiometer threshold value. If the read value is more than the threshold, it sends a positive value to the Arduino. On the other hand, if the value is lower, it sends a negative value to the microcontroller. For this research, a two-state approach is not suitable, since the adaptive system needs in-between values for leaves to adjust to the environmental noise.

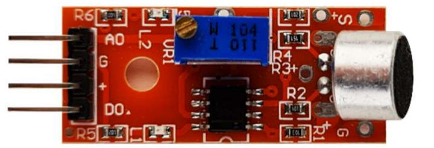

Figure 3.19 : KY-037 Sound Intensity Sensor.

The analog read function of this sensor is used in this research in order to have the noise values as a wider spectrum. This value is sent to the microcontroller, using a wire from the A0 pin. In Arduino, this value is then used in the algorithm as a variable and the servo positions are adjusted to this calculation.

3.1.9 Microcontroller

Arduino Nano board is used in this research as the sensor value processor and also for motor control. Values taken from the sound sensor are processed and mapped to the corresponding servo motors, as a form of turning value in degrees. A hand-soldered pertinax board is used to organize the power and signal cables, for both servos and sensors (Figure 3.20). The Pertinax board also allows power distribution to the necessary components. Header pins are used in order to easily attach Arduino boards, servo connectors, sensor connectors, and power cables. This way, if any of the components get damaged or needs adjustment, that said component can be easily removed and replaced without disturbing any other components.

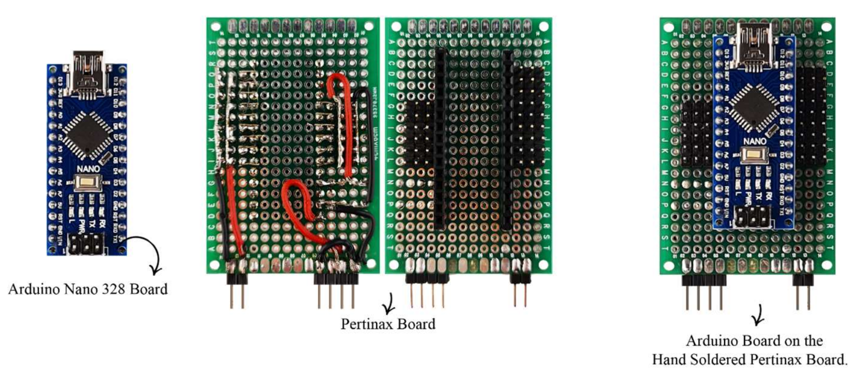

Figure 3.20 : Arduino Nano 328 Board and Hand Soldered Pertinax Board.

3.1.10 Kinematics

The main movement source for the modules is the electric motors (Figure 3.21). Complemented with the gears, these motors allow the system to be adaptive. Electric servo motors are used rather than the traditional brushed, continuously rotating motors, in order to have exact rotational value implemented on the system.

Durability, working noise level, working voltage, torque, unit cost, and weight parameters are the defining properties of this servo selection. MG995 Servos are used in this study, in regard to their properties.

Figure 3.21 : MG995 Metal Gear 6V Servo Motor.

It was also possible to use Step motors regarding the controlling accuracy, but compared to the step motors, servo motors were 7 times more affordable. Also due to their kinematic nature, a step motor that would do the same job in this system would weigh (1200gr) 21 times more than the servo that was used (55gr) in this project. Considering each module has 6 motors, the collective weight would be 7000 grams more if step motors were to be used, instead of the servo motors, of which all six of them only weigh 330 grams.

MG995 has metal gears inside, hence the name, which is used to transfer the movement into the servo head from the inner electric motor. Metal gears sustain more torque, relative to the plastic alternatives, which can be seen in the cheaper models. Also, well-greased metal gears and metal ball bearings reduce friction between internal servo motor parts, causing them to make a lot less sound, which lowers the initial system noise, generated while the system works.

MG995 servo motor's working voltage is between 4.8 and 7.2 volts. As instructed in the manufacturer's spec sheet, this servo performs best, in the means of torque and lifespan, when supplied with 6 volts. Each motor draws about 1,5 ampers while under load. In order to supply this constant voltage and amper, a step-down voltage converter has been used with the power supply, which will be going to be detailed in the Signal and Power Management section.

It is also notable that the shape of the servo motor and the position of the servo head is the most suitable for this application, due to the low profile design and ease of access to the rotational center. The limited rotation angle can be counted as the only downside for MG995 can be listed as This model has the mobility of 120 degrees, which was limiting the range of the diaphragm motion, in the initial system design. This problem has been overcome with the gear ratios. In order to increase the range of motion on the diaphragm, the translation rate of the movement has been optimized. This is achieved by increasing the radius of the servo gear.

3.1.11 Signal and power management

A laptop power adapter is used to supply the needed wattage to the system. Incoming 19 Volts from the adapter, needs to be converted into 6 volts to supply the servos without damaging the electronics. The internal voltage regulator of the Arduino board is used to step down the supplied 19 volts into 5 Volts to power the sensors and the Arduino itself. An external Voltage regulator, LM2596 in this case, was used to step down the supplied 19 volts into 6 Volts, for servo motors to use (Figure 3.22).

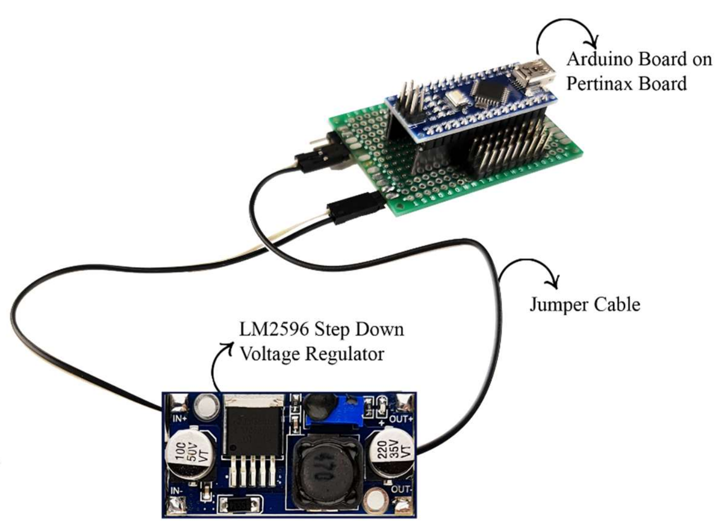

Figure 3.22 : LM2596 Step-Down Voltage Regulator.

3.2 Algorithm for the Impulse and Response of Sound

The code for the Arduino Nano board is written and then compiled on Arduino IDE. Servo code libraries are used as a package in order to reduce the amount of code written by hand. Servo library (<servo.h>) has been imported at the beginning of the coding. This allows the system to use pre-written and tested servo controlling algorithms, thus easing the process of writing servo control code and reducing problematic aspects of the data. Mainly, the system reads the values sent from the sound sensors and maps these values to the corresponding servo motor in order to turn and adapt the diaphragm gap. Averaging algorithms are used to discard the possible misreadings from the sensors. In addition to that, smoothing algorithms are used to slow down the sensor motor movements, which leads to lesser noise generated by the system's moving parts including servos, leaves, and gears (Figure 3.23).

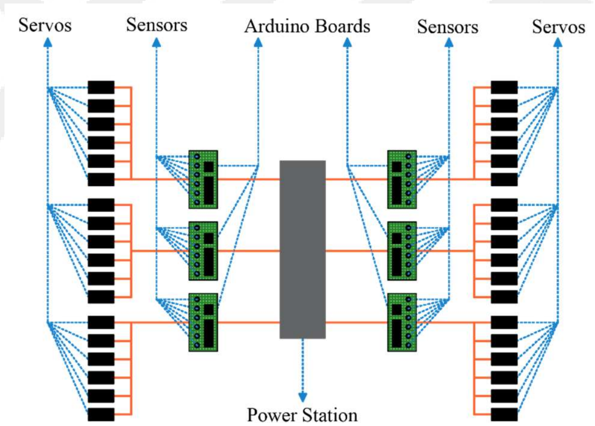

Figure 3.23 : Noise Response Elements Scheme.

At the starting of the assembling process, servos are rotated in their zero degree point with an additional zeroing code (Figure 24).

After implementing the servo library, each servo motor in the system (6 pieces for this example) is named as initials of "Servo Motor" and then a consecutive number is added, which results in names as sm1, sm2, sm3, sm4, sm5, and sm6.

Zeroing value has been individually assigned to each servo. Due to the slight manufacturing inconsistencies in the servos, each servo needs a correction offset when zeroing the gear and servo head positions. Zeroing values are then assigned to the servos and servo heads turn, as servo gears are fixed in the position where they fit together with the diaphragm wheel. After everything is fixed in place, the Arduino board is powered down. Completing this process, code is revised and re-uploaded to the Arduino, for the system to work with the sensor values, as intended.

```
thesis_code_zeroing
#include <Servo.h> ////servo motor library

Servo sm1; //servo motor no:1
Servo sm2; //servo motor no:2
Servo sm3; //servo motor no:3
Servo sm4; //servo motor no:4
Servo sm5; //servo motor no:5
Servo sm6; //servo motor no:6

int zeroing_val1=0; //zeroing_value
int zeroing_val2=0; //zeroing_value
int zeroing_val3=3; //zeroing_value
int zeroing_val4=0; //zeroing_value
int zeroing_val5=2; //zeroing_value
int zeroing_val6=0; //zeroing_value

void setup ()
{Serial.begin (9600);
  sm1.attach (2); // attaching servos to th corresponding pins
  sm2.attach (3);
  sm3.attach (4);
  sm4.attach (5);
  sm5.attach (11);
  sm6.attach (12);
  }
  void loop ()
  {
   sm1.write(zeroing_val1);
   sm2.write(zeroing_val2);
   sm3.write(zeroing_val3);
   sm4.write(zeroing_val4);
   sm5.write(zeroing_val5);
   sm6.write(zeroing_val6);

   delay(150); // added delay to avoid jam
   }
Done compiling.
```

Figure 3.24 : Zeroing Code.

The sound adaptive code differs from the zeroing code in a way that variables are based on the sound sensor values. Sensors are attached to the Arduino Nano board pins that have analog read capability. Just like servo motors, sensor attachments are defined in the code with their initials and consecutive numbers. “Sound Sensor Value” is shortened as; ssv1, ssv2, ssv3, ssv4, ssv5, ssv6. Thereafter the definition of the sensors in the code, each value is assigned to the sensor readings from the corresponding analog pin. This way, in every code loop, ssv variables are equalized to the values that are read from the sound sensors. This allows the system to accurately measure the noise level in the middle of each hexagon, thus adapting its opening accordingly.

After successfully reading the sound data and assigning it to the ssv variables, these values are mapped. This action is needed because of the value range difference between the servo rotation value of 0 to 120 degrees and the sound sensor value which is between 0 to 1024. The map function is used in order to manage this range difference. 1024 value from sensor reading is mapped to 120 degrees so that the maximum amount of noise will have the maximum amount of diaphragm gap. After the mapping, ssv values are re-written with the mapped value.

This new mapped value is then written into the corresponding servo angle degree value. This way, diaphragm gaps are arranged according to the noise value that they are subjected to. With all servos rearranged, a delay function has been added to the code just before the code loop ends. Servo motors do give feedback to the microcontroller so that Arduino knows the exact angular position of the servo head. This feedback sometimes causes loop errors, if another move order has been given to the servo before it can execute the previous order. A 150 ms delay allows servos to travel to the desired angle degree, thus preventing the code from loop error (Figure 3.25). After this delay, the whole read-map-servowrite-delay repeats until the system is powered down.

```
thesis_code
#include <Servo.h> ////servo motor library

Servo sm1; //servo motor no:1
Servo sm2; //servo motor no:2
Servo sm3; //servo motor no:3
Servo sm4; //servo motor no:4
Servo sm5; //servo motor no:5
Servo sm6; //servo motor no:6

int ssv1; //Sound sensor no:1 value
int ssv2; //Sound sensor no:2 value
int ssv3; //Sound sensor no:3 value
int ssv4; //Sound sensor no:4 value
int ssv5; //Sound sensor no:5 value
int ssv6; //Sound sensor no:6 value

void setup ()
{
  Serial.begin (9600);
  sm1.attach (2); // attaching servos to th corresponding pins
  sm2.attach (3);
  sm3.attach (4);
  sm4.attach (5);
  sm5.attach (11);
  sm6.attach (12);

  }

  void loop ()
  {
   ssv1 = analogRead(2); // reading sensor values from the sound sensors
   ssv2 = analogRead(3);
   ssv3 = analogRead(4);
   ssv4 = analogRead(5);
   ssv5 = analogRead(11);
   ssv6 = analogRead(12);

   ssv1 = map(ssv1, 20, 1023, 15, 120); //mapping sensor values into motor movement
   sm1.write(ssv1);

   ssv2 = map(ssv2, 20, 1023, 15, 120);
   sm2.write(ssv2);

   ssv3 = map(ssv3, 20, 1023, 15, 120);
   sm3.write(ssv3);

   ssv4 = map(ssv4, 20, 1023, 15, 120);
   sm4.write(ssv4);

   ssv5 = map(ssv5, 20, 1023, 15, 120);
   sm5.write(ssv5);

   ssv6 = map(ssv6, 20, 1023, 15, 120);
   sm6.write(ssv6);

   delay(150); // added delay to avoid jams


    }

Done compiling.
```

Figure 3.25 : Responsive System Code.

When the system is in its inactive state, the leaves are closed. This state results in the sound waves not being able to reach the sound-absorbing foam, and sound waves can only interact with the front of the module, the surface of the module acts as a sound-reflecting surface. When the system is activated, leaves are repositioned according to the noise level in the environment. The noise sensors in the middle of the diaphragms constantly measure the noise level that reaches them. Each sound sensor is placed in the center of the diaphragms, in between the front and back panels. The sensor value is then processed thru the algorithm in the microcontroller. This process lets the sensor value to be corrected and smoothed (Figure 3.26).

```
#include <Servo.h> ////servo motor library

Servo sm1; //servo motor no:1
Servo sm2; //servo motor no:2
Servo sm3; //servo motor no:3
Servo sm4; //servo motor no:4
Servo sm5; //servo motor no:5
Servo sm6; //servo motor no:6

int ssv1; //Sound sensor no:1 value
int ssv2; //Sound sensor no:2 value
int ssv3; //Sound sensor no:3 value
int ssv4; //Sound sensor no:4 value
int ssv5; //Sound sensor no:5 value
int ssv6; //Sound sensor no:6 value

void setup ()
{
  Serial.begin (9600);
  sm1.attach (2); // attaching servos to th corresponding pins
  sm2.attach (3);
  sm3.attach (4);
  sm4.attach (5);
  sm5.attach (11);
  sm6.attach (12);

  }
```

Figure 3.26 : Defining servos and variables in the code.

The smoothing algorithm is written in two parts. Normally, the used sound sensor outputs data between 0 to 1024 units. The sensor is set to read value every 100 milliseconds. First, initial readings have been made in a silent environment in order to determine the sensor offset. The level of “silent” noise level is measured as 20 dB in the test environment. Other than the environmental noise, sensor offset is also considered in the zeroing algorithm.

This sensor offset value is the value that the sensor puts out, even though there isn’t any detectable noise. This is caused by the analog interface of the sensor and is also affected by the fluctuations in the electrical grid. Initial readings show that environmental factors and electrical current fluctuations in Kasımpaşa - Taksim region in Turkey, causes a sinus waveform of readings between 0 to 256. With this measurement in mind, the algorithm is set to map, any sensor reading that is lower than 256 units, to the value of 256 units. This mapping ensures that in a no-noise environment, the sensor value is stays corrected, even though there are value corrupting factors. For the maximum noise value, 80 decibels of noise level have been measured with a decibel meter and the observed value is noted down as the maximum viable noise factor. This 80-decibel noise level is measured as 650 units in the sound sensor, based on this, any value that is measured bigger than 650 units is mapped to 650. With this second mapping algorithm, the sound sensor value changes between 256 to 650 units. This range of 394 units is then mapped to servo movements, which range from 0 to 180 degrees.

In order to smooth out the sudden changes in the noise level, an averaging algorithm is used. This algorithm takes the first ten of the mapped readings and divides the sum of those reading into ten, in order to calculate the average of one second of the noise level (Figure 3.27).

```
void loop ()
{
  total = total - readings[readIndex];

  readings[readIndex] = analogRead(inputPin);      //sensor read

  total = total + readings[readIndex];

  readIndex = readIndex + 1;


  if (readIndex >= numReadings) {

    readIndex = 0;
  }


  average = total / (numReadings);

  if (average <= 232)
  {
    average = 232;
  }
  else if (average >= 600)
  {
    average = 600;
  }
  else
  {
    average = average;
  }
  Serial.println(average);

  int average = analogRead(0);
  average = map(average, 232, 600, 0, 180);
```

Figure 3.27 : Smoothing Algorithm.

The average value is then written as the servo value. The respective servo motor turns according to this value, closing or opening the diaphragm, depending on the calculated noise average (Figure 3.28).

```
    sm1.write(average);
    sm2.write(average);
    sm3.write(average);
    sm4.write(average);
    sm5.write(average);
    sm6.write(average);

    Serial.println(average);
    delay(100);


    // delay(150); // added delay to avoid jam
  }
```

Figure 3.28 : Controlling servos.

In this working mechanism, if the noise level arises in the environment, the opening of the diaphragms widens, allowing more soundwaves to pass thru and be absorbed by the acoustic foam inside the module. Considering the used algorithm, it can be said that the modules works best in the noise levels between 20dB and 80dB noise levels.

3.3 Assembly and Operation of Prototype

Soldering, 3D Printing, Plastic Welding, Sanding, Laquer coating are the techniques used during the manufacturing process.

Parts of the systems are designed in Rhinoceros 6 3D modeling software. Hexagon geometry has been chosen for several reasons, such as stack abilities of the geometry and the ratio of the diaphragm gap to solid surface ratio optimization. First of, for the diaphragm gap to solid surface ratio optimization, due to the designed iris mechanism, the main gap is in a circle shape. This calls for the surface outline to be a polygon in order to maximize the gap area and minimize the solid surface area. Pentagon, Hexagon, and Octagon geometries have been considered respectively to this ratio requirement. In a pentagon array, it would require additional geometries, such as tetragons as filler pieces, to form a continuous surface.

The system has been designed to be modular. It consists of six frontal hexagons and a central hexagon. The front-facing side of the panels is covered with a wood sheet in order to reduce the reflected sound waves, meanwhile giving a warmer look for interior design purposes.

The main structure is built upon the front panels with supporting side panels. As shown previously, the layered design of the panels lets multiple moving parts operate freely in a limited space. The leaves both turn and slide in the predefined rails in the system, this way, they contract and retract in order to control the diaphragm gap, which regulates the amount of sound waves that pass to the back of the system. At the back of this electro-mechanical system, there lies the sound-absorbing material. The PU sound-absorbing material's main function is to absorb the sound waves that pass through the diaphragm gap. That being said, the PU sound-absorbing material also helps to reduce the mechanical noise that is being generated from the mechanism and the servo motors.

The end product and a detailed shot are presented in Figure 3.29, Figure 3.30, Figure 3.31 and Figure 3.32.

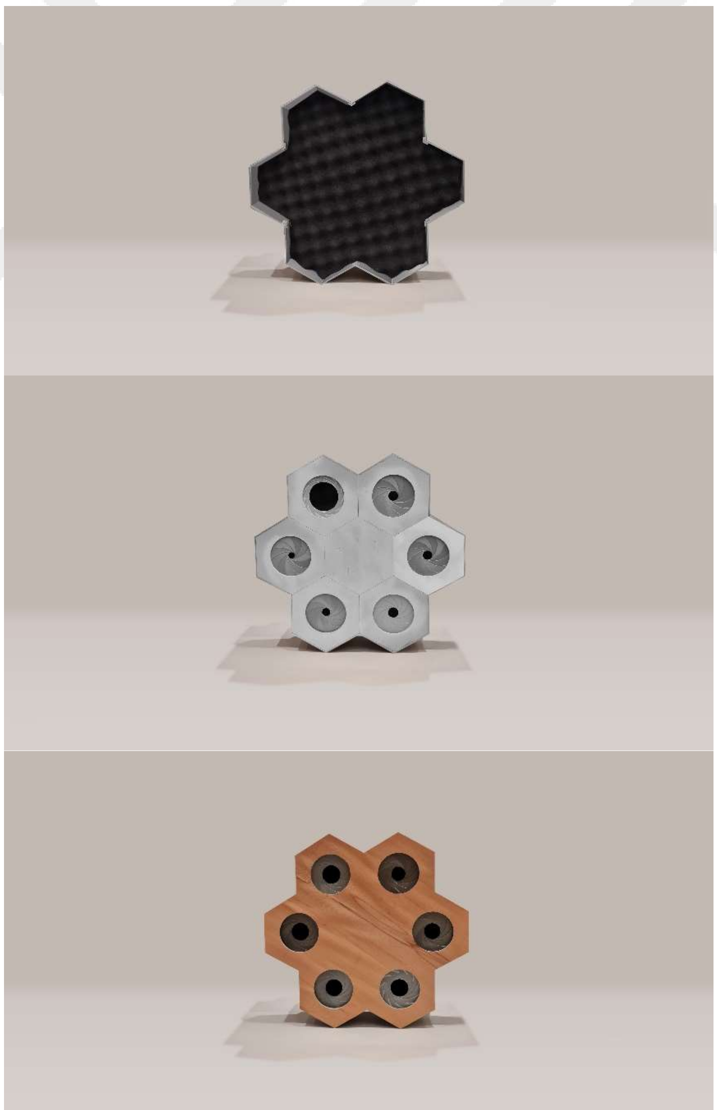

Figure 3.29 : Layers of the units.

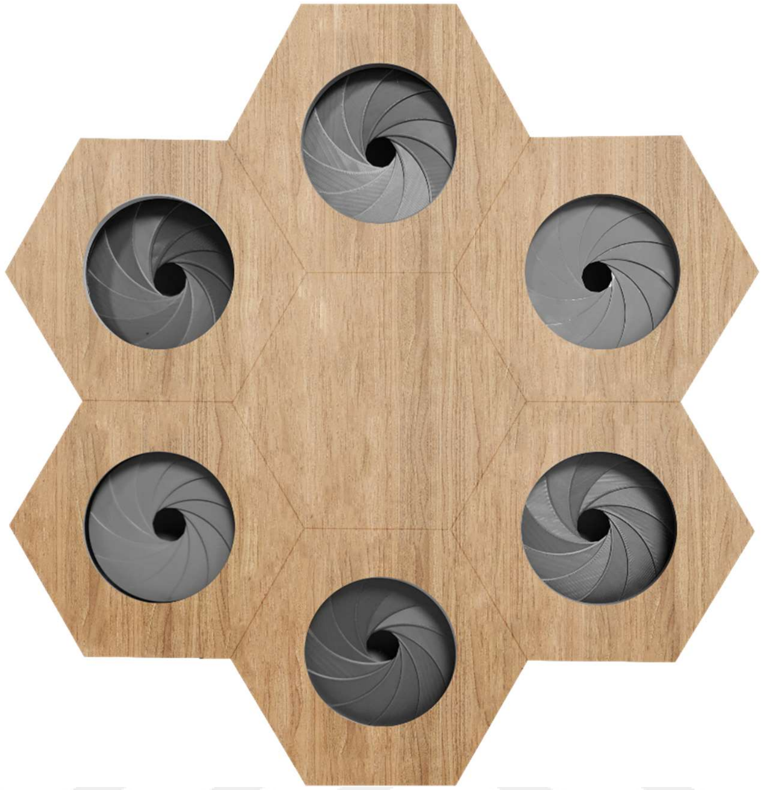

Figure 3.30 : Front view from the finished module of seven.

Figure 3.31 : Cross-section from the finished module of seven.

As seen in Figure 3.32, outer hexagons array around the central hexagon, which supplies the much-needed space for the electronics and the motors. On top of the center hexagon, the servo motor rig is located. The servo motor rig has the role of giving system rigidity with its structure, meanwhile creating a surface for the diaphragm collector hexagons, it also houses the servo motors.

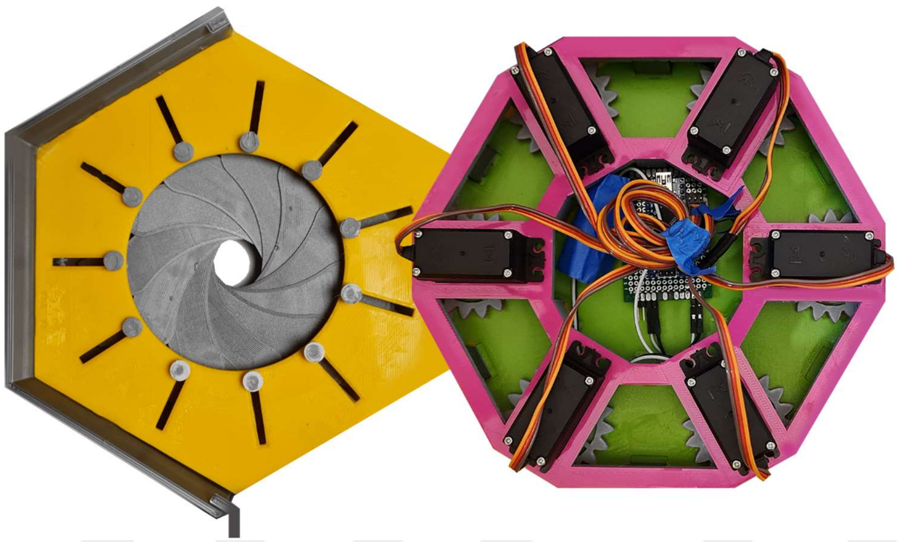

Figure 3.32 : Close up of a responsive unit.

Nearly all the structural and many of the mechanical parts of the system have been manufactured with the additive manufacturing technique. There are several different technologies in 3D printing. For this research, FDM has been chosen.

FDM type 3D printers work with depositioning the melted plastic through a nozzle, which moves in 3-dimensional space, with the help of motors, in control of a computer. Granulated plastic material is reformed into a string, which is called a filament. Different types of 3D printers use different kinds of filaments. Filament selection is based on the required performances of the manufactured part, but also, are limited to the 3D printer model and the capabilities of the machine. Due to the time, it takes to manufacture the pieces with FDM-type additive manufacturing technologies, time-saving methods are used in the process. Several different models of 3D printers have been used in this research to print the modules to overcome the time-consuming aspect of 3D printing technologies. In this research, 4 different 3D printers have been used and some of them have been modified in order to print more effectively. Several methods have been used to reduce the print time. These machines are as follows, Creality Ender 3 Pro, Creality Ender 3 Pro v2, Ultimaker 3, and Ultimaker S5 Pro Bundle.

The main speed variables in the FDM type 3D printing are listed as layer height, print speed, and infill percentage. These variables can be modified through the slices software (computer software that turns a 3D solid model into the code that 3D printers can understand and act accordingly.) with sacrifice on the surface quality and the part durability. The speed and surface quality of the 3d printed parts are inversely proportional, this means speeding up the printing process lowers the surface quality of the 3D printed part. Also, part durability is inversely proportional to the infill percentage.

There is one other aspect that can be modified via hardware modification, which is the nozzle diameter of the 3D printer. The nozzle of the Creality Ender 3 Pro's has been modified by drilling a 0.4mm nozzle diameter into a 1.0 mm nozzle diameter. This is done in order to speed up the printing process.

Broadly speaking, increasing the nozzle size 2.5 times allows 250% more material deposition in the same unit of time. This allows prints jobs to complete in 2/5th of the time it would have taken with an unmodified printer. As mentioned before, this modification exchanges speed with the surface quality. Because of this, this printer is used to print the side panels of modules, which are less if not non-visible at all. Other than the nozzle, layer height also affects the surface quality. Because of this, other than the front panels being printed in 0.1-micron resolution, all the parts are printed in 0.3-micron resolution in order to reduce the printing time. Feeder systems of both Creality printers have been modified too.

Stock feeder mechanisms were built from injection-molded plastics, which does flex on higher print speeds. Also, the stock mechanism strips off the filament when faster prints are set. Therefore the feeder mechanism on both printers has been swapped out and changed with a metal version of the filament extruder, which is manufactured by a 3rd party company.

Aside from the printer nozzle diameter, the printing area of the printers varies between models. Ultimaker S5 has the largest build volume in the machines that are used in this study. This allows hexagon parts to be printed as one piece, that way structural stability is improved, and the assembly processes are simplified. With all these modifications and fine-tunings, the print time of the modules has decreased by 60 percent, compared to printing with stock machines.

To maximize efficiency and minimize costs, in both time and money, some tunings were made in the 3D design of the parts as well. This is done mainly to avoid support structures, which increases the amount of needed post-processing, also decreasing the amount of material that had been used. This approach lowers the electricity, material costs as well as wear and tear in the machines.

The 3D Printing process is presented in Figure 3.33. As seen from Figure 3.33, diaphragm leaves and gears are designed to be printed flat, to avoid support material and post-processing that would require cleaning the parts. However, this design entails post-processing in the assembly process.

Figure 3.33 : 3D printing process.

Parts of the 3D printing filament have been used as plastic rods. They had been straightened out and cut as 10mm pieces to be used in the diaphragm mechanism. These mini plastic rods have been attached to the corresponding holes on the leaves, and then heat-fixated into place. The heat sealing process is presented in Figure 3.34 and Figure 3.35.

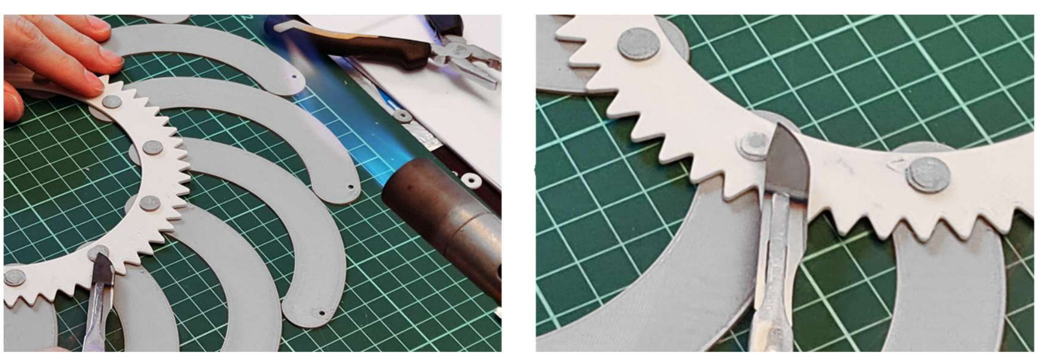

Figure 3.34 : Heat sealing diaphragm leaves onto the wheel.

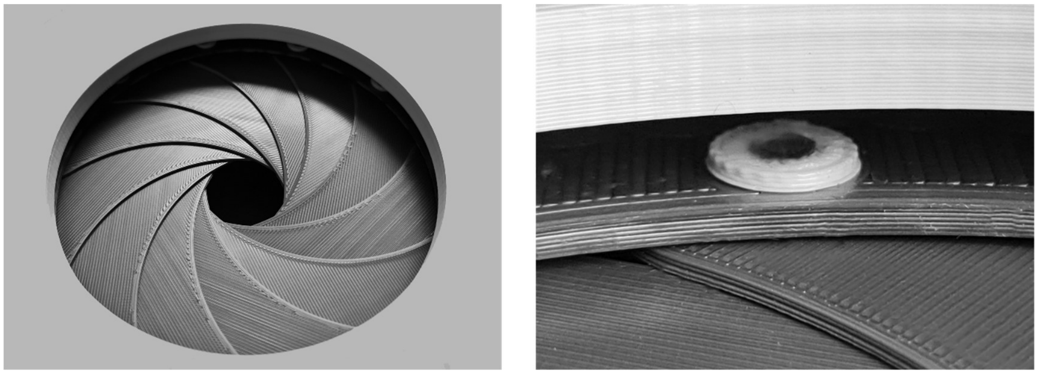

Figure 3.35 : Close up from heat-sealed diaphragm leaves.

This method works as follows: A piece of metal, a hobby knife for this instance, has been heated up, and while it's still hot, it has been used to melt one end of the plastic rod into the leaf. After flattening it, the new leaf has been installed on the gear, via putting a plastic rod through one of the holes on the main gear. After this process is repeated eleven times for each gear, the same method has been used to fix the other end of the leaves into the diaphragm collector hexagon. This process has been repeated for all 6 hexagons, before the main assembly.

While assembling the module parts, the friction welding technique has been used in order to fix the printed parts together. This technique is selected to have stronger and uniformly fixed parts. A rotary tool is used in this process, Dremel 4000 for this instance. 30mm of the filament has been fixed into the rotating end of the tool, and the tool is set to 800 rpm. Then while rotating, the filament has been forced onto the intersection of the desired parts, and the heat generated from the friction melts all parts together, fixing them on a molecular scale. This method has been used instead of traditional cyanoacrylate adhesives because it prevents joints from breaking while allowing fixed points to flex (Figure 3.36).

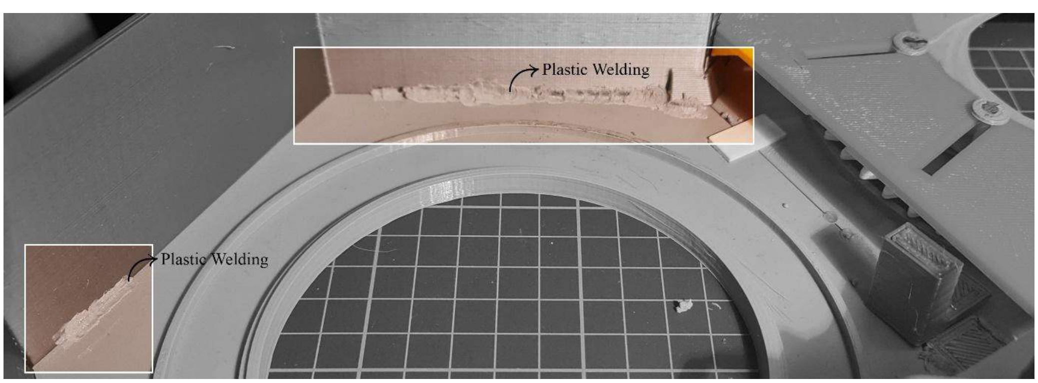

Figure 3.36 : Friction plastic welding.

After the module's physical assembly process has finished, the electronic assembly and soldering process is dealt with. A custom board has been soldered in order to have tidy wiring management. Header pins are soldered on top of the pertinax board to ease of access in case of a controller replacement is needed. Power management is also solved on the custom board as well. The Arduino board uses 12V as the input voltage but servos use 6 volts and the sound sensors use 5 Volts. To overcome this voltage difference, a step-down voltage converter has been used in order to convert the 12 Volts power supply into the 6 Volts. 12 volts that come from forks at the unit, one line goes directly to the Arduino board and powers it, the other goes to the voltage converter, drops down to the 6 volts, and then it is connected to the servos voltage input.

The Arduino board has its own onboard voltage converter and it supplies 5V 200ma from its pins, so this is used to power up the sound sensors. This way all the electronics with one 12 volts 20 amper power supply. The soldering and testing process is presented on Figure 3.37.

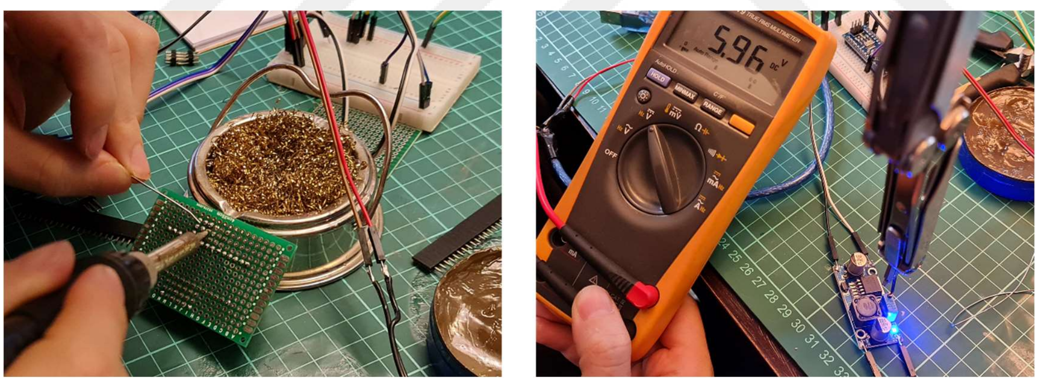

Figure 3.37 : Soldering and testing process of electronics.

For initial setup, servos needed to be zeroed, in order to set the gear position in the right angle and leaf placement. Zeroing values are then assigned to the servos and servo heads turn accordingly. While in this position, servos are placed onto the servo holder and screwed in, while servo gears are fixed in the position where they fit together with the diaphragm wheel. After this process, the code is revised and re-uploaded to the Arduino for the system to work as intended.

Visual representation of the front view of the project with multiple modules is seen on Figure 3.38. Axonometric representation of the project with multiple modules is seen on Figure 3.39.

Figure 3.38 : Render from a composition of multiple modules.

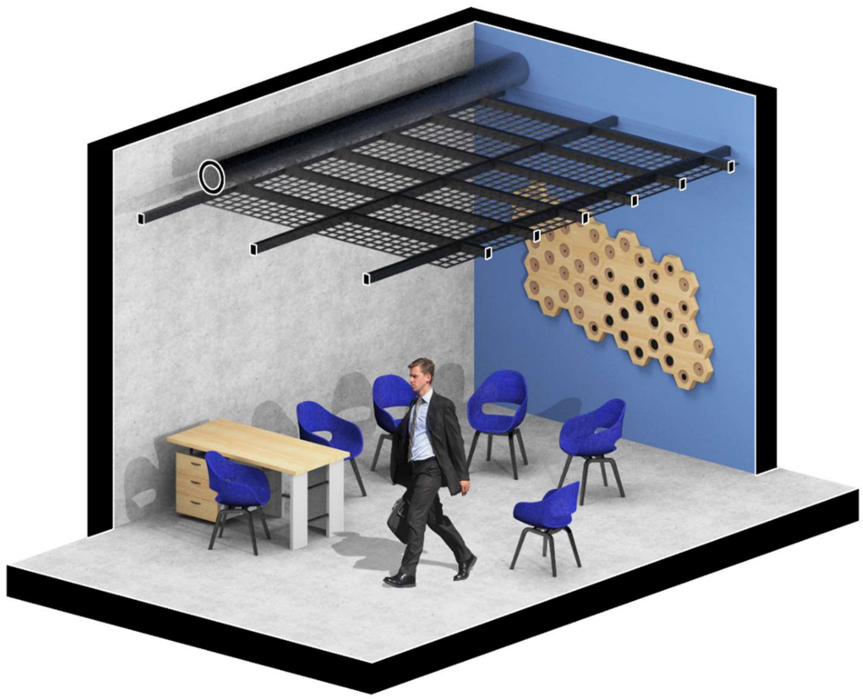

Figure 3.39 : Axonometric render of a group of responsive acoustic modules in an office environment.

According to the real room tests and simulations, it is calculated that one module is sufficient for every 6 square meters when the room height is 3 meters. For higher ceilings, a solution of hanging the panels from the ceiling can be implemented, in order to increase the acoustical comfort (Figure 3.40). It should be also noted that if the distance between the noise source and the module is more than 10 meters, it is suggested to add another module to the opposite side of the room.

While working on the research, it is considered that the output of this research is adaptable to be a commercial product. Regarding this, several commercial potentials have been researched as in indoor usage scenarios as well as outdoor possibilities.

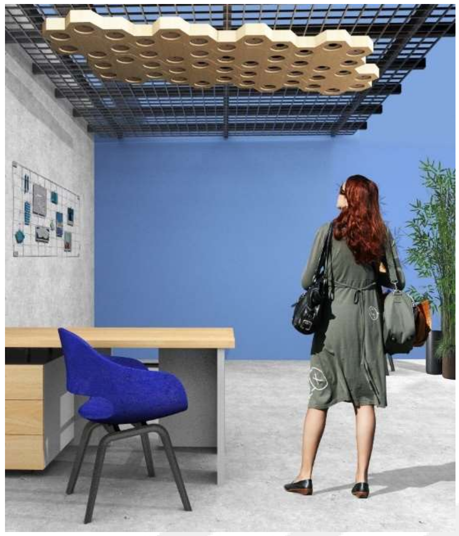

Figure 3.40 : Render from a composition of multiple modules on the celing.

Other than using modules as sound-absorbing panels, it is also have been discussed to use the said modules as volume separators, regarding their standalone stackability. For another usage scenario, the module’s potential in expo spaces, as both, using sound-absorbing and separating potential together, have been researched. It is also discussed that the modules might have a usage scenario as a form of interactive new media installation (Figure 3.41).

With all these in mind, a patent application has been considered and paperwork has been started in order to apply and protect possible commercial application potential.

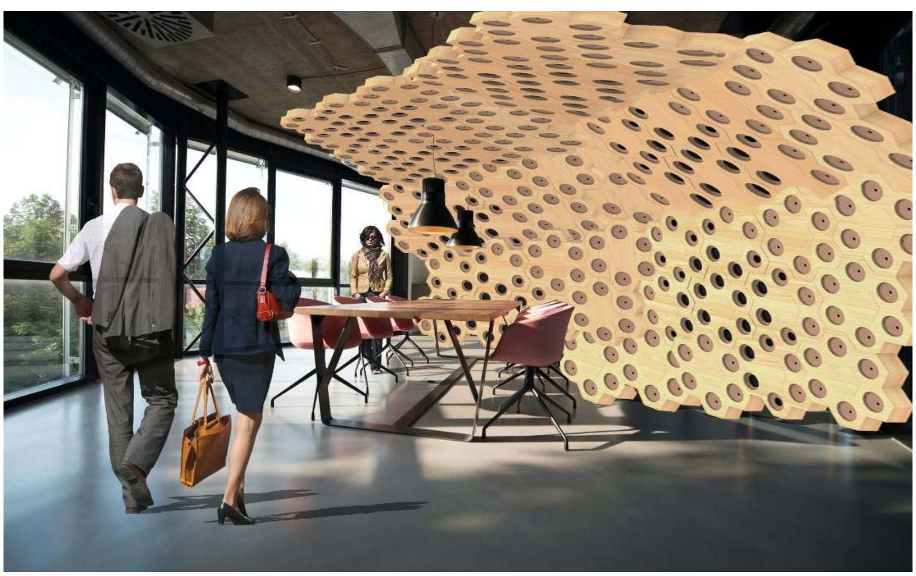

Figure 3.41 : Render of a group of responsive acoustic modules in an office environment with a high ceiling.

3.4 Simulation

Simulation of the responsive modules is prepared on Rhino software with the assistance of the Grasshopper plug-in. The screenshots from the animation generated from Rhino are presented in Figure 3.42. The visual programming of the process related to “the action and the response” is represented in Figure 3.43.

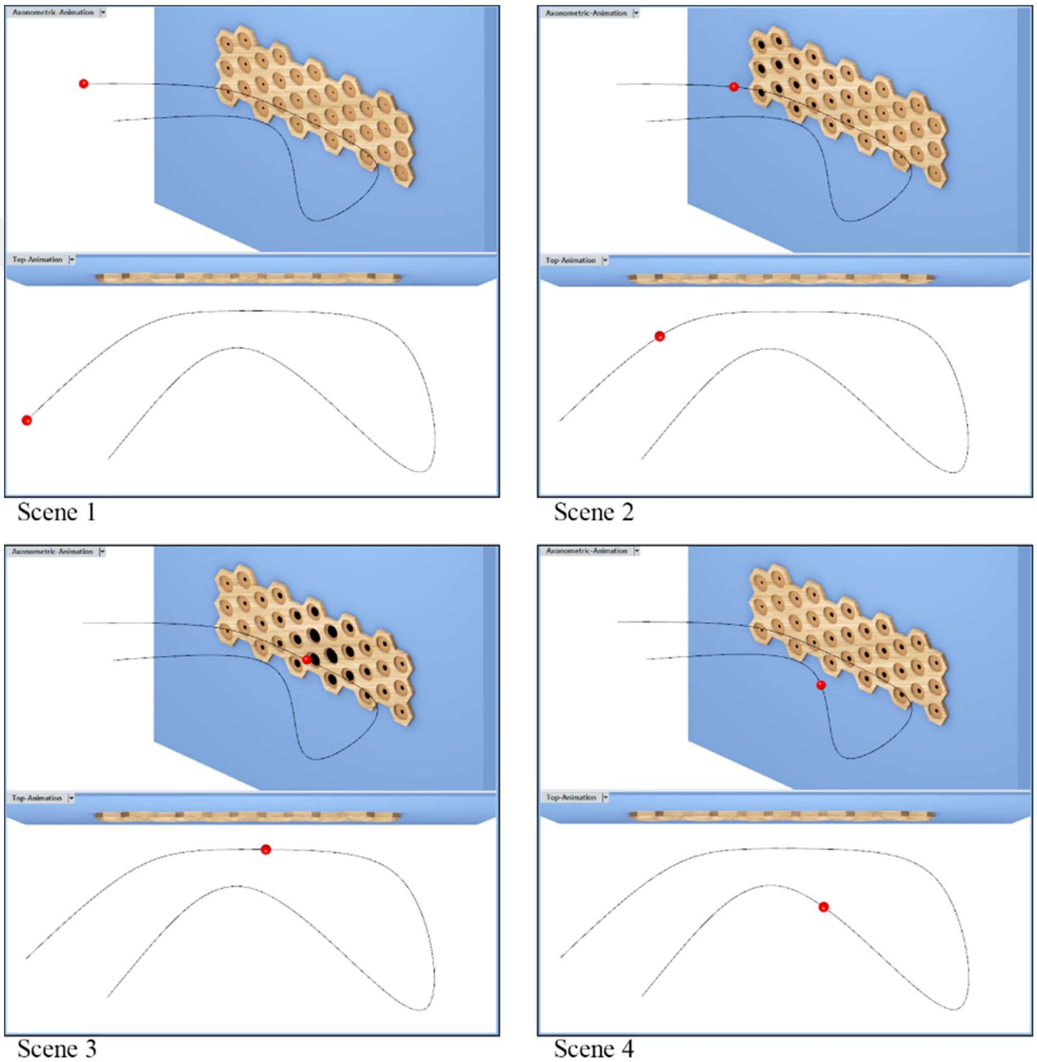

Figure 3.42 : Screenshots from the Grasshopper simulation of the responsive system.

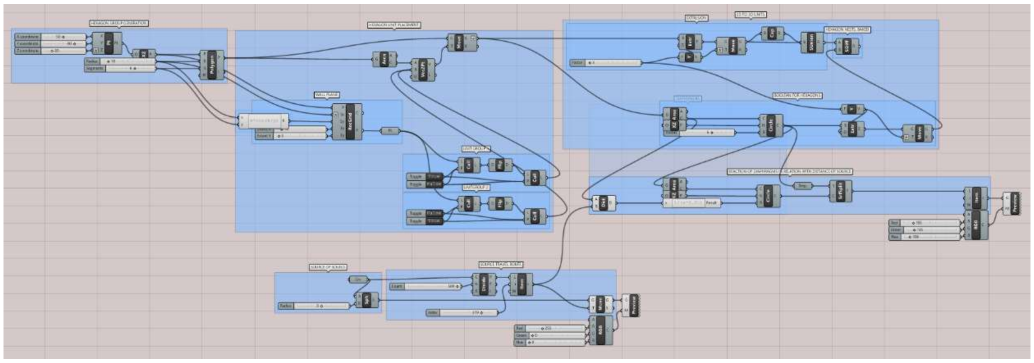

Figure 3.43 : Screenshot of visual programming interface.

The coding starts with the representation of hexagon units and continues with the stacking of the units as it is designed to be built in the real world. The number of columns and rows as well as the dimensions of hexagons are determined in this section (Figure 3.44).

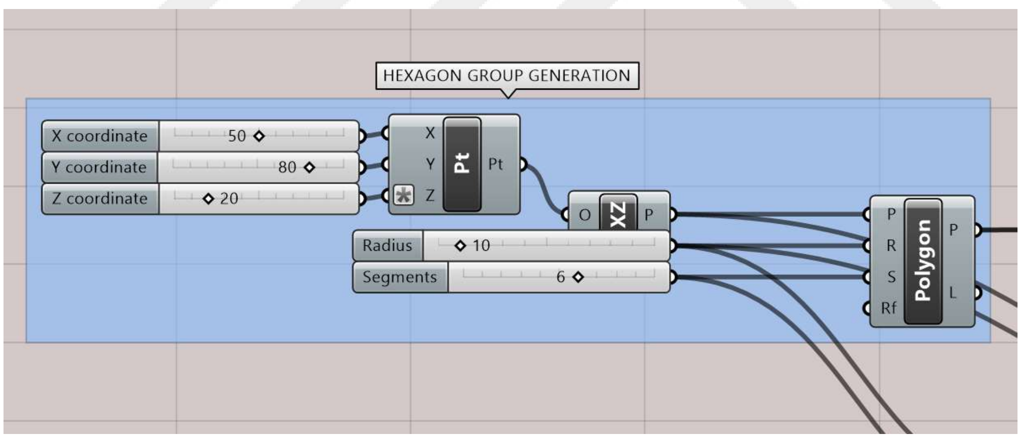

Figure 3.44 : Hexagon group generation.

In order to stack the hexagon units in the right way, the geometrical expression has been used. A wall plane has been constructed, units have been grouped in two and one of them is shifted in that plane according to that expression. With this method, the horizontal and vertical transpositions have been dealt with in the Hexagon Unit Placement section (Figure 3.45).

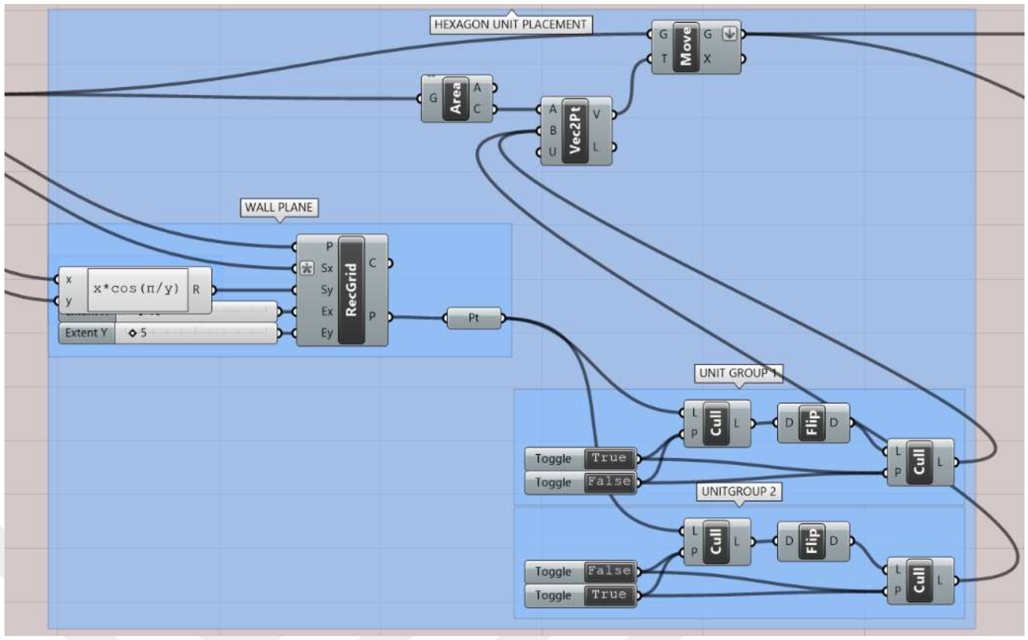

Figure 3.45 : Hexagon unit placement.

The next step is to ensure that the units, which are produced as a single one, reproduced in a certain number, and which undergo a special displacement while multiplying, become the last module in production by making them 3D. For this, two-dimensional hexagon information has been extruded by Move and Cap, passed through the boolean operation to become a hollow module, and solidified by Baking. On the other hand, while the diaphragms are represented as a total surface, the shape they form with the movement of the wheel is represented as circular spaces that grow and shrink on this surface (Figure 3.46).

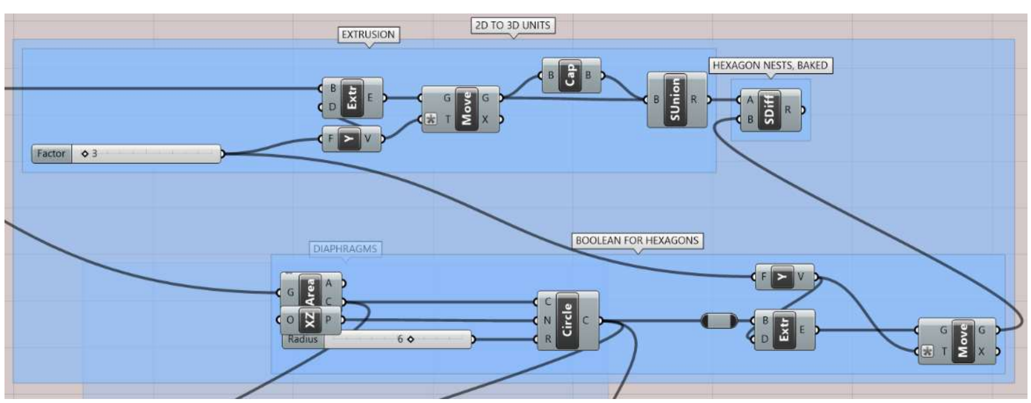

Figure 3.46 : Extrusion, 3D and Boolean operations.

A mobile source of sound has been defined to animate the simulation. In order to observe the different reactions of this sound source on the panels, a non-uniform route was created and the source was provided to proceed on this route (Figure 3.47).

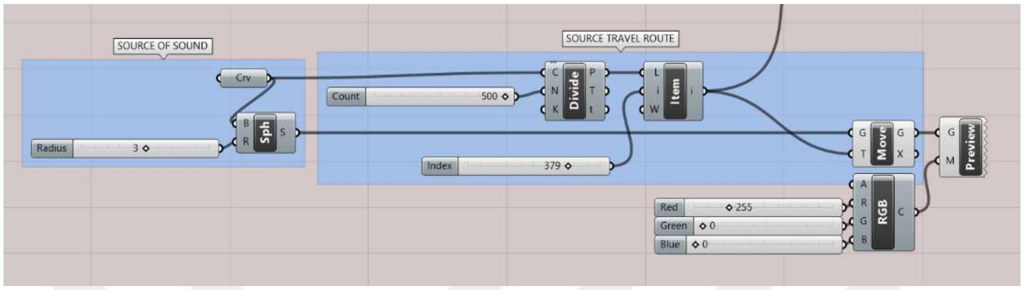

Figure 3.47 : Source of sound.

The final part is designing the reaction of diaphragms in relation to the distance of the source. The cause and effect relationship between motion and reaction is established by associating the diaphragm gaps with the instantaneous distance of the source to each hexagonal unit (Figure 3.48).

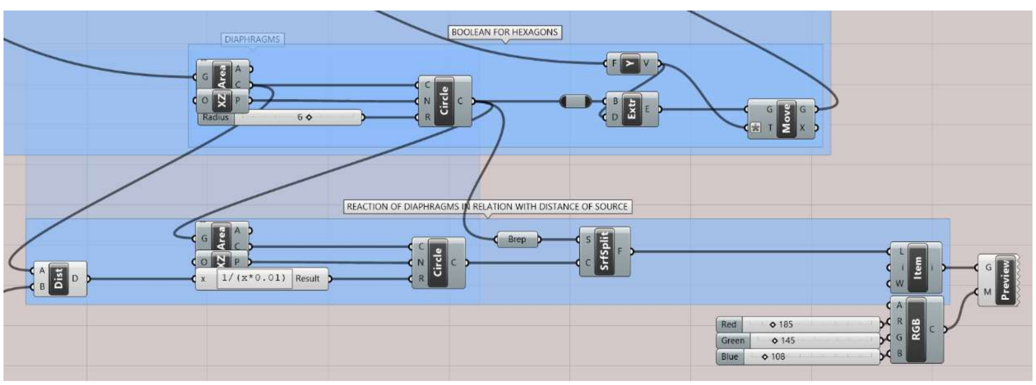

Figure 3.48 : Reaction of diaphragms in relation with distance of source.

In parallel with the simulation, real-world tests were conducted based on the interaction between the sound source, sound intensity, sensor and diaphragm movements (Figure 3.49).

Figure 3.49 : Real-world reaction of diaphragms.

A module was mounted on a wall in the test setting, and two experiments were carried out. A perceptible difference in the reverberation was measured in both test groups using a steady noise emitted by a speaker. The speaker is set to emit a 30 dB noise and pointed to the module from a distance of 5m while the module system is turned off. Because the front panels of the module are meant to refract sound, this setup had a considerable echo and a lot of reverberation.

The module system is turned on in the second scenario, and the initial test is repeated with the same variables. The dynamic surface area of the diaphragm changes as the sound source approaches the panels, and the opening in the diaphragm widens. This permits sound waves to travel through and get absorbed in the sound-absorbing foam. This absorption minimizes the quantity of sound that reverberates off the panel surface, lowering echo and reverberation. This time, echoes and reverberations were below the hearing range and therefore undetectable. The targeted acoustical comfort improvement has been attained in this manner.

3.5 Evaluation

The production and simulation sections as well as experiences based on real-time physical applications show that it is possible to improve the acoustical comfort of indoor spaces, with the help of transforming responsive modules. The findings of this research show that there is a potential for improvement for the indoor solutions related to acoustical performance. When rooms are properly treated, echo and reverberation are minimized. Sound absorption and diffusion by soundproofing and acoustic treatment are two strategies for treating these problematic interiors. While the echo of loud sound and noise is prevented with the sound-absorbing sponge, the amount of sound to be absorbed is regulated with the reflective leaf modules.

In addition, layers in three dimensions cause the source sound to be refracted in different directions in different amounts, thus increasing the acoustic quality and increasing intelligibility. In this way, it is aimed to optimize acoustic comfort in the office environment.

Last but not least, the adaptability of the system and its instantaneous response to sound enable visualization of ambient noise and thus observing the amount of noise that the users of the space are exposed to in their daily life without being aware of it.

Due to the usage of home-use 3D printers in this research, it is repeatable by any other 3D printer owner, who has a qualified 3D printer for this production. As an example of using 3d printers in responsive adaptive projects, Yi et. al. (2020) introduce a user-fabricable 3D-printed kinetic shading device. This enables the possibility of decentralized manufacturing, which lets any user customize and repeat the results of this research/module. Electronic components are chosen from widely available consumer-level developer electronics so that they can be accessed nearly anywhere in the world.

Even though the Grasshopper algorithm was simulated with predetermined variables, the initial idea was to connect the module's internal sound sensors, the grasshopper algorithm can simulate the usage scenarios according to the real-time noise data from the environment. Due to the time constraints of the research, this was not possible but it is noted as a further research topic. In the more advanced versions of the module, this connection can be achieved via Bluetooth connection.

4. CONCLUSION AND RECOMMENDATIONS

Due to the obvious rapid increase in technological developments, people's regular needs are as dynamic as they have never been. With the integration of new computer and communication technologies into daily life, architectural components are also impacted by this dynamism. As a result, in the architectural community, research and development on interactive and adaptive building elements have become a growing trend.

The effects of computers and computer-aided design programs are reflected not only on presentation techniques but also on architectural thinking and creativity (Ünver, 2007). Changes in the structure of the surfaces can be listed as mobilization, smartening, and hybridization with electronic devices such as computer programs, receivers, cameras, and sensors so that the architectural elements act as a bridge or an interface between the virtual world and the physical world. The use of informatics in architecture now brings interactivity, not only in the field of design but also in the function of the built space.

The responsive design approach has become prominent as the most common example of this interactivity in the literature of architectural design. Now, building elements are also smart and react to environmental factors. However, this interaction has been linked to heat and light in the façade elements, and sound comfort studies are few and far between. This thesis focuses on the research and development of sound-absorbing responsive panels, as acoustic indoor system solutions. The goal of this thesis is to research, comprehend, and develop responsive architectural components. The responsive approach is not new to architecture; nevertheless, a wider span of potential has only begun to be examined. Research and experimentation are essential to look at the possibilities in this growing area, and the architect must understand the concept of sensors, actuators, and control systems (Meyboom et al., 2011).

The study's spatial scope is a shared office space with varying acoustic requirements throughout the day. For dynamic noise range detection, sound simulations and real-world tests were carried out in a 20-square-meter office building in Kasımpaşa. It has been studied at the prototyping scale in the context of computational, fast, and customizable production.

The method of this thesis study is as follows: a review of current literature, the making of a prototype, and the evaluation of the product based on design criteria. Prototyping and testing out possible scenarios were used as a research method in this thesis. The prototype of this system was created using computer-controlled additive manufacturing techniques, specifically 3-dimensional printing with the Fused Deposition Method.

This research differentiates from existing acoustical panel proposals in the topics of form, material, and manufacturing techniques. Concepts related to form in the literature are diversified as origami, triangulation, hyperboloid, and tetragon, and in this thesis study, the hexagon was studied with stackability, dynamic surface area, and connection concerns in mind.

The Modular Kinetic System Proposal presented in this thesis uses biodegradable plastic with FDM 3D printing as the main production method while similar other approaches use materials such as Plaster, HDPE, EPP, Fiberfloat, bamboo and utilize CNC Laser and similar subtractive methods. While static samples do not have electromechanical attachments on them, the thesis proposal, which is a kinetic system, is equipped with sensors and controls in order to react instantly to ambient sounds.

Similar to this thesis research, Resonant Chamber and Manta projects are equipped with sensors, connectors, and control elements. However, responsive acoustic panels that are manufactured in this research, do respond to the environmental noise within seconds, rather than adapting over time. This creates a potential to improve the acoustical comfort of indoor spaces which has dynamic noise profiles, based on the help of sound-absorbing adaptive modules. The findings of this study suggest that there is potential for development in terms of acoustic performance for indoor solutions.

The study continued with module prototype manufacturing processes. The manufacturing and implementation process was critical in establishing the real influence of the proposal on an acoustic space. The module consists of seven hexagons, one located in the center, and the other six are adjacent to each edge of the central hexagon. The system has a four-layer design, which are front panel, diaphragm leaves, sound-absorbing foam, and the back panel. The proposed panels are physically produced in 1x1m dimensions with an electro-mechanical exterior and a sound-absorbing material interior for this purpose. The controller mechanism of the modules contains an Arduino Board, actuators, and sound level sensors.

The diaphragms of the system are closed when the system is inactive. This state prevents sound waves from reaching the sound-absorbing foam, and sound waves can only interact with the front of the module, which acts as a sound-reflecting surface. When the system is triggered, the leaves are repositioned based on the level of noise in the environment. Each sound sensor is located in the diaphragms' center, between the front and back panels. The noise sensors in the diaphragms' centers constantly measure the level of noise that reaches them. The sensor value is then processed by the microcontroller's algorithm. Actuators control the openness of the front plates and the sound waves that travel to the absorber located behind the system. As a result, the system is able to control the amount of sound that is absorbed or scattered using the dynamic surface area of the front panels. If the noise level in the environment increases, the opening of the diaphragms widens, allowing more soundwaves to pass through and be absorbed by the acoustic foam inside the module. Based on the algorithm used, the modules perform best in levels of noise, ranging from 20dB to 80dB.

The system responds to auditory inputs from the environment both performatively and visually. Digital simulations are used to assess the dynamism of structure and reactions at various sound levels. As a result, the system also differs from other responsive architectural components in that it focuses on both sound performance and visualization. The Adaptive Kinetic Module proposal was evaluated as a performative acoustic comfort enhancer with a visual representation of environmental noise as a result of this research.

In addition to using modules as sound-absorbing panels, it has been proposed to use the same modules as volume separators, due to their standalone stackability. For another application scenario, the module's potential in expo spaces has been investigated, as both sound-absorbing and separating potential had been combined. It is also suggested that the modules could be used as a type of interactive new media installation with audio-based performances. In light of this, a patent application has been explored, and paperwork to apply for and protect commercial application potential has begun.

It is a fact that the implication of widespread adoption of responsive elements in all means of daily life is complicated to anticipate. However, it will undoubtedly result in substantial breakthroughs influencing our culture, behaviors, and cities.

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