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EXPLORING ACOUSTIC PERFORMANCE INTEGRATION AT EARLY STAGE OF ARCHITECTURAL DESIGN

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ABSTRACT

Most commonly, an architectural room is designed without any consideration for acoustic behavior. Acoustic efficiency is improved *ex post*, by addition of corrective panels, often absorptive, sometime reflective, more rarely diffusive. Acoustic design is although complex and requires a global and integrated approach considering the whole space: volume geometry, surface pattern, material location and extension, which are already chosen before the evaluation of the acoustic performances. This leads to lack in proper integration into the overall design and higher costs. Since 2020, the international workshop MOGE (Material Optimization and Geometric Exploration) focuses on acoustic design for architects. The design approach developed within this framework is based on: (1) multi-factorial design of global shape and local details; (2) improvement of material by digital, and *vice versa*; (3) embodied pedagogy through physical experiences. The paper will present the pedagogical process of the workshop as well as students works. The goal is to promote the design process for future architects, involving the acoustic performances *ex ante* and developing adaptative systems.

Keywords: *integrated acoustic design , digital fabrication , parametric optimization , embodied pedagogy*

1. INTRODUCTION

Current development in digital design and integration with building performance has drawn attention to performance-based design and parametric modelling in architecture [1]. Both the design workflow and design outcome are affected by essential knowledge and assessment components supported by new tools applied since early design phases. Performance-based design and parametric modelling current application in the acoustic field has been little exploited in architectural practice. However, it has been object of several explorations at a pedagogical level demonstrating successful applications of an integrated design [2] developed in an educational framework that actively involved students through summer schools and workshops. Previous educational experiences with the performance-based design approach have been also documented in [3-5].

A complete workflow relies on interactions between disciplines and requires a customization of existing software or creation of new computational design tools through computer-programming [6]. As highlighted by Whitehead [7] most designers already think programmatically, but since they are lacking the time and the inclination to learn programming skills, they cannot express or explore these patterns of thought. Therefore, a new professional figure might be needed to embrace design and acoustic knowledge in order to generate valid solutions from both aesthetical and acoustic point of view with smaller effort.

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Despite the wide range of possibilities offered by custom tools, the programming skills and acoustic knowledge required in their development and application are normally not available to architectural firms. However, currently the availability of several online coding courses and of platforms such as ACOUCOU [8], which offers free education materials on acoustics, may help to fill the gap. Furthermore, the introduction of performance-based design approach in architectural education would help students to become more familiar with building performance and simulation tools.

This work presents the framework of the Material Optimization and Geometric Exploration - MOGE workshop. It focuses on the pedagogical process of the workshop as well as students experience and work. The goal is to promote the design process for future architects, involving the acoustic performances *ex ante* and developing adaptative systems.

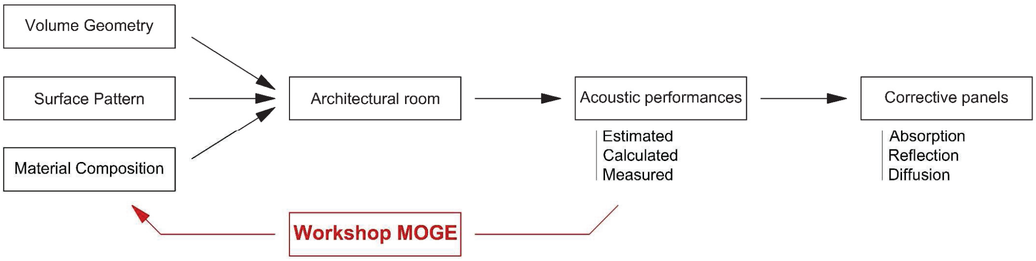

Figure 1. Schematic view of the common acoustic design process.

2. WORKSHOP MATERIAL OPTIMIZATION AND GEOMETRIC EXPLORATION

Material Optimization and Geometric Exploration (MOGE) is an international workshop started in 2015. It identifies interdisciplinarity and cultural exchange as key features of student education [9]. For this reason, the workshop involves three different universities in three different cities. The involved departments are DiARC at the Federico II University of Naples, the ENSA Paris Belleville and DENERG at Politecnico di Torino.

The first phase takes place in Naples and welcomes about 40 students in architecture selected from the different institutions involved. These are chosen from among those who demonstrate a basic knowledge of computational design software. The program of the first phase includes seminars on the topics of geometry and acoustics, and an in-depth study of the use of computational design software, with specific focus on the control of complex geometries and acoustic verification. Since 2020 these computational methods are aimed at designing a component and/or artifact with specific acoustic characteristics. The design is based on a combination of theoretical lessons, model development, and actual spatial acoustic experiences. During this phase, geometrical room acoustic simulations are used to assess the performances of the design proposals and compare different scenarios, to gain a greater understanding of the impact of different alternatives on acoustic performances.

Figure 2. First Phase in Naples: Lessons and acoustic real experience in PLINIVS room (MOGE 2023)

The second phase of the Workshop takes place in Paris and is intended for students who have taken the first phase. The program is focused on the fabrication and construction of mockups at a 1:1 scale and a small-scaled model of the whole project developed in the first phase. The possibility of being able to test the mockup allows a progressive improvement of a project. The elements that constitute the designs are made by digital manufacturing and different iterations between design and fabrication allow to optimize the aesthetic, structural and acoustic features.

Figure 3. Second Phase in Paris: building the mockup. (MOGE 2022)

In the last phase, which takes place at the Department of Energy of Politecnico di Torino (Turin, Italy), the performances of the produced mockups are tested. The measurement is performed in a 1:5 scale reverberation room and aim at characterizing the sound absorption coefficients of the mockups in accordance to Standard ISO 354:2003. Additionally, some insertion loss tests have been carried out in a full anechoic chamber. This was using a sound source emitting a white noise and a SPL-meter and comparing the sound pressure level with and without the sample between source and receiver position. Downstream of these, the relevant test reports are prepared.

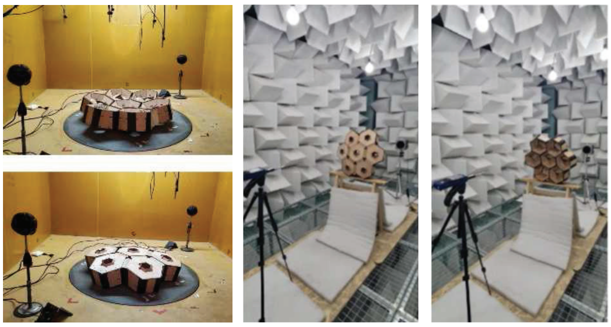

Figure 4. Third Phase in Turin: sound absorption and sound transmission measurements (MOGE 2022)

One of the goals of MOGE is to reverse the attention paid to acoustic issues, and to approach it as an element that could "*shape the space*". The short and intense workshop time allows to quickly grasp the stakes of acoustics, understand the science behind it, and immediately apply it to the field of architecture, thus making it concrete and palpable. Physical and mathematical data take shape under the pencil, modifying the design of a module, adapting the structure, or shifting an angle. By closely associating the advice of experts in acoustics with that of structural engineers, making it possible to achieve a project that is as effective acoustically as it is structurally, putting one at the service of the other.
Manipulating several radically different sciences with the spatial and aesthetic constraints of a single architectural project, is extremely formative exercise for any architect. Finally, the fact of testing in real time, through the model, the scale 1:1 manipulation, the digital tools, or the acoustic measurements made the experience more concrete, with an understanding of the implications of the applied design, prototyping and testing methods on the final architectural solution.

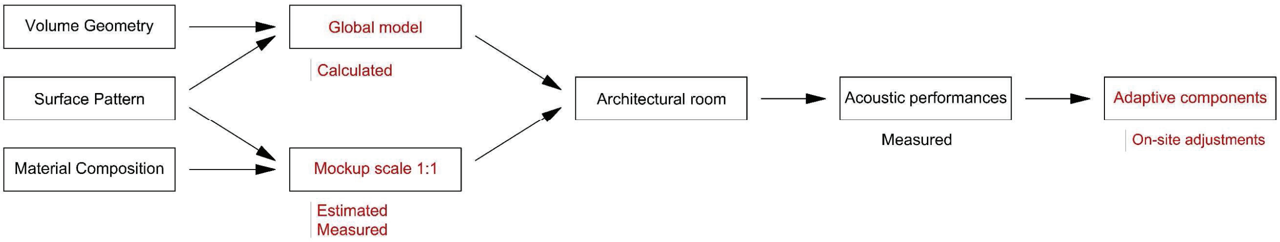

Figure 5. Schematic view of the acoustic design process in workshop MOGE

3. MULTI-FACTORIAL DESIGN

3.1 Innovation and evolution: “Techno-evolution” and “bio-evolution”

Considering multiple factors, technical design must be considered as a continuous evolution of already existing solutions working more by analogy than by analysis [10]. The biological evolution is another process that create “*new efficient solutions*” facing multiple factors. The comparison with “technical evolution” has been already done in a previous work [11], using studies of historians/prehistorians (André Leroi-Gourhan [12]), and philosophers of techniques (Gilbert Simondon [13]) as well. These thinkers have noted the necessity to “*objectivize*” the process of techno-evolution and obviously not to reduce it to a purely biological one.

In both cases, the evolution process can be separated conceptually in two phases: the “*structural re-organization*” and the “*selection process*”, called “*concretization”* by Simondon, defined as the progressive assimilation of all the constrains.

3.2 Structural re-organization: Phylogenetic diagram

The phylogenetic tree can be “*rooted*”. It is so a classification tool, used in biology to show the evolutionary relationships between different species or individuals. Each branch is divided according to similarities and differences between the physical or genetic characteristics of the species. Closer the division between two branches of the diagram is, more related the species are. Reversely, more remote the division is, less related they are.

Phylogenetic trees can also be unrooted (without common ancestors). These are used today in the fields of logic, computer science and taxonomy. Each split branch represents a level of morphological classification. In Architecture, FOA (Foreign Office Architects, founded by Farshid Moussavi and Alejandro Zaera Polo), uses frequently phylogenetic trees to classify their own projects [14] and to present the different structural organization of historical buildings [15]. The phylogenetic tree is not only an *ex post* representation graph, but also an *ex ante* generative tool. A good use of phylogenetic trees as generative tool was made by the architect George L. Legendre [16].

During the workshop MOGE, the initial step of design is to question the “*structural re-organization*”. From a tool of classification, the unrooted phylogenetic trees are becoming a useful exploration tool, able to show different combinatorial possibilities for the project. In MOGE 2023 for example, the topic was to design a room for teaching made by movable wood-structure. The bifurcations of the phylogenetic tree were organized in four levels: at first the “*static scheme*” (according to the type of support reactions of the structure), then the “*Scene*” around the speaker (according to the configuration of the reflective panel), after that the “*Lateral*” absorption (according to the location of absorptive panels) and finally the “*Back*” wall (if Absorptive or diffusive).

Using the phylogenetic tree, each student group briefly designs 24 project configurations, one for each final branch of the tree, exploring so different typologies of project. Afterwards, each group decides to start from one of the final branches. The selection is decided according to the efficiency of the proposals. That way, the innovative design cover multiple “*structural re-organization*”.

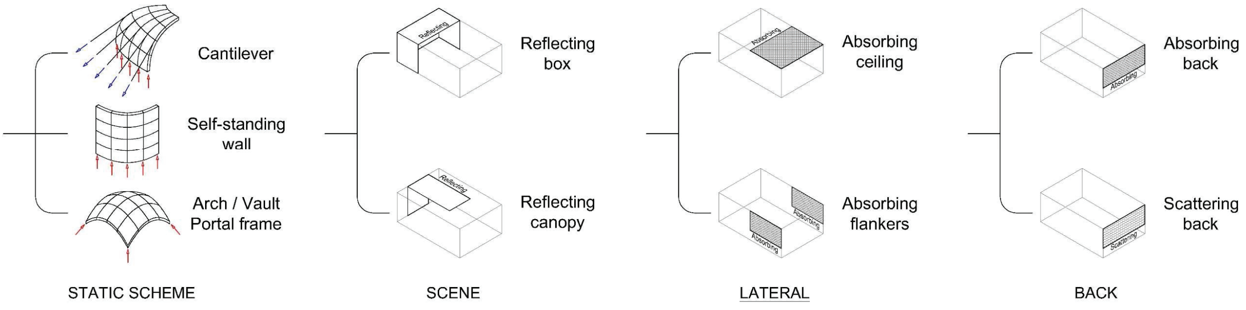

Figure 6. The four levels of bifurcations in the phylogenetic tree (MOGE 2023)

3.3 Concretization: Parametric design and progressive integration of constraints

Parametric design is often associated with wavy, complex shapes that only interest programming enthusiasts. However, this new tool raises important questions related to architecture. Authors such as Antoine Picon [17] have shown how parametric architecture still questions 18th century issues. Pedagogically, parametric design requires to clearly define the "Form" what is constant in the project (Morphogenesis) and the design what is adaptable (Parameters). Thus, the project can successively integrate the different constraints either by extending the morphogenesis with new operations or by adapting the parameters. The case study of the evolution of the construction details of the project "*Crossing lines*" (MOGE 2022) illustrates the process of "*concretization*".

Starting with the concept of the "*cross panel*", the original detail is based on a grid of two parallel square panels, alternately nested within each other. Then the introduction of acoustic notions influenced the shape of the chosen module by modifying the inclination of vertical panels to control sound reflections while leaving a visual opening. After a series of tests on the Pachyderm software (see below section §4), the modifications took place at the scale of the room by introducing a curve on one of the walls and by differentiating the two walls according to their acoustic qualities: one refractive and the other absorbent. The angle of the curve, as well as the height of the panels was obtained by optimization with Grasshopper, to fit the shape of the existing shelf. To add absorbing qualities to the system, calculations of the percentage of perforation of the panels were made, designed to absorb the low, medium, and high frequencies. The distance between the two layers of panels was adapted accordingly. Finally, structural tests with the realization of the mockup, first by hand and then with a laser cutter, have improved the stability of the structure. Indeed, the system of crossing of the panels was modified to obtain a better mesh. Other horizontal panels were also added to stabilize the whole and maintain the angle of curvature.

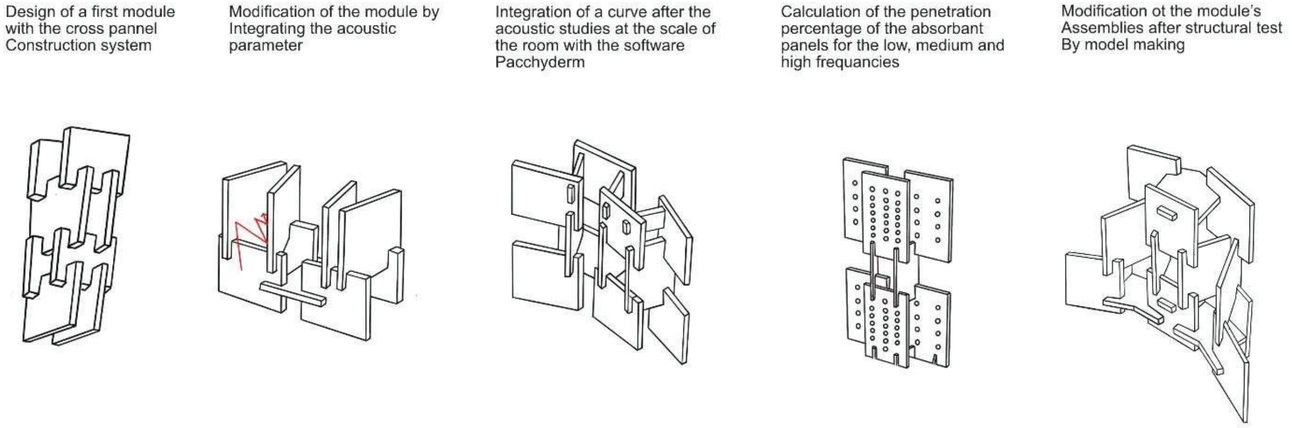

Figure 7. Evolution of construction details from project "Crossing lines" (MOGE2022)

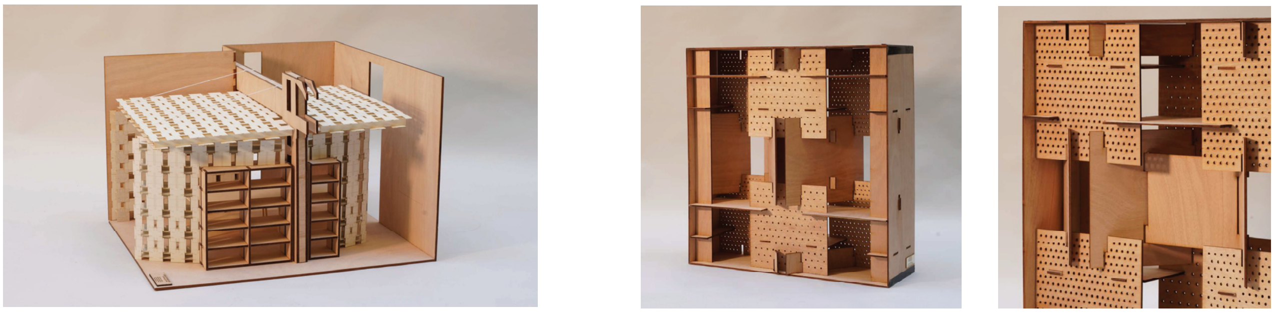

Figure 8. Model of the room (scale 1/10) and mockup for test (scale 1/1) from project "Crossing lines"

4. MATERIAL AND DIGITAL

During the first phase of the workshop, the students are provided with a pre-set algorithm to be used to run acoustic simulations in Pachyderm, a free tool integrated in Grasshopper/Rhinoceros. Pachyderm is based on geometrical room acoustic principles and allows to quickly run simulations and gather useful performance feedback on the way a given design proposal interact with the acoustic environment. The students have been encouraged to run two types of tests. A preliminary test is based on ray tracing and allows to visualize the rays emitted by a sound source, and the way they propagate in the environment, including specular reflections over surrounding surfaces. Despite its simplicity, this quick analysis can promote a greater awareness and control over the way sound interacts with the design proposals and can be a valid support in conceptual design phases. At a later stage, geometrical room acoustic simulation can be run to better assess the acoustic performances. Given the limited time available and the students' variegated background knowledge on acoustics, a pre-set algorithm is made available for simplicity. Students are asked to input their design proposals and to select between a pool of material options combining different sound absorption, sound scattering and transparency properties. The simulation settings and the sound source and receiver positions are instead already defined. The simulation output allows to compare the computed acoustic performances, e.g. A-weighted sound pressure level, reverberation time, to assess relevant perceptual aspects of the scenario being assessed.

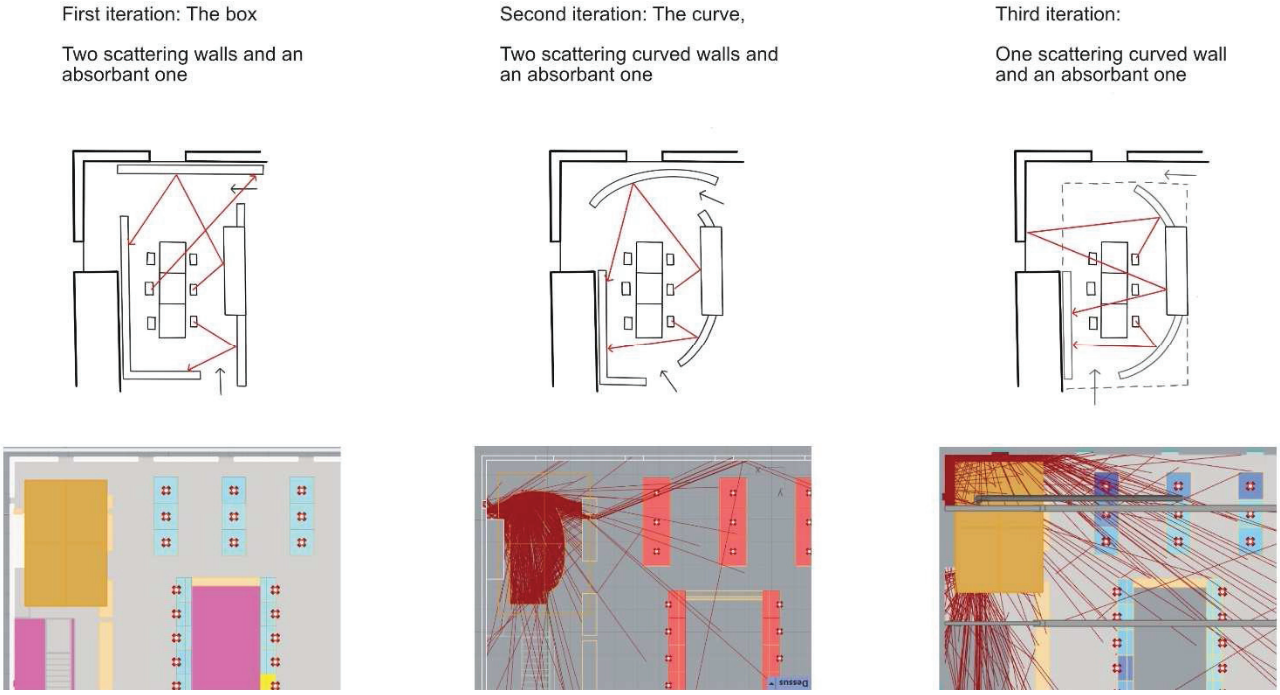

Figure 9. Evolution of project using Pachyderm software (MOGE2022)

5. EMBODIED PEDAGOGY

By the simplified but fast acoustic simulation, the student can first optimize geometrically his design, but especially thanks to the representation (SPL-map or raytracing), he develops gradually an intuition of the acoustic phenomenon. By "*shaping the digital space*", he gradually develops the relationship between form and acoustic performances.

One of the core pedagogical aspects of the MOGE workshop is related to experimentation and testing. While the support of the DENERG laboratory of the Polytechnic of Turin offers the possibility of testing the outputs produced during the workshops with highly sophisticated instruments and thus

obtaining very accurate scientific outcomes, on the other hand, the use of more intuitive tools and methods makes it easier to transfer complex notions related to acoustic design even to non-experts such as the workshop students, who consequently assume a greater level of awareness not only regarding the physical phenomenon itself but of the impact that their design choices can have on a specific performance.
The facilitation and knowledge transfer process are carried out by researchers in the field of acoustic design from the DENERG of the Politecnico di Torino and includes both a lecturing part characterized by frontal lectures concerning fundamental notions of acoustics, and an interactive part in which the students are directly involved in the acoustic testing phase. In this regard, in the context of the MOGE workshop 2023, the students' involvement in the testing phase took place in the meeting room of the PLINIVS study center at the University of Naples Federico II. The peculiarity of this place lies in the presence of a suspended ceiling specifically designed to improve the acoustic performance of the room: in particular, shape, size, materials and arrangement of reflecting surfaces and absorbing devices were optimized with the support of Algorithm Aided Design (AAD) tools to ensure the correct acoustic behavior of the room according to its designated applications.

Figure 10. PLINIVS room: interactive test phase (MOGE 2023)

In a meeting room, it is crucial that the sound coming from the speaker's position spreads adequately over the entire audience. For this reason, the aim of the tests was to measure the level of various acoustic performance indicators (e.g. Sound Pressure Level and reverberation time) in different parts of the room, placing the sound source in the part of the room designated for the speaker.
During the interactive testing process, the students assumed the role of the source, while the expert researcher assumed the role of the audience in the following way: starting from a condition of silence, the students blew up some balloons, representing the sound source, while the expert researcher carried out the measurement with a sound level meter. The test was repeated by placing the sound level meter in different points of the room in order to assess the diffusion of sound over the whole space.
Giving students access to the room to understand and test the functioning of the ceiling guided by experienced researchers was fundamental from a pedagogical point of view. The facilitation process in the testing phase reduced the knowledge gap on several levels, allowing students to better understand the complex relationships between design object, material and information.

6. CONCLUSION

Since its beginning in 2015 until today, the workshop MOGE has been constantly evolving, with the aim of developing a pedagogy that combines both the digital (more virtual) and the material (more concrete). The acoustic quality of spaces is a suitable subject for Performance-Based Design: sound is a physical phenomenon - known to everyone but whose behavior is not intuitive – easy to some extent to be modeled digitally, and that concerns the quality of space.
The future goal is to develop the pedagogical methods to further improve the three axes presented here: multi-factorial design, relationship between material and digital and the embodied pedagogy. Future architects should not consider acoustics as a feature of their spaces, but as a raw material to shape them since the beginning. To this aim more reliable and faster computational models and integrated in the digital design process would be necessary.

7. ACKNOWLEDGMENTS

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