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ENVIRONMENTAL NOISE REDUCTION USING GEOMETRIC GROUND SHAPING: RESULTS FROM SCALE MODEL EXPERIMENTS

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ABSTRACT

Noise pollution is a significant environmental and public health challenge, particularly near urban infrastructure such as highways and airports. Traditional mitigation methods, such as vertical barriers, often disrupt landscapes and ecosystems. Ground shaping, an innovative approach that modifies terrain to reduce noise propagation, remains largely unexplored despite its promising potential. Building on prior research that simulated its effectiveness, this study empirically evaluates the noise reduction performance of specific ground shapes. Using a 1:500 scale model in a controlled acoustic environment, a robotic arm was used to create precise three-dimensional ground forms. These forms were positioned between a noise source emitting broadband noise (100–16,000 Hz) at 65 dB SPL and a miniature microphone at a scaled distance equivalent to 425 meters. Results demonstrate that ground shapes reduce noise to varying degrees, with specific geometries achieving an average reduction of over 2.5 dB and a maximum exceeding 7.5 dB. These findings highlight the potential of ground shaping as a sustainable alternative to traditional noise mitigation, offering empirical support for its integration into urban and environmental planning while enhancing public health and minimizing ecological disruption.

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1. INTRODUCTION

Ground shaping, though potentially effective for noise reduction, has yet to be experimentally validated. Schiphol Airport in the Netherlands implemented a landscape design plan to combat noise through ground shaping, but its effectiveness remains largely unquantified due to the lack of specific experimental research [1]. Additionally, noise monitoring studies have highlighted the significant impact of aircraft noise on nearby communities [2].

Environmental acoustics software—such as SoundPLAN, CadnaA, TNM, Predictor-LimA, and IMMI—use standardized models (e.g., ISO 9613, CNOSSOS-EU, TNM) to predict noise levels and assess mitigation strategies like vertical barriers [3, 4]. While widely used in urban planning, these tools are not well-suited to simulate non-standard interventions like ground shaping, and often rely on idealized input data. As such, empirical measurements remain essential to capture site-specific effects and validate model assumptions.

This research aims to fill that gap by using robotic earthmoving and scale models to experimentally evaluate the noise reduction effectiveness of different ground forms in high-noise environments. Rather than relying solely on simulations, we focus on direct measurement to explore the acoustic potential of terrain shaping under controlled but realistic conditions.

1.1 Rationale

Ground forming involves reshaping terrain to influence environmental factors. This study aims to empirically evaluate its effectiveness in reducing urban noise levels near airports. It addresses a significant gap in current noise mitigation strategies by systematically exploring the relationship between ground shapes and noise reduction. The goal is to generate insights into terrain acoustics and contribute to the broader field of environmental acoustics, architecture, landscape design, and robotic earthmoving.

1.2 Novelty

Unlike traditional vertical noise barriers, ground forming offers a sustainable, landscape-friendly alternative that can simultaneously reduce noise and enhance urban spaces. This research employs robotic earthmoving to create specific ground shapes in a lab environment, allowing for precise experimental control and repeatability. By bridging simulation and reality, the study aims to enhance the reliability of noise reduction models and contribute valuable insights to environmental noise management.

2. STATE OF THE ART

This section reviews the current knowledge of environmental noise, urban noise mitigation methods, and the role of robotic earthmoving in noise reduction. The subsections focus on the challenges posed by noise pollution, existing mitigation strategies, and innovations using terrain shaping.

2.1 Environmental and Urban Noise

Environmental noise is a significant public health issue, contributing to a range of adverse health effects, including cardiovascular diseases, cognitive impairment, and sleep disturbance [5]. Long-term exposure to environmental noise is associated with increased risks of ischemic heart disease, hypertension, and mental health issues [6]. The World Health Organization (WHO) guidelines recommend road traffic noise levels not exceeding 53 dB Lden (day-evening-night average) to avoid adverse health effects, or 45 dB Lnight to prevent sleep disturbance [7].

Recent studies highlight the increasing issue of urban noise pollution and its impact on public health. Studies show that exposure to noise levels exceeding the WHO guidelines for road traffic noise has significant adverse effects. Despite the recognition of these risks, few studies explore outdoor noise reduction techniques beyond traditional barriers, especially in environments near airports and highways.

2.2 Urban Noise Mitigation Methods

Traditional mitigation techniques have predominantly focused on reducing indoor noise levels, with some outdoor solutions, like the use of vertical barriers, being common. These barriers are generally effective in reducing noise from road traffic, but they often disrupt the landscape, negatively impacting local ecosystems and human activities [7–9]. In urban settings, the deployment of vertical barriers often presents challenges, such as limiting land use and not integrating seamlessly into the landscape [10].

However, these approaches have been shown to reduce noise, with mixed effectiveness depending on design and context. Additionally, low-frequency noise from aircraft remains a major challenge for standard noise barriers [11]. A key problem with vertical barriers is that they limit land use and do not integrate well into the surrounding environment. Urban planners are now seeking alternatives that reduce noise while maintaining the aesthetic and environmental value of urban landscapes.

2.3 Robotic Earthmoving and Terrain Modification

Advancements in robotic earthmoving technology have significantly improved our ability to create precise and repeatable terrain modifications [12]. These robots have been employed in various soil manipulation tasks, including leveling, shifting, and piling [13]. The development of autonomous systems and mobile robotic platforms for earthworks has opened up new possibilities for large-scale, highly accurate terrain reshaping [14].

Recent research has demonstrated the use of robotic technologies for autonomous terrain manipulation. These technologies enable precise shaping of the landscape in a repeatable manner, allowing for highly controlled experimental testing [15]. Robotics in earthmoving allows researchers to produce ground shapes that can be tested for noise mitigation capabilities, ensuring accuracy and precision in experiments.

2.4 Recent Innovations in Noise Mitigation Using Ground Shaping

In addition to traditional vertical barriers, recent innovations have explored terrain modifications as a means to mitigate noise in outdoor environments. Previous studies have shown that certain terrain shapes, like concave and convex forms, can significantly alter the propagation of sound waves, creating acoustic shadows that reduce noise exposure [16, 17]. These studies found that mounds with varying heights could reduce noise by up to 28 dB under ideal conditions, with larger terrain shapes achieving better results.

These studies demonstrated that altering the ground shape could help reduce the reflection of sound waves, with notable reductions in noise levels. Despite promising simulation results, there is a lack of empirical data validating these simulations in real-world settings.

2.5 Research Gaps

While simulation studies have made significant progress in predicting the potential benefits of terrain shaping for noise reduction, there is a lack of empirical validation in actual field environments. Key gaps in the research include: (1) a lack of direct comparisons between different ground shapes and their effectiveness in noise reduction across a range of frequencies; (2) insufficient exploration of how robotic technologies can be employed to create accurate ground forms for testing; and (3) limited understanding of how terrain modification can be effectively integrated into urban planning and landscape design. This research aims to fill these gaps by conducting scale model experiments with controlled acoustic conditions and robotic earthmoving technology, providing empirical data to validate the effectiveness of ground shaping for noise reduction.

3. OBJECTIVES AND SIGNIFICANCE

This study aims to empirically evaluate the effectiveness of ground shapes in reducing noise levels using scale model experiments that simulate real-world urban noise conditions. The key objectives include: (1) identifying the most effective ground forms for reducing noise in scale models; (2) analyzing the potential for applying these findings to full-scale outdoor scenarios; and (3) exploring how scale models and robotic technologies can advance our understanding of terrain-acoustic interactions.

The expected significance of this work lies in the development of more sustainable and integrated noise reduction strategies. By providing empirical validation for terrain shaping, the research offers a potential alternative to conventional vertical barriers—one that can be better integrated into urban planning and landscape design, with implications for future environmental policy.

4. METHODOLOGY

This section describes the experimental approach used to assess the effectiveness of different ground shapes in reducing noise. It covers the scale model setup, the robotic earthmoving process, and how noise attenuation is measured.

4.1 Experimental Setup

The experimental setup (seen in Fig. 1) uses a 1:500 scale model to replicate urban noise conditions, allowing controlled experimentation while maintaining key real-world acoustic interactions [18]. Ground shapes, including convex, concave, tri-convex, and random, were created using robotic earthmoving technology (see Fig. 2). Noise is generated using a speaker, and its attenuation along the shaped ground is measured using a high-precision microphone. This setup allows for controlled, repeatable experiments to assess the impact of different ground shapes on noise propagation.

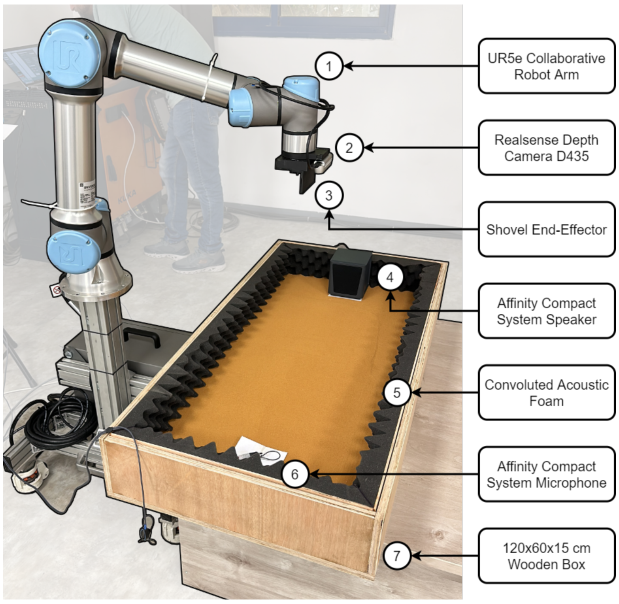

Figure 1: The experimental setup: (1) UR5e robot, (2) Intel RealSense D435 depth camera for 3D scans, (3) a custom 10×5 cm shovel for robotic earthmoving, (4) Interacoustics Affinity speaker (noise source), (5) convoluted acoustic foam , (6) Interacoustics Affinity microphone for noise measurement, and (7) a 120×60×15 cm box for the terrain model.

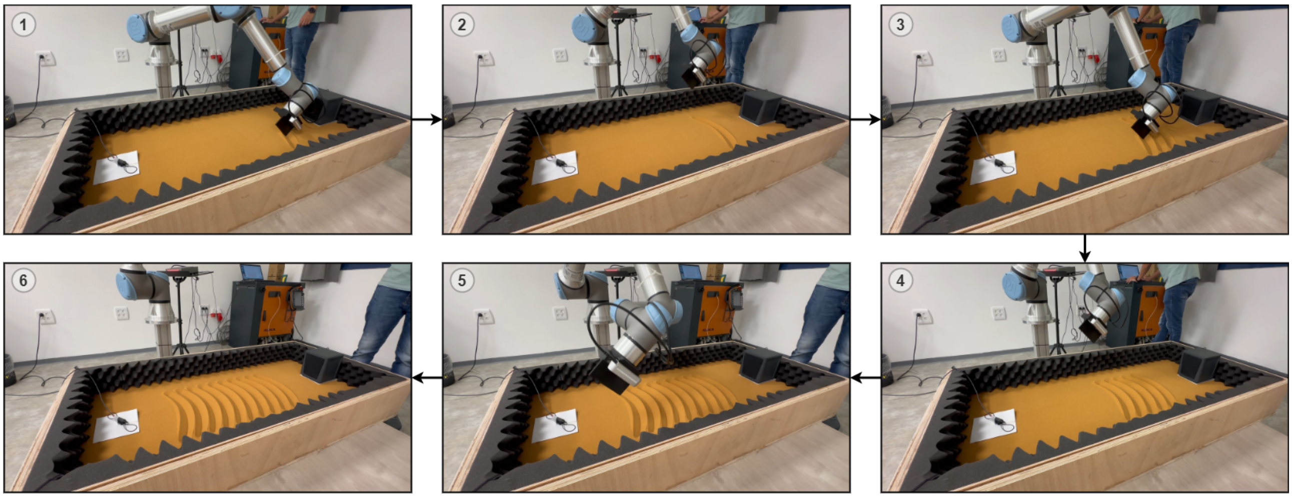

Figure 2: The robotic earthmoving process displayed on the Convex toolpath.

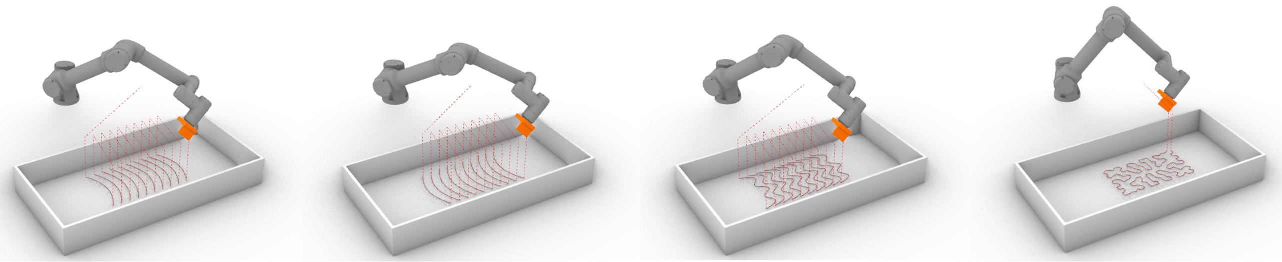

Figure 3: The robotic toolpaths designed for shaping ground forms (left to right): (a) Convex, (b) Concave, (c) Tri-Convex, (d) Random.

Figure 4: The resulting ground shapes (left to right): (a) Convex, (b) Concave, (c) Tri-Convex, (d) Random.

4.2 Robotic Earthmoving

The robot was pre-programmed to produce each of the four geometries, following toolpaths corresponding to each shape (see Figs. 3–4). The terrain, consisting of sifted dry sand, was leveled using a custom tool before creating the next shape. To eliminate any other noise, all non-essential electronic equipment in the lab was turned off during measurements.

4.3 Noise Measurements

Each terrain geometry underwent five consecutive noise measurements to minimize variability and ensure robust data. The microphone was manually positioned at one end of the box, maintaining a fixed 85 cm distance from the speaker. An initial noise measurement, referred to as 'Base' in the graph, was performed on a leveled ground surface to provide a controlled baseline for comparison.

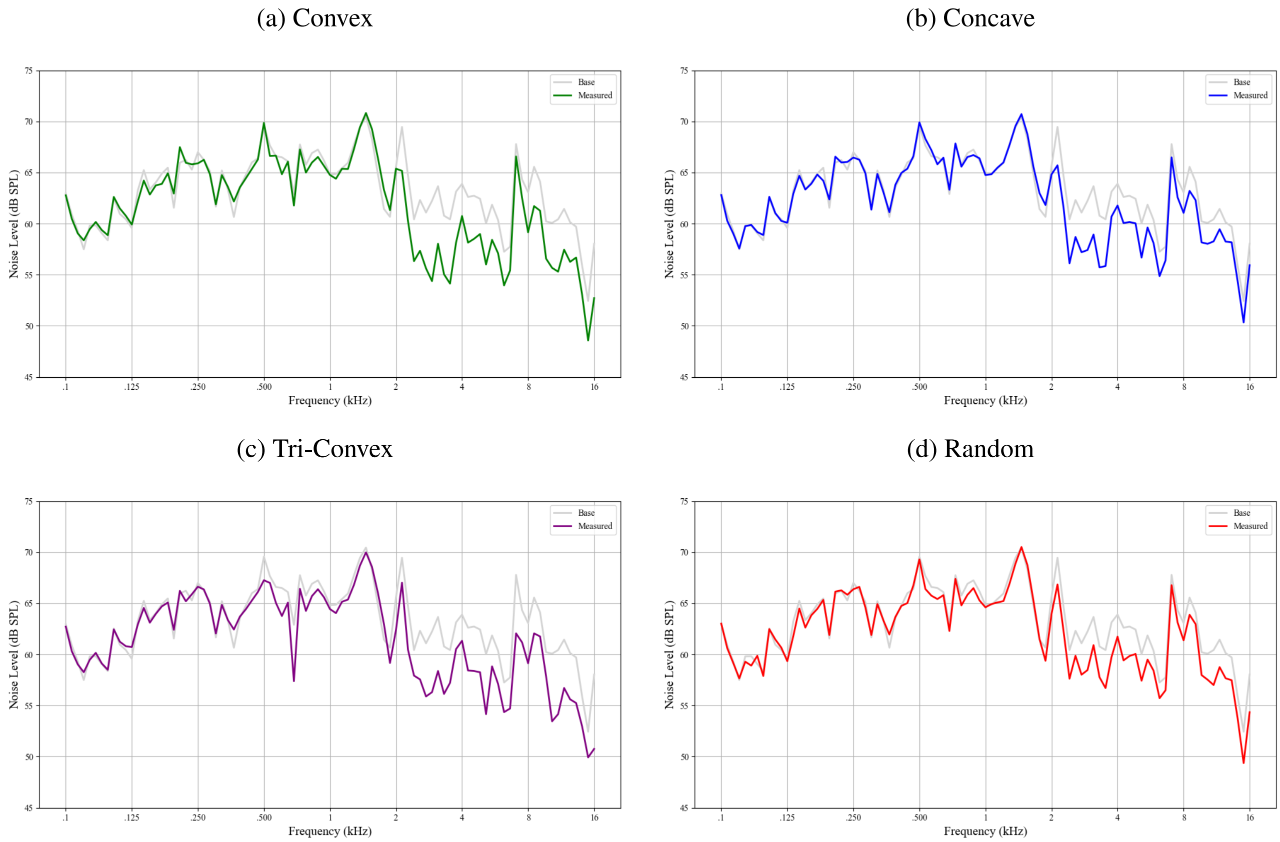

Figure 5: Noise attenuation for each tested ground shape compared to the 'Base' measurement (gray). Each plot illustrates the frequency-dependent noise reduction achieved by the specific terrain configuration.

5. RESULTS

All tested ground shapes showed a measurable reduction in noise level compared to the base especially for frequencies higher than 2kHz, with some proving more effective than others (see Table 1 and Figs. 5 and 6). Among the tested geometries, the concave shape achieved the greatest maximum reduction, with a 7.86 dB decrease in noise levels. The tri-convex shape followed closely with a maximum reduction of 7.27 dB, while convex and random shapes exhibited lower peak reductions of 5.06 dB and 3.77 dB, respectively.

The average attenuation values were calculated within the measurable frequency range of the setup (400–16,000 Hz). On average, the tri-convex shape reduced noise by 2.61 dB, followed by concave (2.37 dB), convex (1.55 dB), and random (1.55 dB). These results suggest that terrain shaping influences noise propagation, with the tri-convex shape providing the most consistent noise reduction, while the concave shape exhibited peak attenuation.

Table 1: Noise reduction summary for the tested ground shapes, showing the attenuation (Δ dB) relative to the base measurement.

Shape	**Avg Δ (dB)**	**Max Δ (dB)**
Convex	1.55	5.06
Concave	2.37	**7.86**
Tri-Convex	**2.61**	7.27
Random	1.55	3.77

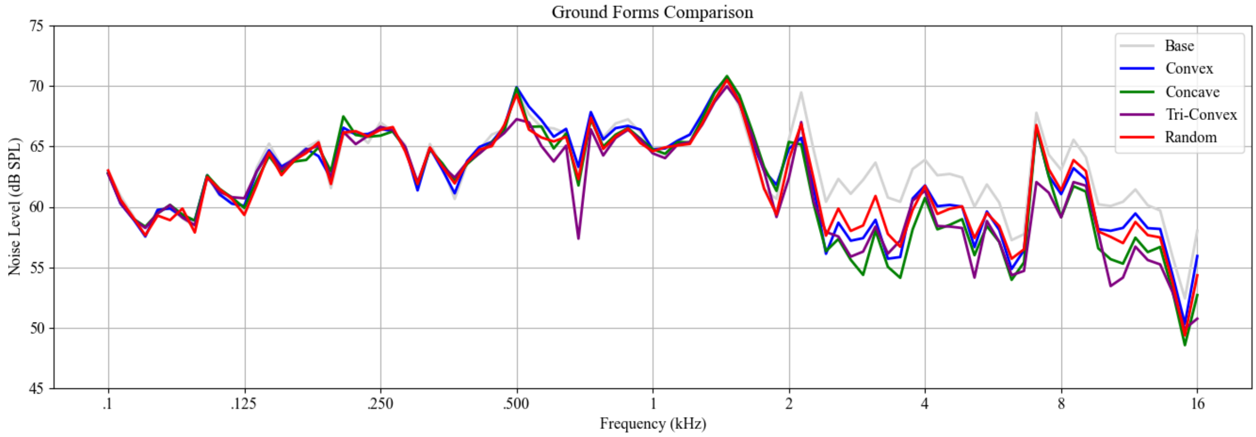

Figure 6: Comparison of noise attenuation across all tested ground shapes. The graph presents the frequency-dependent reductions in noise level relative to the 'Base' measurement, highlighting variations in attenuation effectiveness among the different geometries.

6. CONCLUSIONS

This study addresses a crucial gap in understanding how terrain modifications can mitigate urban noise. By using advanced robotic technologies to shape ground forms and validate their effectiveness through scale model experiments, the research offers a new approach to noise reduction.

While the findings provide valuable insights, three limitations should be noted: (1) the speaker–microphone distance constrains the measurement of frequencies below 400 Hz, as the corresponding wavelengths do not complete a full cycle within the setup; (2) the Sound-Level-Meter captures frequencies only up to 16,000 Hz, excluding higher frequencies that may be relevant in real-world conditions; and (3) although the tested ground shapes demonstrated measurable noise reduction, further exploration of alternative geometries—including variations in height and spacing—could enhance attenuation.

Future work will address these limitations by broadening the frequency range of analysis, scaling up experiments, and testing a wider range of geometric configurations. Nevertheless, the presented findings already demonstrate the potential of robotic earthmoving to precisely manipulate terrain for noise control. These insights may influence urban planning practices and environmental policies, offering a sustainable, landscape-integrated alternative to traditional noise barriers.

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