Real-Time Noise Sensing at Construction Sites based on Spatial Interpolation for Effective Reduction Measures

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Abstract. Construction site noise needs to be properly managed because it affects the health and safety of workers and nearby residents. Therefore, the authors attempted to develop a real-time noise information mapping system for construction sites that can support the establishment of noise reduction measures by practitioners using spatial interpolation. Field constraints were identified to ensure that the noise-estimation model has high accuracy without disturbing workers. Spatial interpolation was utilized to develop the noise-estimation model, and the performance was evaluated by installing sensors in an experimental environment according to the field constraints. The model showed optimal performance, with maximum and minimum accuracies of 97.5% and 92.4%, respectively, when using eight sensing points as inputs. The research results were visualized through the Unity 3D Engine for the convenience of field workers. Through the results of this study, practitioners will be able to easily understand information on high-noise areas that need to be managed, thereby minimizing the cost and time required for on-site noise management.

1. Introduction

Proper noise monitoring at construction sites is crucial because noise pollution causes numerous health and safety issues and civil complaints (Ballesteros et al., 2010; Eom and Paek, 2009; Hughes et al., 2015; Jung et al., 2020; Kang et al., 2021). In practice, the field manager installs sound-level meters on the site fences to measure the noise, which does not help to understand the noise propagation mechanism of the site. Accordingly, it is difficult for the contractors to prepare appropriate countermeasures when civil complaints arise due to site noise, which hinders the construction process (Choi et al., 2021; Hong et al., 2021a; Kwon et al., 2016).

This disparity has led to many studies being conducted focusing on simulating noise using noise propagation models rather than collecting and analyzing noise through sensors. (Cai et al., 2015; Gulliver et al., 2015; Hong et al., 2021b; Lee et al., 2008). The results of these approaches are suitable for one-off environmental impact assessments; however, there are technical limitations to applying the results to monitoring noise that is constantly generated during the construction stage. Estimating field noise pattern with a noise propagation model requires the real-time directivity and location of the on-site noise source. However, it is challenging to accurately collect such information in real time given the changing field environment over time. For instance, since field noise sources perform their tasks while moving, it is impossible to collect directivity by placing sensors at the same distance from the noise source according to the regulations.

To overcome the application limitations of the previous approaches using the noise propagation model, in the construction stage, the research team aims to develop a method to sense real-time noise of the overall construction site using spatial interpolation. The spatial interpolation can estimate the noise levels of the desired area if only the noise levels at some points and the distances between the sensors are known, enabling it to be applied at the construction stage more accurately and efficiently compared to the noise propagation model.

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2. Literature Review

Most of the research on estimating the noise patterns of construction sites is conducted based on noise propagation models specified in international standards such as ISO 9613-1 and 2 (Di et al., 2018; Gilchrist et al., 2003; Hong et al., 2015; Liu et al., 2021). The researchers have mainly analyzed how construction site noise spreads to the outside to respond to civil complaints that may occur during construction (Cai et al., 2015; Gannoruwa and Ruwanpura, 2007; Gulliver et al., 2015; Hong et al., 2021b; Lee et al., 2008; Santos de Oliveira et al., 2019). The propagation model calculates noise information at each point, considering the directivity of the noise source, the noise level for each octave band, as well as the surrounding terrain, temperature, and humidity. If the model has specific input data available, the noise level near the site can be estimated with good performance; as such, it can be used to estimate the damage caused by the field noise based on the equipment specification at the design phase. However, the detailed information about the input data is tricky to collect during the actual construction phase due to the constantly changing field environments. Thus, applying the propagation model to real-time monitoring of construction sites that continually change and have high levels of uncertainty is limited in practice.

Some researchers eventually decided that sensors should be utilized to obtain noise information reflecting irregularly changing field characteristics. Therefore, their research focused on developing a wireless sensor network that can be used more efficiently in construction sites by solving the inconvenience of installation and data transmission of conventional measurement systems. (Hong et al., 2022; Hughes et al., 2015; Kang et al., 2021). However, it is difficult to provide information to help practitioners manage noise by simply measuring the noise level at specific points like in practice.

It is true that existing studies have solved various problems that can occur due to construction noise, but attempts to derive meaningful information by analyzing the noise patterns generated during the construction stage were insufficient. Field managers still have a hard time checking which construction factors are the main cause when construction noise causes problems. If the problem cannot be responded to promptly, the construction must be stopped according to regulations, which inflicts significant financial damage on the contractors. For the purpose of bridging this research gap, the authors developed a method to sense and visualize the noise of the overall construction site in real time based on spatial interpolation.

3. Research Process

The process of this study consists of three steps. The first step involves identifying field constraints to be considered when placing sensors to ensure the performance and field applicability of the proposed system. Second, a low-computational yet accurate noise estimation model is developed to achieve real-time noise levels at every spot of the site. Lastly, in order to map the noise information at the grid level, the maximum noise value is extracted in units of 10m x 10m, and it is visualized in three dimensions (3D) by setting a representative value for each grid. The processing and analysis of the research data were implemented using Python version 3.7.10, and Unity 3D Engine version 2020.3.23f1 was utilized for visualization.

3.1 Identifying Field Constraints

There are various noise sources and factors that can affect noise propagation on construction sites. In addition, it may not be possible to install sensors at some points due to safety and productivity issues and space constraints. Accordingly, the authors identified field constraints that must be considered to minimize the number of sensor placements while maximizing the spatial interpolation performance without compromising safety and productivity. Based on 18 site experiments performed at different times, it was confirmed that to achieve satisfactory performance, the noise-estimation results must reflect the local extremum. This is because the spatial interpolation method estimates the noise level of the non-sensed points based on the measurement values of the surrounding sensors. In terms of noise, the local extremum points are located at the noise sources or around obstacles blocking the propagation path. Following the consultation of field workers, the authors found that noise-emission equipment, site fences (i.e., outer boundaries), steep slopes, and sound barriers were the points where sensors should be installed to detect noticeable noise changes.

On the other hand, the work areas and equipment traveling paths cannot be approached within a certain distance for various reasons. According to the safety management manual, the access restriction distance is determined differently depending on the type of work (MOLIT, 2014). In the case of earthworks covered in this study, 15m was defined as the access restriction distance. Therefore, this value was adopted as the minimum distance required when installing sensors near work areas and equipment traveling paths.

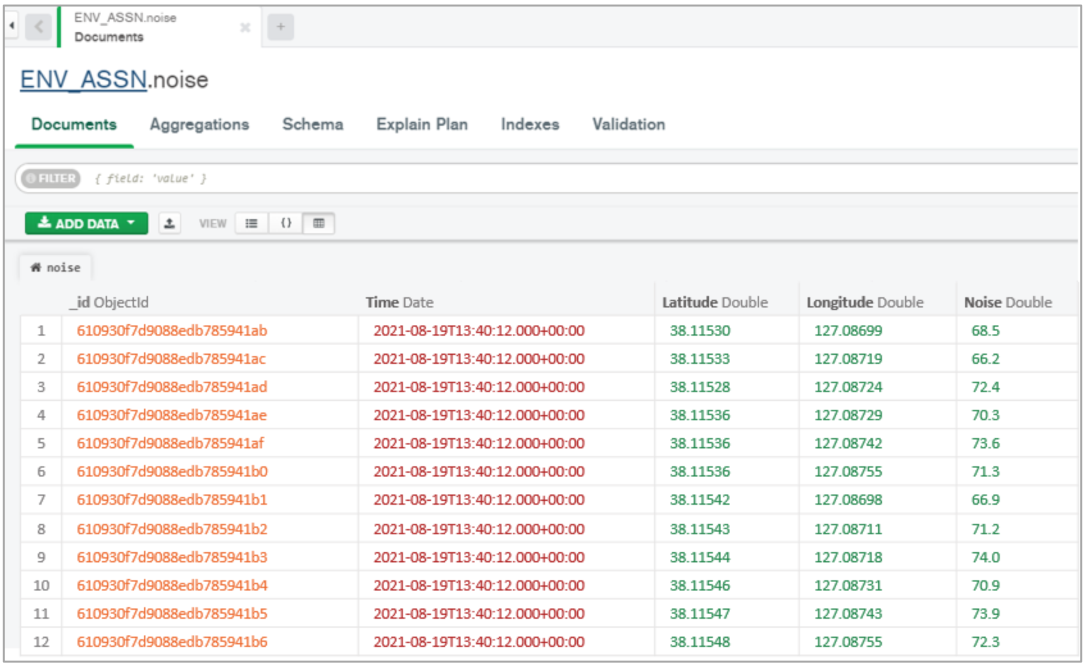
3.2 Developing Noise-Estimation Model

The authors developed a noise-estimation model based on spatial interpolation to obtain real-time noise levels at every spot of the site. Inverse Distance Weighted (IDW) interpolation, which gives greater weight to measurements near the estimated point, was utilized as the basis for the noise-estimation model. IDW is suitable for real-time estimation because it has the smallest amount of computation among the various interpolation methods. In addition, users can customize the equation in an uncomplicated way to achieve the desired results. The estimated noise level is calculated as shown in Equations 1 and 2 by the proposed model, where x^*, x_i, w_i, n, and d_i indicate the estimated noise level, actual value from the sensing data, weight, the number of measurement points, and distance between measured and estimated points, respectively. Since noise attenuation is largest at a location closest to the noise source (i.e., where the noise level is relatively high in the construction site), the weight of IDW was customized for this study by dividing it by the actual noise value. In this way, relatively low weights can be given to the points with high noise values to increase the attenuation effect for the points close to the noise source.

$$x^* = \sum_{i=1}^{n} \frac{x_i \cdot w_i}{w_i} \tag{1}$$

$$w_i = \frac{1}{(d_i \cdot x_i)^2} \tag{2}$$

The model's performance was verified through an experiment in a similar environment to the earthworks. In the experiment, noise sources were built to simulate construction site noise, and the system consisted of a passive speaker, an amplifier, and a mixer. The researchers selected the system components, considering whether they could generate loud noises like heavy equipment (i.e., more than 120dB). The excavator noise data acquired at the earthworks site were used as a sound source. The Tnsmars 103 sensor was selected, which complies with the international standard for sound level meter manufacturing. The error range of the sensor is decent at 1.5dB, while the cost is low at US$145, which is suitable for applying a large number of sensors for the experiment. The scale of the area was set to 200m x 50m by targeting the road construction site. The sensors were placed at intervals of 10m, and two noise sources were positioned. According to the field constraints, the experiment assumed that the sensor must be located more than 15m away from each noise source. The data collected from the placed sensors were stored in MongoDB, a NoSQL-based database system. The data contained time, latitude, longitude, and noise level information, as shown in Figure 1, and were sorted in ascending order by time. By randomly changing the input data, the interpolation model estimated the value from the remaining sensors. For instance, if noise data were collected by ten sensors installed at random positions among the 111 placement points, the interpolation model estimated the noise levels of the 101 non-sensed points. The performance of the model was evaluated as the difference between the actual ground truths and the estimated values.



	_id ObjectId	Time Date	Latitude Double	Longitude Double	Noise Double
1	610930f7d9088edb785941ab	2021-08-19T13:40:12.000+00:00	38.11530	127.08699	68.5
2	610930f7d9088edb785941ac	2021-08-19T13:40:12.000+00:00	38.11533	127.08719	66.2
3	610930f7d9088edb785941ad	2021-08-19T13:40:12.000+00:00	38.11528	127.08724	72.4
4	610930f7d9088edb785941ae	2021-08-19T13:40:12.000+00:00	38.11536	127.08729	70.3
5	610930f7d9088edb785941af	2021-08-19T13:40:12.000+00:00	38.11536	127.08742	73.6
6	610930f7d9088edb785941b0	2021-08-19T13:40:12.000+00:00	38.11536	127.08755	71.3
7	610930f7d9088edb785941b1	2021-08-19T13:40:12.000+00:00	38.11542	127.08698	66.9
8	610930f7d9088edb785941b2	2021-08-19T13:40:12.000+00:00	38.11543	127.08711	71.2
9	610930f7d9088edb785941b3	2021-08-19T13:40:12.000+00:00	38.11544	127.08718	74.0
10	610930f7d9088edb785941b4	2021-08-19T13:40:12.000+00:00	38.11546	127.08731	70.9
11	610930f7d9088edb785941b5	2021-08-19T13:40:12.000+00:00	38.11547	127.08743	73.9
12	610930f7d9088edb785941b6	2021-08-19T13:40:12.000+00:00	38.11548	127.08755	72.3

Figure 1: Example of the Data Collected from the Placed Sensors.

3.3 Noise Information Visualization

Finally, the noise information of the entire site derived by the noise-estimation model was mapped by 10m grids. The authors visualized in 3D by setting the representative value of each grid as the maximum noise value. In order to obtain 3D data of the experimental site, overlapping images were acquired with a drone, and the collected image data were converted into a point cloud through pix4d (commercially available software). In the case of a geographic coordinate system, it is difficult to visualize in a 3D space because the coordinate units are mixed (i.e., latitude and longitude: degrees, altitude: meters). Therefore, the latitude and longitude coordinates of the collected noise data were converted into the UTM coordinate system in meters, which is the same as the point cloud. Unconverted values were also utilized when presenting information onto the visualizer since the geographic coordinates displayed on the digital map are easier for users to understand. The Unity 3D Engine used to develop the visualizer in this study is a game-based development tool with strengths in rendering, lighting, terrain generation, and special effects. In addition, the user interface (UI) can be designed and implemented with less effort compared to existing Python or JavaScript-based visualization tools, and input data can be updated in real time by linking with the database.

4. Experimental Results

4.1 Noise-Estimation Results

Table 1 shows the results of evaluating the performance of the proposed noise-estimation model by changing the number of input points. The performance was evaluated by calculating the accuracy at each non-sensed point and averaging them. The average accuracy is calculated as in Equation 3, where x_i, x^*, n, and A indicate the actual value from the sensing data, estimated noise level, the number of non-sensed points, and average accuracy, respectively. The input data was set from six to 12 with the condition that the sensors are placed in zones that comply with the field constraints. The maximum and minimum accuracy were evaluated by random sampling of 1,000 sensor placement combinations in each case.

$$A = \frac{100}{n}\left(\sum_{i=1}^{n}\left(1 - \left|\frac{x_i - x^*}{x_i}\right|\right)\right) \tag{3}$$

As a result, the noise-estimation model obtained decent performance for the cost when using eight sensing points as inputs and the remaining 103 points as outputs; the maximum and minimum accuracies were 97.5% and 92.4%, respectively. The maximum accuracy was slightly improved to less than 0.1% per additional sensor as the number of input points increased more than eight, so the authors judged that the efficiency became less important from that number when considering the sensor cost. It was confirmed that the necessary conditions for deriving high performance were to place the sensor at the points of outskirts, noise source, and the region where the directivity and interference effect of the two noise sources existed, as shown in Figure 2. These points showed specific patterns for sensor installation to explain on-site noise distribution and ensure performance.

Table 1: Performance Evaluation Result of the Noise Estimation.

Number of input points	Number of remaining (estimated) points	Maximum accuracy (%)	Minimum accuracy (%)
6	104	95.36	95.36
7	103	96.71	93.73
8	102	97.50	92.42
9	101	97.56	92.15
10	100	97.49	92.13
11	99	97.70	91.90
12	98	97.64	91.92

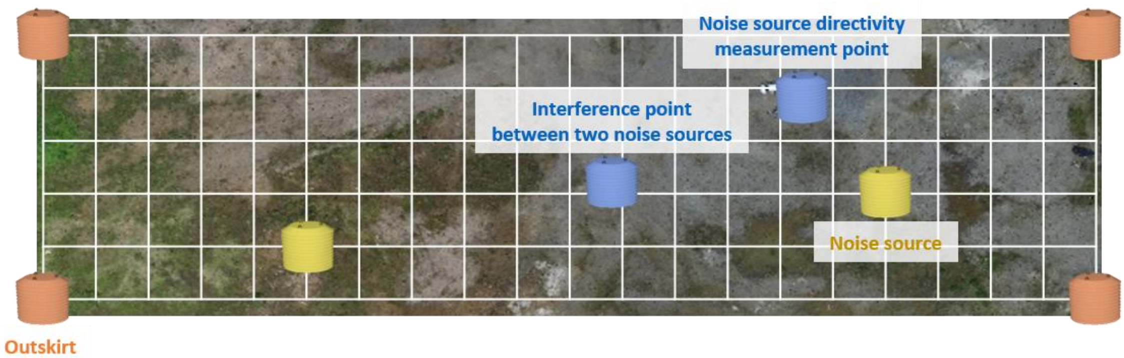
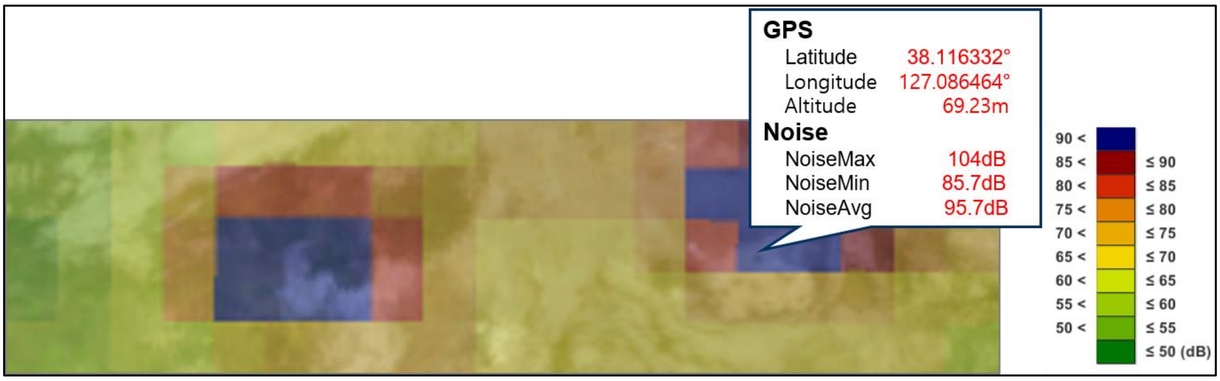


Figure 2: Sensor Placement Combination with the Best Performance for the Noise-Estimation Model.

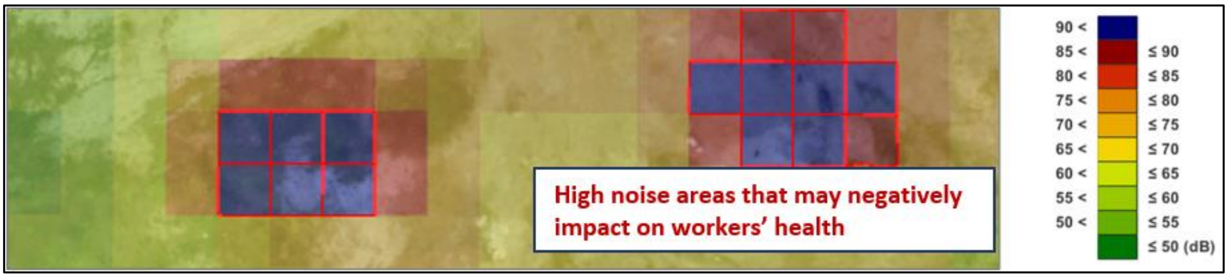
4.2 Noise Information Visualization Results

The noise information estimated based on the sensing data was mapped to the point cloud. The proposed Unity-based visualizer updated the information by calculating each grid's maximum, minimum, and average noise levels every hour. The GPS and noise information of the grid can be displayed by clicking the desired grid in the visualizer (Figure 3(a)). The GPS coordinates were plotted as the center point of the grids. The user could use the Ctrl key to check the grids generating more than 88dB noise, significantly affecting workers' hearing loss (Figure 3(b)). In addition, the Shift key functions to highlight the grids that generate noise of more than 65dB to identify areas where noise regulations are violated (Figure 3(c)).

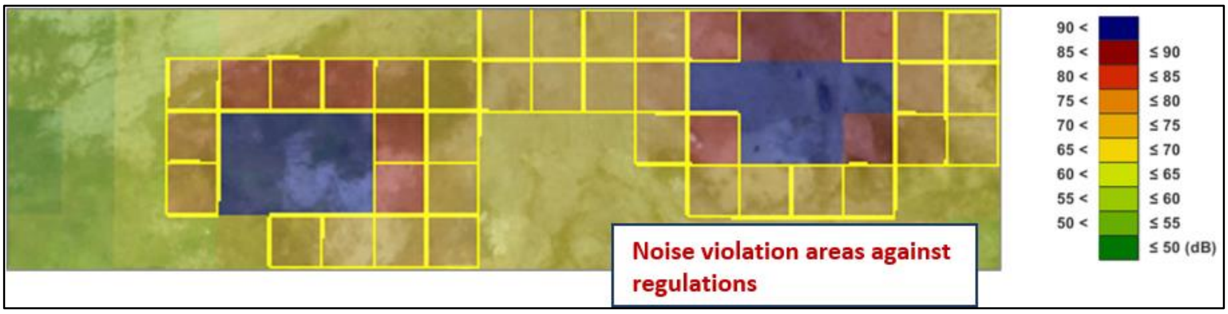
Using the research results, practitioners can easily identify areas that workers should not enter for long periods for health reasons and check how the noise changes in real time depending on the type of work. The authors plan to upgrade the UI to access various field data stored in the database so that such data can be displayed by selecting the target site, date, time, and type of information to be mapped.



(a)



(b)



(c)

Figure 3: Example of Noise Information Visualization: (a) grid information display, (b) highlighted high-noise areas, (c) highlighted noise regulation violation areas

5. Conclusion

This study proposed a system that can monitor real-time noise information based on a spatial interpolation model. The authors experimented in a designed outdoor environment similar to that of a construction site to evaluate the performance of the developed system and obtained satisfactory performance. Since this study is the first study to estimate noise information based on sensing data at a construction site, it was targeted to a road construction site that can have simple acoustic behavior without being significantly disturbed. This study can facilitate noise management in the construction stage by accurately estimating and showing real-time noise information for every spot on the site. In addition, the in-depth on-site noise data derived from the results of this study will be used as an input for noise simulation of construction activities, providing an opportunity for future research to estimate the spread of noise to the outside of the site in real time. The applicability of the model developed in this study will be evaluated in practice through actual field demonstrations.

Acknowledgments

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