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DYNAMIC EMISSION MAPPING OF SOUND AND VIBRATIONS

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This article illustrates the development of a dynamic emission mapping system. By combining a measurement network, monitoring data, AI algorithms and physics-based models, the system is able to map the emission of sound and vibration in an area, which provides insights into the effects of the dominant sources of noise and vibration on their environment. The system is generic and scalable, such that it has a broad range of applications. The conceptual framework of the system is discussed, along with several use cases.

Keywords: monitoring, emission, hybrid AI, physics

1. Introduction

In urban landscapes where infrastructure and industry converge with residential and office buildings, the associated elevated noise and vibration levels lead to significant implications for public health and well-being. The Netherlands, well known for its dense environment, is an example of this conundrum. Economic activities increasingly encroach upon inhabited areas, exacerbating the risk of annoyance and adverse health effects [1][2]. Furthermore, environments such as cleanrooms and laboratories, sensitive to sound and vibration, are also affected by the increasingly perturbed urban landscape [3][4].

Reliable emission information is key in addressing these challenges to optimize the built environment, both at the scale of individual buildings and the scale of entire cities. In this context the novel dynamic emission mapping system discussed in this paper has been developed, offering a dynamic solution for the real-time emission mapping of sound and vibration. Leveraging cost-effective measurement systems, network technology and processing power, this innovative, hybrid approach combines the strengths of monitoring stations with physics-based modelling, augmented by artificial intelligence algorithms.

The ability to autonomously monitoring sound and vibration levels across multiple locations within a designated area and map emissions real-time provides continuous insights into the environmental impact of the individual contribution of diverse sources. Filtering disturbances and noise event classification further augments the autonomous analysis. This system provides both temporal and spatial information for informed decision-making in the era of data-driven governance and digital city twins.

In this paper, an overview of the methodology underpinning the dynamic emission mapping (DEM) system is given. Its practical application is elucidated through case studies drawn from projects in the Netherlands. For clarity, the methodology of dynamic emission mapping is elucidated in this paper using the specific application for noise emission mapping, although the system works analogous for vibration emission. The analogy is subtly interwoven where relevant throughout the paper.

2. Method

2.1 Conceptual framework

The essence of the dynamic emission mapping system is the localization and quantization of individual sources of sound and vibration. To this end a measurement network is constructed, consisting of multiple measurement stations. These measurement stations locally determine the noise and/or vibration levels, which means that different parts of the measurement network can determine elevated levels due to dissimilar sources. This is illustrated in Fig. 1, where the concept of dynamic emission mapping is schematically represented. The emission of sources is detected by the measurement network. The monitoring data is sent to a central computing device where an AI-algorithm goes through an iterative search process with a physics-based model. In this process, the emission of the dominant sources in the vicinity of the measurement network is mapped to fit the occurring sound and/or vibration levels at the location of the measurement stations. Due to this mapping, also the sound and/or vibration levels caused by the dominant sources can be found at locations where no measurement station is located. A full map of the acoustic/vibrational climate and detailed statistics of emissions can be obtained.

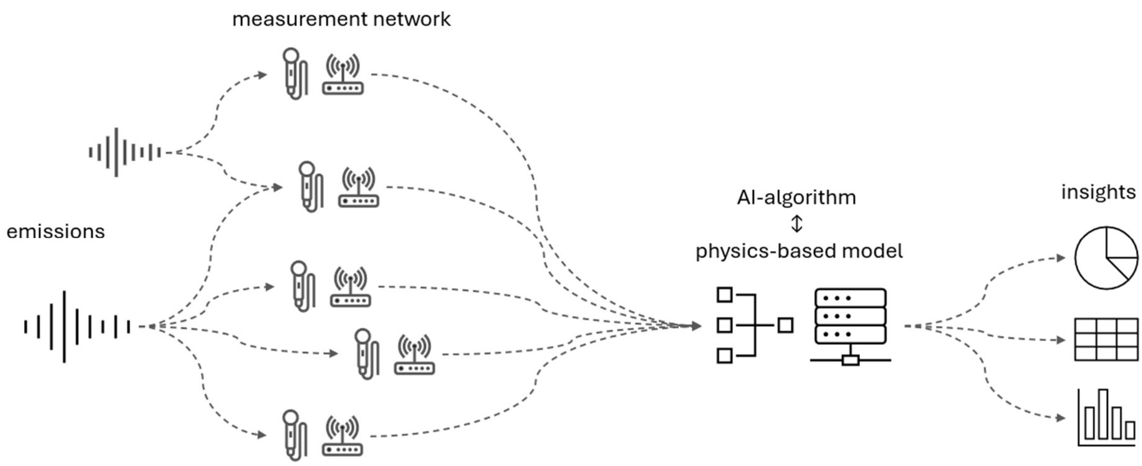

Figure 1: Schematic representation of dynamic emission mapping.

The process of emission mapping is performed with time equivalent measurement samples among measurement stations. For noise, this means that the time equivalent sound pressure level L_{eq} is obtained for all measurement stations:

$$L_{eq} = 10 \log \left[\frac{1}{T} \int_{t1}^{t2} \left(\frac{p(t)}{p_0} \right)^2 dt \right] \tag{1}$$

Here p is the instantaneous sound pressure, p_0 is the reference sound pressure and $T = t_2 - t_1$ the integration time. Analogously, a calculation can be done for obtaining equivalent vibration levels. Computing time equivalent samples is pivotal to the efficacy of the dynamic emission mapping system, as will be discussed in Section 2.3.

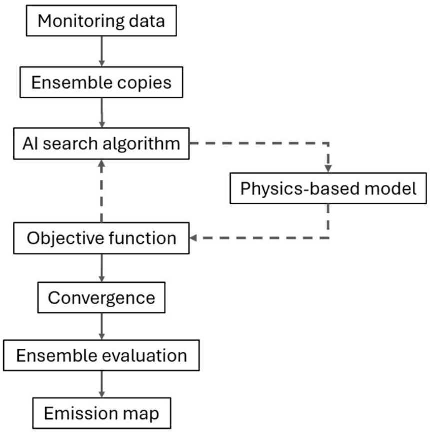

Figure 2: Process of dynamic emission mapping.

The core process of dynamic emission mapping is depicted in Fig. 2. Data consisting of the equivalent noise levels at the measurement stations is collected, together with data about the locations of the measurement stations (in case of dynamic locations) and data about meteorological conditions. The data is fed to an AI search algorithm that performs an optimized parameter search. The result of this parameter search is fed to a conceptual physics-based model, which maps the found parameters to compute the associated noise levels at the measurement stations. The computed noise levels are evaluated in an objective function against the measured noise levels. Based on the outcome of this evaluation, the process is repeated until convergence is reached. The result of this hybrid AI search is a statistical emission map associated with the measured noise levels. Non-uniqueness of solutions is resolved through ensemble evaluation.

2.2 Physics-based modelling

Underlying the dynamic emission mapping is the fundamental knowledge of sound or vibration propagation. The physics-based knowledge provides a framework that puts constraints on the possible solutions in the search space of the AI algorithm. This optimizes the search and increases the interpretability of the result. Furthermore, the application of context through implementation of physics-based modelling prevents algorithmic bias.

In general, the noise level at distance r due to a source with noise power L_w is given by the following expression [5]:

$$L_p = L_w - H(r) \tag{2}$$

In this expression $H(r)$ is a transfer function representing attenuation effects. Similar physics-based considerations can be applied for dynamic emission mapping of vibrations, where the characteristics of the specific soil in which the vibrations propagate are to be considered [6].

2.3 Configurational requirements

For localization of individual sources, it is of pivotal importance that the emission of a specific source can be detected by multiple measurement stations in the network. This puts constraints on the distances between neighbouring measurement stations in the network. The constraint is dependent on the local background noise level and the expected range of sound power levels of sources in the relevant area. The following inequality should hold for the detected noise level at multiple measurement stations:

$$L_p > L_b \tag{3}$$

For two-dimensional localization of a source at least three measurement stations are required. Assuming an approximately rectangular measurement grid, the largest distance between a source and three nearest measurement stations is when the source is in the proximity of one station. Then the largest distance is the grid spacing. A rudimentary transfer function of noise consists of geometric attenuation, air absorption and ground reflection, given by:

$$H(r) = 20 \log r + 0.005\, r\ + 9 \tag{4}$$

For the noise emitted by the source to be detected by the measurement stations, the inequality of Eq. (3) should hold. Attenuation by absorption through air only becomes relevant for large distances or high frequencies. Therefore, the term $0.005 \cdot r$ in Eq. (4) can be neglected for the approximation of the minimal required grid spacing. Substituting the grid spacing into the simplified Eq. (4) ($H(r) = 20 \log r + 9$) leads to an approximate upper bound of the grid spacing as required for localization.

$$d < 10^{\left(\frac{L_w - L_b - 9}{20}\right)} \tag{5}$$

For the DEM system to work, time delays caused by sound propagation should be negligible. This is achieved through use of time equivalent samples and putting constraints on the integration time in Eq. (1). The integration time must obey the inequality:

$$T > \frac{2d}{c} \tag{6}$$

Here d is the spacing between measurement stations and c is the propagation speed of the sound through the air or vibration through specific soil. This requirement increases the likelihood that the measured levels at neighbouring measurement stations are caused by similar sources, which is imperative for localization.

In practice, it could be challenging to exactly meet the above requirements because of availability of suitable installation locations. Therefore, a feasibility study is performed beforehand to design an appropriate measurement network for specific applications.

3. Uses cases

3.1 Construction noise

3.1.1 Determination of noise levels at dwellings due to piling work in the vicinity

The dynamic emission mapping system has a broad range of applications. The first use case discussed here is related to the determination of noise levels occurring at dwellings, resulting from piling work at a construction site. In many cases it is difficult to perform direct measurements of the occurring noise levels near dwellings for several reasons. The most pertinent obstacle is the disturbance of the noise measurements by other environmental noises, other than the noise source of interest. Secondly, it is impractical to monitor the occurring noise levels at all dwellings in the vicinity.

The dynamic emission mapping system is used in this case to map the noise caused by the piling installation on the construction site to the noise levels occurring at the dwellings. To this end, noise measurement stations are located at the boundaries of the construction site and the piling installations are equipped with GPS loggers. Because of the GPS loggers located on the piling installations, lesser measurement stations are needed, because the locations of the sources are known and only the sound power levels of the installations need to be found, simplifying the problem that needs to be solved by the emission mapping algorithm. The situation is depicted in Fig. 3.

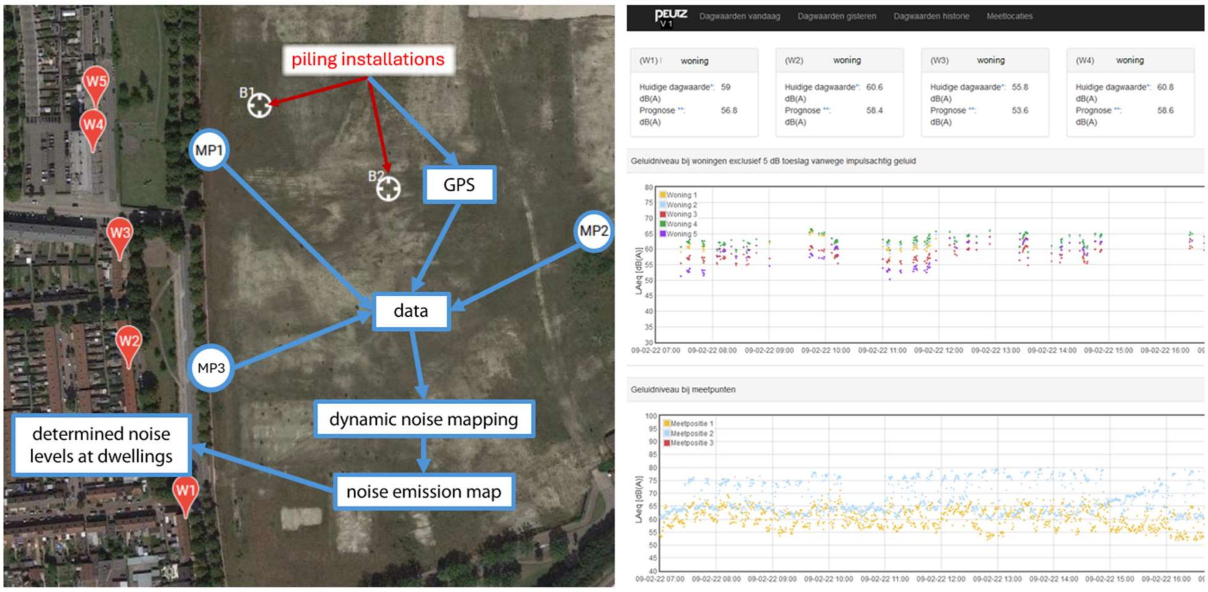

Figure 3: Application to map the noise emissions of piling installations to the occurring noise levels at dwellings in the vicinity (left) and determined noise levels near dwellings (top right) together with measured noise levels which are input for DEM (bottom right).

In Fig. 3, results are shown for the application of dynamic emission mapping. In the bottom right panel measured noise levels at the border of the construction site are shown. DEM is applied to process the monitoring data, detect piling noise and separate it from the background, compute the associated sound power levels and map these to obtain the noise level near the dwellings, which are shown in the top right panel of Fig. 3. This provides information about the current and the predicted day value of the noise level specific due to piling work. In this specific use case, there is a limit to the allowed day value due to piling work. DEM therefore provides a tool to monitor the impact of piling work on the environment and intervene when the daily noise limit is exceeded.

3.1.2 Determination of sound power levels during soil remediation

For some construction permits it is required to provide real time insight in the noise emission during the construction activities. The dynamic emission mapping system is highly suitable for such requirements. The use case discussed in this section is concerned with soil remediation. The dominant noise sources during the soil remediation activities are sheet pile driving and demolition work. Figure 4 shows the situation in the left panel.

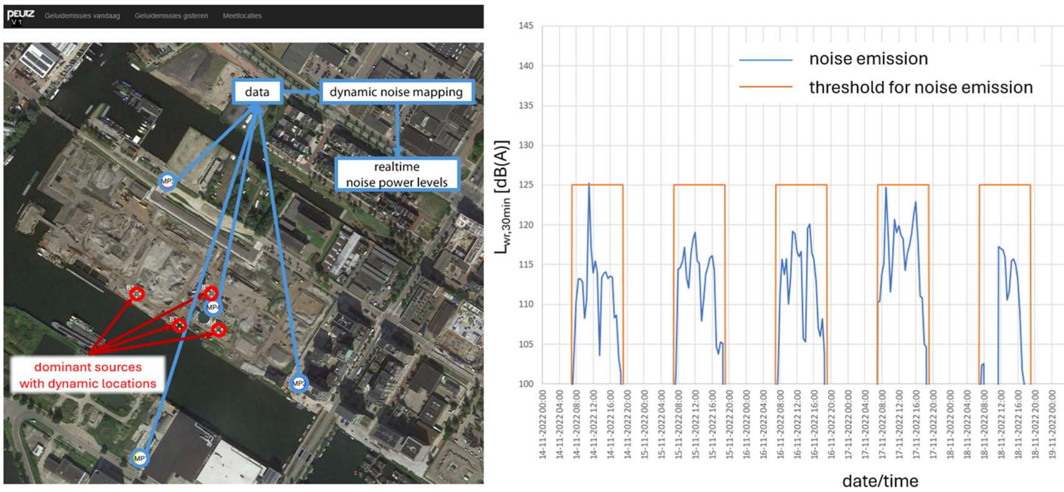

Figure 4: Construction site for which real-time noise emission is required (left) and an example of the determined sound power level compared to the threshold (right).

Results of the dynamic emission mapping for the soil remediation activities are shown in the right panel of Fig. 4. The determined noise emission is compared to a specified threshold value for the noise emission as part of the construction permit. The threshold value applies to the total noise emission of the soil remediation activities. However, because the noise emission is determined for all individual dominant sources, also insight into the spatial distribution of the noise emission for longer periods of time can be acquired. Figure 5 shows such spatial distribution of noise emission. The highest emission is found at the southwest border of the construction site. This coincides with the area where most of the sheet pile driving activities are. As the sound power level of sheet pile driving can be up to 130 dB(A) and demolition activities are typically 110 – 120 dB(A) [7], the obtained noise map is in agreement with the expectations of noise emission accumulated over longer periods of time. Also, the found sound power levels in Fig. 4 are within the expected range.

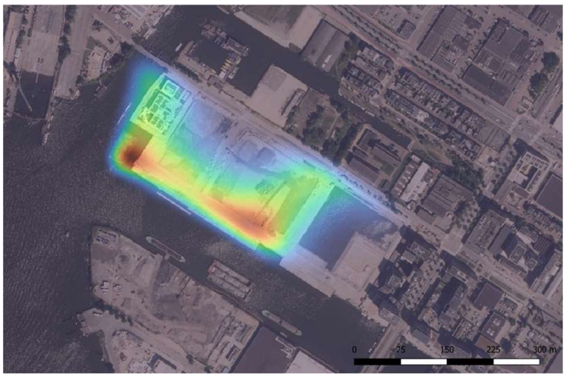

Figure 5: Noise emission during soil remediation activities accumulated over a longer time period.

3.2 Automatic determination of sound power level of moored sea vessels

The final use case of the dynamic noise emission mapping system discussed in this article is a large-scale monitoring project that aims at determining representative noise emission values of moored sea vessels. Sea vessels are diverse in usage. Therefore, per type of sea vessels the representative noise emission is to be determined. The information acquired in this monitoring project provides input for noise prognosis studies to determine the expected noise load in the neighbourhood of harbours, relevant for optimizing urban environments in order to minimize nuisance and related health risks. In Fig. 6, one of the measurement networks is shown.

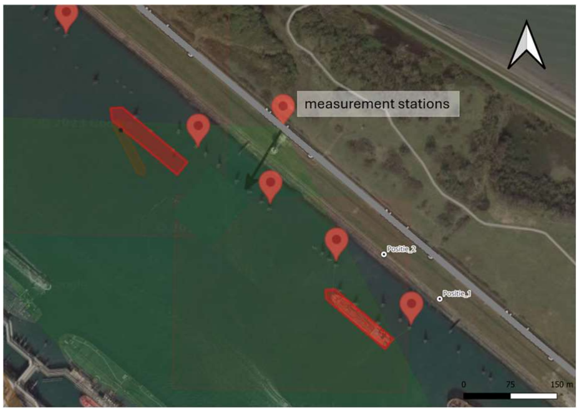

Figure 6: Measurement network to automatically determine the sound power level of moored sea vessels.

The multiple measurement networks in the harbour automatically determine the sound power level of a large amount of sea vessels. To this end, noise from the environment is filtered from noise originating from sea vessels using a separate data driven filtering technique. When the conditions are such that it is ensured in the system that the dominant source of measured noise is a sea vessel, the dynamic emission mapping system computes the acoustic centre of the sea vessel and the associated sound power level, which are then stored in a large database.

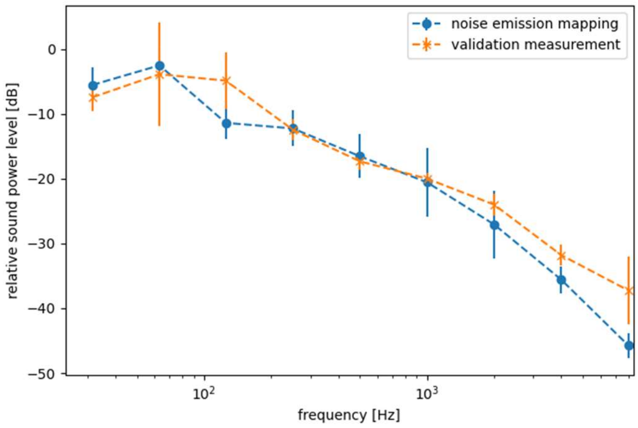

Figure 7: Comparison of automatically determined relative sound power level of a moored sea vessel with a manual validation measurement. The absolute sound power level determined automatically deviates 0.7 dB from the manually determination.

To validate the automatic determination of sound power level of a moored sea vessels also manned validation measurements are performed. A comparison of the relative sound power spectrum of a moored sea vessel determined by the automated DEM system and by manual measurement is given in Fig. 7. The result of DEM is found to be in good agreement with the validation measurement. The absolute sound power determined by DEM is also in excellent agreement with the manual determination, deviating by only 0.7 dB.

4. Conclusion and future work

In this article, the development of a dynamic emission mapping system is discussed and real-world use cases are presented. The system is scalable through the flexible setup of a measurement network and the adaptable implementation of physics-based models. The presented use cases show a broad range of applications for emission mapping of noise from different types of sources.

The generic development of the dynamic emission mapping system makes the system also applicable for vibration emission mapping. First tests are performed for mapping the vibrations originating from road infrastructure in an urban area, shown in Fig. 8.

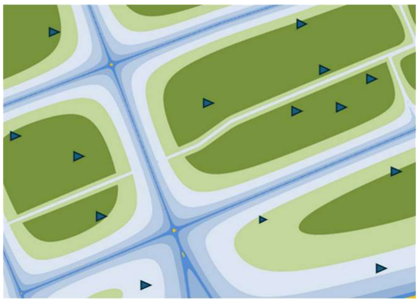

Figure 8: Vibration emission mapping of road infrastructure in an urban area, with measurement stations shown.

Future work will be devoted to large-scale application of dynamic emission mapping for multiple environmental aspects. Focus is towards integration of the system in digital city twins, in order to provide insights for informed dynamic decision making [8].

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