Sonification for 3D Printing Process Monitoring

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ABSTRACT

In order to monitor a 3D printing industrial process in a context of sensory overload and potential inattentional deafness, we designed a sonification of the information sent in by the printer. This sonification focuses not only on proper communication of the system's state, but also on lowering the amount of stress usually induced by prolonged listening. To this end, we made use of a combination of synthetic and natural sounds whose perceptual properties were modulated according to the data influx using parameter mapping. Then an experiment was conducted on the recognition of various normal and abnormal behaviours, also allowing the participants to assess the amount of stress they experienced upon listening. The results are quite promising, but also highlight a confusing overlap in the natural sounds used, which will need to be fixed in future iterations. For now, tester opinion is mostly positive on the stressful aspect. However, listening times may need to be longer in further experimentation to better assess how stressful this sonification is.

1. INTRODUCTION

Sonification as defined by Kramer et al. [1] consists in the transformation of data into a non-verbal acoustic signal to communicate information. Further narrowing of the definition by Hermann [2] specifies that this transformation must be "systematic, objective and reproducible", which implies the use of an algorithmic procedure. One of the most common applications of sonification is for process monitoring in contexts where visual perception is already saturated. The idea then is to communicate various measurements in real time by mapping them to perceptual dimensions in a carefully crafted soundscape, which can evolve into specific alarms in case of malfunctions. So far, alarms have mainly been designed according to the principle of "better safe than sorry" [3], which consists in making them loud enough to be easily noticed. Little effort was made

to properly communicate the nature of the emergency, and industrial processes were not spared by those issues [4]. The challenge in newer projects is for sounds to keep the listener's attention high enough for a quick and appropriate reaction to alarms. However those sounds must avoid becoming needlessly stressful so they can be listened to for a prolonged time without causing mental strain. In particular, if the visual context is already overloaded, there is a risk of inattentional deafness. An example of that is the way aircraft pilots sometimes tune out alarms in sensorially demanding contexts [5]. Our goal in this study is to utilize what is currently known about auditory display, especially in the field of alarms, to design a new sonification for process monitoring, geared toward an efficient and unstressful real-time communication of the system's state. We start by describing the industrial process being monitored, then the mapping choices that were made so the sounds represent the data, before reporting on the evaluation that was conducted. This evaluation shows promising results, which will be taken into account for further improvement of the sonification.

2. 3D PRINTING PROCESS
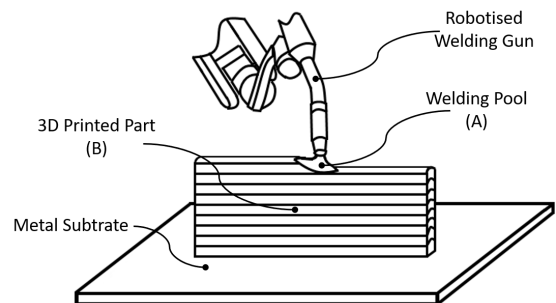
Figure 1. Illustration of the 3D printing process. **A** is the weld pool, where molten metal accumulates as the printer head moves along. **B** is the part, formed layer by layer as the weld pool cools off and hardens.

The process monitored in the present study is the automated 3D-printing of mechanical parts using molten metal. As illustrated on Figure 1, this process consists in building up layer after layer of material by deposition of droplets into the weld pool (**A** on Figure 1), which progressively cools down and sets as the printer head moves along, then forming the part (**B** on Figure 1). Sensors placed on the device take various measurements during the printing, indicating whether or not the process is going well, so that

an operator can assess the situation and interrupt it if necessary. We will refer to these measurements as "criteria". In the current state of the project, these are actually theoretical and are acquired through a simulation of the system. They are as follows: weld pool height (WPH), weld pool width (WPW), weld pool temperature (WPT), part height (PH) and part temperature (PT). PH is to be monitored in relation to its expected value (normal height of a layer multiplied by the number of layers). WPW and WPH will be grouped together as the single criterion weld pool dimensions (WPD). The sonification will be heard through noise-reducing headphones. It must give a clear representation of each of these criteria and indicate when to react in case of malfunction. In those cases, the listener must also be able to tell which criteria are deviating. See Table 1 for a list of the criteria, their ideal values, and their tolerated deviations.

Criterion	Ideal value	Tolerance
WPH	$3.00mm$	$+/-10\%$
WPW	$4.00mm$	$+/-10\%$
WPT	2000^oC	$+/-10\%$
PH	Expected PH	$+/-1.5mm$
PT	600^oC	None

Table 1. Ideal values and tolerances for each of the criteria. PH is always compared to its expected value for the current layer (number of layers multiplied by the height of a layer). PT has no tolerance value, only a threshold that can not be exceeded.

3. PARAMETER MAPPING

Sonification for this project was based on the parameter mapping model. As the focus of this study is to produce an unstressful sound for prolonged listening, the soundscape was designed as ambiant music with the inclusion of natural sounds. Previous work worth mentioning is a recent study by Matinfar et al. [6], that explores the potential use of ambient musical sonification for surgical operation monitoring. Their evaluation focuses more on the pleasant nature of the sounds than on the efficiency of information communication, but in the present study we will consider both as equally important. Although alarm design usually requires particular attention to ambient noise in the application context [7], the fact that it is intended to be heard through noise reducing headphones in this case makes this concern less of a priority than usual. Each criterion is mapped to the loudness of a sound entity, as it has been suggested that loudness is, along with pitch, one of the best parameters to display data [8]. According to Ho et al. [9], this may be due to the fact that people react to a sound warning more promptly if it seems to occur closer to them. It also ensures that the sound noticeably emerges as anomalies appear. The criteria are grouped together into sounds of a similar nature: geometrical dimensions are conveyed through synthetic tonal sounds and temperatures through sampled natural sounds related to the weather. This is expected to help in the learning process by occupying distinct cognitive areas of the listener's attention. Indeed, studies have suggested that natural sound recognition is encoded in specific neural areas that allow listeners to react faster than with synthetic sounds [10, 11].

This also helps clarify the relation between small scale (WPH, WPW, and WPT), and large scale (PH and PT), criteria. Auditory display performance can be improved by combining several parameters for a single criterion [12], so both loudness and pitch are modulated at the same time for the tonal synthetic sounds. Our previous experiments with this project showed that basic synthetic sounds alone (sine waves, noise) still make the sonification too stressful and have indicated, to a degree, the saliency of some perceptual parameters: pitch can be efficient, but should be restricted to musical notes to be better recognized and avoid inducing stress, and loudness should be modulated to make the sound less overwhelming when there is no anomaly.

Each of the four criteria is mapped to a distinct sound: a succession of high-pitched musical notes for WPD, a low-pitched drone for PH, a continuous sound of rain for WPT, and the sound of thunder for PT. More precisely, the mapping choices for this sonification are the following:

- WPD: an arpeggio played by a synthetic instrument. This arpeggio is always played according to the same intervals and in the same order (first note, first note + 2 tones, and first note + 4 tones), with the first note selected by a mapping with WPH (note values between C5 and F7) and the time interval between each note modulated by WPW (values between 0.1 and 1.0 second) so that the arpeggio is faster in case of a WPW anomaly. The volume of this melody is also computed as the mean of two amplitude values mapped to WPH and WPW respectively (each a multiplier between 0.05 and 0.2), thus making it louder if one of these dimensions differs too much from the norm. Usually, when WPH or WPW starts varying too much, the arpeggio will be interrupted and start over from the new first note computed, with the corresponding new duration. We expect the abrupt changes to be sufficient indicators that WPH and WPW are evolving, with no need to actually recognize which one is, or by how much.

- WPT: volume modulation on a sound sample of rain. Inaudible as long as the temperature is within the accepted range and loud otherwise, using an amplitude multiplier mapped between 0.0 and 1.0. This sound is also accelerated (up to twice as fast) in case of a high temperature and slowed down (up to a fourth of the original speed) in case of a low temperature, in order to convey the polarity of the anomaly.

- PH: volume and pitch modulation of a low-frequency synthetic binaural drone. Its pitch is chosen by a linear mapping between notes D3 and A#4, such that if the part is higher (resp. lower) than it should be, the drone will become higher (resp. lower) in pitch. The loudness is modulated so that if PH differs too much from its expected value, the drone will become louder (amplitude multiplier between 0.1 and 0.4).

- PT: a sudden alarm in the form of a sound sample of thunder. This sound starts playing when PT passes its threshold and plays in its entirety. It can only be triggered again once it has played to completion.

The sound is generated using a program written for the SuperCollider [1] platform. The program reads row by row from .csv files that contain simulated sensor data for vari-

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[1] https://supercollider.github.io/ - Accessed 01/10/20

ous situations. The reading and sound synthesis are done by time frames of 0.06 seconds to reproduce the temporal resolution of the sensors.

4. EVALUATION

An evaluation was conducted to assess the efficacy of the sonification in terms of information communication and user comfort.

4.1 Data

The data sonified for this evaluation consist in simulations of the measurements during 30 second phases of the process. They are extracted from the simulation of a wall printing, built by piling up straight lines of metal. A total of 10 situations were selected: 5 of a normal printing sequence and 5 in which various anomalies occur (2 WPT variations with abnormal WPD, 1 PH variation with abnormal WPD, 1 PT alarm, and 1 general malfunction where WPT, WPD and PH all diverge).

4.2 Test Subjects

A total of 9 test subjects (7M, 2F) took part in the evaluation. All have some knowledge of the concept of auditory display. Ages range from 23 to 61 with a mean of 34.5.

4.3 Evaluation Process

Participants were presented with a webpage [2] that included a text description of the project, an explanation of the mapping choices, a video allowing them to listen to each of the isolated sounds, and a grid at the bottom presenting them with the task they had to accomplish: listen to 10 sonified situations and for each one check the boxes indicating which criteria are behaving abnormally, or leave them unchecked if no anomaly was detected. The number of criteria was narrowed down to 4 with the fusion of WPH and WPW as WPD, as they are displayed by a single sound entity (see Section 3). A text box was also added for test subjects to share their comments. At the end of the evaluation phase, we computed the precision (P), recall (R) and F-measure (F) of each criterion for each of the situations, considering that a true positive is when a box was correctly checked or left unchecked, a false positive is when a box was checked despite the absence of an anomaly for that criterion, and a false negative is when a box was left unchecked despite an anomaly for that criterion.

5. RESULTS

When analysing the results in Table 2, we notice the following:
- WPD anomalies were almost always recognized, with only one false negative in one situation (WPT, WPD).
- PH was always noticed in situations where it was evolving abnormally, but has also given way to many false positives.
- WPT was generally well recognized by test subjects, with the exception of two situations. One for which it was improperly reported as abnormal, and the other where it was

Anomaly	WPD	PH	WPT	PT
None	P=1.00 R=1.00 F=1.00	**P=0.87** R=1.00 F=0.93	**P=0.93** R=1.00 F=0.96	P=1.00 R=1.00 F=1.00
PT	P=1.00 R=1.00 F=1.00	**P=0.55** R=1.00 F=0.71	**P=0.55** R=1.00 F=0.71	P=1.00 R=1.00 F=1.00
WPT, WPD	P=1.00 **R=0.94** F=0.97	**P=0.55** R=1.00 F=0.71	P=1.00 **R=0.83** F=0.91	P=1.00 R=1.00 F=1.00
WPD, PH	P=1.00 R=1.00 F=1.00	P=1.00 R=1.00 F=1.00	P=1.00 R=1.00 F=1.00	P=1.00 R=1.00 F=1.00
WPD, PH, WPT	P=1.00 R=1.00 F=1.00	P=1.00 R=1.00 F=1.00	P=1.00 R=1.00 F=1.00	**P=0.55** R=1.00 F=0.71

Table 2. Results of the evaluation. For each situation tested, we computed the precision (P), recall (R) and F-measure (F) for the recognition of each criterion. For those computations, we consider that a true positive is when a box was properly checked or left unchecked, a false positive is when a box was checked despite the absence of an anomaly, and a false negative is when it was left unchecked despite an anomaly. Highlighted in bold font are the precision and recall values that were lowered by false positives and negatives.

ignored.
- PT was well recognized in the situation where it was supposed to be, and correctly left unchecked by test subjects in all but one situation (WPD, PH, WPT), where it was checked by several participants.
- Normal situations (row "None") were usually well recognized as such, with the exception of a few false positives for PH and WPT.

6. DISCUSSION

Taking into account tester comments from the evaluation, as well as post-evaluation conversations with the initiators of the project, we gathered useful feedback on the sonification's ability to communicate information, and its potential cost in terms of stress. In particular we get more context on some of the reoccurring mistakes in the evaluation, and how to improve on them.

6.1 Communication

The use of cognitively separate sound categories for geometric and thermic criteria was generally well received by test subjects. Some users reported that it made the learning process easier for them when starting the evaluation. The sounds used were judged easy to distinguish when listening for anomalies. The only exception to this is the sounds of thunder and rain ambiguously overlapping (distant rain can be heard in the sample of thunder and faint thunder has been reported by some testers in the sample of rain), which can explain the amount of false positives for WPT in the PT situation. The reoccurring mistakes in identifying PH anomalies were due to the pitch and amplitude variations being too abrupt, even for small irregularities. This can be improved upon by setting the threshold for PH higher, thus making the modulations less sensitive. Furthermore, there is a risk that in the case of PH becoming too low, the drone may become low-pitched and difficult to perceive. The WPT alarm was deliberately ignored in one situation

by some of the test subjects because the temperature did not deviate as intensely as for the other WPT anomalies, so it did not sound as loud. It should be made clearer in the learning process that whenever rain is heard, even on low volumes, it means the temperature is deviating from the norm. The mapping of the rain sound's playback speed to WPT polarity went unnoticed but was still received as an interesting idea upon post-evaluation discussion. Further attempts to convey the polarity of anomalies are still to be made.

6.2 User comfort

Test subjects reported that this sonification was definitely less stressful than previous attemps that used basic sine waves and white noise. Some even described it as soothing. Though, it was suggested that the use of some sounds commonly considered as startling, such as thunder, may be counterproductive in reducing stress. However, as this sound is expected to occur in critical situations, its stressful nature is still considered necessary to catch the listener's attention. Participant consensus also suggests that the sounds in general should be even slower and quieter in normal situations, so that accelerations and amplifications can be heard more efficiently.

7. CONCLUSIONS AND PERSPECTIVES

In order to monitor a 3D printing process and avoid the pitfalls of inattentional deafness, we created a sonification that consists in a quiet, repetitive soundscape that mutates into louder unusual sounds when anomalies occur. Upon testing, this sonification shows promising results, both in intelligibility and in suitability for long-term listening. However, testing should now be conducted on a larger population sample to confirm these results on a larger scale. For more conclusive results on the issue of prolonged listening, we will also need to have test subjects listen to this sound for longer periods of time. Sonification for process monitoring is still a rather novel domain, with no general way of telling whether or not a model will be applicable. Because of this, experiments where operators supervise printers while listening to this model should be conducted in order to establish how well the system fares in real life situations. The evaluation also suggests a few ways this sonification can be improved in later iterations. In particular, it highlighted the existence of a perceptual and cognitive overlap between the two natural sounds used for temperatures WPT and PT. Thus, further experimentation will need to be conducted using preprocessed natural sound samples, or even replacing them with synthesized sounds, to get rid of possibly confusing artifacts. This second option of synthesizing "natural" sounds would allow for a better manipulation of their perceptual properties. Sensitivity also needs to be lowered on the PH drone in order to get rid of false alarms for this criterion. Once the results are confirmed to be satisfactory for the current task, we can start taking on more complex related tasks, such as detecting WPW and WPH separately, possibly while still encoding them into a single sound entity, or conveying the polarity of anomalies in the sound. In the long run, we hope to help the general paradigm for process monitoring progress by establishing more efficient mapping strategies for common dimensions such as temperature or geometrical dimensions.

8. REFERENCES

[1] G. Kramer, B. N. Walker, T. Bonebright, P. Cook, J. Flowers, and N. Miner, "The Sonification Report: Status of the Field and Research Agenda. Report prepared for the National Science Foundation by members of the International Community for Auditory Display," in *International Community for Auditory Display (ICAD)*, Santa Fe, NM, 1999.

[2] T. Hermann, "Taxonomy and definitions for sonification and auditory display." in *Proceedings of the 14th International Conference on Auditory Display (ICAD2008)*, Paris, France, 2008.

[3] R. D. Patterson, "Auditory warning sounds in the work environment," *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, vol. 327, no. 1241, pp. 485–492, 1990.

[4] H. Lazarus and H. Höge, "Industrial safety: acoustic signals for danger situations in factories," *Applied Ergonomics*, vol. 17, no. 1, pp. 41–46, 1986.

[5] F. Dehais, M. Causse, F. Vachon, N. Regis, E. Menant, and S. Tremblay, "Failure to Detect Critical Auditory Alerts in the Cockpit: Evidence for Inattentional Deafness," *Human Factors The Journal of the Human Factors and Ergonomics Society*, vol. 56, pp. 631–644, 06 2014.

[6] S. Matinfar, T. Hermann, M. Seibold, P. Fürnstahl, and a. N. N. Farshad, M, "Sonification for Process Monitoring in Highly Sensitive Surgical Tasks," in *Proceedings of the Nordic Sound and Music Computing Conference 2019 (Nordic SMC 2019)*. Stockholm, Sweden: KTH.: In Press, 2019.

[7] S. James, "Audio warnings for military aircraft," *Audio Effectiveness in Aviation*, 1997.

[8] B. N. Walker and G. Kramer, "Mappings and Metaphors in Auditory Displays: An Experimental Assessment," *ACM Trans. Appl. Percept.*, vol. 2, no. 4, p. 407–412, Oct. 2005.

[9] C. Ho and C. Spence, "Using Peripersonal Warning Signals to Orient a Driver's Gaze," *Human Factors*, vol. 51, no. 4, pp. 539–556, 2009.

[10] O. Schwartz and E. Simoncelli, "Natural signal statistics and sensory gain control," *Nature Neuroscience*, vol. 4, p. 819–825, 08 2001.

[11] M. Lewicki, "Efficient coding of natural sounds." *Nature Neuroscience*, vol. 5, pp. 356–63, 05 2002.

[12] S. C. Peres and D. M. Lane, "Auditory Graphs: The effects of redundant dimensions and divided attention," in *Proceedings of the 11th International Conference on Auditory Display (ICAD2005)*, Limerick, Ireland, 2005, pp. 169–174.