THE SOUNDS OF JEAN TINGUELY: FRIBOURG

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The Sounds of Jean Tinguely: Fribourg

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Abstract

Jean Tinguely, a known Swiss kinetic artist, created visual and auditory experiences through his artwork. Since his passing, conservators have worked to preserve his legacy and works as they deteriorate over time. This project explored the use of an acoustic camera as a non-invasive method to monitor and document the condition of his sculptures over time using acoustic emission recordings. As product of this research, a guidebook was created to aid those involved in future conservation efforts by explaining how to break down a sculpture into its components, take recordings using the acoustic camera, and analyze data. This project encourages recordings to be taken at a consistent, repeatable time interval for consistent data comparison of future recordings.

Executive Summary

Kinetic art is a specialized form of artistic expression that fits into a variety of art movements. It mostly takes the form of a sculpture or installation and includes mechanized components (Hanor, 2003). Kinetic art is a technology-based form of artwork that went beyond painting and stationary sculptures and was appealing to the younger generation of post-World War II artists. The term "useless machine" was often used to describe the idea behind these kinetic works of art, as the sculptures did not complete any specific tasks (Hanor, 2003).

Jean Tinguely was a renowned Swiss artist that spent his life creating kinetic sculptures that have a mind of their own and provided a full sensory experience to the viewers. His artwork is in several museums all around the world, with many of them still residing in Tinguely's home country of Switzerland (Doerr, 1998). For many sculptures, Tinguely's creativity blends with his thoughts on consumerism, the cycle of life, and a post-World War II society (Bek, 2004). Due to Tinguely's

Figure ES1

Image of *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire*

values and motivation when creating artwork, along with the wear over time of the numerous moving parts, the condition of his sculptures is far from new. The unique movements of kinetic artwork make conservation efforts more challenging than traditional static works of art (Bek, 2004), (Hanor, 2003). Preserving Tinguely's legacy, and the intent behind his artwork has been the main challenge conservators have been facing since Tinguely's passing in the early 90s. Documenting the wear and current condition of Tinguely's sculptures is the path that conservators are taking to ensure the sculptures remain as original as possible.

With the help of Eidgenössische Materialprüfungs-und Forschungsanstalt (EMPA) and Haute École Arc (HE-Arc), the goal of this project was to create preliminary efforts for museum conservators to evaluate the state of Jean Tinguely's kinetic sculptures using acoustic emission recordings. To accomplish this goal, recordings were in the Musée d'Art et d'Histoire (MAHF) in Fribourg, Switzerland, and focused on *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* (1990) by Jean Tinguely.

Figure ES2

Image of the team measuring and documenting the location of the camera

Initial recordings of the entire sculpture were taken from the front, left, and right sides. The heatmaps created by BeamformX software were used to determine and document sites producing the most prominent frequencies. These areas were localized in the next set of recordings by placing the camera directly in front of the selected area. The camera was set up in three distinct placements when taking final recordings, each placement including three trials for redundancy. The first set of recordings were taken directly in front of the site, then 200 cm to the left at 40°, and finally 200 cm to the right at -40°. This set of baseline data was documented to be used in future conservation efforts by providing initial data to be compared to.

Figure ES3

Image of the team performing data analysis

From these goals and methods, the *Guidebook for Acoustic Conservation of Kinetic Art* was created. This guidebook was continually iterated and improved through the data collection process to test the validity of recommendations within it. Using the methods developed for the guidebook, data sets were collected using the ACAM 120 acoustic camera and analyzed using BeamformX and MATLAB. From this analysis the following conclusions were generated:

1. The acoustic camera creates consistent and repeatable data.

2. Acoustic emissions recorded facing a wall created higher power results when compared to those not directed at a wall.

To prove that the acoustic camera produces precise data, a set of nine trials were completed. Each of the nine trials consisted of taking three recordings from a given location around the sculpture. There are multiple ways to analyze these recordings. A spectrogram, is a visual representation of the spectrum of f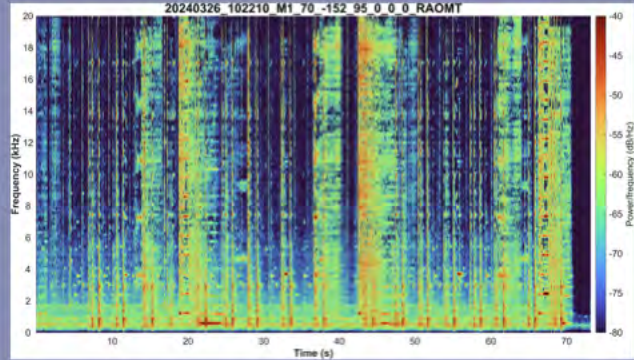requencies as it varies over time as seen in figure x. A power spectra, is a spectrogram where time is no longer considered and is power over frequencies as seen in figure x. Finally, a heatmap-like video, shows where specific sounds and frequencies are coming from as seen in figure x. Each of these were examined for discrepancies between the trials. From the generated spectra, it was clear that the acoustic camera created precise data.

Figure ES4

Example spectrogram

Figure ES5

Example power spectra
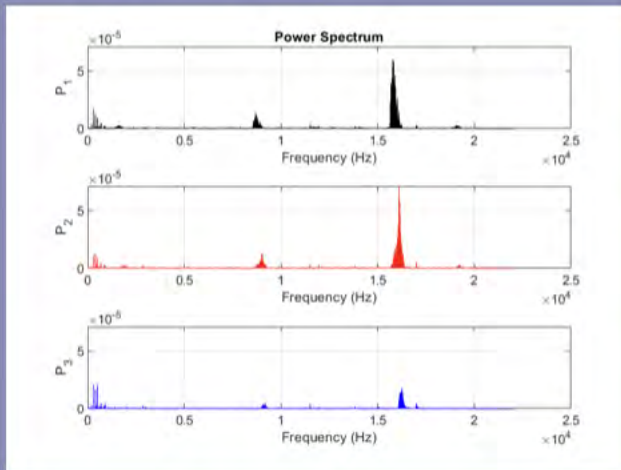
The power spectra were also used to compare the different recording locations within the room. Trials were set up from different places around the space to test how camera placement affects the readings. The conclusion was drawn that placement drastically affects the readings. Researchers must be careful when considering sound reflection within the space. The power spectra show the difference between a reading taken facing a wall and one not facing a wall. The readings facing a wall have much higher

power content when compared to readings facing away from a wall. When examining this phenomenon on BeamfomX, it became clear that the high-power content in these signals was due to reverberance in the room.

The research and data collected shows a potential for using well documented acoustic emission data to track wear in kinetic artwork. The camera has demonstrated how its repeatability and precision can be crucial to documenting the state of kinetic artwork. The data collected will serve as a baseline for future documentation and for conservators to intervene in the areas experiencing the most wear. The guidebook will be a useful resource for future documentation and analysis.

Figure ES7

Image of the team working at the MAHF in Fribourg

In conclusion, the findings from our research offer several recommendations for enhancing data collection. Firstly, the creation of separate coordinate systems for each motor system for more in-depth analysis, particularly in more complex and larger sculptures. Secondly, having a centralized database for all acoustic emission data could encourage collaboration and ensure structured and organized data documentation. Another recommendation is addressing the limitations of data collection, such as ambient noise and sound bouncing off surrounding surfaces. Acoustic treatment of the room is one way to improve these limitations. This could be done by applying acoustic foam to surrounding walls or utilizing

specially designed rooms. Additionally, managing feedback from multiple systems by running only one motor system at a time could aid in isolating frequencies of interest. Finally, annual data collection and analysis is recommended, to maintain consistency and enable meaningful comparison. By implementing these strategies, we can enhance the accuracy and reliability of data analysis of kinetic artwork, ultimately advancing the conservation of these remarkable sculptures.

Meet the Team

Fiona Leitner

Fiona is an Aerospace Engineering major with a minor in Astrophysics from New York. She is involved in various outreach programs for underrepresented groups in STEM and enjoys participating in volunteer events on campus. Fiona has loved exploring Switzerland and taking scenic walks along Lac Léman.

William Merry

Will is a Robotics Engineering Student with a minor in Computer Science at WPI, pursuing a Masters Degree in Artificial Intelligence. He is originally from Massachusetts. At WPI he plays music in several bands and is a teaching assistant for the physics department. During his time in Switzerland he enjoyed skiing and spending time outdoors.
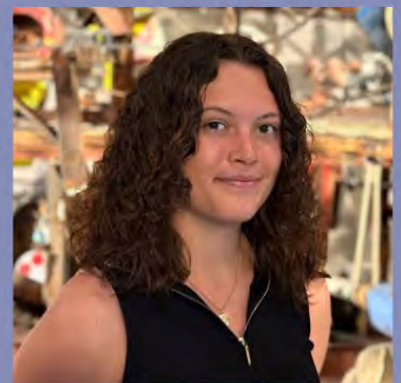

Mary Ramirez-Richer

Mary is a junior at WPI from Vermont majoring in Aerospace Engineering with a minor in Environmental and Sustainability Studies. She is a member of the Chi Omega Sorority and on the Alpine Ski Team. During her time in Switzerland she enjoyed visiting different towns by train, skiing, and going to cafes.

Taylor Walker

Taylor is completing her Bachelors of Science in Civil Engineering with a minor in Fire Protection Engineering. She grew up in Massachusetts. During her time at WPI she has competed for the Varsity Women's Swim Team. During her time in Switzerland, she spent most of it outside either exploring, hiking, or reading in a park.

Acknowledgements

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1 Introduction

1.1 Objectives and Themes

Swiss artist Jean Tinguely's elaborate creations have proven to be a unique challenge for conservators as they try to evaluate the condition of his kinetic art pieces. With various connected moving parts and differing materials, it has been difficult to develop non-invasive procedures to assess the state of his works. The acoustic camera, a device used to measure the frequencies made by sound, has been introduced as a potential method to document the condition of a sculpture without coming into direct contact with it. With the help of Eidgenössische Materialprüfungs-und Forschungsanstalt (EMPA) and Haute École Arc (HE-Arc), the goal of this project was to create preliminary efforts for museum conservators to evaluate the state of Jean Tinguely's kinetic sculptures using acoustic emission recordings.

An initial set of documented data was created for *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* by Jean Tinguely in the Musée d'Art et d'Histoire (MAHF) in Fribourg, Switzerland. Acoustic emission recordings were taken using the Signal Interface Group's ACAM 120 Acoustic Array, and data was collected through BeamformX and converted to spectrograms using MATLAB. By creating baseline data for this piece and establishing a guidebook, the project encourages continuous use of acoustic emission recordings to assess the condition of kinetic sculptures. Having a guidebook for taking acoustic emission recordings of kinetic art is important for ensuring that steps can be replicated in future conservation efforts. This also contributes to accurate comparison of data taken over the years, allowing for conservators to evaluate the state of each piece and make necessary repairs. This guidebook is not specific to Jean Tinguely's work and can be followed to take acoustic recordings of other kinetic artwork.

1.2 Rationale

Kinetic art is a specialized form of artistic expression that fits into a variety of art movements. It mostly takes the form of a sculpture or installation and includes mechanized components. Abstract art was influential post World War II in Paris, France. The three main art movements happening in Paris in the 1950s were Abstract Impressionism, Constructivism, and Surrealism (Hanor, 2003). With these movements taking Paris by storm, kinetic art was the next big step in abstract artwork. A more technology-based form of artwork that went beyond painting and stationary sculptures was appealing to the younger generation of post-World War II artists. With technological advancements on

the rise, interest for an integration of artwork and technology was at an all-time high.

Kinetic artwork moves with no end in sight, continuing to always move and change. The term "useless machine" was often used to describe the idea behind these kinetic works of art. There is humor and irony that goes along with kinetic art, as the sculptures never complete a task or have a stopping point. This irony and humor are an homage to the Futurism and Dada movements that included other ironic contemporary art styles (Hanor, 2003). The purpose behind kinetic art was not to complete a task, as many machines are meant to do, but to create an aesthetic spectacle to be observed, not used. Works of art that fit into the kinetic sector of Dada and Futurism categories were inspired by technology and the moving parts they included. Cars, printing presses, wheels, pistons, and machines in general are some of the technology-inspired artworks.

Another important aspect of kinetic art that further adds to its uniqueness is how the location of the sculptures and installations is crucial to ensuring the best experience of the artwork. The space that kinetic works of art are kept in is important to make sure there is enough room for them to work properly and be displayed in the specific way they were meant to be. Installations specifically require the proper amount of space as they engulf their surroundings. Lighting is another key component to highlighting and extenuating what the artist wants to convey to the viewers. This can be seen in Figure 1.An additional unique challenge that arises with kinetic art is that the art must be assembled. Reconstruction and assembly are difficult and must be done properly to keep the authenticity and intentions of the piece (Caianiello, 2018). Additionally, the wear and tear on kinetic artwork is far more intense than it would be on a static sculpture or painting. The mechanical systems are extremely complex and require different maintenance and conservation strategies.

Figure 1
Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire by Jean Tinguely at The Musée d'art et d'histoire in Fribourg, Switzerland
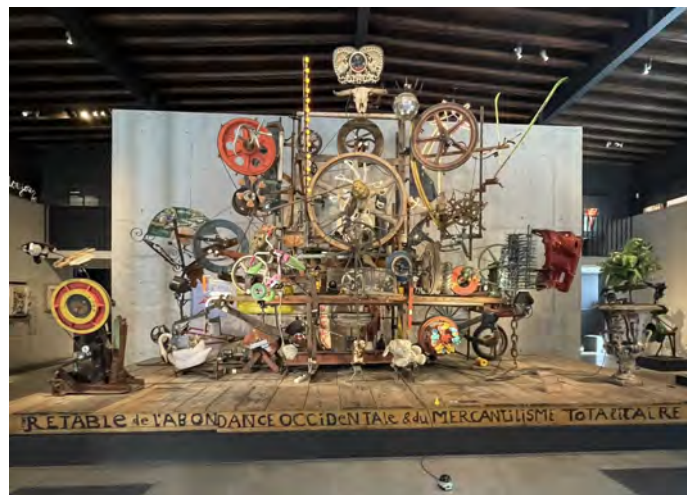
Jean Tinguely was a Swiss artist that focused on kinetic sculptures and installations and first got started with his significant works of art in the early 1950s. Born in 1925 in Fribourg, Switzerland, Jean Tinguely was an artist with an affinity for movement in art and unique ways to express motion. He began his exposure to art and design at a young age in 1944, when he learned about window styling and began taking classes at the Allgemeine Gewerbeschule School of Applied Arts in Basel, Switzerland (Doerr, 1998). Although his formal artistic training was far from extensive, Tinguely's art remains significant and appreciated, especially in his home country of Switzerland. However, since his death in 1991, conserving his artwork has proven challenging and has raised ethical concerns surrounding the preservation and authenticity of his sculptures.

It was not until 1954 that Jean Tinguely created his first meta-mechanical piece of artwork. He began to dabble in kinetic art shortly after moving to Paris in 1953 to better absorb the contemporary art movements. This first relief was Constructivist-influenced, including rotating geometric and biomorphic shapes on top of flat boxes that were solid colors. Throughout his artistic career, Tinguely changed his color schemes to soon adopt the simplicity of black and white. His inspiration to use garbage in his artwork came from the connection he made with a post-World War II society (Bek, 2004). In 1958 he began using deconstructed pieces of technology including radio and broadcasting equipment components. These new mediums he was using opened a new door for him, as he began incorporating welding into his work. The broad use of materials expanded the possibilities of Tinguely's artwork.

The mechanical components of Tinguely's work were another fascinating feature of the sculptures. Although the electrical cords that could be seen from behind the artwork, Tinguely was intentional about the visibility of the motors that drove the sculptures' motion. Tinguely's motors were composed of an intricate web of pulley systems, as can be seen below in Figure 2.

Figure 2
Annotated Photo of a Complex Subsystem in *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* by Jean Tinguely
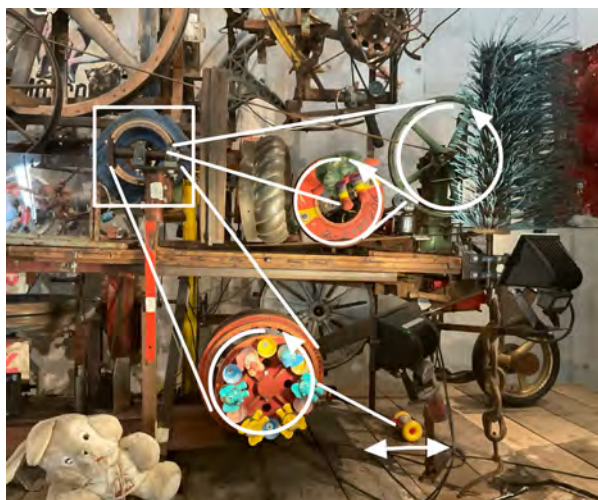
To ensure the artwork's meaning was not taken away, and the movement of the elements remained mysterious, the motors were not visible to the public during exhibitions and in galleries. The repetition of the motors and movement of the pieces gave an endless feel to the sculptures. They were always changing with no end in sight, making it a unique art style. The intricate systems that create the motion of the pieces contribute a wide variety of sounds that add to the uniqueness of Tinguely's artwork. *Méta-Matics* was the title Tinguely gave to his elaborate works of art that were more than just a visual experience. The sculptures generate an abundance of sounds, smells, and visual experiences. He had machines that created art, produced smells, and even destroyed themselves (Bek, 2004). Tinguely went against the typical definition and purpose for machines. Machines are designed and built to complete pre-determined tasks, however, Tinguely strived to have the machines do the opposite; nothing.

Jean Tinguely's kinetic sculptures critiqued society and overproduction during the late 1900s. The waste created by consumerism and overproduction inspired many of Tinguely's pieces. Much like other kinetic artists during the period, Tinguely played with the concept of time (Chau, 2014), and many of his pieces were made to fall apart or break over time. Similarly, Tinguely created satirical works commenting on how modern society and work culture promote a life that does not involve living in the moment. He challenged the current work-dominated lifestyle and encouraged people to enjoy the smaller things. Tinguely even stated, "Be permanent by being static!" (Brett and Grandas, 2000). Creating movement and activity influences life around you; the memories you develop and share with others will ensure that your impact will be remembered.

The sculpture this project is focused around is *Le Retable de l'Abondance occidentale et du Mercantilisme totalitaire*. This piece was made in 1989/90 and was originally displayed in Moscow, Russia until it was moved to Espace Jean Tinguely - Niki de Saint Phalle at The Museum of Art and History (MHAF) in Fribourg, Switzerland. The meaning behind this sculpture is to look at the consumer society and "to illustrate the subject of total colossal idiocy of our industrial capitalism"(Tinguely). The building in which the sculpture is displayed in originally housed the Fribourg tram depot in 1900. It was then converted into a space that pays tribute to the creativity of a legendary couple of 20th-century artists (MHAF, 2023). For more information on the history of the sculpture see Appendix A.

Conserving Tinguely's art is especially challenging, as he particularly used unconventional materials in his kinetic sculptures. Tinguely used scrap metal and automobile parts that were considered junk as materials for his sculptures. This choice contributed to his critique of the overproduction of technological parts. These materials that were previously unused were prone to fracture and wear away more easily. By assembling these components in an unstructured manner, the original work can be difficult to accurately replicate when conducting repairs (Meijer et al., 2018). Many of Tinguely's pieces were made to deteriorate over time, prompting the question of whether it is ethical to conserve the piece at all. In 1984, Tinguely stated in an interview, "My works are not intended for eternity, they'll wear themselves out and land back on the garbage heap whence they came." Unfortunately, due to his passing in

1991, Tinguely is unable to approve or disapprove of conservation efforts. When asked about the conservation of his piece, *Sculpture méta-mécanique*, "Tinguely did not consider replication here, choosing instead to boldly embrace the inevitable consequence of 'failure' inherent in kinetic art. He often played with the concept of the 'breakdown' of his own works as a metaphor for the possible 'breakdown' of technology and even society" (Bek, 2018). Despite past vocalizations against the conservation of his works, the protection of his legacy and the significance of his works both culturally and to the movement of kinetic art have prompted museums to implement different conservation techniques.

Using proper and ethical methods to conserve Tinguely's work is necessary to preserve his legacy (Doerr, 1998). Without Tinguely being able to restore his own works of art, it is important that the authenticity is preserved when restored by other art conservators. Preserving the movement, sounds, and intent of the artwork is challenging but worth keeping the sculptures around for as long as possible.

Tinguely's artwork poses an abundance of challenges regarding the conservation of the sculptures (Bek, 2004), (Hanor, 2003). Invasive conservation techniques can significantly alter a pieces' original purpose, resulting in a loss of authenticity. To avoid this issue, conservators are looking for non-invasive or minimally invasive methods to use in future conservation efforts. Another challenge that is unique to Tinguely's artwork surrounds the issue of collecting consistent data of something that never behaves the same. The constant movement and wear that comes with the unpredictable motion of the sculpture is difficult to track and adds to the complexity. In addition to the originality and movement of the sculptures, the materials that make up the sculptures are unique and part of the intent behind the artwork. Tinguely used deconstructed pieces of technology including radio and broadcasting equipment components, and some of his sculptures are meant to break down over time. This makes the ethics surrounding conservation of his artwork challenging. Many pieces of Tinguely's art were inspired by World War II, and he expressed this by creating art with old, run down materials (Bek, 2004). Keeping the grunge appearance and intent of Tinguely's work is challenging and can only be accomplished using as non-invasive methods of conservation as possible.

1.3   State of the Art

Due to the many moving parts of Jean Tinguely's work, it is vital to examine the ways the mechanical systems within a sculpture are worn over time. A past study showed how acoustic emissions are generated at the sites of sliding of materials resulting in material wear (Hanchi and Klamecki, 1991). A result of this study was how acoustic emission energy measurements can be related to important physical parameters and can be used as a tool to investigate basic aspects of the wear process in materials. Another study presents the same conclusion in how data collection and analysis of acoustic emission signals from lubricated sliding contacts can show the wear process occurring in materials (Boness and McBride, 1991). Examining acoustic emissions of a kinetic sculpture is a useful tool when examining

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wear of mechanical systems. The Signal Interface Group ACAM 120 Acoustic Array camera is able to record specific sound frequencies as it is made of 40 digital microphones on a 40 cm x 40 cm plate and a 5-megapixel camera in the center of the microphones (Group, 2017). Due to this setup, it can record videos, display the spectrogram as seen in Figure 3, and display heatmap-like images as seen in Figure 4. These are useful tools when comparing acoustic emission data over time to track wear.

Figure 3
Example of spectrogram of *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* by Jean Tinguely
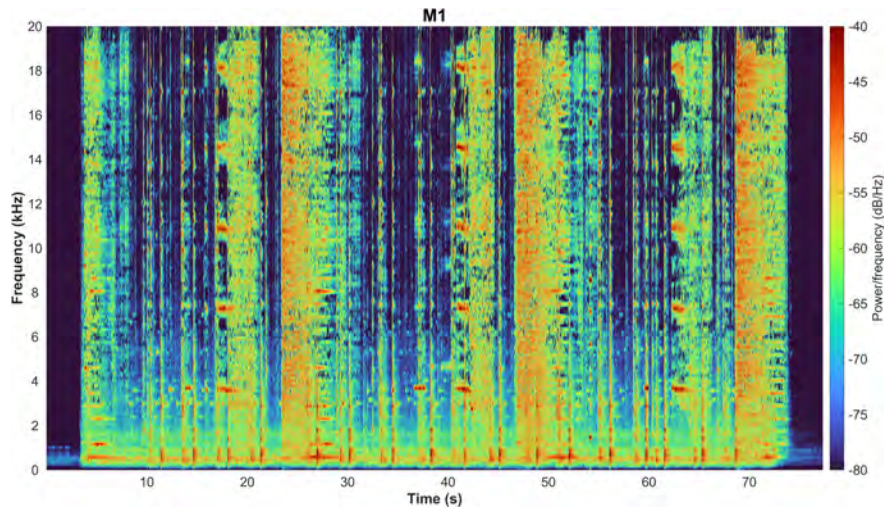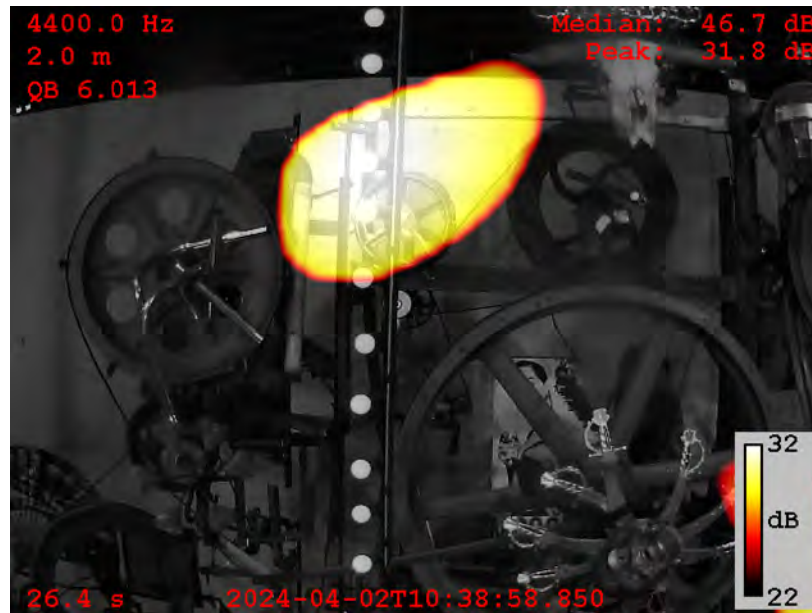

Figure 4
Example heatmap of for *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* by Jean Tinguely

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Past efforts of Worcester Polytechnic Institute (WPI) students have used the acoustic camera technique to document damages and assist with the conservation of Tinguely's work. A previous project completed in 2017 gathered information about the values of stakeholders in Jean Tinguely's sculptures. The study showed how stakeholders have deep emotional connections to his artwork, and the importance of the sounds made by the sculptures are to the experience (Skeggs et al., 2017). The second project completed in 2022 developed a shared database for private professionals and Swiss Museums about conservation efforts (Bolshakov et al., 2022). The last project, completed in 2023, was using an acoustic camera on Jean Tinguely's sculptures to find sources of specific sounds made by the sculptures (Rodriguez Plassa et al., 2023). These projects spanning from 2017-2023 have contributed to understanding the values and conservation efforts associated with Jean Tinguely's kinetic artwork. They emphasized the importance the acoustic emissions of Jean Tinguely's sculptures and how it these sculptures are hard to maintain. However, past projects used inconsistent methods compared to the previous groups, making it difficult to use data for future comparisons.

1.4   Approach

The focus of this project was to deliver a guidebook for the conservation of kinetic sculptures created by Jean Tinguely. This practice, serves as a guidebook and outline the best ways to log data and conserve kinetic art. In researching different methods of acoustic emission recordings, a data set was gathered. This was a part of the final deliverables as well. This collection and analysis were completed in a different manner for each project and there does not appear to be a solid line of reasoning as to why the researchers chose to record and analyze the data the way they did. This project continues efforts to conserve his work by filling in the gaps left by past researchers. This project explored the methods of the past researchers and created unique methods using the acoustic camera to find the best practices for conservation of Jean Tinguely's artwork.

1.5   Summary

Jean Tinguely was a historic artist whose art is influential to Swiss culture. His kinetic art is being displayed and conserved by museums throughout Switzerland and other European countries. Through conservation, questions have been raised regarding the ethics of conserving Tinguely's art as many believe it was made to deteriorate with time. Although there have been many different conservation efforts for Tinguely's work, the use of the acoustic camera is not yet adopted by many as there is no standardized procedure.

2   Methods

2.1   Project Goals

With the help of Eidgenössische Materialprüfungs-und Forschungsanstalt (EMPA) and Haute École Arc (HE-Arc), the goal of this project was to create preliminary efforts for museum conservators to evaluate the state of Jean Tinguely's kinetic sculptures using acoustic emission recordings. To accomplish this goal, the objectives were to:

1. Gather acoustic emission data for *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* in the Musée d'Art et d'Histoire (MAHF) in Fribourg, Switzerland.

2. Analyze acoustic emission data using BeamformX and MATLAB.

3. Create a guidebook for analyzing kinetic artwork.

2.2   Objectives

2.2.1   Gather acoustic emission data for *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* in the Musée d'Art et d'Histoire (MAHF) in Fribourg, Switzerland

The first objective was to obtain data on the sound intensity and frequency of the sounds made by Jean Tinguely's sculptures. To do so, an acoustic camera was used to take recordings of Tinguely's pieces. The specific camera model used was the Signal Interface Group (SIG)'s ACAM 120. Due to the sensitivity of the camera to noise, data collection occurred when the museum was closed on Tuesdays to ensure that there was no interference from visitors or other audio sources disrupting the data. The sculpture is mounted on a 696cm x 306cm rectangular platform and each side was labeled; front, left, right, and back. The camera positioning followed a defined coordinate system to ensure consistency and repeatability throughout the data collection. The setup included the acoustic camera on a tripod standing at a documented distance using the created coordinate system, which allowed for allowed for accurate replication of camera setup if recordings needed to be redone. The location of the camera was measured and recorded from the edge of the platform in an x, y, z coordinate system, with the z-coordinate being the height of the center of the camera measured from the platform of the sculpture. The origin of this coordinate system was the front left corner. The angle of the camera was measured and recorded with a θ, ϕ, ψ coordinate system that followed the

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path of the unit circle, with zero degrees being the back. These two coordinate systems can be referenced in Appendix B. Using a log of components and motors provided by the museum, a system details table was used to record the specific section of the sculpture, position of the camera, angle of the camera, and the ambient temperature. The table can also be referenced in Appendix C. This process was repeated for all acoustic emission recordings taken with the acoustic camera.

Once the camera was set up, the first recordings taken were general overall recordings on each side of the sculpture. These general recordings were analyzed to localize the systems generating the most noise, which is correlated to the wear the components are experiencing. Once these areas were identified, the camera was moved and properly positioned to capture close-up recordings of the wear-prone systems. This sculpture had three areas where the noise was prominent. These three spots were focused on for the final data collection. Recordings were taken a total of 27 times for the systems that exhibited high levels of noise. Three different camera positions and three different angles were record for each system. Each one of the individual recordings was done three times with the exact same setup to ensure consistency in the data. Each time a recording was taken, it was saved with a specific file name. It is as follows: $yyyymmdd\_hhmmss\_system\_x\_y\_z\_\theta\_\phi\_\psi\_name$. The file name consists of date and time followed by the system identifier and camera pose indicated by the respective coordinate system.

2.2.2 Analyze acoustic emission data using BeamformX and MATLAB

Data analysis took place Wednesday through Friday as a part of the project timeline. This data analysis involved the use of BeamformX, a software by OptiNav. As previously discussed, this software works with the acoustic camera to gather and analyze data. The data analysis tools included in BeamformX, are not the most up-to-date technology, so data analysis also took place in MATLAB. MATLAB is a powerful computing and programming language used by many. First, a detailed list of components for the sculpture was created. This list included any moving part large enough to be picked up by the acoustic camera. For example, each bearing was not included but larger parts such as linkages were. Next, BeamformX was used to isolate frequency ranges to determine the frequency and acoustic pressure that each listed part is emitting. This allowed the team to keep a record of each part individually. Next, the raw audio from each of these acquisitions was exported and a spectrogram was created using a fast Fourier transform. The raw audio was also used to create power spectra. These will be further explored in section 3.2.

2.2.3 Create a guidebook for analyzing kinetic artwork

Another objective was to create a guidebook. The goal of the guidebook is for a step-by-step process of analyzing kinetic artwork with acoustic emissions to be used in the present and future to track wear over time. This

guidebook was started before data analysis but was continuously worked on throughout the whole duration of the project. The guidebook draft that was started before data collection was used as an outline for the start of data collection. As data was collected, the process of data collection and the data itself was analyzed. Then, the guidebook was changed to reflect the issues in the data and revised data collection steps. The updated guidebook was tested in the next visit, and the steps were repeated until the guidebook was satisfactory. The data collection and analysis that was completed throughout those visits served as an example throughout the guidebook.

2.3   Ethical Considerations

No physical contact was made with *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* during data collection to ensure there was no potential damage. The team only conducted data collection and did not physically restore the sculpture. The goal of the project was to create a guidebook and not actively practice conservation-restoration.

2.4   Project Timeline

The timeline for the project was to take recordings for the second through fifth Tuesday of the eight-week work-span. The rest of the week was spent analyzing the data, updating the standard practice, and developing a report. The first week was used to gain familiarity with the acoustic camera and view Jean Tinguely's work in person. The data and guidebook were continuously reviewed with sponsors, Dr Rowena Crockett, and Dr Laura Brambilla. Figure 5 shows the weekly timeline of the project. The term concluded with the presentation of the work to the sponsors, museum director, and project advisors.

Figure 5
Project Timeline

Week	3/11-3/15	3/18-3/22	3/25-3/29	4/1-4/5	4/8-4/12	4/15-4/19	4/22-4/26
Deliverables							
Good Practice Guidebook							
Gather Data							
Take Acoustic Emission Recordings							
Analyze Data							
Localize Sounds							
Upload Data							

3 Results and Analysis

3.1 Gather Acoustic Emission Data for *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* in the Musée d'Art et d'Histoire (MAHF) in Fribourg, Switzerland

Final recordings were collected on 04/09/2024 and 04/16/2024 and documented in a table with all necessary metadata as seen in Table 1. Data taken on 04/09/2024 was analyzed and it was determined that a set of three recordings needed to be retaken due to a consistent inference that did not appear in any other recordings. The source was identified to be coming from M5, which can be referenced in Figure 6, and produced a frequency of roughly 23 kHz. As the sculpture was run multiple times, the frequency faded in each subsequent recording. The rerecorded data on 04/16/2024 picked up the same 23 kHz frequency which added significant noise to the data.
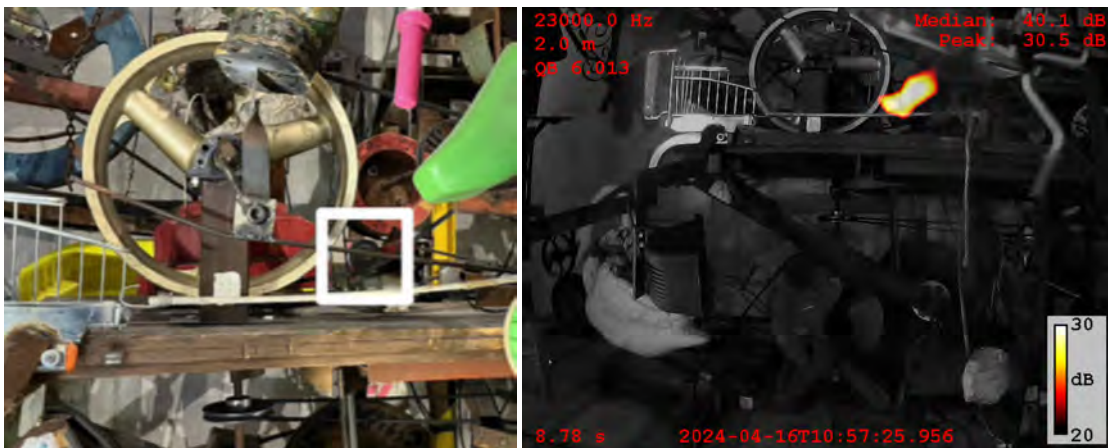
Figure 6
Images of M5

Table 1
Recording Location Data

Date	Time	X	Y	Z	θ	ϕ	ψ
04/09/2024	10:27:31	440	-138	85	0	0	0
04/09/2024	10:34:58	440	-138	85	0	0	0
04/09/2024	10:41:20	440	-138	85	0	0	0
04/09/2024	10:51:44	640	-138	85	0	0	320
04/09/2024	11:00:39	640	-138	85	0	0	320
04/09/2024	11:06:00	640	-138	85	0	0	320
04/09/2024	11:12:52	240	-138	85	0	0	40
04/09/2024	11:20:05	240	-138	85	0	0	40
04/09/2024	11:31:44	240	-138	85	0	0	40
04/09/2024	11:49:00	825	201	85	0	0	270
04/09/2024	12:12:56	825	201	85	0	0	270
04/09/2024	12:20:10	825	201	85	0	0	270
04/09/2024	12:30:01	825	401	85	0	0	230
04/09/2024	12:41:17	825	401	85	0	0	230
04/09/2024	12:45:10	825	401	85	0	0	230
04/09/2024	12:53:07	825	1	85	0	0	310
04/09/2024	13:04:57	825	1	85	0	0	310
04/09/2024	13:08:34	825	1	85	0	0	310
04/09/2024	13:36:31	-151	224	85	0	0	90
04/09/2024	13:41:43	-151	224	85	0	0	90
04/09/2024	13:45:30	-151	224	85	0	0	90
04/09/2024	14:03:10	-151	24	85	0	0	50
04/09/2024	14:08:17	-151	24	85	0	0	50
04/09/2024	14:12:50	-151	24	85	0	0	50
04/09/2024	14:36:17	-151	424	85	0	0	130
04/09/2024	14:41:33	-151	424	85	0	0	130
04/09/2024	14:46:17	-151	424	85	0	0	130
04/16/2024	10:13:07	825	201	85	0	0	270
04/16/2024	10:19:35	825	201	85	0	0	270
04/16/2024	10:23:22	825	201	85	0	0	270

It is important to note that there was a missing piece of the sculpture when data collection began. A large metal arm in the front of the piece, which would smash down on O35, was previously removed for repairs. The arm was reattached after data collection concluded, so there is expected to be a significant addition of noise to future recordings. Future data collectors should identify the new frequencies and effectively separate them from past recordings before data comparison. Additionally, the team noted the lack of movement from a hand trolley rolling on two tires (O8) and a plush toy on a metal bar (O44) in several recordings. Previous recordings were inspected to identify if the components were static at other dates and times. It was identified that the lack of movement from O44 did not have any acoustic effect on any recordings, while O8 produced a noticeable frequency. The museum conservators were notified of the issues and small repairs were made before continuing the data collection. Recordings where O8 were redone to keep consistency across the data set. See Figure 7 for images of the parts referenced above.

Figure 7
Images of referenced parts, from left to right, O35, O8, and O44

When collecting data, not all recordings began at the same time as there is no accurate method of beginning a recording and turning on the sculpture at the same time. Many recordings have a few seconds of silence before any noise is recorded. This does not affect data analysis, as .mp4 files can be cut to the appropriate size, and spectrograms can be overlayed and lined up for comparison. This has no effect on coherence estimation calculations as time is not a relevant factor.

The environment in which the recordings were taken played a significant role in the data. Documenting the temperature of the room in degrees Celsius is necessary and must be input into BeamformX settings before beginning recordings. Furthermore, the acoustics of the concrete room and glass ceiling often amplified small noises and produced notable echoes. The reflective properties of the concrete walls and wooden platform often appeared in recordings. Each day before data collection commenced, the ambient noise of the room was identified. The typical ambient noise of the room was roughly 11 decibels on 04/09/2024 and 15 decibels on 04/16/2024. The increase was largely due to rain, which was heard clearly through the glass ceiling. This change must be considered as background noise can affect the signal-to-noise ratio visualized within the created spectrograms. Other sources of interference were identified, such as the HVAC system, wind, and street noise.

Finally, the depth of the sculpture posed issues when trying to localize parts, as many components were layered in front of others, effectively blocking them from the camera view. This issue occurred most frequently regarding parts positioned within the center of the sculpture. Recordings were taken at multiple locations and angles to confirm the produced frequencies of the localized parts.

3.2   Analyze Acoustic Emission Data Using BeamformX and MATLAB

Analysis was completed on the gathered data in both BeamformX and MATLAB. The MATLAB analysis was completed using the script in appendix D. The script in Listing 1 extracts the audio from a given .mp4 file and performs a Fast Fourier Transform to generate a spectrogram. The script in Listing 2 takes a given video and extracts the audio. From the audio, a set of power spectra is created and exported. For the sculpture as mentioned above, 11 broad readings and 27 close-up readings were taken. While some preliminary analysis on the broad readings was taken, the close-up findings are more relevant to the current research. The preliminary analysis of the broad readings was used in order to determine the locations for close-up readings. Spectrograms and power spectra of close-up readings can be found in Appendix E. As this is the control data, no conclusions can be made regarding the state of the sculpture. Despite this, conclusions can still be drawn about the acoustic camera The conclusions drawn from the close-up readings are as follows:

1. The acoustic camera creates consistent and repeatable data.

2. Acoustic emissions recorded facing a wall created higher power results when compared to those not directed at a wall.

3.2.1   The acoustic camera creates consistent and repeatable data

For this project, the acoustic camera's precision is extremely important. In order to test this, a 9 sets of data with 3 trials each was gathered. All trials in each set were completed from the same pose and in a similar environment. To test the repeatability, spectrograms and power spectra were generated. See Figure 8. In each of these spectrograms, three vertical bands are visible. These vertical bands consist of high density content at all frequencies. These bands occur at approximately 25 second intervals. This was found to be due to part O4. See Figure 9 for an image of part O4. There are also horizontal bands visible at 4 kHz, 10 kHz, 12 kHz, 14 kHz, and 17 kHz, and a developing band at 15 kHz. These bands are visible in each of the three recordings.

Figure 8

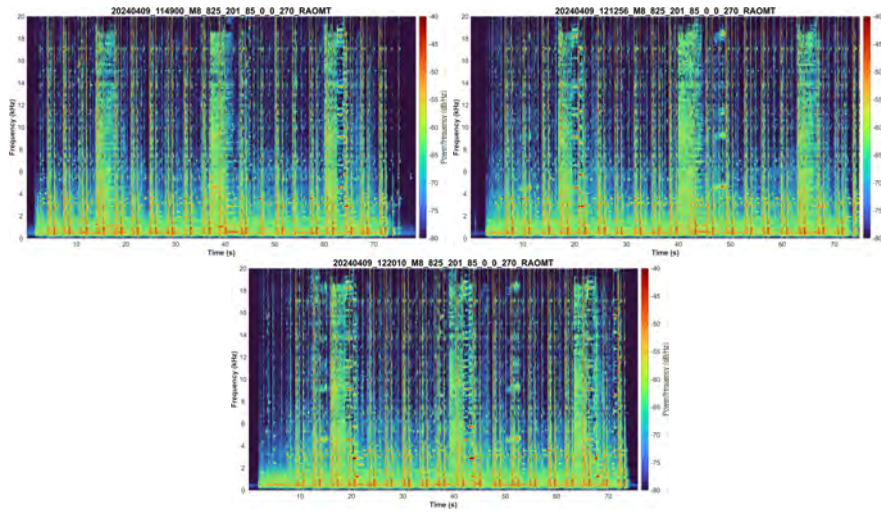Spectrograms showing three trials to prove consistency

Figure 9

Image of O4

To confirm these findings, power spectra were generated. See the spectra in Figure 10. The power spectra show similar results to the spectrogram and the power spectra of each of the trails present similar data. A power spectrum is an easier representation to analyze, compared to a spectrogram, as it only examines power and frequency without considering time. Each of the power spectra shows peaks at 4 kHz, 10 kHz, 12 kHz, 14 kHz, and 17 kHz. These are the same frequencies as those found in the bands in the spectrograms in Figure 8. Using BeamformX, the emission site of these frequencies was determined to be 048. See Figure 11 for an image of O48. When collecting acoustic emission data to be compared over time it is important that there is consistency among the various recordings. The data collected was a representation of the repeatability that the acoustic camera is capable of.
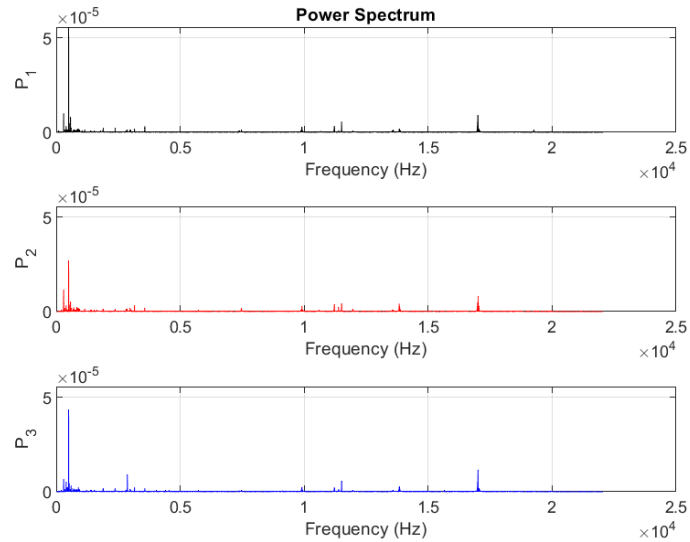
Figure 10
Power spectra showing consistency

Figure 11
Image of O48

3.2.2 Acoustic emissions recorded facing a wall created higher power results when compared to those not directed at a wall

When examining acoustic emission recordings facing a wall, it can be noted that the power spectra of the recordings show a higher power density at all frequencies when compared to recordings facing away from walls. This phenomenon can be seen clearly in Figure 12. The spectrum on the left side is from a recording where the camera is partially facing a concrete wall and the spectrum on the right is from a recording where the camera is facing away from any walls. This can also be represented in spectrograms. See Figure 13. The spectrogram on average shows higher

average power at all readings. See Figure 6 for photos of where the recordings were taken. The acoustic camera demonstrated how precise it can be and how position, angle, and environment can affect the readings.

Figure 12
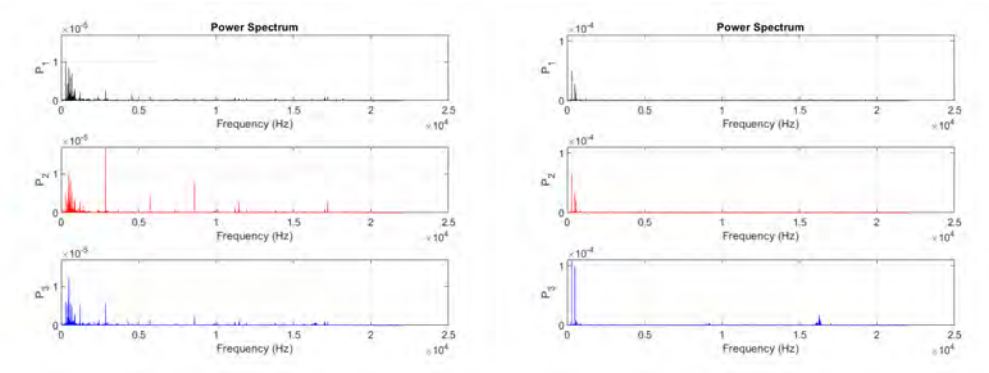Power spectra of reading facing wall (left) and away from wall (right)

Figure 13
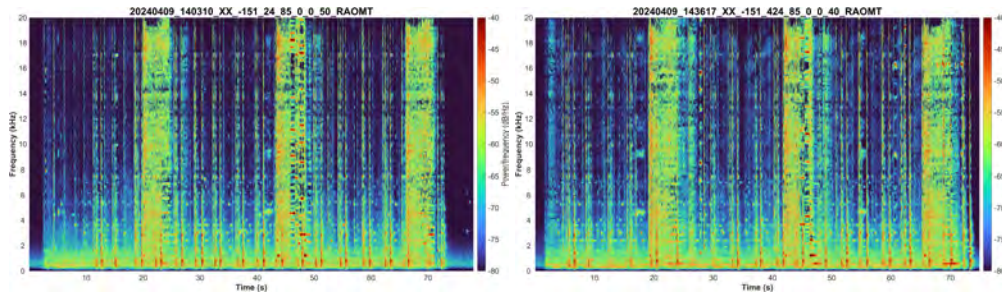Spectrogram of reading facing wall (left) and away from wall (right)

Figure 14
Power spectra locations

3.3 Create Guidebook for Analyzing Kinetic Artwork

A deliverable that was created from research and data collection was a guidebook for using an acoustic camera to gather acoustic emissions data from kinetic art to track wear and breakage. In the guidebook, the readings completed on *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire* acted as an example. This book aims to have recordings taken at consistent, repeatable time intervals to establish an accurate procedure to track wear of the sculpture over time. The guidebook serves as a tool for anyone to use when analyzing a sculpture. It outlines a step-by-step process for a sculpture's first analysis and the following steps for repeated analysis.

The first step in the guidebook when analyzing a sculpture is to break the sculpture into components and categories. This strategy was implemented because it was found useful when understanding larger sculptures as a whole. With the complexity of Jean Tinguely's work, understanding the sculpture and its movements plays a crucial role in tracking wear with acoustic emissions. When breaking the sculpture into its components, the observer can gather an understanding of the materials, moving parts, and what drives them. With projects on a larger scale, being able to understand how each system is driven and moving lets users get acoustic emission data focused on specific systems. Compiling the sculpture breakdown into tables also creates a mapped-out understanding of the sculpture for the following data collector. This breakdown also creates ease for referencing components within the file name for each acoustic emission recording.

The second main point of the guidebook is defining a coordinate system for the positioning of the camera. A system was needed for accurate camera positioning and consistent replication of data collection. By having a well-defined coordinate system, any ambiguity of camera positioning and recording location can minimized. When collecting data for long-term use, repeatability is crucial in order to have accurate and useful data. A coordinate system was also found to be a useful tool when logging recordings and creating a naming convention for the files. A traditional Cartesian coordinate system was used for camera positioning, as it is a commonly used system and can be applied to other sculptures in the future. A roll, pitch, yaw coordinate system was used for the camera angle. These coordinate systems were represented by x, y, z and ϕ, θ, ψ, respectively.

After definition, the guidebook walks through data acquisition with the acoustic camera. This section of the guidebook provides in-depth instructions for using the camera and BeamformX software. In addition, this section provides guidelines for large and small sculptures, as the size of the artwork varies from piece to piece. The naming convention for files is also outlined to keep an organized log of what has been measured and ensure consistency with current and future data. The method of data acquisition is crucial to ensure the most effective and least invasive methods are being used. Due to the materials and state of kinetic art, a no-contact approach for data acquisition is best suited.

The last section of the guidebook outlines how data is analyzed. It provides the process for analyzing the data from the acoustic camera in BeamformX and MATLAB. It dives deeper into the background behind the two programs and the process it is using to create spectrograms from the .mp4 files. This section also provides the information needed to read spectrograms and highlight the areas of interest. A sample of MATLAB code and an example of an annotated spectrogram from this project are included to be referenced and used in the future.

The nature of kinetic art, especially art created by Jean Tinguely, poses challenges when trying to create a standardized practice to take acoustic emission recordings. A previous conservation effort for Tinguely sculptures was the implementation of buttons and timers to allow the sculptures to rest when not being observed. This creates limitations because most sculptures stopped at different positions each time they were run. When comparing data, it is important to line up spectrograms based on frequencies and not time.

4 Recommendations

4.1 Coordinate Systems

It is recommended that coordinate systems are defined for taking acoustic emission readings to accurately replicate data collection. The complexity of Jean Tinguely's sculptures indicated that a systematic approach of data collection must be done to improve repeatability of the process. There are a number of ways coordinate systems can be defined, and they all depend on the shape and complexity of the sculpture. While two were used for this project, several more could be added to further isolate the subsystems that make up the sculpture. Each subsystem could be given a new coordinate system to increase how exact the camera position measurements are. Each coordinate system will vary and be unique to a specific sculpture.

4.2 Database

Due to the complexity and amount of data needed for comparison over time, a shared database to store data for for all Tinguely sculptures would be a useful tool in future conservation efforts. It will further promote collaboration and continued documentation with the information shared among multiple conservators. A database will promote data consistency and integrity by enforcing the standardized format outlined in the guidebook. Another advantage of a database is limiting the risk of errors and inconsistency by simplifying data management and eliminating the need for duplicate data storage. It will ensure the data is stored in a structured and organized manner. Overall, a database could serve as a powerful resource for promoting documentation and consistency in a structured manner.

4.3 Acoustic Treatment

For future iterations of this project, acoustic treatment of the space would help limit these challenges that were encountered. Given that the walls and floors in MAHF are concrete, acoustic treatment would significantly decrease the reverb of the room. Sounds produced by the sculpture resonate in the room and this interferes with the accuracy of readings. This is discussed further in 3.2. Acoustic treatment, similar to what audio engineers do in recording studios or concert venues, would significantly reduce this issue. In Figure 15, sound can be seen bouncing off the back wall. To solve this, adding acoustic treatment such as acoustic foam to the concrete walls for more sound

absorption would help. Another challenge that was faced was interference from other parts of the sculpture. A possible solution for future work would be to add acoustic panels to isolate certain acoustic emission sources.

Figure 15
Example BeamformX recording with sound bouncing off walls
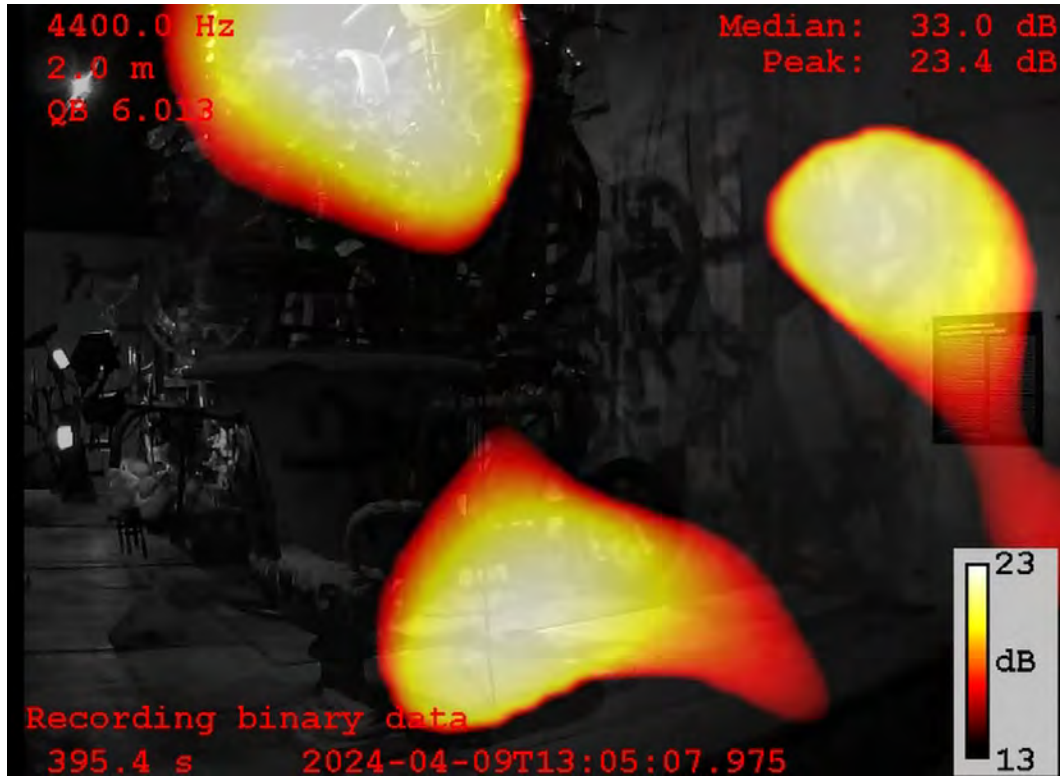
4.4   System Isolation

The results showed the most prominent frequency bands occurred at roughly 4 kHz, 10 kHz, 12 kHz, 14 kHz, and 17 kHz. All frequencies mainly originated from O48 and EW2. The localization of other parts proved to be difficult as the sound produced by O48 and EW2 often overwhelmed that of other components. An in-depth focus on localizing other parts should be conducted to accurately identify frequency sources as indicated by the heatmap-like images in each recording. Similar to using acoustic foam to isolate systems, another suggestion for future research would be to disable motors or actuators on large sculptures similar to *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire*. Research on large Tinguely sculptures has shown difficulty with distinguishing the source of acoustic emissions. Disabling motors or actuators would possibly solve this issue. Curators would have to be consulted prior to this to ensure that disabling portions would not cause any damage.

4.5 Annual Recordings

Taking annual recordings to keep track of the wear in the sculptures is a way to make the data collection for documentation more effective for conservators. Documenting the wear over time of a sculpture with an acoustic camera is a useful analytical method for data collection. However, to track the wear over time, acoustic emission readings must be taken several times so the recordings can be compared. There are currently a number of Tinguely sculptures that have had acoustic emission readings taken of them throughout the years. Some of these sculptures have been recorded multiple times, and the recordings have been compared to analyze the wear the sculptures are experiencing. While these recordings have been helpful, the time between each recording has not been consistent. Implementing annual recordings for documenting sculptures of interest will increase the effectiveness of the analysis over time. Being able to track the degradation with known, consistent time spans will allow for trends in the data to show up more clearly. With this consistency, it will become more explicit where the noisy areas are and how they are changing with time. Annual recordings will improve the accuracy of collected data, allowing for easy data comparison. From these comparisons, conclusions about can be drawn and information can passed along to conservators who can intervene if needed.

4.6 Limitations

The use of BeamformX limited the efficiency of the project, as it often froze or did not begin recording data at the indicated time. Users had to assume the software would buffer before taking recordings to ensure that the data would not be accidentally cut off. The user interface can be difficult to navigate and may not be easily accessible as it can only run on computers that have Java 64-bit installed. An updated or new software would greatly improve the accuracy of data and ease the data collection process.

5 Conclusion

It is necessary to create a well-documented set of baseline data with proven repeatable results across multiple trials. Noting the exact location of the camera in the file name will ensure that the information is easily accessible, reducing the chances of error in replicated recordings and aiding in accurate data comparison. The use of coherence estimation allows for easier data comparison as the percentage of frequency difference is directly calculated, while comparing spectrograms from different trials cannot be done in the same numerical sense as it is difficult to identify frequency changes solely from overlaying spectrograms, which are time dependent.

The consistency of repeated recordings has proven that the acoustic camera is an accurate and useful tool for taking acoustic emission recordings for the documentation of the state kinetic art pieces. This project encourages the use of the acoustic camera as a device for evaluating the conditions of kinetic sculptures in future conservation efforts.

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Appendices

A Description of *Le Retable de l'Abondance Occidentale et du Mercantilisme Totalitaire*

This work was created for the retrospective of the sculptor's work in Moscow, organized by the Tretiakov Gallery. "Festival of Absolute Mercantilism" according to Jean Tinguely himself, this work, composed of a great diversity of everyday objects and pieces of scrap metal, expresses the artist's critical look at consumer society. He did not skimp on allusions to Western opulence with items that waver, swing, and rotate in an infinite and absurd variety of movements.

Tinguely: "I wanted to show the Russians the richness of our way of life – and its ridiculous side too... with this altar I wanted to illustrate the subject of total and colossal idiocy of our industrial capitalism"

Translated from sculpture description at MAHF. (MHAF, 2023)

B Guidebook

Guidebook for Acoustic Conservation of Kinetic Art

Written by Fiona Leitner, William Merry, Mary Ramirez-Richer, and Taylor Walker

Preface

Why create a guidebook?

Jean Tinguely's artwork is full of complex components and mechanisms. Without the traditional consistency that more common types of artwork exhibit, the conservation process becomes more challenging. An acoustic camera is a non-invasive way to collect data surrounding the wear and degradation to pinpoint where conservators need to intervene. This guidebook provides a path for data collectors and conservators to follow while using an acoustic camera. By having a consistent method for data collection, comparing acoustic recordings becomes easier and more accurate. The guidebook includes chronological systematic chapters that highlight the four main steps to good conservation: inventory, definition, recording, and analysis. The appendix includes annotated photos of the subsystems that make up the sculpture that can be referenced throughout the project. A link to the folders containing the baseline acoustic recordings and an example system detail recording sheet can also be found in the appendix. The guidebook is written in English, German and French. In addition to Jean Tinguely's sculptures, this guidebook can be adapted and used for other types of kinetic art.

Thank you for taking the time to focus on conserving Jean Tinguely's art and other works of kinetic art.

Inventory

The first step to good conservation is gathering an inventory of all parts within the sculpture. The inventory only needs to be completed once for each individual sculpture. It must be stored in a way to be easily passed down. Below is the procedure used for the inventory of a sculpture:

1. Break all parts of the sculpture into three categories, motors (M), energy transfer devices (E), and other miscellaneous objects (O). Energy transfer devices can include belts, pulleys, sprockets, wheels, etc.
   a. In this example, energy transfer devices will be further separated into subcategories for wooden (EW) and metal (EM) wheels.
2. Go through each category, starting with M, then E, then O, and label the parts accordingly in a chart for each category. To do this, start in the front, left corner of the sculpture, and move right and back labeling each object with a corresponding identifier.
   a. Identifiers should be numbered from left to right. For example, motors would be labeled M1-Mx.
   b. For each motor, track what the motor drives through the sculpture as movement flow.
   c. An extra step is color coding each motor to specific placements. For example, the location on pedestal is blue and location on frame is purple.
3. Compile each list into its own table:
   a. Motors should have three columns. Number, location, and movement flow.
   b. Energy transfer devices should have three columns. Number, dimensions and inscriptions, and belts.
   c. Objects will have three columns. Number, description, and material.

For example, see tables below:

Motors on pedestal
Motors on 1st floor
Motors on metal frame

| Motor	Location (numbering, assembly)	Movement Flow
M1	On the free element on the far left	M1 à EW1 à moves plush toy and metal element
M2	To the right of EW4, behind Swan (3, 4)	M2 à EW4 à Swan
M3	Between EW2 and EW13 (12, 20) Back	M3 à EM2 (Gingerbread) à EW2 à Compartments M3 à EM2 (Gingerbread) à EW2 à on the road Metal rods with parts of metal railing à via metal rod small light element with Santa louvers and fairy lights with flowers

| | | M3 à EM2 à on axle EM2a à EW3 à on axle chrome linkage |
| | | M3 à EM2 à on Axis Gingerbread Hearts |

EW1 – EW20	Wooden wheel (dimensions and inscriptions)	Belts (ground for spare parts)
EW1	Red-yellow	Strap
		Black V-belt
		21950 B / 046 / Made in ??? / TEXROPE / 84 / Z76 / 1001950 / 10 x 1930 LI
EW2	Blue	Green perforated strap
EW3	Red with 6 holes	

O1 – O53	Object Description	Masse / Material
O1	Plush toy	Textile
O2	Metal part	Metal
O3	Fan	Holz / Paper

4. Using an image of the sculpture, outline the energy transfer devices for future reference

For example, see image below:
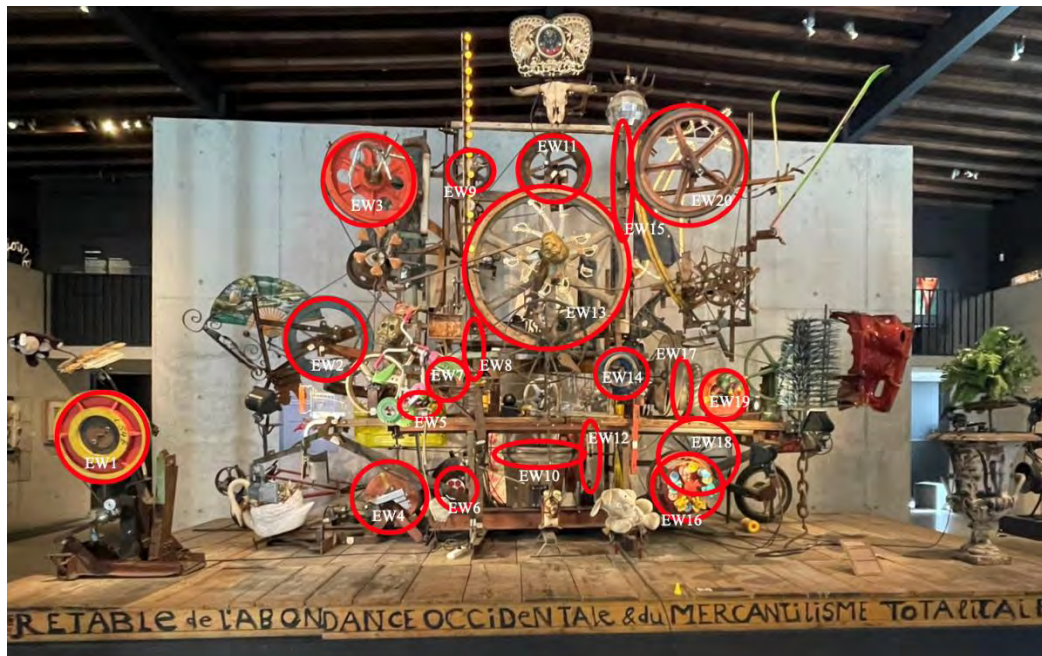
Definition

One must define the different systems and subsystems within a sculpture, as well as define the coordinate system for which they will be taking measurements in. The definition and coordinate system only needs to be completed once for each individual sculpture. It must be stored in a way to be easily passed down.

A system is defined as a portion of the sculpture that all moves together. To find a system, one should start at a motor and follow all methods of energy transfer to the end. A subsystem is a small system within a larger one. Subsystems should be defined when the larger system is too large to accurately record in one acoustic emission recording. The image below shows an example of a system drawing.
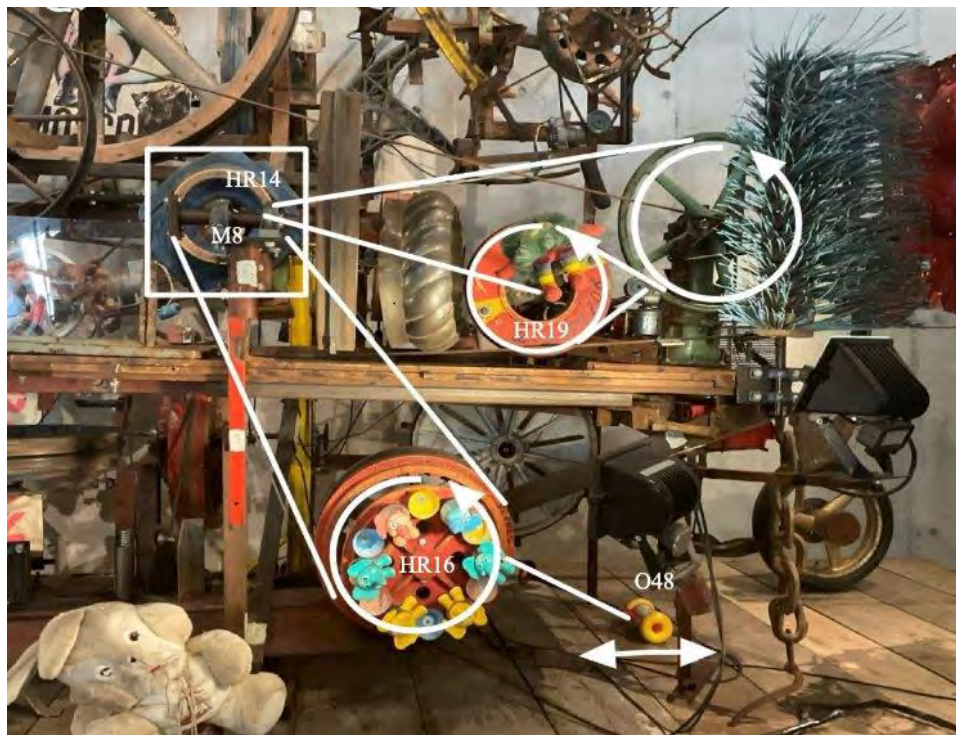
It is necessary to define the coordinate system that will be worked in so future data collectors can accurately acquire location metadata for acoustic emission recordings. Using the front left base of the sculpture to be the origin of (x, y, z) as (0, 0, 0). The positive directions of the coordinate system are shown below. The image below shows an example of a coordinate system.

Roll , Pitch , Yaw
(ϕ, θ, ψ)
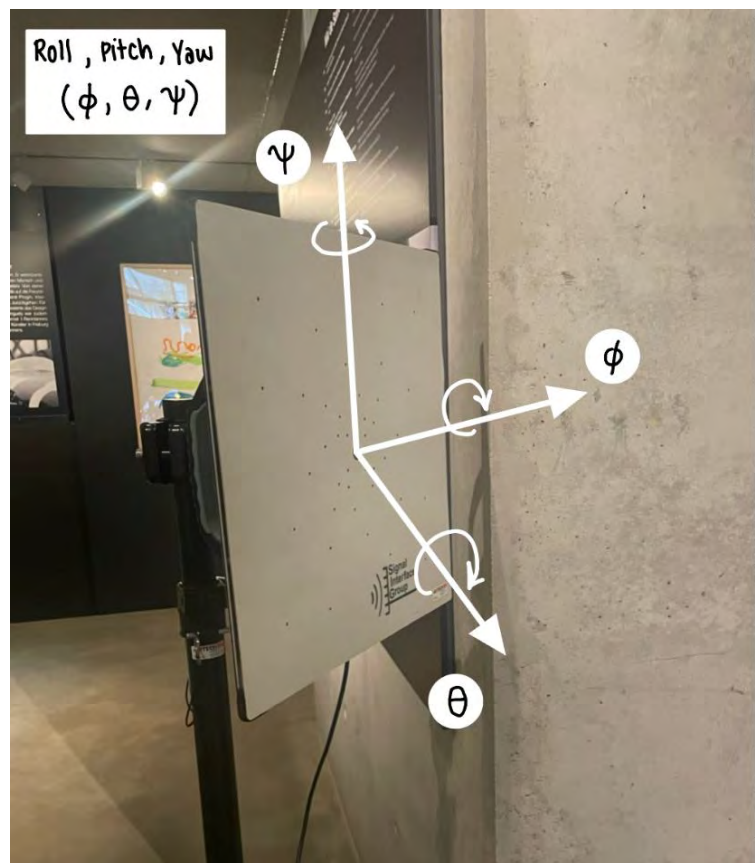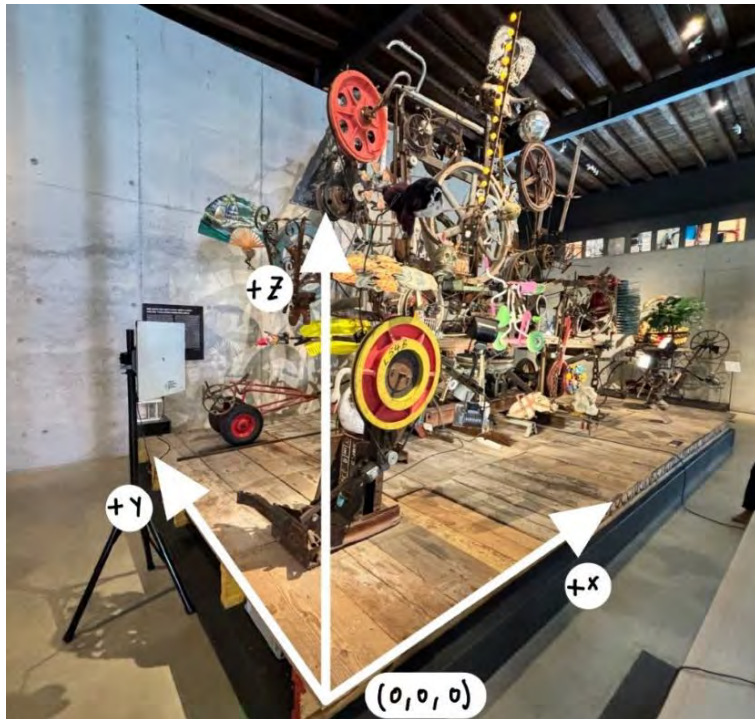
Coordinate System:
(x, y, z)
(θ, φ, ψ)
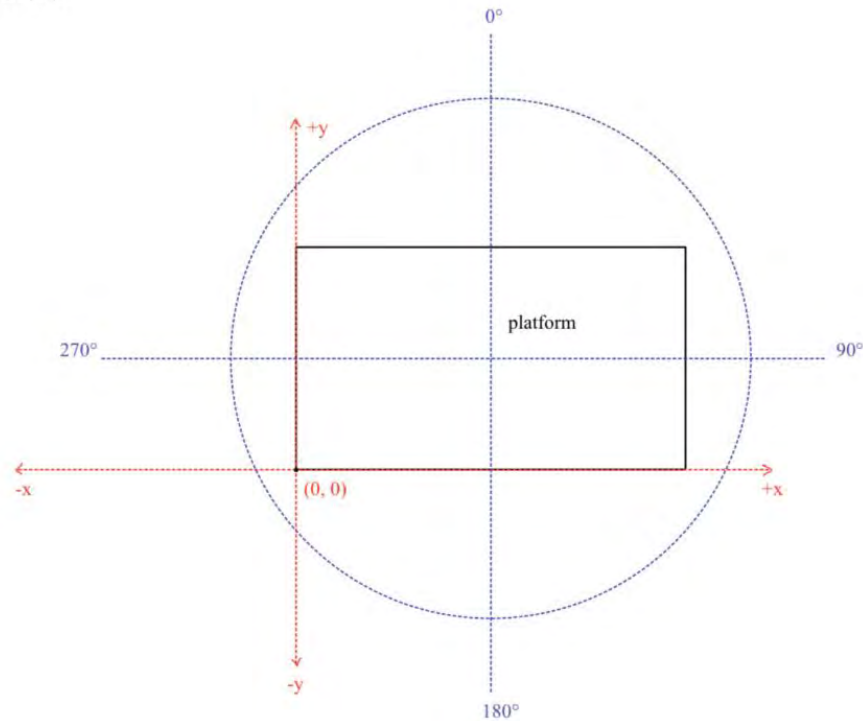
Below is a procedure to follow to define the sculpture:

1. Break it down into smaller subsystems to isolate the noisiest regions.
   a. Start by looking for motors and following what they are moving and attached too.
   b. This is helpful to get a more in-depth understanding of the innerworkings of the sculpture and allows for the most effective localization.
2. Compile a list of components, motors, belts, energy transfer systems, etc.
   a. This will be useful when recording data and referring to it.
3. Define coordinate systems. A minimum of two coordinate systems will be the most effective way to capture both the positioning angles of the acoustic camera.
   a. An x, y, z coordinate system for position, and a φ, θ, ψ coordinate systems for the camera angle are a good way to denote the two without confusion.
4. Create a table, spreadsheet or log to record the details of the subsystem being focused on and the camera positioning.
   a. The exact object, motor and energy transfer component. This will also include the exact positioning and angle of the camera, along with the ambient temperature, as this can affect recordings.
   b. An example of this can be found below:

System Details			
Motor			
Object			
Wooden Wheel/Energy Transfer			
System/Objective Description			
Measurements for Camera Positioning			
Distance from Platform (cm)	**x**	**y**	**z**
Angles (°)	**φ**	**θ**	**ψ**
Ambient Temperature (°C)			

Data Acquisition

During data acquisition, .bin and .mp4 files will be saved. They should be saved using this standard naming convention. This convention accounts for all metadata that a researcher would need to recreate the shot. The naming convention is as follows, yyyymmdd_hhmmss _system_x_y_z_theta_phi_psi_name. The first two parts are date and time, followed by the system identifier and then camera pose. The camera pose is broken into 2 different parts. The location of the camera in cartesian coordinates and the direction described using Euler angles. Lastly, the name of the sculpture that the recordings were taken of.

Camera Set Up Procedure
1. Position the camera so that the desired amount of the sculpture is within the frame.
2. Starting from the center of the camera, measure and record the height and distance from the origin of the established x, y, z coordinate system.
3. Measure and record the three angles of the camera setup according to the established φ, θ, ψ coordinate system.

General ACAM 120 Procedure
1. Set up the camera to the desired location. Plug in the cord to both the camera and the laptop.
2. Open BeamformX and type in the OptiNav License Key on the camera. Under the Data Source option, select "Connected Array." Click okay at the bottom of the screen to proceed. The application should display the camera view.
3. Open Settings.
    a. Set "Beamforming bandwidth or Engine order" to 1/3 Octave Band.
    b. Set "Contrast" to normal.
    c. Create a folder on the computer or hard drive that data will be stored in. Copy as a path and insert into the "Folder for binary Log data and PNG images" text box. Be sure to remove quotation marks from the beginning and end.
    d. Record temperature and type into text box.
4. To begin recording data click "Log .bin data" then "Rec BF" directly after. Assume the software will buffer for a few seconds before actual recording begins.
5. To stop recording, click "Stop Rec" and "save .mp4" to save a video file.

For Larger Sculptures
Larger sculptures will have many different emission sources. To properly record the sculpture, the following procedure should be followed.
1. Take emission recordings from all 4 sides of the sculpture being sure to include the full work in each recording.
2. From each sculpture, identify the points of the most acoustic emission. See Figure x for an example.

3. Using the list of the points of the most emissions, begin taking emission recordings starting with the points with the most emissions in dB. Follow the General ACAM 120 Procedure.
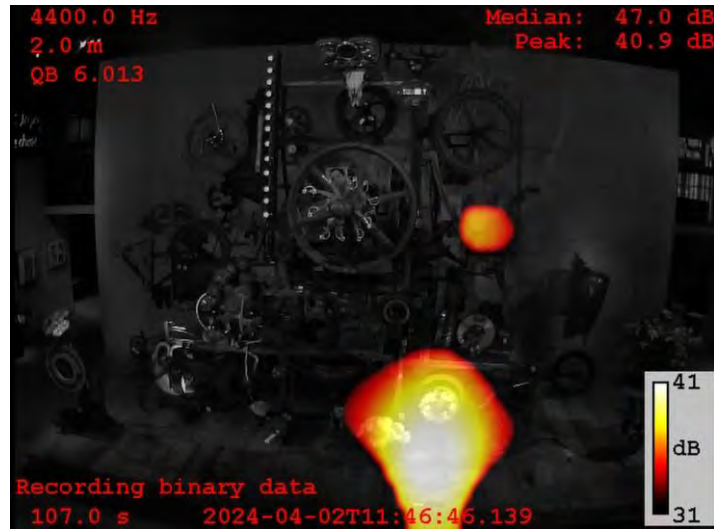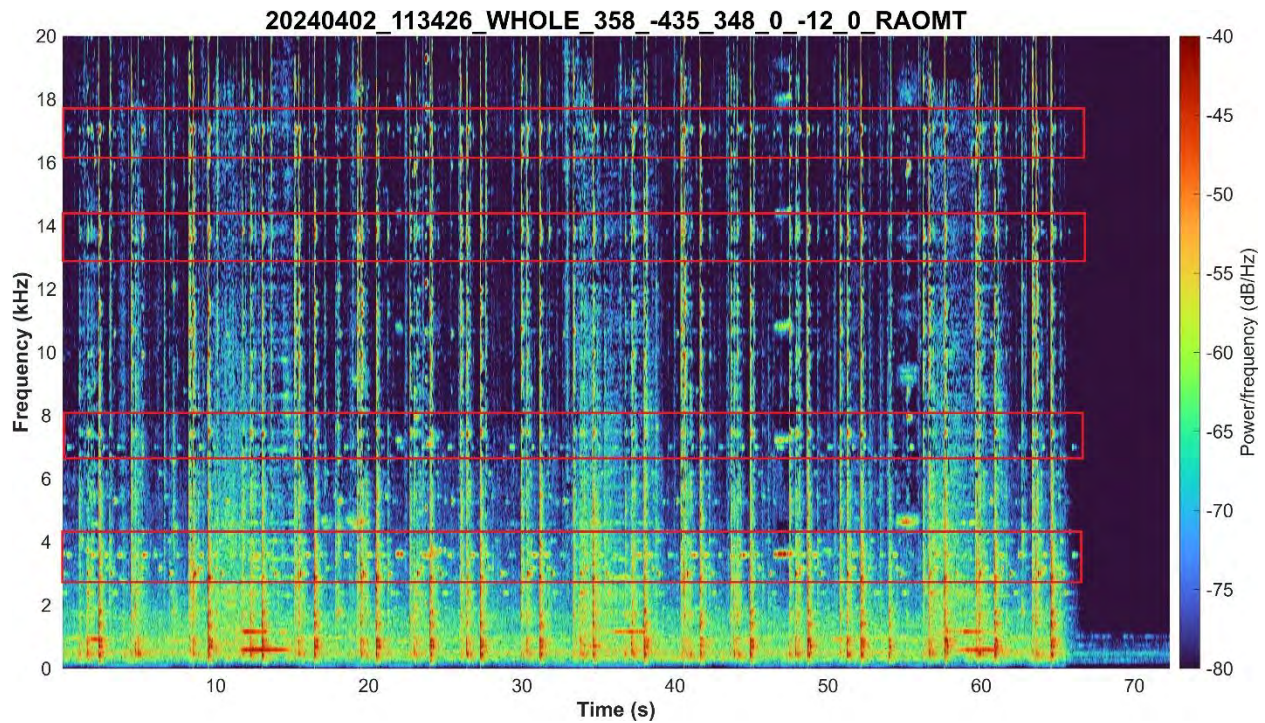

For Smaller Sculptures

For smaller sculptures, the procedure is less complex. Simply record the acoustic emissions of the entire sculpture following the General ACAM 120 Procedure from each side of the sculpture. If the entire sculpture doesn't fit into the frame, restart with the large sculpture section.

Data Analysis

       To analyze data, the taken .mp4 files are input into MATLAB by placing the file path into the script given in script. The script creates spectrograms using fast Fourier transforms (FFTs). On the created spectrograms, different frequency bands are identified and taken note of. An example spectrogram with multiple visible bands can be seen in the image below. The bands are highlighted in red and noted at 17 kHz, 14 kHz, 8 kHz and 4 kHz. To properly analyze data, a control sample is needed. When comparing a control to a current sample, one must identify frequencies which have changed over time. For example, a band may not be visible at 12 kHz in the control but is visible 2 years later. Once the frequency is identified, a current video must be analyzed in BeamformX to identify sources of 12 kHz acoustic emissions. Conservators can then inspect these locations for signs of wear.

```matlab
    fileName = ...
    raw = audioread(fileName); % read audio from bfx-generated video
    fs = 44100; % set sample rate and time limits
    dt = 1/fs;
    t = (0:dt:5-dt);
    window = hamming(512);
    N_overlap = 256;
    N_fft = 1024;
    [S,F,T,P] = spectrogram(raw,window,N_overlap,N_fft,fs,'yaxis'); % generate
spectrogram
    figure
    surf(T,F,10*log10(P),'EdgeColor','none');
    axis tight;
    view(0,90);
    colormap(turbo); %set view range and color map
    set(gca,'clim',[-80,-40]); % determines decibel range, variesby sculpture
    ylim([0 20000]);
    % minimum -maximum hz range for spectro. should be usually kept at 0-20khz
    yt = get(gca, 'YTick')
    set(gca, 'YTick',yt, 'YTickLabel',yt/1E+3)
    % fix frequency bar to display kHz instead of Hz
    xlabel('Time (s)','FontSize',15,'FontWeight','bold');
    ylabel('Frequency (kHz)','FontSize',15,'FontWeight','bold');
    exportName = fileName(1:end-4);
    graphTitle =exportName(94:end)
    title(graphTitle,'FontSize',20,'Interpreter', 'none'); % main title, change
for each sculpture/angle
    ax = gca;
    ax.XAxis.FontSize = 15;
    ax.YAxis.FontSize = 15;
    a = colorbar; % gen. colorbar w/ label
    a.Label.String = "Power/frequency (dB/Hz)";
    a.FontSize = 15;
    set(gcf, 'Units', 'Pixels', 'Position', [0, 1000, 1570, 820]);
    exportName = exportName + ".png";
    exportgraphics(ax,exportName,'Resolution',300);
  end
```

In addition to generating spectrograms, power spectra were also generated. A power spectrum is a type of graph that plots signal power against frequency. This is very similar to a spectrogram but differs as it is at an instant of time rather than over a period. Below is an example power spectrum and the code segment used to generate them.


```
a1 = ...
a2 = ...
a3 = ...

sig1 = audioread(a1);
sig2 = audioread(a2);
sig3 = audioread(a3);
len = max([length(sig1),length(sig2),length(sig3)]);

s1 = vertcat(zeros((len-length(sig1)),1),sig1);
s2 = vertcat(zeros((len-length(sig2)),1),sig2);
s3 = vertcat(zeros((len-length(sig3)),1),sig3);

Fs = 44100;

[P1,f1] = periodogram(s1,[],[],Fs,'power');
```

```matlab
[P2,f2] = periodogram(s2,[],[],Fs,'power');
[P3,f3] = periodogram(s3,[],[],Fs,'power');


[pk1,lc1] = findpeaks(P1,'SortStr','descend','NPeaks',3);
P1peakFreqs = f1(lc1);

[pk2,lc2] = findpeaks(P2,'SortStr','descend','NPeaks',3);
P2peakFreqs = f2(lc2);

[pk3,lc3] = findpeaks(P3,'SortStr','descend','NPeaks',3);
P3peakFreqs = f3(lc3);

maxY = max([max(P1), max(P2), max(P3)]);

subplot(3,1,1)
plot(f1,P1,'k')
ylim([0, maxY]);
grid
ylabel('P_1')
title('Power Spectrum')

subplot(3,1,2)
plot(f2,P2,'r')
ylim([0, maxY]);
grid
ylabel('P_2')
xlabel('Frequency (Hz)')

subplot(3,1,3)
plot(f3,P3,'b')
ylim([0, maxY]);
grid
ylabel('P_3')
xlabel('Frequency (Hz)')

[Cab,f] = mscohere(s1,s2,[],[],[],Fs);
[Cbc,~] = mscohere(s2,s3,[],[],[],Fs);
[Cac,~] = mscohere(s1,s3,[],[],[],Fs);

exportName = erase(a1, ".mp4")
exportName = exportName + ".png";
saveas(gcf,exportName);
```

Leitfaden für die akustische Konservierung der kinetischen Kunst

Geschrieben von Fiona Leitner, William Merry, Ellie Ramirez-Richer und Taylor Walker

Erstellt für einen Bericht über ein interaktives Qualifikationsprojekt (IQP), der an die Fakultät des WORCESTER POLYTECHNIC INSTITUTE in teilweiser Erfüllung der Anforderungen für den Bachelor of Science eingereicht wurde. Das WPI veröffentlicht diese Berichte routinemäßig auf seiner Website ohne Redaktion oder Peer-Review. Weitere Informationen zum Projektprogramm am WPI finden Sie unter http://www.wpi.edu/Academics/Projects.

Vorwort

Warum einen Reiseführer erstellen?

Jean Tinguelys Kunstwerk steckt voller komplexer Komponenten und Mechanismen. Ohne die traditionelle Konsistenz, die gängigere Arten von Kunstwerken aufweisen, wird der Konservierungsprozess zu einer größeren Herausforderung. Eine akustische Kamera ist eine nicht-invasive Methode, um Daten über den Verschleiß und den Zerfall zu sammeln, um genau zu bestimmen, wo Restauratoren eingreifen müssen. Dieser Leitfaden bietet Datensammlern und Restauratoren einen Weg, dem sie bei der Verwendung einer akustischen Kamera folgen können. Durch eine konsistente Methode zur Datenerfassung wird der Vergleich von akustischen Aufnahmen einfacher und genauer. Der Leitfaden enthält chronologische, systematische Kapitel, in denen die vier Hauptschritte einer guten Konservierung hervorgehoben werden: Inventarisierung, Definition, Erfassung und Analyse. Der Anhang enthält kommentierte Fotos der Subsysteme, aus denen die Skulptur besteht, auf die während des gesamten Projekts verwiesen werden kann. Einen Link zu den Ordnern mit den akustischen Basisaufnahmen und einem Beispiel für ein Systemdetailaufzeichnungsblatt finden Sie ebenfalls im Anhang. Das Handbuch ist auf Deutsch, Englisch und Französisch erhältlich. Neben den Skulpturen von Jean Tinguely kann dieses Buch auch für andere Arten der kinetischen Kunst adaptiert und verwendet werden.

Vielen Dank, dass Sie sich die Zeit genommen haben, sich auf die Erhaltung der Kunst von Jean Tinguely und anderer kinetischer Kunstwerke zu konzentrieren.

Inventar

Der erste Schritt zu einer guten Konservierung ist das Sammeln eines Inventars aller Teile der Skulptur. Die Inventur muss für jede einzelne Skulptur nur einmal durchgeführt werden. Es muss so gelagert werden, dass es leicht weitergegeben werden kann. Im Folgenden finden Sie das Verfahren für die Inventarisierung einer Skulptur:

1. Unterteilen Sie alle Teile der Skulptur in drei Kategorien: Motoren (M), Energieübertragungsgeräte (E) und andere verschiedene Objekte (O). Energieübertragungsgeräte können Riemen, Riemenscheiben, Kettenräder, Räder usw. umfassen.
   a. In diesem Beispiel werden Energieübertragungsgeräte weiter in Unterkategorien für Holz- (EW) und Metallräder (EM) unterteilt.
2. Gehen Sie jede Kategorie durch, beginnend mit M, dann E und dann O, und beschriften Sie die Teile entsprechend in einem Diagramm für jede Kategorie. Beginnen Sie dazu in der vorderen linken Ecke der Skulptur und arbeiten Sie sich nach rechts und hinten durch, wobei Sie jedes Objekt mit einer entsprechenden Kennung beschriften.
   a. Bezeichnungen sollten von links nach rechts nummeriert werden. Zum Beispiel würden Motoren mit M1-Mx beschriftet werden.
   b. Verfolgen Sie für jeden Motor, in Reihenfolge, alle Komponente, die der Motor durch die Skulptur bewegt.
   c. Ein zusätzlicher Schritt ist die Farbcodierung jedes Motors für bestimmte Positionen. Beispielsweise ist die Position auf dem Sockel blau zu markieren und die Position auf dem Rahmen lila.
3. Kompilieren Sie jede Liste in eine eigene Tabelle:
   a. Motoren sollten drei Spalten haben. Anzahl, Ort und Bewegungsablauf.
   b. Energieübertragungsgeräte sollten drei Spalten haben. Anzahl, Abmessungen und Beschriftungen sowie Gürtel.
   c. Objekte haben drei Spalten. Anzahl, Beschreibung und Material.

Siehe z. B. die folgenden Tabellen:

Motoren auf Sockel
Motoren im 1. Obergeschoss
Motoren auf Metallrahmen

Motor	Standort (Nummerierung, Montage)	Bewegungsablauf
M1	Auf dem freien Element ganz links	M1 à EW1 à bewegt Plüschtier und Metallelement
Quadratmeterzahl M2	Rechts von EW4, hinter Swan (3, 4)	M2 à EW4 à Swan

M3	Zwischen EW2 und EW13 (12, 20) Zurück	M3 à EM2 (Lebkuchen) à EW2 à Fächer M3 à EM2 (Lebkuchen) à EW2 à auf der Straße Metallstangen mit Teilen aus Metallgeländer à über Metallstab kleines Lichtelement mit Weihnachtslamellen und Lichterketten mit Blumen M3 à EM2 à auf Achse EM2a à EW3 à auf Achsverchromung M3 à EM2 à auf Axis Lebkuchenherzen

EW1 – EW20	Holzrad (Maße und Beschriftungen)	Riemen (geschliffen für Ersatzteile)
EW1-KARTON	Rot-gelb	Riemen Schwarzer Keilriemen 21950 B / 046 / Hergestellt in ??? / TEXROPE / 84 / Z76 / 1001950 / 10 x 1930 LI
EW2-KARTON	Blau	Grünes perforiertes Armband
EW3-KARTON	Rot mit 6 Löchern	

O1 – O53	Objektbeschreibung	Masse / Material
O1	Plüschtier	Textil
O2	Metallteil	Metall
O3	Ventilator	Holz / Paper

4. Skizzieren Sie anhand eines Bildes der Skulptur die Energieübertragungsvorrichtungen als zukünftige Referenz

Sehen Sie sich zum Beispiel das Bild unten an:
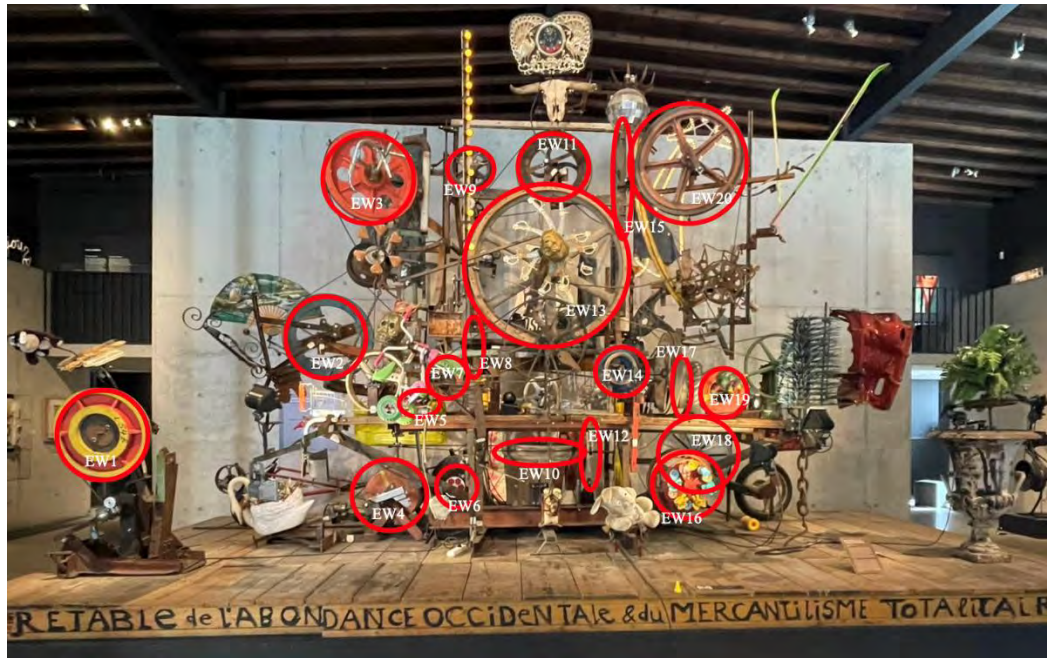
Definition

Man muss die verschiedenen Systeme und Subsysteme innerhalb einer Skulptur sowie das Koordinatensystemdefiniens, in dem gemessen wird, definieren. Das Definitions- und Koordinatensystem muss für jede einzelne Skulptur nur einmal ausgefüllt werden. Es muss so gelagert werden, dass es leicht weitergegeben werden kann.

Ein System ist definiert als ein Teil der Skulptur, der sich gemeinsam bewegt. Um ein System zu finden, sollte man bei einem Motor anfangen und alle Methoden der Energieübertragung bis zum Ende verfolgen. Ein Subsystem ist ein kleines System innerhalb eines größeren. Subsysteme sollten definiert werden, wenn das größere System zu groß ist, um in einer einzigen akustischen Emissionsaufzeichnung genau aufzuzeichnen. Die folgende Abbildung zeigt ein Beispiel für eine Systemzeichnung.
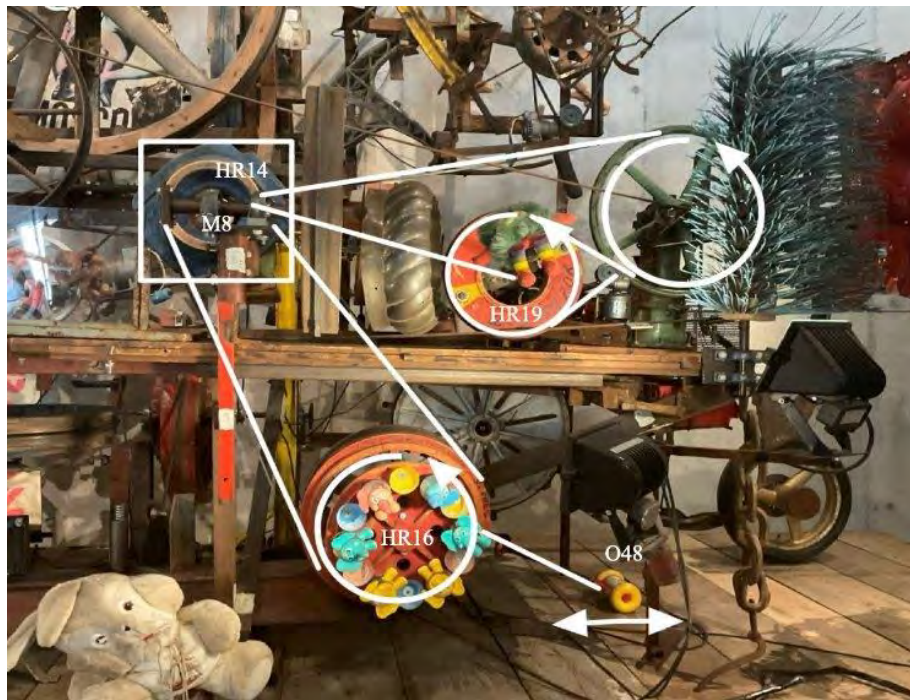
Es ist notwendig, das Koordinatensystem zu definieren, in dem gearbeitet wird, damit zukünftige Datensammler Standortmetadaten für akustische Emissionsaufzeichnungen genau erfassen können. Die vordere linke Basis der Skulptur wird als Ursprung von (x, y, z) als (0, 0, 0) verwendet. Die positiven Richtungen des Koordinatensystems sind unten dargestellt. Die folgende Abbildung zeigt ein Beispiel für ein Koordinatensystem.
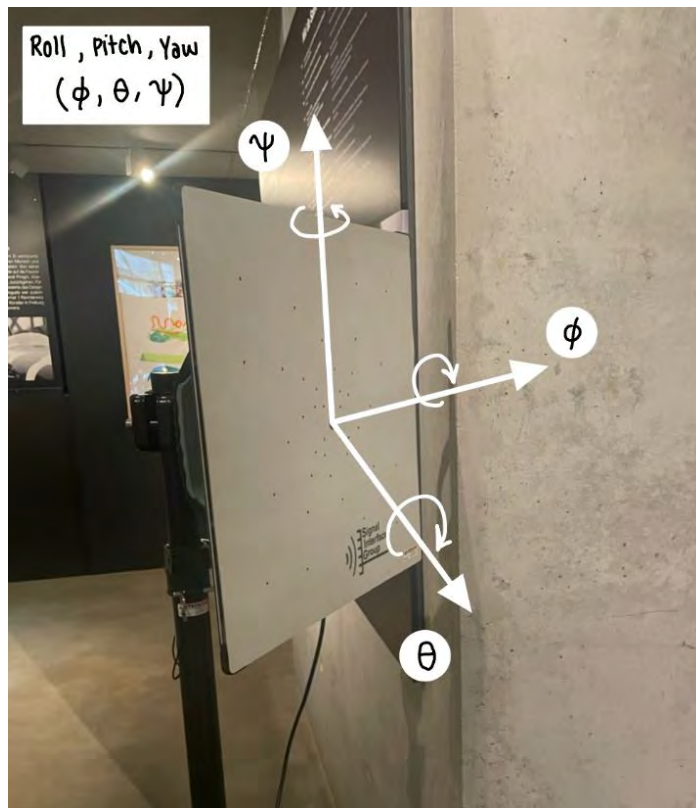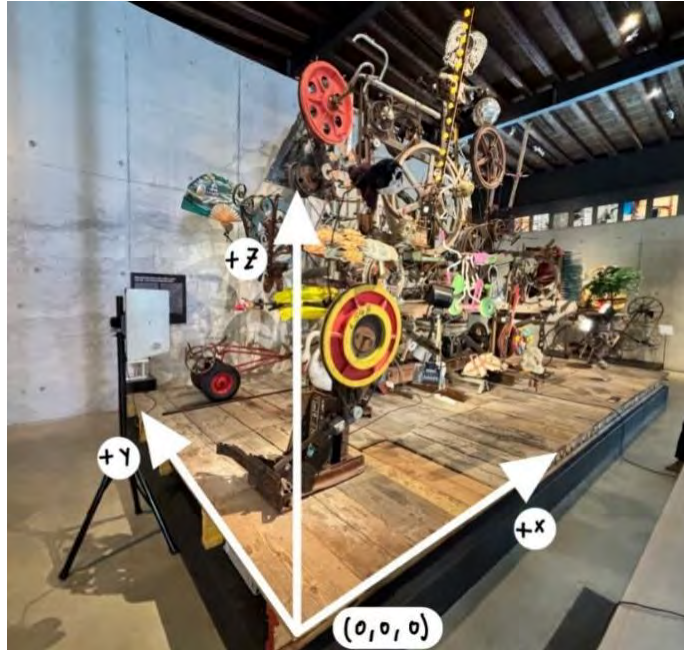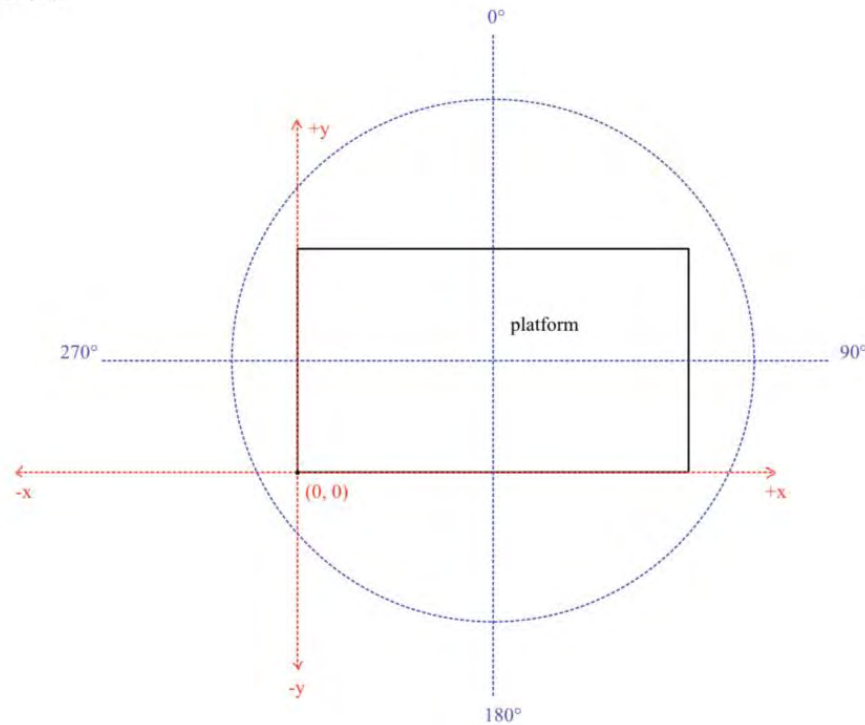
Im Folgenden finden Sie ein zu befolgendes Verfahren, um die Skulptur zu definieren:

1. Unterteilen Sie es in kleinere Subsysteme, um die lautesten Regionen zu isolieren.
    a. Beginnen Sie mit der Suche nach Motoren und verfolgen Sie die bewegten Komponenten und die Halterung der Motoren
    b. Dies ist hilfreich, um ein tieferes Verständnis für das Innenleben der Skulptur zu erlangen und ermöglicht die effektivste Lokalisierung.
2. Erstellen Sie eine Liste von Komponenten, Motoren, Riemen, Energieübertragungssystemen usw.
    a. Dies ist nützlich, wenn Sie Daten aufzeichnen und darauf verweisen.
3. Definieren Sie Koordinatensysteme. Mindestens zwei Koordinatensysteme sind die effektivste Methode, um die Positionierung und den Winkel der akustischen Kamera zu erfassen.
    a. Ein x-, y-, z-Koordinatensystem für die Position und ein φ-, θ- ψ-Koordinatensystem für den Kamerawinkel sind eine gute Möglichkeit, die beiden ohne Verwechslungen zu bezeichnen.
4. Erstellen Sie eine Tabelle, eine Tabelle oder ein Protokoll, um die Details des fokussierten Subsystems und die Kamerapositionierung aufzuzeichnen.

a. Das genaue Objekt, der Motor und die Energieübertragungskomponente. Dazu gehören auch die genaue Positionierung und der Winkel der Kamera sowie die Umgebungstemperatur, da diese die Aufnahmen beeinflussen kann.
b. Ein Beispiel dafür finden Sie unten:

Systemdetails			
Motor			
Objekt			
Holzrad/Energieübertragung			
System-/Zielbeschreibung			
Messungen zur Kamerapositionierung			
Abstand vom Bahnsteig (cm)	**x**	**y**	**z**
Winkel (°)	**φ**	**θ**	**ψ**
Umgebungstemperatur (°C)			

Datenerfassung

Während der Datenerfassung werden .bin und .mp4 Dateien gespeichert. Sie sollten mit dieser Standardbenennungskonvention gespeichert werden. Diese Konvention berücksichtigt alle Metadaten, die ein Forscher benötigt, um die Aufnahme zu rekonstruieren. Die Namenskonvention lautet jjjjmmtt_ssmmss _system_x_y_z_theta_phi_psi_name wie folgt. Die ersten beiden Teile sind Datum und Uhrzeit, gefolgt von der Systemkennung und dann der Kamerapose. Die Kamerapose ist in 2 verschiedene Teile unterteilt. Die Position der Kamera in kartesischen Koordinaten und die Richtung, die mit Euler-Winkeln beschrieben wird. Zum Schluss noch der Name der Skulptur, von der die Aufnahmen gemacht wurden.

Prozedur zur Einrichtung der Kamera

1. Positionieren Sie die Kamera so, dass sich die gewünschte Menge der Skulptur innerhalb des Bildausschnitts befindet.
2. Messen und notieren Sie ausgehend von der Mitte der Kamera die Höhe und den Abstand vom Ursprung des festgelegten x-, y- und z-Koordinatensystems.
3. Messen und zeichnen Sie die drei Winkel der Kamerapose gemäß dem festgelegten φ-, θ-ψ Koordinatensystem auf.

Allgemeines ACAM 120 Verfahren

1. Stellen Sie die Kamera an der gewünschten Stelle auf. Schließen Sie die Kamera mittels Kabel an den Laptop an.
2. Öffnen Sie BeamformX und geben Sie den OptiNav-Lizenzschlüssel auf der Kamera ein. Wählen Sie unter der Option "Datenquelle" die Option "Verbundenes Array" aus. Klicken Sie unten auf dem Bildschirm auf OK, um fortzufahren. Die Anwendung sollte die Kameraansicht anzeigen.
3. Öffnen Sie die Einstellungen.
   a. Stellen Sie "Beamforming-Bandbreite oder Engine-Reihenfolge" auf 1/3 Oktavband ein.
   b. Stellen Sie "Kontrast" auf Normal.
   c. Erstellen Sie einen Ordner auf dem Computer oder dem Speichermedium, auf dem die Daten gespeichert werden. Als Pfad kopieren und in das Textfeld "Ordner für binäre Protokolldaten und PNG-Bilder" einfügen. Achten Sie darauf, Anführungszeichen am Anfang und Ende zu entfernen.
   d. Zeichnen Sie die Temperatur auf und geben Sie sie in das Textfeld ein.
4. Um mit der Datenaufzeichnung zu beginnen, klicken Sie auf "Daten protokollieren" und direkt danach auf "Rec BF". Gehen Sie davon aus, dass die Software einige Sekunden lang puffert, bevor die eigentliche Aufzeichnung beginnt.
5. Um die Aufnahme zu beenden, klicken Sie auf "Stop Rec" und dann auf "Save .mp4", um die Aufzeichnung als Videodatei zu speichern.

<u>Für größere Skulpturen</u>

       Größere Skulpturen haben viele verschiedene Emissionsquellen. Um die Skulptur richtig aufzunehmen, sollte die folgende Vorgehensweise befolgt werden.

1. Machen Sie Emissionsaufnahmen von allen 4 Seiten der Skulptur und stellen Sie sicher, dass Sie das gesamte Werk in jede Aufnahme aufnehmen.
2. Identifizieren Sie aus jeder Skulptur die Punkte mit der größten akustischen Emission. Ein Beispiel finden Sie in Abbildung x.
3. Beginnen Sie anhand der Liste der Punkte mit den meisten Emissionen mit den Emissionsaufzeichnungen, beginnend mit den Punkten mit den meisten Emissionen in dB. Befolgen Sie das allgemeine ACAM 120-Verfahren.
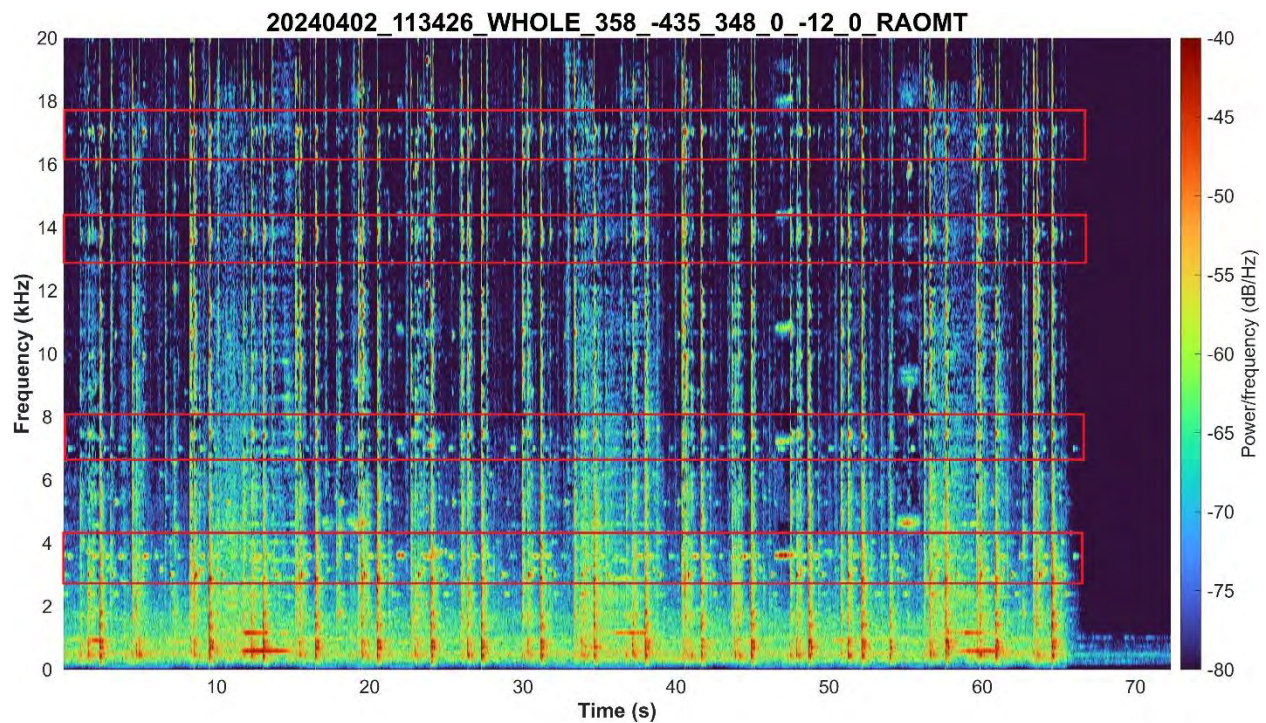
<u>Für kleinere Skulpturen</u>
Bei kleineren Skulpturen ist das Verfahren weniger aufwendig. Zeichnen Sie einfach die akustischen Emissionen der gesamten Skulptur nach dem allgemeinen ACAM 120-Verfahren von jeder Seite der Skulptur auf. Wenn nicht die gesamte Skulptur in den Rahmen passt, beginnen Sie mit dem großen Skulpturenabschnitt neu.

Datenanalyse

Um Daten zu analysieren, werden die entnommenen .mp4 Dateien in MATLAB eingegeben, indem der Dateipfad in das im Skript angegebene Skript eingefügt wird. Das Skript erstellt Spektrogramme mit schnellen Fourier-Transformationen (FFTs). Auf den erstellten Spektrogrammen werden verschiedene Frequenzbänder identifiziert und notiert. Ein Beispielspektrogramm mit mehreren sichtbaren Banden ist in der folgenden Abbildung zu sehen. Die Bänder sind rot hervorgehoben und bei 17 kHz, 14 kHz, 8 kHz und 4 kHz notiert. Um die Daten richtig zu analysieren, wird eine Kontrollprobe benötigt. Wenn man eine Kontrolle mit einer aktuellen Probe vergleicht, muss man Frequenzen identifizieren, die sich im Laufe der Zeit verändert haben. Zum Beispiel kann es sein, dass ein Band bei 12 kHz in der Steuerung nicht sichtbar ist, aber 2 Jahre später sichtbar ist. Sobald die Frequenz identifiziert ist, muss ein aktuelles Video in BeamformX analysiert werden, um Quellen von 12-kHz-Schallemissionen zu identifizieren. Restauratoren können diese Stellen dann auf Gebrauchsspuren untersuchen.

```matlab
    fileName = ...
    raw = audioread(fileName); % read audio from bfx-generated video
    fs = 44100; % set sample rate and time limits
    dt = 1/fs;
    t = (0:dt:5-dt);
    window = hamming(512);
    N_overlap = 256;
    N_fft = 1024;
    [S,F,T,P] = spectrogram(raw,window,N_overlap,N_fft,fs,'yaxis'); % generate
spectrogram
    figure
    surf(T,F,10*log10(P),'EdgeColor','none');
    axis tight;
    view(0,90);
    colormap(turbo); %set view range and color map
    set(gca,'clim',[-80,-40]); % determines decibel range, variesby sculpture
    ylim([0 20000]);
    % minimum -maximum hz range for spectro. should be usually kept at 0-20khz
    yt = get(gca, 'YTick')
    set(gca, 'YTick',yt, 'YTickLabel',yt/1E+3)
    % fix frequency bar to display kHz instead of Hz
    xlabel('Time (s)','FontSize',15,'FontWeight','bold');
    ylabel('Frequency (kHz)','FontSize',15,'FontWeight','bold');
    exportName = fileName(1:end-4);
    graphTitle =exportName(94:end)
    title(graphTitle,'FontSize',20,'Interpreter', 'none'); % main title, change
for each sculpture/angle
    ax = gca;
    ax.XAxis.FontSize = 15;
    ax.YAxis.FontSize = 15;
    a = colorbar; % gen. colorbar w/ label
    a.Label.String = "Power/frequency (dB/Hz)";
    a.FontSize = 15;
    set(gcf, 'Units', 'Pixels', 'Position', [0, 1000, 1570, 820]);
    exportName = exportName + ".png";
    exportgraphics(ax,exportName,'Resolution',300);
  end
```

Neben der Generierung von Spektrogrammen wurden auch Leistungsspektren erzeugt. Ein Leistungsspektrum ist eine Art Diagramm, das die Signalleistung gegen die Frequenz darstellt. Dies ist einem Spektrogramm sehr ähnlich, unterscheidet sich aber dadurch, dass es zu einem bestimmten Zeitpunkt und nicht über einen bestimmten Zeitraum erfolgt. Im Folgenden finden Sie ein Beispiel für ein Leistungsspektrum und das Codesegment, das zu ihrer Generierung verwendet wird.
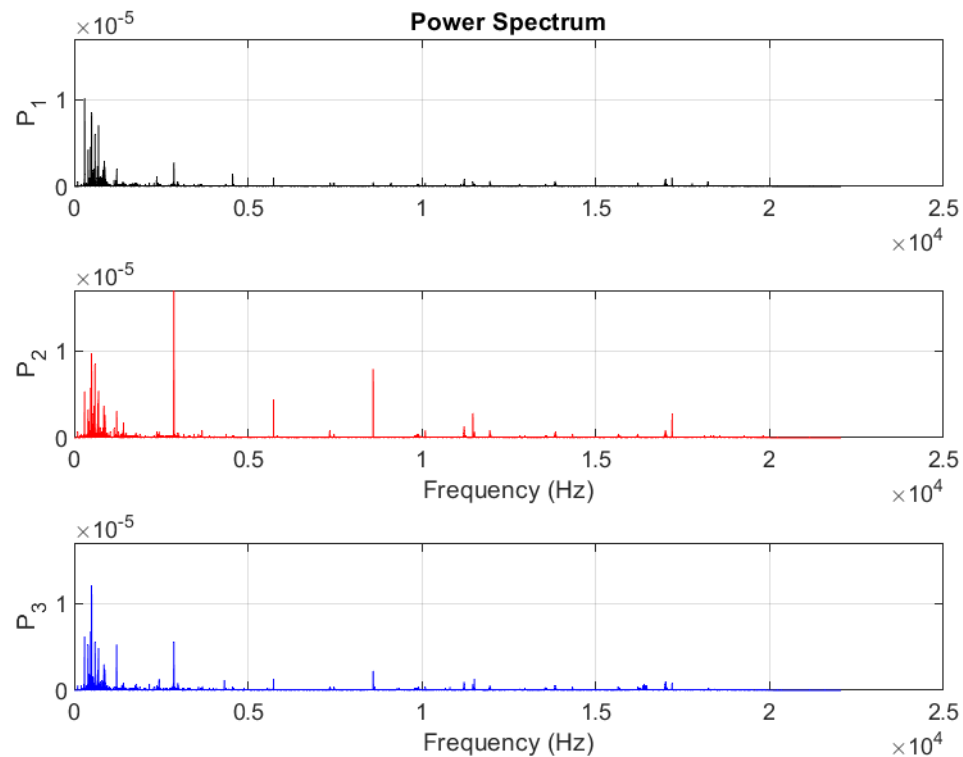

```
a1 = ...
a2 = ...
a3 = ...

sig1 = audioread(a1);
sig2 = audioread(a2);
sig3 = audioread(a3);
len = max([length(sig1),length(sig2),length(sig3)]);

s1 = vertcat(zeros((len-length(sig1)),1),sig1);
s2 = vertcat(zeros((len-length(sig2)),1),sig2);
s3 = vertcat(zeros((len-length(sig3)),1),sig3);

Fs = 44100;
```

```matlab
[P1,f1] = periodogram(s1,[],[],Fs,'power');
[P2,f2] = periodogram(s2,[],[],Fs,'power');
[P3,f3] = periodogram(s3,[],[],Fs,'power');


[pk1,lc1] = findpeaks(P1,'SortStr','descend','NPeaks',3);
P1peakFreqs = f1(lc1);

[pk2,lc2] = findpeaks(P2,'SortStr','descend','NPeaks',3);
P2peakFreqs = f2(lc2);

[pk3,lc3] = findpeaks(P3,'SortStr','descend','NPeaks',3);
P3peakFreqs = f3(lc3);

maxY = max([max(P1), max(P2), max(P3)]);

subplot(3,1,1)
plot(f1,P1,'k')
ylim([0, maxY]);
grid
ylabel('P_1')
title('Power Spectrum')

subplot(3,1,2)
plot(f2,P2,'r')
ylim([0, maxY]);
grid
ylabel('P_2')
xlabel('Frequency (Hz)')

subplot(3,1,3)
plot(f3,P3,'b')
ylim([0, maxY]);
grid
ylabel('P_3')
xlabel('Frequency (Hz)')

[Cab,f] = mscohere(s1,s2,[],[],[],Fs);
[Cbc,~] = mscohere(s2,s3,[],[],[],Fs);
[Cac,~] = mscohere(s1,s3,[],[],[],Fs);

exportName = erase(a1, ".mp4")
exportName = exportName + ".png";
saveas(gcf,exportName);
```

Guide pour la conservation acoustique de l'art cinétique

Par Fiona Leitner, William Merry, Ellie Ramirez-Richer et Taylor Walker

Créé pour un rapport de projet de qualification interactif (IQP) soumis à la faculté de l'INSTITUT POLYTECHNIQUE DE WORCESTER en réponse partielle aux exigences du diplôme de baccalauréat ès sciences. Ces reportages sont publiés régulièrement sur le site web WPI sans examen éditorial ou critique par les pairs. Pour plus d'informations sur le programme de projets de WPI, veuillez consulter http://www.wpi.edu/Academics/Projects.

Préface

Pourquoi créer un guide ?

L'œuvre de Jean Tinguely regorge de composants et de mécanismes complexes. Sans la cohérence traditionnelle que présentent les types d'œuvres d'art les plus courants, le processus de conservation devient plus difficile. Une caméra acoustique est un moyen non invasif de collecter des données sur l'usure et la dégradation afin de déterminer où les restaurateurs doivent intervenir. Ce guide fournit aux collecteurs de données et aux restaurateurs un chemin à suivre lors de l'utilisation d'une caméra acoustique. En disposant d'une méthode cohérente de collecte de données, la comparaison des enregistrements acoustiques devient plus facile et plus précise. Le guide comprend des chapitres chronologiques systématiques qui mettent en évidence les quatre principales étapes d'une bonne conservation : l'inventaire, la définition, l'enregistrement et l'analyse. L'annexe comprend des photos annotées des sous-systèmes qui composent la sculpture et qui peuvent être référencées tout au long du projet. Un lien vers les dossiers contenant les enregistrements acoustiques de base ainsi qu'un exemple de feuille d'enregistrement des détails du système se trouvent également en annexe. Le guide est rédigé en anglais, allemand et français. Outre les sculptures de Jean Tinguely, ce guide peut être adapté et utilisé pour d'autres types d'art cinétique.

Merci d'avoir pris le temps de vous concentrer sur la conservation de l'art de Jean Tinguely et d'autres œuvres d'art cinétique.

Inventaire

La première étape d'une bonne conservation consiste à créer un inventaire de toutes les parties de la sculpture. L'inventaire ne doit être complété qu'une seule fois pour chaque sculpture. Il doit être stocké de manière à pouvoir être facilement transmis. Vous trouverez ci-dessous la procédure utilisée pour l'inventaire d'une sculpture :

1. Divisez toutes les parties de la sculpture en trois catégories : les moteurs (M), les dispositifs de transfert d'énergie (E) et d'autres objets divers (O). Les dispositifs de transfert d'énergie peuvent inclure des courroies, des poulies, des pignons, des roues, etc.
    a. Dans cet exemple, les dispositifs de transfert d'énergie seront séparés en sous-catégories pour les roues en bois (EW) et en métal (EM).
2. Parcourez chaque catégorie, en commençant par M, puis E, puis O, et étiquetez les parties en conséquence dans un tableau pour chaque catégorie. Pour ce faire, commencez par l'avant, le coin gauche de la sculpture, et déplacez-vous vers la droite et vers l'arrière en étiquetant chaque objet avec un identifiant correspondant.
    a. Les identificateurs doivent être numérotés de gauche à droite. Par exemple, les moteurs seraient étiquetés M1-Mx.
    b. Pour chaque moteur, suivez ce qu'il entraîne dans la sculpture au fur et à mesure que le mouvement s'écoule.
    c. Une étape supplémentaire consiste à attribuer un code couleur à chaque moteur à des emplacements spécifiques. Par exemple, l'emplacement sur le piédestal est bleu et l'emplacement sur le cadre est violet.
3. Compilez chaque liste dans son propre tableau:
    a. Trois colonnes pour les moteurs: Nombre, emplacement et flux de mouvement.
    b. Trois colonnes pour les dispositifs de transfert d'énergie:-Numéro, dimensions et inscriptions, et ceintures.
    c. Trois colonnes pour les objets divers: Numéro, description et matériau.

Par exemple, consultez les tableaux ci-dessous :

| Moteurs sur piédestal |
| Moteurs au 1er étage |
| Moteurs sur châssis métallique |

Moteur	Localisation (numérotation, assemblage)	Flux de mouvement
M1 (en anglais seulement)	Sur l'élément libre à l'extrême gauche	M1 à EW1 à déplace peluche et élément métallique
M2 (en anglais seulement)	À droite de l'EW4, derrière Swan (3, 4)	M2 à EW4 à Swan
M3 (en anglais seulement)	Entre EW2 et EW13 (12, 20) Précédent	M3 à EM2 (Gingerbread) à EW2 à Compartments M3 à EM2 (Gingerbread) à EW2 à on the road Tiges métalliques avec parties de garde-corps métallique à via une tige métallique petit élément lumineux avec persiennes du Père Noël et guirlandes lumineuses avec des fleurs M3 à EM2 à sur essieu EM2a à EW3 à sur essieu tringlerie chromée M3 à EM2 à on Axis Gingerbread Hearts

EW1 – EW20	Roue en bois (dimensions et inscriptions)	Courroies (rectifiées pour les pièces de rechange)
EW1	Rouge-jaune	Courroie Courroie trapézoïdale noire 21950 B / 046 / Fabriqué en ??? / TEXROPE / 84 / Z76 / 1001950 / 10 x 1930 LI
EW2	Bleu	Bracelet perforé vert
EW3	Rouge avec 6 trous	

O1 à O53	Description de l'objet	Masse / Matériel
O1	Peluche	Textile
O2	Pièce métallique	Métal
O3	Éventail	Holz / Papier

4. À l'aide d'une image de la sculpture, décrivez les dispositifs de transfert d'énergie pour référence ultérieure

Par exemple, voir l'image ci-dessous :
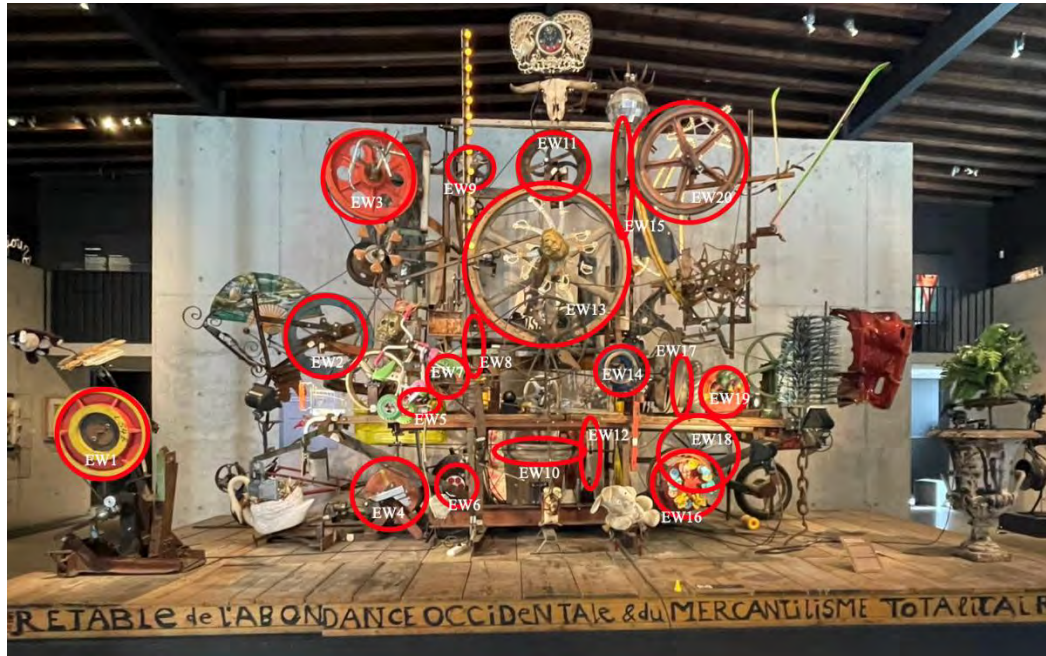
Définition

       Il faut définir les différents systèmes et sous-systèmes au sein d'une sculpture, ainsi que définir le système de coordonnées pour lequel ils prendront des mesures. La définition et le système de coordonnées ne doivent être complétés qu'une seule fois pour chaque sculpture individuelle. Il doit être stocké de manière à pouvoir être facilement transmis.

       Un système est défini comme une partie de la sculpture qui se déplace tous ensemble. Pour trouver un système, il faut commencer par un moteur, et suivre toutes les méthodes de transfert d'énergie jusqu'au bout. Un sous-système est un petit système à l'intérieur d'un plus grand. Les sous-systèmes doivent être définis lorsque le système le plus grand est trop grand pour être enregistré avec précision dans un seul enregistrement des émissions acoustiques. L'image ci-dessous montre un exemple de dessin de système.
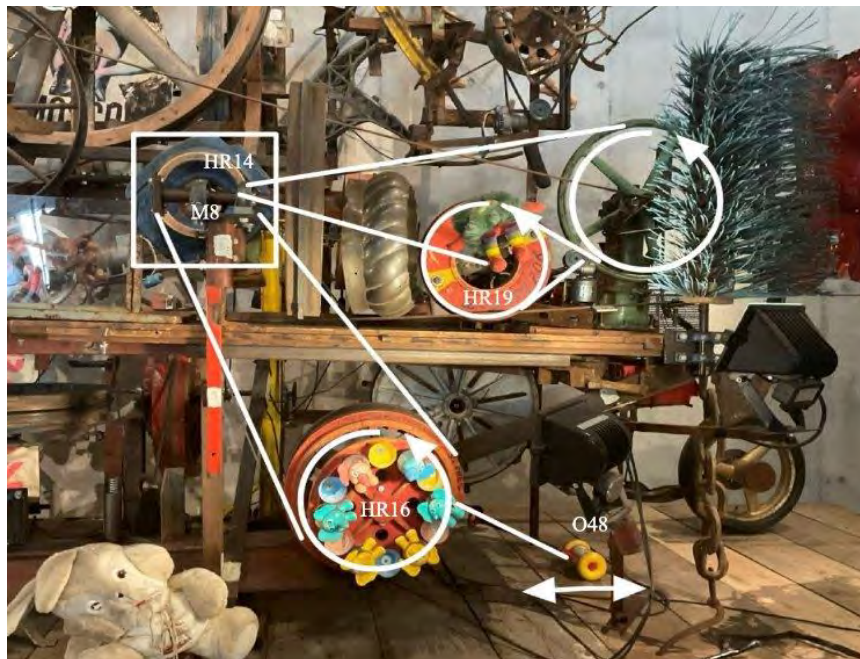
Il est nécessaire de définir le système de coordonnées dans lequel le travail s'effectuera, afin que les futurs collecteurs de données puissent acquérir avec précision les métadonnées de localisation pour les enregistrements d'émissions acoustiques. En utilisant la base avant gauche de la sculpture comme origine de (x, y, z)en tant que (0, 0, 0). Les directions positives du système de coordonnées sont indiquées ci-dessous. L'image ci-dessous montre un exemple de système de coordonnées.
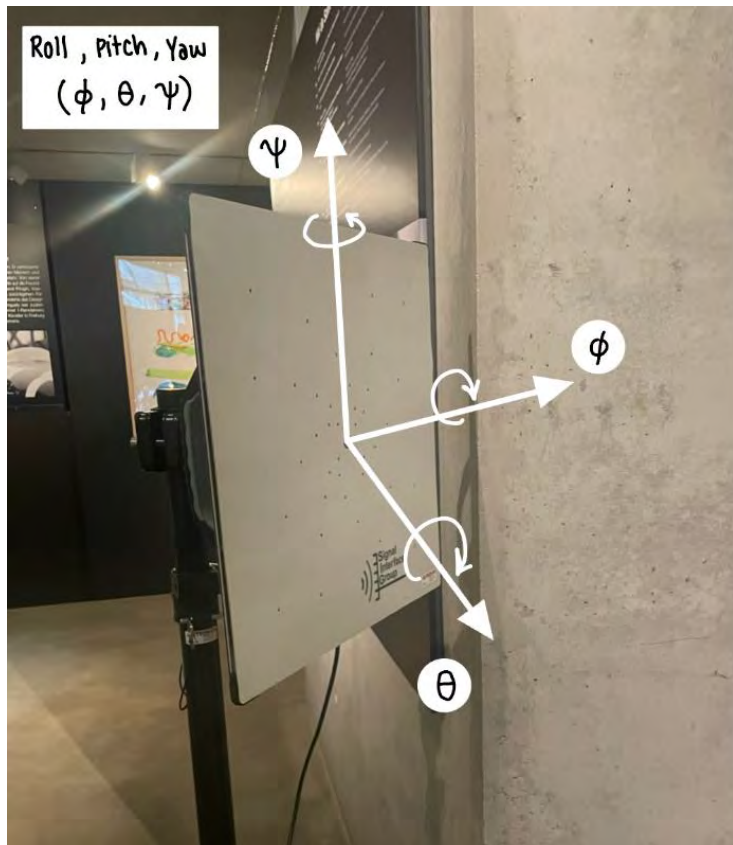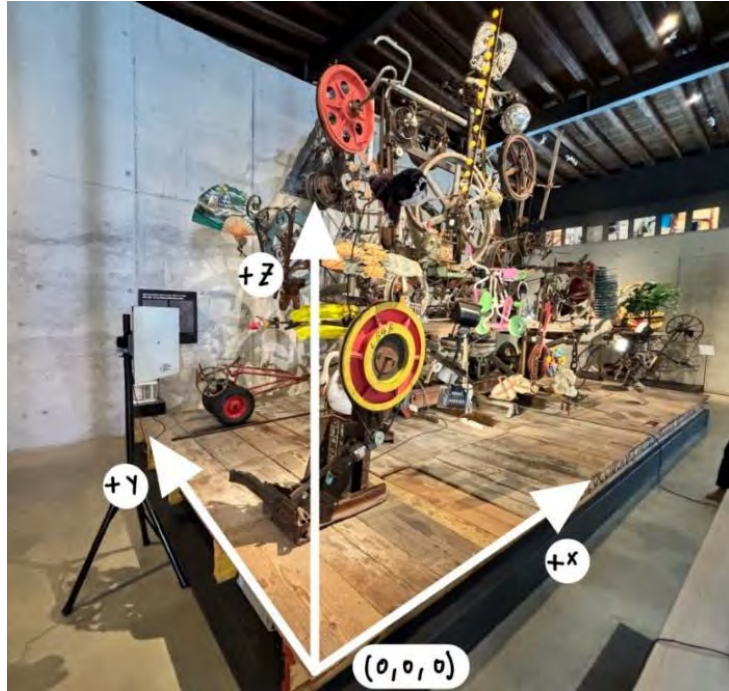
Coordinate System:
(x, y, z)
(θ, φ, ψ)
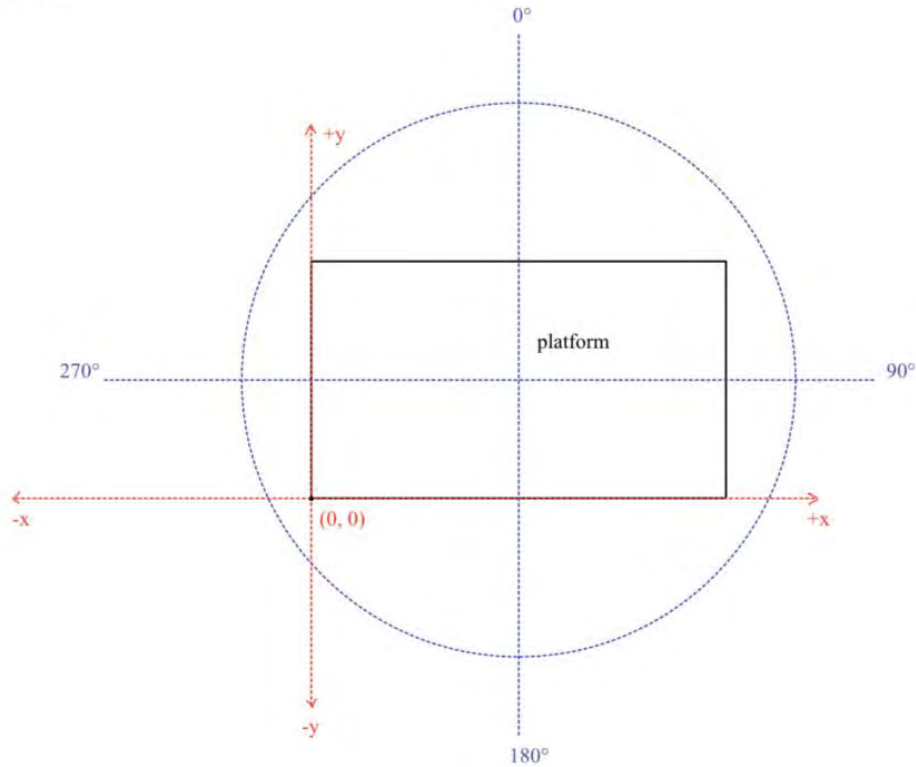
Vous trouverez ci-dessous une procédure à suivre pour définir la sculpture :

1. Décomposez-le en sous-systèmes plus petits pour isoler les régions les plus bruyantes.
   a. Commencez par rechercher les moteurs et suivez ce qu'ils déplacent et attachent aussi.
   b. Ceci est utile pour obtenir une compréhension plus approfondie du fonctionnement interne de la sculpture et permet la localisation la plus efficace.
2. Créez une liste des composants, des moteurs, des courroies, des systèmes de transfert d'énergie, etc.
   a. Cela sera utile lors de l'enregistrement des données et de la référence à celles-ci.
3. Définissez des systèmes de coordonnées. Un minimum de deux systèmes de coordonnées sera le moyen le plus efficace de capturer les deux angles de positionnement de la caméra acoustique.
   a. Un système de coordonnées x, y, z pour la position et un système de coordonnées φ, θ ψ pour l'angle de la caméra sont un bon moyen de désigner les deux sans confusion.
4. Créez un tableau, une feuille de calcul ou un journal pour enregistrer le positionnement de la caméra, et les détails du sous-système sur lequel vous vous concentrez.

a. L'objet, le moteur et le composant de transfert d'énergie exacts. Cela inclura également le positionnement et l'angle exacts de la caméra, ainsi que la température ambiante, car cela peut affecter les enregistrements.
b. Vous trouverez un exemple ci-dessous :

Détails du système			
Moteur			
Objet			
Roue en bois/transfert d'énergie			
Description du système/de l'objectif			
Mesures pour le positionnement de la caméra			
Distance de la plate-forme (cm)	**x**	**y**	**z**
Angles (°)	**φ**	**θ**	**ψ**
Température ambiante (°C)			

Acquisition de données

Lors de l'acquisition des données, les fichiers .bin et .mp4 seront enregistrés. Ils doivent être enregistrés à l'aide de cette convention de dénomination standardisée. Cette convention tient compte de toutes les métadonnées dont un chercheur aurait besoin pour recréer la photo. La convention de nommage est la suivante, yyyymmdd_hhmmss _system_x_y_z_theta_phi_psi_name. Les deux premières parties sont la date et l'heure, suivies de l'identifiant du système, puis de la pose de la caméra. La pose de la caméra est divisée en 2 parties différentes. L'emplacement de la caméra en coordonnées cartésiennes et la direction décrite à l'aide des angles d'Euler. Enfin, le nom de la sculpture dont les enregistrements ont été réalisés.

Procédure de configuration de la caméra
1. Positionnez la caméra de manière à ce que la quantité souhaitée de la sculpture se trouve dans le cadre.
2. En partant du centre de la caméra, mesurez et enregistrez la hauteur et la distance à partir de l'origine du système de coordonnées x, y, z établi.
3. Mesurez et enregistrez les trois angles de la configuration de la caméra en fonction du système de coordonnées φ, θ ψ établi.

Procédure générale de l'ACAM 120
1. Configurez la caméra à l'emplacement souhaité. Branchez le cordon à la fois à l'appareil photo et à l'ordinateur portable.
2. Ouvrez BeamformX et saisissez la clé de licence OptiNav sur la caméra. Sous l'option Source de données, sélectionnez « Réseau connecté ». Cliquez sur OK en bas de l'écran pour continuer. L'application doit afficher la vue de la caméra.
3. Ouvrez Paramètres.
   a. Réglez « Bande passante de formation de faisceaux ou ordre du moteur » sur Bande de 1/3 d'octave.
   b. Changez « Contraste » en normal.
   c. Créez un dossier sur l'ordinateur ou le disque dur dans lequel les données seront stockées. Copiez en tant que chemin d'accès et insérez-le dans la zone de texte « Dossier pour les données de journal binaires et les images PNG ». Assurez-vous de supprimer les guillemets du début et de la fin.
   d. Enregistrez la température et tapez-la dans la zone de texte.
4. Pour commencer l'enregistrement des données, cliquez sur « Enregistrer les données .bin », puis sur « Rec BF » directement après. Supposons que le logiciel se mette en mémoire tampon pendant quelques secondes avant le début de l'enregistrement.
5. Pour arrêter l'enregistrement, cliquez sur « Arrêter l'enregistrement » et « Enregistrer .mp4 » pour enregistrer un fichier vidéo.

Pour les sculptures plus grandes

Les sculptures plus grandes auront de nombreuses sources d'émission différentes. Pour enregistrer correctement la sculpture, la procédure suivante doit être suivie.

1. Prenez des enregistrements d'émission des 4 côtés de la sculpture en vous assurant d'inclure l'œuvre complète dans chaque enregistrement.
2. À partir de chaque sculpture, identifiez les plus grands points d'émission acoustique. Voir la figure x pour un exemple.
3. À l'aide de la liste des points d'émissions les plus élevées, commencez à enregistrer les émissions en commençant par les points ayant le plus d'émissions en dB. Suivez la procédure générale ACAM 120.
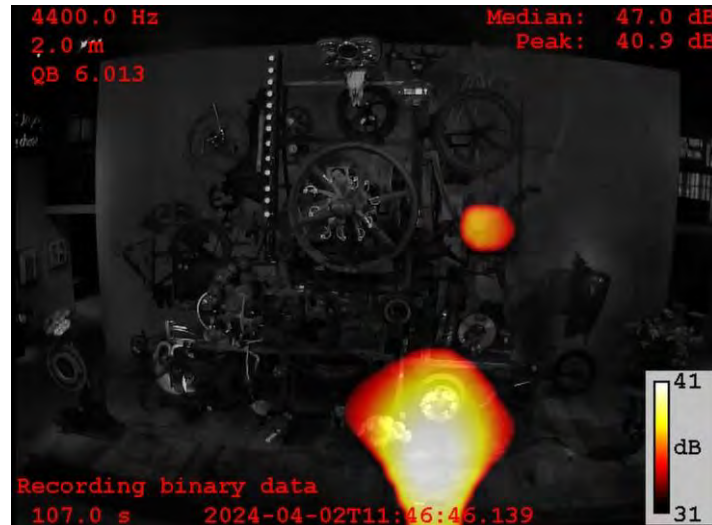
Pour les petites sculptures

Pour les sculptures plus petites, la procédure est moins complexe. Il suffit d'enregistrer les émissions acoustiques de l'ensemble de la sculpture en suivant la procédure générale ACAM 120 de chaque côté de la sculpture. Si l'ensemble de la sculpture ne rentre pas dans le cadre, recommencez avec la grande section de sculpture.

Analyse des données

Pour analyser les données, les fichiers .mp4 pris sont saisis dans MATLAB en plaçant le chemin d'accès au fichier dans le script donné dans le script. Le script crée des spectrogrammes à l'aide de transformées de Fourier rapides (FFT). Sur les spectrogrammes créés, différentes bandes de fréquences sont identifiées et notées. Un exemple de spectrogramme avec plusieurs bandes visibles peut être vu dans l'image ci-dessous. Les bandes sont surlignées en rouge et notées à 17 kHz, 14 kHz, 8 kHz et 4 kHz. Pour analyser correctement les données, un échantillon de contrôle est nécessaire. Lorsque l'on compare un témoin à un échantillon actuel, il faut identifier les fréquences qui ont changé au fil du temps. Par exemple, une bande peut ne pas être visible à 12 kHz dans le contrôle, mais l'être 2 ans plus tard. Une fois la fréquence identifiée, une vidéo en cours doit être analysée dans BeamformX afin d'identifier les sources d'émissions acoustiques de 12 kHz. Les restaurateurs peuvent ensuite inspecter ces endroits à la recherche de signes d'usure.

20240402_113426_WHOLE_358_-435_348_0_-12_0_RAOMT

```
    fileName = ...
    raw = audioread(fileName); % read audio from bfx-generated video
    fs = 44100; % set sample rate and time limits
    dt = 1/fs;
    t = (0:dt:5-dt);
    window = hamming(512);
    N_overlap = 256;
    N_fft = 1024;
    [S,F,T,P] = spectrogram(raw,window,N_overlap,N_fft,fs,'yaxis'); % generate
spectrogram
    figure
    surf(T,F,10*log10(P),'EdgeColor','none');
    axis tight;
    view(0,90);
    colormap(turbo); %set view range and color map
    set(gca,'clim',[-80,-40]); % determines decibel range, variesby sculpture
    ylim([0 20000]);
    % minimum -maximum hz range for spectro. should be usually kept at 0-20khz
    yt = get(gca, 'YTick')
    set(gca, 'YTick',yt, 'YTickLabel',yt/1E+3)
    % fix frequency bar to display kHz instead of Hz
    xlabel('Time (s)','FontSize',15,'FontWeight','bold');
    ylabel('Frequency (kHz)','FontSize',15,'FontWeight','bold');
    exportName = fileName(1:end-4);
    graphTitle =exportName(94:end)
    title(graphTitle,'FontSize',20,'Interpreter', 'none'); % main title, change
for each sculpture/angle
    ax = gca;
    ax.XAxis.FontSize = 15;
    ax.YAxis.FontSize = 15;
    a = colorbar; % gen. colorbar w/ label
    a.Label.String = "Power/frequency (dB/Hz)";
    a.FontSize = 15;
    set(gcf, 'Units', 'Pixels', 'Position', [0, 1000, 1570, 820]);
    exportName = exportName + ".png";
    exportgraphics(ax,exportName,'Resolution',300);
 end
```

En plus de générer des spectrogrammes, des spectres de puissance ont également été générés. Un spectre de puissance est un type de graphique qui trace la puissance du signal en fonction de la fréquence. Ceci est très similaire à un spectrogramme, mais diffère car il est à un instant de temps plutôt que sur une période. Vous trouverez ci-dessous un exemple de spectre de puissance et le segment de code utilisé pour les générer.


```
     a1 = ...
a2 = ...
a3 = ...

sig1 = audioread(a1);
sig2 = audioread(a2);
sig3 = audioread(a3);
len = max([length(sig1),length(sig2),length(sig3)]);

s1 = vertcat(zeros((len-length(sig1)),1),sig1);
s2 = vertcat(zeros((len-length(sig2)),1),sig2);
s3 = vertcat(zeros((len-length(sig3)),1),sig3);

Fs = 44100;

[P1,f1] = periodogram(s1,[],[],Fs,'power');
```

```matlab
[P2,f2] = periodogram(s2,[],[],Fs,'power');
[P3,f3] = periodogram(s3,[],[],Fs,'power');


[pk1,lc1] = findpeaks(P1,'SortStr','descend','NPeaks',3);
P1peakFreqs = f1(lc1);

[pk2,lc2] = findpeaks(P2,'SortStr','descend','NPeaks',3);
P2peakFreqs = f2(lc2);

[pk3,lc3] = findpeaks(P3,'SortStr','descend','NPeaks',3);
P3peakFreqs = f3(lc3);

maxY = max([max(P1), max(P2), max(P3)]);

subplot(3,1,1)
plot(f1,P1,'k')
ylim([0, maxY]);
grid
ylabel('P_1')
title('Power Spectrum')

subplot(3,1,2)
plot(f2,P2,'r')
ylim([0, maxY]);
grid
ylabel('P_2')
xlabel('Frequency (Hz)')

subplot(3,1,3)
plot(f3,P3,'b')
ylim([0, maxY]);
grid
ylabel('P_3')
xlabel('Frequency (Hz)')

[Cab,f] = mscohere(s1,s2,[],[],[],Fs);
[Cbc,~] = mscohere(s2,s3,[],[],[],Fs);
[Cac,~] = mscohere(s1,s3,[],[],[],Fs);

exportName = erase(a1, ".mp4")
exportName = exportName + ".png";
saveas(gcf,exportName);
```

C   Work Documentation

The following was adapted from a previous version created by the MAHF.

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Office of Culture KA

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Museum of Art and History MAHF

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ETAT DE FRIBOURG
STAAT FREIBURG

Work Documentation
Retable de l'Abondance occidentale et du Mercantilisme totalitaire
1997-107

Loaners:	MAHF
Work. No.:	1997-107

Artist:	Jean Tinguely
Title:	Altarpiece of Western Abundance and Totalitarian Mercantilism
Year:	1989-1990
Technology:	Metals, synthetic and organic materials, electric motors
Mass:	505.00 x 590.00 x 265.00 cm

1. Working photo

2. Historical Background

Created for his retrospective in Moscow (1990) and placed in front of the Artist's Central House, adjacent to the Tretjakov Gallery. Donated by Niki de Saint Phalle in 1995

Place of execution: Atelier de la Verrerie

Exhibitions:
1990 Moscow, Tretjakov Gallery, Jean Tinguely retrospective; 1991 Fribourg, MAHF, Jean Tinguely retrospective

3. Description of the object / Description of the work

3.1. Objects

Moving Objects: O1 - Ox
Items loosely listed from left to right

O1 – O53	Object Description	Masse / Material
O1	Plush toy	Textile
O2	Metal part	Metal
O3	Fan	Wood / Paper
O4	Fence part metal	Iron
O5	Dwarf	Plastic
O6	3 spotlights on the left (now LED)	Plastic / Glass / LED Bulbs

O7	Flower box swan with plastic plants	Plastic
O8	Carette red with two tires	Plastic / Painted Metal Vorderes Pneu: SCHWALBE / MADE IN KOREA / K / 400 x 100 / Felge 2.50 A x 8 / 2 PR / Tube type / 8101 Hinteres Pneu: HWA FONG / Not for Highway use / 3018 / Load Range a max. Inflation 35 p.s.i. (2.4 bar) / 4.80/4.00-8 / HF-207-14 / Nylon / Made in Taiwan / 2 p.r.
O9	Part of shopping cart	Metall / Kunststoff
O10	Mirror	Plastic
O11	Chrome-plated metal tubes	Metal
O12	Gingerbread on metal scaffolding 6	Dough
O13	Skull with two figures (artist where Tinguely collected Podesta)	Paper-Mache
O14	Small fairy lights (flowers) with Saint Nicholas	Plastic / small lamps
O15	Porcelain doll	Porcelain / Textile
O16	Children's bike green / pink	Metal / Plastic
O17	Sleigh	Plastic
O18	Betonklotz an Metallarm	Concrete
O19	Placette Logo	Plastic
O20	Fairy lights on metal rod	Plastic / Lamps
O21	Doll	Plastic / Textile
O22	Small antlers on wooden plate	Horn / Bone / Wood
O23	Snowboard	Plastic / Metal
O24	Crown	Plastic
O25	Skull large	Horn / Bone
O26	Poster	?
O27	Make-up Box	Plastic
O28	Mask and plush panther in front of swords	Plastic / Plush Textile
O29	Nana with headlight	?
O30	Horse Head with Chain Metal	Metal
O31	Disco Ball	Plastic
O32	Tea Deck	Plastic
O33	Plastic element foam?	Construction foam?
O34	Detergent container	Plastic with paper
O35	Stuffed Bunny / Plush Toy	Textile
O36	Star of Lights	Plastic
O37	Mirror right	Metal
O38	Metal Rods	Metal
O39	Rollbrett	Plastic

O40	Bronze element	Bronze?
O41	Mug Elephant Plastic	Plastic
O42	Ski	Plastic / Metal
O43	Grittibänze	Dough
O44	Plush toy colored	Textile
O45	2 spotlights	Glass / Plastic / LED
O46	Car wash part	Plastic / Metal
O47	Auto part	Metal
O48	Rotary drum Fisher Price	Plastic / Metal
O49	Motorcycle Wheel	Plastic / Metal
O50	Fern	Plastic
O51	Planters	Metal
O52	Plinth	Wood
O53	Wooden panel 1st floor	Wood

3.2. Wooden wheels (cast models) and belts

The wood-cast models of the von Roll company were found by Jean Tinguely in 1985 on a disused factory building of the company in Olten and incorporated into his works.

EW1 – EW20	Wooden wheel (dimensions and inscriptions)	Belts (ground for spare parts)
EW1	Red-yellow	Strap Black V-belt 21950 B / 046 / Made in ??? / TEXROPE / 84 / Z76 / 1001950 / 10 x 1930 LI
EW2	Blue	Green perforated strap
EW3	Red with 6 holes	
EW4	Red-yellow drum	Black perforated strap (10mm), 220cm
EW5	Red? Horizontal position with porcelain doll	
EW6	Wood without paint with placette logo	
EW7	Red small behind bike	
EW8	Holz Snowboard	Strap to wooden wheel Belt on metal wheel to the right of it Black V-belt Optibelt-vb / Made in Germany / S=C plus / 10x2120 / Z83 ½ → Belt Ordered
EW9	Without color	
EW10	Blue, Horizontally	Black perforated strap (10mm), 400cm
EW11	Without color	
EW12	Rotten, right to weigh	
EW13	Without color	
EW14	Blue, angular	There are two straps on the front and one strap on the back Green perforated strap (9mm), approx. 320cm (connected to EW 16)
EW15	Horizontally	
EW16	Red	Green perforated strap (10mm), approx. 320cm → Order March 14, 2023
EW17	Vertical red / black	In the rear area
EW18	White	green perforated strap (13mm), approx. 250cm → Order March 14, 2023
EW19	Red	
EW20	Red	

3.3. Metal wheels and belts

EM1 – EM11	Metal wheel	Strap
EM1	Cast wheel with golden coating, 4 spokes which split at the end and run in opposite direction to form a triangle. At the front, a T-element with a triangular surface is mounted. At the rear end of the rod is welded a corroded metal arm, which is welded to the red carette by a screw and nut and an additional corroded metal plate.	
EM2		
EM3		Black perforated strap (13mm), 160cm
EM4		
EM8a	Wheel on axle of EW8	
EM8b	Small wheel vertical on axis of carriage	
EM5	Kl. Rad horizontal	
EM6		
EM7		
EM8		
EM9		
EM10		

3.4. Motors

The 16 engines are numbered from left to right
Naming:
Motor: M1 – 16

| Motors on pedestal |
| Motors on 1st floor |
| Motors on metal frame |

Motor	Location (numbering, assembly)	Movement
M1	On the free element on the far left	M1 → EW1 → moves plush toy and metal element
M2	To the right of EW4, behind Swan (3, 4)	M2 → EW4 → Swan
M3	Between EW2 and EW13 (12, 20) Back	M3 → EM2 (Gingerbread) → EW2 → Compartments M3 → EM2 (Gingerbread) → EW2 → on the road Metal rods with parts of metal railing → via metal rod small light element with Santa louvers and fairy lights with flowers M3 → EM2 → on axle EM2a → EW3 → on axle chrome linkage M3 → EM2 → on Axis Gingerbread Hearts
M4	21 Back	M4 → EW8 → Snowboard M4 → EW8 → on Axis EM8a → on Axis Doll M4 → EW8 → on axle EM8a (forgotten) → EM8b (kl wheel) → on axle carriage and dwarf
M5	In front of Placette logo (5) at the top right of it Black engine	M5 → EW10 → on Nana axle M5 → on axis EW5 (horizontal) → on axis porcelain doll
M6	Engine behind Nana on floor (6, 13, 22, 23, 38) Two rollers EW 7 (left) and via EM6 (right)	M6 → EM6 → on axle EM6a → on axle Squirrel M6 → EM6 → on axle EM6a → via belt EW6 → on axle front Placette logo M6 → EM6 → on axle EM6a → via belt EW6 → pneucarette → EM1

		M6 → EW7, → EW13 → via metal rod, two nuts with rods, which move the two side altars forwards and backwards → , on the rod on the left a wheel made of swords is attached via nut, with plush and mask (G28) Both sides M6 → EW7 → on axle EM7a → via belt EM3 → skull of artist → via metal rod to the far right blue element of car wash M6 → EW7 → on axle EM7b → via belt EM5 → on axle Wooden trunk with chain which moves horse's head M6 → EW7 → on the road children's bike
M7	Behind EW13 (24, 39) Back	M7 → EM4 → on axle EM4 wheel → EW9 → kl. Antler M7 → EM4 → EW11→ via metal rod front antlers with crown plastic M7 → EM4 → EW11→ via metal rod rear advertising poster M7 → EM4 → EW11→ via metal rod at the rear Light star → via metal wire Speigel right
M8	Links of EW 14	M8 → to engine foam element M8 → EW14 → EW16 → On Axle Front Wooden Wheel With Elephant M8 → EW14 → EW16 → on axle rear metal rod which moves plastic toy on the ground (rotating drum) M8 → EW14 → EM9 → via metal rod red car element M8 → EW14 → EM9 → via long metal rod far to the left Light garland on metal rod vertical
M9	Bottom right of EW10, behind plush bunny (7) 11, 12, 35	M9 → EW12 → Metal part which presses on metal rod and lets it fall → Boom from back to front with wax container that hits the plush bunny M9 → EW12 → on axle EM12a kl. Wheel → via belt EW15 → on axle make-up box M9 → EW15 → Make-up Box
M10	Behind Disco Ball	M10 → Disco Ball

M11	On China Teapot Back (27)	MA11→ Teapot
M12	Back Height of rolling board, (28, 34)	M12 → EW17 → via metal rod roller board M12 → EW17 → on axle EM 7a → via belt EM7 → on axle brass element round
M13	Rear of rotary drum Next to White Wheel (29)	M13 → EW18 → on axle Metal rod via axle and two blue things wheel (formerly EM10) moves from left to right
M14	Below skis, below EM8 (36)	M14 → EM8 → on axle metal linkage front M14 → EM8 → on axle rear 6 Gritti dances M14 → EM8 → on axle EM8a → via strap EW 20 → on axle (front and rear) two metal bars that move both skis
M15	To the right of EW19	M15 → EW19 → On Axle Colored Plush Toy (rear on axle grinds belt of EM9)
M16	On the free element Right-hand side	M16 → EM10 → on Ivy Axis

D MATLAB Code

Listing 1

MATLAB script for spectrogram generation based on script used in previous work (Rodriguez Plassa et al., 2023)

```matlab
raw = audioread(fileName); % read audio from bfx-generated video
fs = 44100; % set sample rate and time limits
dt = 1/fs;
t = (0:dt:5-dt);
window = hamming(512);
N_overlap = 256;
N_fft = 1024;
[S,F,T,P] = spectrogram(raw,window,N_overlap,N_fft,fs,'yaxis'); % generate spectrogram
figure
surf(T,F,10*log10(P),'EdgeColor','none');
axis tight;
view(0,90);
colormap(turbo); %set view range and color map
set(gca,'clim',[-80,-40]); % determines decibel range, variesby sculpture
ylim([0 20000]);
% minimum -maximum hz range for spectro. should be usually kept at 0-20khz
yt = get(gca, 'YTick')
set(gca, 'YTick',yt, 'YTickLabel',yt/1E+3)
% fix frequency bar to display kHz instead of Hz
xlabel('Time (s)','FontSize',15,'FontWeight','bold');
ylabel('Frequency(kHz)','FontSize',15,'FontWeight','bold');
exportName = fileName(1:end-4);
graphTitle =exportName(94:end)
title(graphTitle,'FontSize',20,'Interpreter', 'none'); % main title, change for each
    sculpture/angle
ax = gca;
ax.XAxis.FontSize = 15;
ax.YAxis.FontSize = 15;
a = colorbar; % gen. colorbar w/ label
a.Label.String = "Power/frequency (dB/Hz)";
a.FontSize = 15;
set(gcf, 'Units', 'Pixels', 'Position', [0, 1000, 1570, 820]);
exportName = exportName + ".png";
exportgraphics(ax,exportName,'Resolution',300);
```

Listing 2

MATLAB script for power spectrum generation

```matlab
1    a1 = ... % Define the filepaths for the 3 bfx videos
2    a2 = ...
3    a3 = ...
4
5    sig1 = audioread(a1);
6    sig2 = audioread(a2);
7    sig3 = audioread(a3);
8    len = max([length(sig1),length(sig2),length(sig3)]); %Time align all signals
9
10   s1 = vertcat(zeros((len-length(sig1)),1),sig1);
11   s2 = vertcat(zeros((len-length(sig2)),1),sig2);
12   s3 = vertcat(zeros((len-length(sig3)),1),sig3);
13
14   Fs = 44100; %Set the Sample Rate
15
16   [P1,f1] = periodogram(s1,[],[],Fs,'power');
17   [P2,f2] = periodogram(s2,[],[],Fs,'power');
18   [P3,f3] = periodogram(s3,[],[],Fs,'power');
19
20   %Find the peaks for each signal
21   [pk1,lc1] = findpeaks(P1,'SortStr','descend','NPeaks',3);
22   P1peakFreqs = f1(lc1);
23   [pk2,lc2] = findpeaks(P2,'SortStr','descend','NPeaks',3);
24   P2peakFreqs = f2(lc2);
25   [pk3,lc3] = findpeaks(P3,'SortStr','descend','NPeaks',3);
26   P3peakFreqs = f3(lc3);
27   maxY = max([max(P1), max(P2), max(P3)]);
28
29   %Generate the three subplots
30   subplot(3,1,1)
31   plot(f1,P1,'k')
32   ylim([0, maxY]);
33   grid
34   ylabel('P_1')
35   title('Power Spectrum')
36   subplot(3,1,2)
37   plot(f2,P2,'r')
38   ylim([0, maxY]);
39   grid
```

```
40      ylabel('P_2')
41      xlabel('Frequency (Hz)')
42      subplot(3,1,3)
43      plot(f3,P3,'b')
44      ylim([0, maxY]);
45      grid
46      ylabel('P_3')
47      xlabel('Frequency (Hz)')
48
49      %Export the plot as the name of the first image
50      exportName = erase(a1, ".mp4")
51      exportName = exportName + "PowerSpectrum" + ".png";
52      saveas(gcf,exportName);
```

E   Acoustic Imaging Data

Figure 16
Spectrograms and Power Spectra for 27 Acoustic Camera Readings

(1) Spectrogram 1
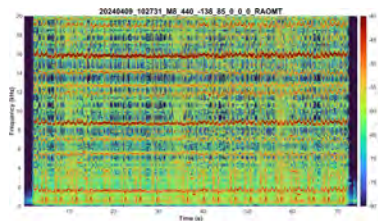
(2) Spectrogram 2
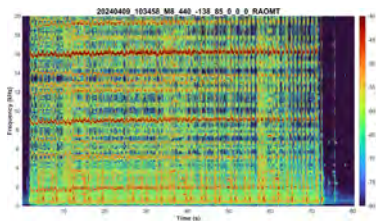
(3) Spectrogram 3
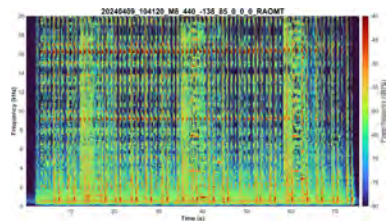
(4) Spectrogram 4
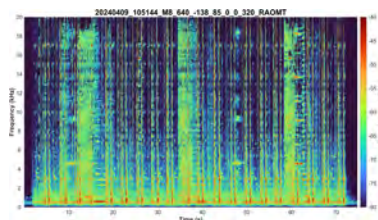
(5) Spectrogram 5

(6) Spectrogram 6

81
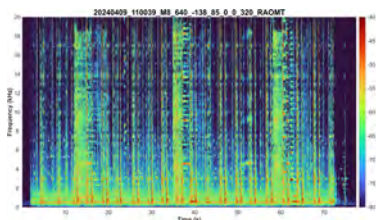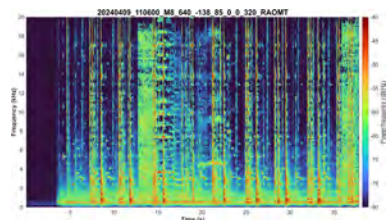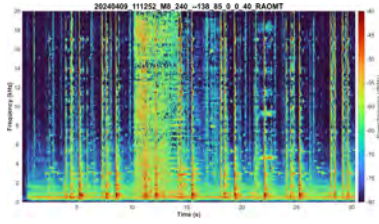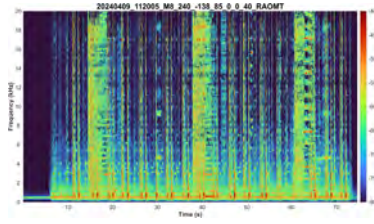
(7) Spectrogram 7

(8) Spectrogram 8
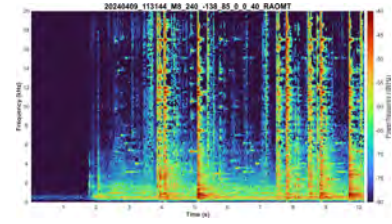
(9) Spectrogram 9
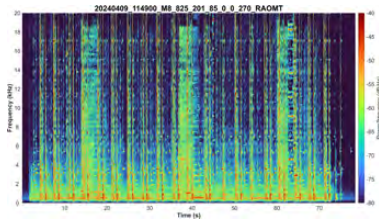
(10) Spectrogram 10
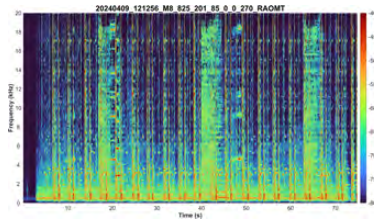
(11) Spectrogram 11
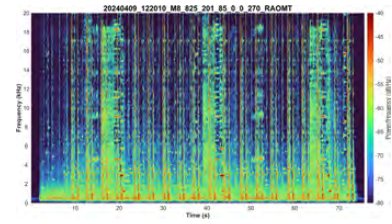
(12) Spectrogram 12
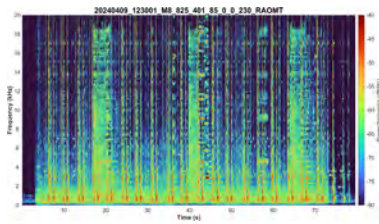
(13) Spectrogram 13
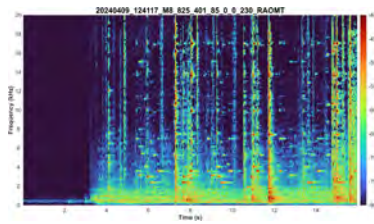
(14) Spectrogram 14
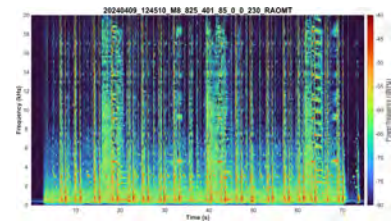
(15) Spectrogram 15
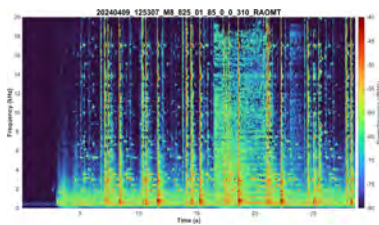
(16) Spectrogram 16
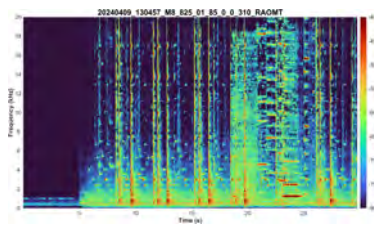
(17) Spectrogram 17
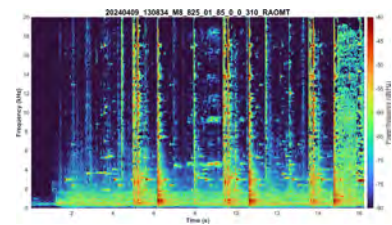
(18) Spectrogram 18
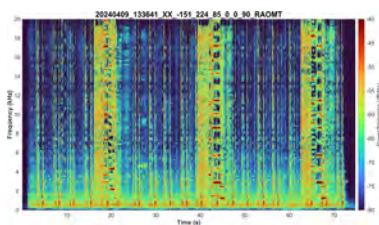
(19) Spectrogram 19
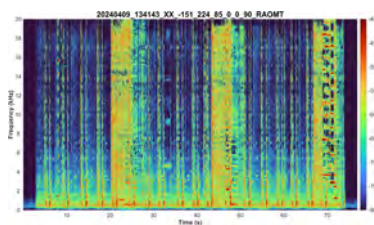
(20) Spectrogram 20
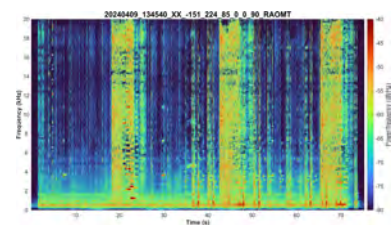
(21) Spectrogram 21
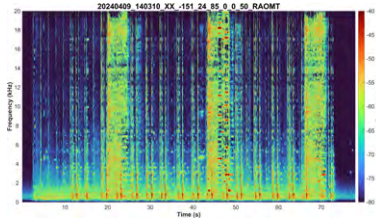
(22) Spectrogram 22
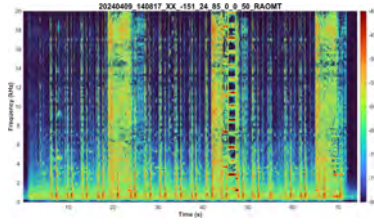
(23) Spectrogram 23
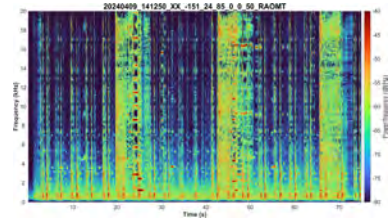
(24) Spectrogram 24
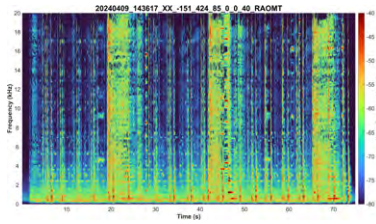
(25) Spectrogram 25
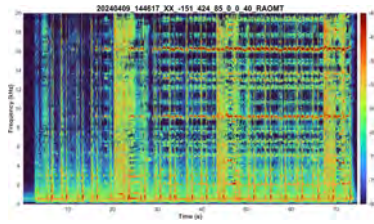
(26) Spectrogram 26
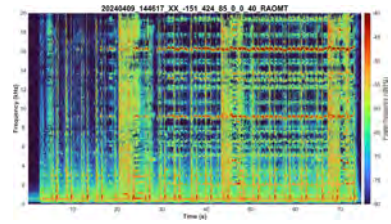
(27) Spectrogram 27
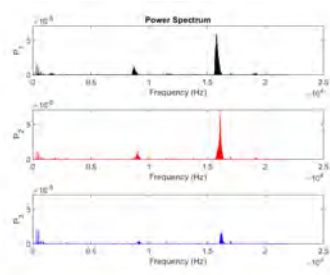
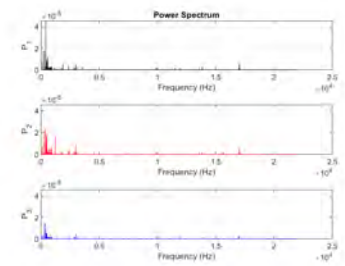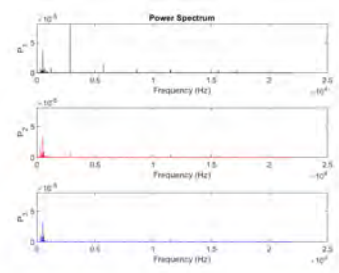**(28)** Power Spectra 1
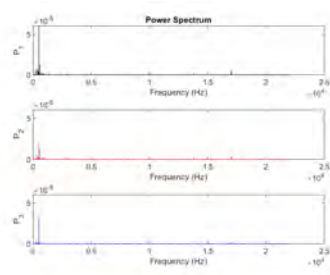
(29) Power Spectra 2
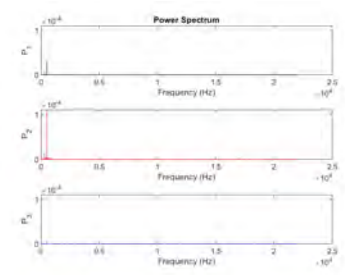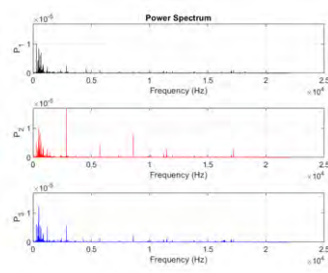

(30) Power Spectra 3
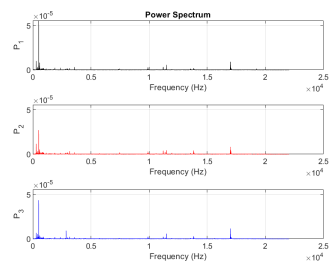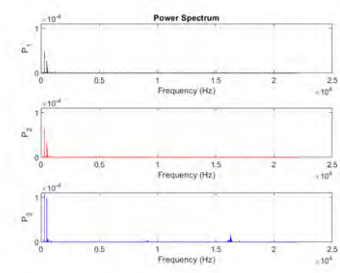

(31) Power Spectra 4
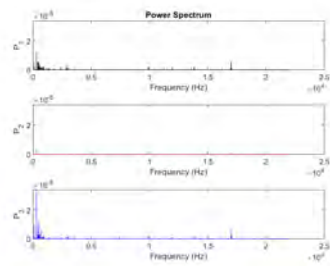
(32) Power Spectra 5

(33) Power Spectra 6

(34) Power Spectra 7

(35) Power Spectra 8

(36) Power Spectra 9