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TEACHING ACOUSTICAL BEAMFORMING VIA ACTIVE LEARNING

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Abstract

Beamforming is an acoustic imaging technique widely applied in sound source localization. Its basic principles rely upon an array of receivers (usually microphones, in acoustics) that sample the sound field, thus creating time data, which is processed via computational digital signal processing (DSP) techniques. Such application integrates different branches of knowledge, beginning with acoustics, passing through instrumentation and programming, and ending in DSP. Furthermore, concepts like windowing and sampling are addressed across time and spatial domains. Thus, as a university assignment, the technique has the potential role to gather distinctive topics to consolidate abstract knowledge into concrete ones. This article presents the experience of using Active Learning (AL) approaches in teaching acoustical beamforming to undergraduate students of the Acoustical Engineering (EAC) Program at the Federal University of Santa Maria (UFSM), in southern Brazil. These techniques focus upon increasing knowledge retention, being the Problem-Based Learning (PBL) one of its family. The strategy is the *practice by doing*, combining the learned knowledge with real situations. In EAC, beamforming is taught along two front lines, one is within the subject of acoustical experiments — exploring pre- and post-processing, as well instrumentation and measurement — and during students' Bachelor's Theses, where there is also space to include research and prototypes.

1 INTRODUCTION

Beamforming [35] is a technique with several applications in mechanical and electromagnetic wave fields. Among them, it is possible to cite focusing, mapping, filtering, and localizing sources. Considering electromagnetic waves, beamforming is largely applied to mobile communication, for example. In 2019, an amazing application became well-known, the *picture of a black hole* or, in a more correct way, the *imaging of an event horizon*, as presented by the EHT Collaboration [58] and Katie Bouman [5]. This has drawn the attention of the general public to the array's techniques. In acoustics, the applications also range in diverse directions, extending from aeroacoustics, underwater acoustics, building acoustics, noise control, NHV[1], among others. In fact, since both *worlds* deal with waves, often times they exchange techniques. For example, CLEAN by Högbom [30] from the *astronomy world* was adapted to CLEAN-SC by Sijtsma [55] for the *acoustical world*.

It is possible to browse through diverse videos with demonstrations, applications and tutorials/seminars about beamforming on YouTube [60]. Furthermore, university lectures about the topic are already available with free access, for example, on the Edx platform (course Applications in Communication Acoustics [14]). That is, microphone arrays are no longer limited to research inside universities (and/or institutes) but have reached the general public with the emergence of several commercial models in the last two decades [8, 22, 45]. Fig. 1, verifies the results from searching over the last 25 years for *beamforming* in the three big knowledge databases: ProQuest[2] Dissertations & Theses [47], Science Direct [54], and IEEE Xplore [32] (along with the number of BeBeC published[2] papers). Michel's paper presents a comprehensive historical review of beamforming in acoustical applications (up to the year 2006) [42].

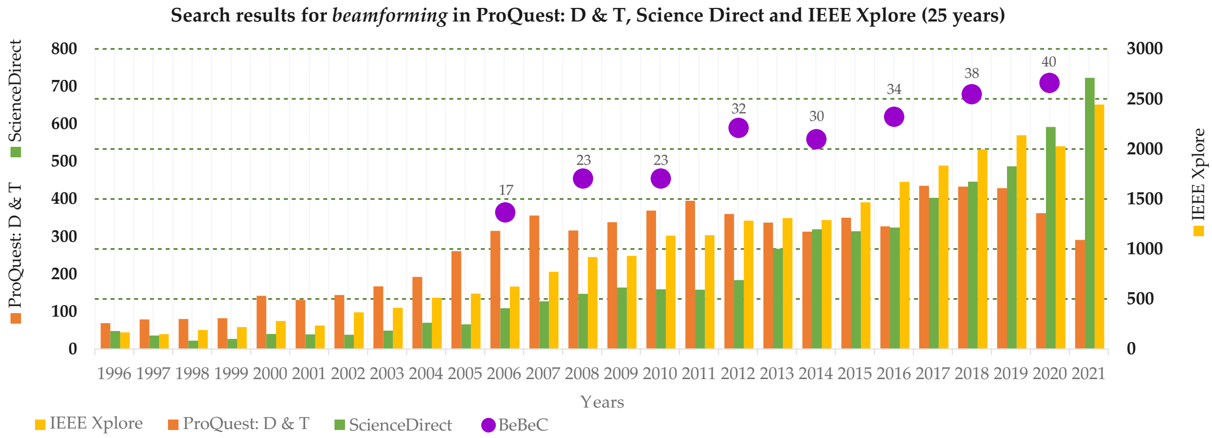


Figure 1: "Beamforming" keyword search results in ProQuest D&T, Science Direct (left scale), and IEEE Xplore (right scale), along with BeBeC papers in the last 25 years.

[1] Noise Vibration and Harshness.

[2] It is possible to notice a decline in the ProQuest publications in 2020, this is probably because of the pandemic situation during 2020–2022. Moreover, although the BeBeC's papers were published in 2020, they were not presented due to the same reason. The authors believe that the increase of BeBeC's papers depends on the growth of the conference, either in the sense of days and/or parallel sessions.

From Fig. 1 one can observe that publications from different databases follow a similar trend throughout the years. With the increased popularity of computers and gadgets, beamforming techniques have become a topic with even broader applications (either for the mechanic or electromagnetic waves), especially because of the reduced costs of high computational power available nowadays. For example, at the present time, in contrast with the past (up to the year 2000), equipment for hybrid meetings (remote and in-person) have embedded hardware and software to focus on a particular speaker, suppressing noise from other directions. Even some models of personal computers have small microphone arrays to improve voice capture.

In Brazil, the research (inside universities) upon acoustic array processing began around the year 2005. In the following years, several Master's and Doctoral Theses have emerged in different branches of the topic, the common applications are instrumentation, DSP[3] techniques, transportation, underwater, and aerospace [6, 13, 48, 57]. Generally, the initiatives have been building systems from scratch (hardware and software) — due to the potentially costly prices with the increasing number of channels — yielding great understanding along each step of the measurement chain [18].

Given the growing development, array techniques are more and more subject to inclusion in universities' undergraduate curriculae. However, how can one approach potentially sophisticated knowledge with students? Universities are teaching with different strategies. Thus, this paper presents that which is applied in the Acoustical Engineering Undergraduate Program (EAC) at the Federal University of Santa Maria (UFSM), Brazil [2, 10, 20]. The strategy used is based upon Active Learning (AL) [46] methods, which search for better engagement (with the learners) and knowledge retention, i.e. indelible capabilities. In the EAC's case, Problem-Based Learning (or PBL, a type of AL) is the main approach used, focusing on *practice by doing*.

2 ACOUSTICAL ENGINEERING PROGRAM

Entirely dedicated to acoustics, vibration, and audio (AVA), the Acoustical Engineering Undergraduate Program (EAC) at UFSM is currently the first of its kind in Brazil [2]. Like other *Bachelor engineering degrees* in Brazil[4], the program comprehends ten semesters, with the last one tenth reserved for a professional internship. During the first four semesters, most of the subjects comprise the fundamentals of calculus, algebra, and physics. The *professional* contents are spread throughout all nine semesters of classwork, although the deeper engineering topics start in the fifth. Over the final four semesters, students must write a Bachelor's Thesis, dedicating their time both to research and application. A summary of the EAC's contents can be seen in Fig. 2.

In a way, the basic contents for understanding acoustic beamforming are initiated during the start of the second half of the EAC curriculum. Topics such as microphone arrays, temporal and spatial windowing, temporal and spatial sampling, as well as the effects arising from real data acquisition, such as aliasing, smearing, and leakage are studied from distinct perspectives. Programming languages also play an important role, with students working on assignments

[3]Digital Signal Processing.

[4]Higher education in Brazil comprehends five years for a Bachelor's degree, two years for a Master's degree, and four years for a Ph.D./Doctoral degree (for an engineering career). The Fall semester usually starts in March and the Spring semester in August. Youngsters usually join the university between 17 and 20 years old. In Brazil, federal and state universities do not charge fees, while private ones have their own monthly payment system.

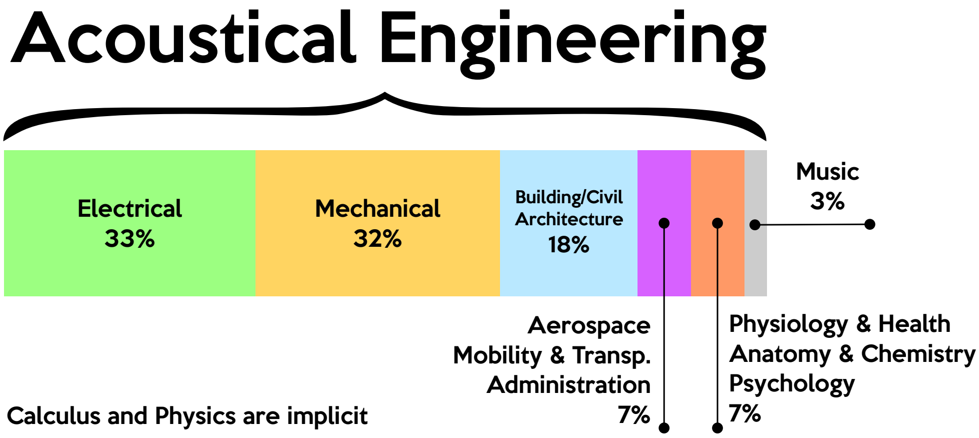


Figure 2: Summary of the Acoustical Engineering Undergraduate Program (EAC) contents.

(mostly) in Matlab and Python. In some they receive excerpts of code and in others they are asked to fully develop a given solution.

As they approach the completion of the EAC program, students establish a solid background in signal processing since they have three semesters dedicated to it (*Signals & Systems* and *Digital Signal Processing I & II*). This knowledge, together with *Fundamentals of Acoustics* and *Instrumentation for Sound & Vibration*, consolidate the principles required to understand microphone array processing. In the ninth semester, the subject *Experimental Methods for Acoustics & Vibration* (MEAV) explores most of the learned themes during the course, by asking the students to work in groups and carry out real experiments in AVA (usually eight to twelve assignments). Within MEAV, array and beamforming techniques are developed with the Active Learning / Problem-Based Learning (PBL), combining theory and practice. In this sense, the EAC program is modern, applying different Project/Problem-Based assignments during the entire professional cycle of learning.

Therefore, organizing only the main subjects that relate to array signal processing (concerning AVA) via a timeline, EAC offers:

- 2nd semester: Principles of Sound (subject: *Noise, Vibrations, and the Human Being*)
- 5th semester: General acoustics (subject: *Fundamentals of Acoustics*)
- 6th semester:
  - Sound fields in closed spaces (subject: *Room Acoustics*)
  - Signals & linear systems (subject: *Introduction to Linear Systems*)
- 7th semester:
  - Microphones (types, principles, and applications) (subject: *Instrumentation in Acoustics and Vibrations*)
  - Fourier Transform & digital sampling (subject: *Digital Signal Processing I*)
- 8th semester: Spatial windowing and spatial sampling (subject: *Dig. Signal Processing II*)

- 9th semester:
  - Hands-on measuring and simulating beamforming (subject: *Experimental Methods in Acoustics and Vibrations*)
  - Sound fields in open spaces (advanced) (subject: *Loudspeaker & cabinets*).

Subjects throughout the program are first approaches, focusing upon understanding the fundamentals of the technique, its capabilities, and its limitations. The second possible way is during the Bachelor's Thesis, where there is also space to include research and prototyping. That is, a more in-depth exploration of array-beamforming techniques — in this last case for students engaged in the theme, according to their research and/or prototype.

2.1 Active Learning Strategies

As reported in the literature, Active Learning (AL) strategies evolved over the years [4, 9, 26, 46]. Even before the revolution of computers and cellphones everywhere, humankind had been gathering the pieces of the *puzzle* on the topic of *how we learn and think*. Advances in medicine combined with subjective evaluation revealed fresh paths for the acquisition of knowledge. Notwithstanding, the substantial challenge at this juncture is the retention of information (or knowledge) given the teaching process. Richard M. Felder & Rebecca Brent state that [17]

> "— *Active Learning (AL) is anything course-related that students in a class session are called upon to do other than simply watching, listening, and taking notes*."

AL may be carried out via different perspectives and propositions. Usually, an educator, teacher, or professor guides students (or apprentices) toward the goal of understanding or attaining a new skill. Within the AL family of strategies, Problem/Project-Based Learning (PBL) is one of the best suited for courses in engineering [3, 53]. Traditional teaching, in general, follows the sequence:

- (1) information transmission ➡ (2) memorization and problem presentation ➡ (3) problem resolution to test knowledge;

while PBL follows the sequence:

- (1) problem presentation ➡ (2) identification of knowledge needed and gathering of information to solve the problem ➡ (3) Learn and apply knowledge to solve the problem.

For instance, given an assignment, students may work in groups to fulfill the serial and parallel phases of a bigger project. Cooperating and teaching themselves may promote rational thinking, instead of promptly asking their educators (or guides). The act of building *brick by brick* forces them to go through and overcome challenges along the way. On that sense, the hands-on approach is one of the powerful instruments for converting abstract concepts into concrete and more permanent knowledge. In general, the achievement of a sophisticated skill requires training and consistency.

2.2 Beamap Software & Infrastructure

The software **Beamap** has been developed mainly by the first author. Initially, the name meant "Beamforming Mapping Software", but the acronym has grown to represent "Beamforming Multiple Analysis Platform" since it has gained new branches in the array field. It has one version coded in LabVIEW and another in Matlab[5], with the latter aimed at educational purposes. They can communicate across languages and have connections to other beamforming toolboxes such as NIMAS (of National Instruments), ITA-Toolbox [12], and others.

The Matlab version is aimed at a quick start for beginners. Thus, the codes are optimized for human reading and not necessarily for the best speed performance. Furthermore, there are automated steps to ease its use. The LabVIEW version is not open-source and is aimed at advanced applications.

At the university, there are mainly three types of data acquisition systems, based on Brüel & Kjær (B&K), National Instruments (NI), and Pro Audio Equipment. Pro Audio Equipment has the highest channel count at thirty-two — see the example of hardware-setup in Fig. 3 (b). The microphones used with Pro Audio Equipment are based upon cost-effective electret capsules [29, 43, 44], although capacitive mics (e.g. B&K) and digital MEMS mics are available as well. The array structure to hold the 32 mics is customizable, granting opportunities for different configurations — which are favorable for teaching and research.

3 HANDS-ON BEAMFORMING

All students have the opportunity to enroll in the subject *Experimental Methods for Acoustics & Vibration* (MEAV), which encompasses the experiment with a microphone array.

Prior to the day at the laboratory (at the silent room), they have a two-hour lecture on the principles of the techniques, the assignments are explained to the groups, and an instruction manual / tutorial is provided that guides the first steps and organizes the task lists. Usually, they have a time frame of one or two weeks between the theoretical class and the experimental hands-on. In the meantime, they are asked to work on a preliminary report. It comprises

1. Numerical simulations

   Students simulate five distinct types of geometries (spiral, circular, random, uniform rectangular array, and uniform linear array), creating synthetic Point Spread Functions (PSF). Thus, they extract parameters like Dynamic Range (DR), Beamwidth (BW), Average Sidelobe Level (ASL), and, when possible, estimate the grating lobe (or alias) positions. The number of receivers, array size, frequencies, and angle of vision are also some parameters that they must vary. To this point, it is understood that they have an understanding of time-windowing (and its effects), aliasing (in time and frequency, and its effects), filtering, and the Fourier Transformation procedure (via FFT). Consequently, they expand these concepts to space, as in space-windowing and aliasing (in space and wavenumber), for instance.

   Following the tutorial, they can fulfill the steps and document with graphs, images, and text. Most functions are ready to use and Conventional[6] and Classical[7] Beamforming are chosen for the task — advanced beamforming and other processing are optional.

[5] Beamap GitHub repository: https://github.com/eac-ufsm/beamap.
[6] Frequency domain CB via matrix notation.
[7] Delay-and-sum over time and frequency domains.

2. Creation of an experimental test matrix and list of procedures

   Here, they must outline a plan for the experiment. Students are required to design a connection diagram, think about a list of procedures, and create an experimental test matrix (containing every single measurement needed). Accordingly, sampling frequency and hard disk space needed are also part of the plan.

   When they accomplish the proposed tasks, they are ready to — one or two weeks later — measure part of the simulated data without being *completely lost*.

Up to this point, students have had the theoretical review and the hands-on numerical simulation. The subsequent steps are the measurement itself and the final report including analysis. By advancing all these phases, the educator expects that as engineering students they also acquire skills to be ready to use a commercial array system, identifying and dealing with details that concern that *black-box*.

During the measurement, groups help each other, taking care of geometries, positions, photos, and environmental stats. For every measurement, they confer the frequency spectrum and run a quick acoustic image. This ensures quality data so they can proceed to the analysis and final part of the report. Depending on the semester, senior (and/or graduate) students from EAC help the endeavor.

Finally, the report of every group is sent and the grading (by the educator) is given considering the steps they took. Even if the quality of the acoustic images is not ideal, the discussion on why such a situation happened is much appreciated, and thus, a teachable moment for all.

4 BACHELOR'S THESIS

As aforementioned, the Bachelor's Thesis (BT) is the opportunity to dive deeper into the array's techniques. Generally, a student willing to advance in the theme becomes a member of one of EAC's research groups[8]. Thus, in accordance with the professor responsible, the development starts. From its beginning to end, the BT spans between one and three years. When the undergrad students graduate, they have also the opportunity to continue their projects by applying for and entering the Graduate Program (at UFSM) for a Master's Thesis (Section 5), for instance. Furthermore, ongoing Research & Development is discussed in Section 6.

Within this section, four Bachelor's Theses are briefly presented and discussed. One important aspect to highlight is that the research advised by the first author deals with the *three pillars of acoustics*: analytical, numerical, and experimental. This yields positive feedback like "*— Professor, look! Our simulations are correct! The equations and methods really work.*". That is, testing and "discovering" themselves that the contents developed are real and not mere assumptions.

4.1 Rotating sources

Captivated by the publication of Ordinance No. 168, on March 23, 2015 — *Conformity assessment requirements for wind turbines* — by the (Brazilian) National Institute of Metrology, Quality and Technology (Inmetro) [33], Electrical and Acoustical Engineering at UFSM joined forces to study electric and acoustic aspects of wind turbines. Concerning the acoustic part, the Brazilian

[8] Usually, the research group with array-related projects is the *Research Group on Acoustics and Vibrations* (GPAV), properly registered on the Brazilian Council for Scientific and Technological Development (CNPq).

document points to the standard IEC 61400:2012 – *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques* [31], stating that standard procedures had to be followed.

Thus, the student (at that time) Thiago Medeiros Sanchez started researching wind turbines, the IEC 61400:2012 procedures, and array techniques in this context to access their acoustic images. Given the complex nature of the procedures involved, instead of measuring a real wind turbine, a scale-size fan was designed and constructed (with wireless loudspeakers attached to its blades, a similar idea as reported by Sijstma et al. [56]) — that is, a kind of smaller wind turbine simulator was created. The objectives, in this case, were

- to apply part of the IEC 61400:2012 standardized measurement procedures adapted to the reduced size fan; and
- to enable the measurement and post-processing (with beamforming) of this rotating sound source.

This project comprised two sets of instrumentation, procedures, and post-processing, observe details in Fig. 3. However, this section is restricted to the one related to beamforming. Complete results and further details are published in Thiago's BT [50] (or a short version in a recently published paper [51]).

Using the aforementioned Beamap software, Thiago could learn beamforming via PSF (Point Spread Function) simulations of diverse array geometries. Accordingly, with EAC's infrastructure, he measured static sound sources (for validation) and with the prototype in movement. However, Beamap did not have yet the tools for rotating sound sources, see Fig. 3 (a). As a consequence, the solution to mapping such sources was to bridge the results to Acoular[9] [27, 52]. From the teaching perspective, the student was able to develop his skills in programming[10] by using both Matlab and Python.

Two circular microphone arrays (radii of 0.35 m and 0.50 m) composed of 32 microphones were used to measure the prototype. Measurements were taken in a silent room. The prototype was 2.00 m away from the array, with its axis aligned with the array's center. Moreover, the fan prototype ran at a fixed 115 RPM (approximately 0.52 s per turn), and while running the speakers were reproducing white noise (≈ 0.25 m from the axis each). The data acquisition system used sufficed the audible frequency range accordingly, observe the measurement chain in Fig. 3 (b). Given this configuration, four types of post-processing[11] were tested, specifically frequency domain fixed focus, time domain fixed focus, time domain moving focus, and frequency domain with a short time-window — frequency domain results were all processed with Conventional Beamforming (CB) [15, 19].

Results are shown in Fig. 4. For simplicity only one case is presented within this section. As expected, frequency domain fixed focus rendered a blurred image (a), while time domain moving focus (b) and frequency domain short time-window (c) depicted the two loudspeakers as *two prominent spots* in the acoustic image.

As his adviser, the first author recognized a great evolution of the student's maturity concerning all the aspects involved. Moreover, the student contributed to the research group, developing prototypes and coding, while implementing all of them. In every step, the student had a hands-on approach, learning from his own errors.

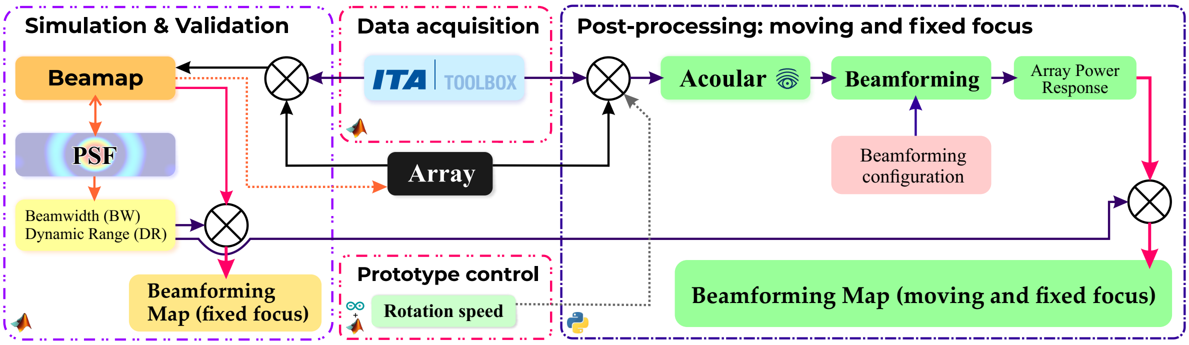
[9] "*Acoular is a framework for acoustic beamforming that is written in the Python programming language.*" It is freely available on its website (acoular.org).

[10] Since an Arduino Due controls the prototype angular speed, C/C++ was also used as a programming language.

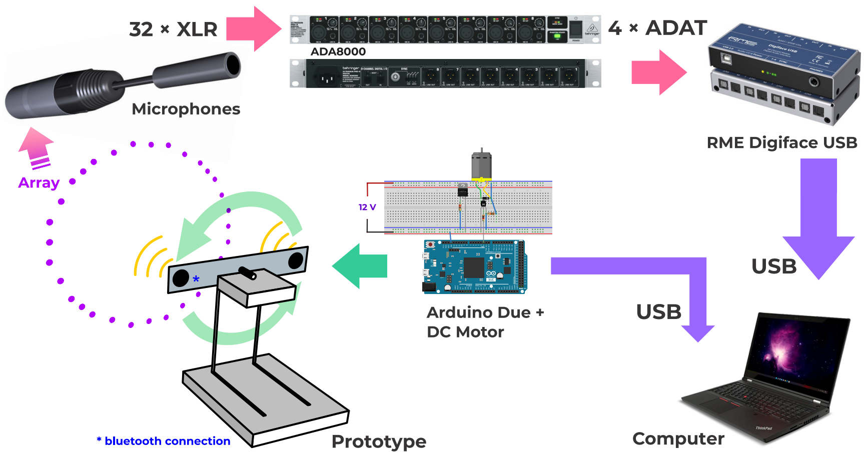
[11] The reader may follow the post-processing by accessing the tutorial *Rotating point source* by Acoular [52].

Nowadays Thiago works professionally with simulations (in Python) and numerical methods for room acoustics, and, in his own words

> "— *The contact with beamforming was a little difficult at first, but with time and study, I was able to greatly improve my knowledge of signal processing and programming languages.*"

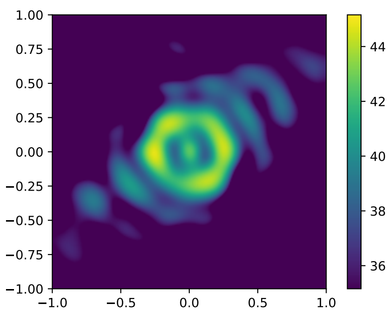


(a) Software data flow.

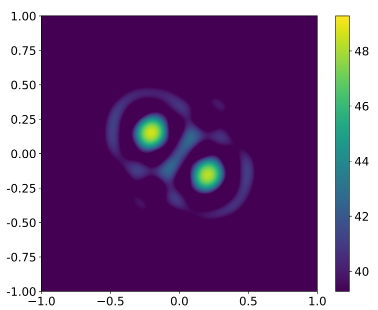


(b) Hardware-setup and connection.

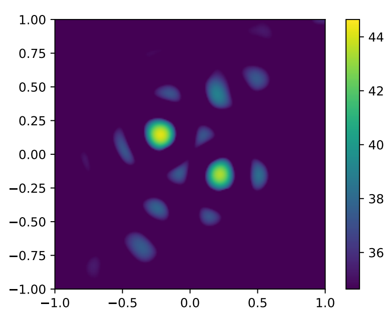
Figure 3: Software processing and hardware-setup for measuring the rotating prototype [51].



(a) Freq. Domain Fixed Focus



(b) Time Domain Moving Focus



(c) Freq. D. Short Time-window

Figure 4: Results of beamforming processing (0.50 m circular array, 3 kHz) for (a) Freq. Domain Fixed Focus; Time Domain Moving Focus; and Freq. Domain Short Time-window [50].

4.2 Moving sources

The research developed by the student Lucas Gomes deals with the topic of beamforming for moving sources. Thus, it includes the account for the Doppler Effect, the dedopplerization procedure [18, 41], time-windowing, and digital signal processing, observe the software data flow summary in Fig. 5 (a).

To ensure the functioning of the dedopplerization, the project started by coding a small Matlab toolbox to include the Doppler Effect for a given stationary signal — for now, only linear movement and constant speed are enabled. This yielded three publications, one discussing the inclusion and removal of the Doppler Effect [23]; another about the computational toolbox (freely available for teaching and research) [24]; and a third combining efforts with binaural research, synthesizing binaural signals for moving sources [25] — the cited *new* capabilities are being included in Beamap. Figure 5 also presents (b) an animation and (c) a dedopplerized result using the tools built into the project. In Fig. 5 (c) it is possible to see the sound source as a spot, instead of a blurred trace, as expected for an acoustic image (of a moving source) without a Doppler correction strategy.

The following steps currently in progress are (i) estimation of the speed of moving objects (without any tracking), for example, a moving car; (ii) dedopplerization techniques combined with advanced beamforming to map sound sources; and (iii) beamsteering to specific regions in the acoustic images to generate space-filtered audios (monoaural and binaural). Finally, all the techniques are going to be applied to real car pass-by noise measurements.

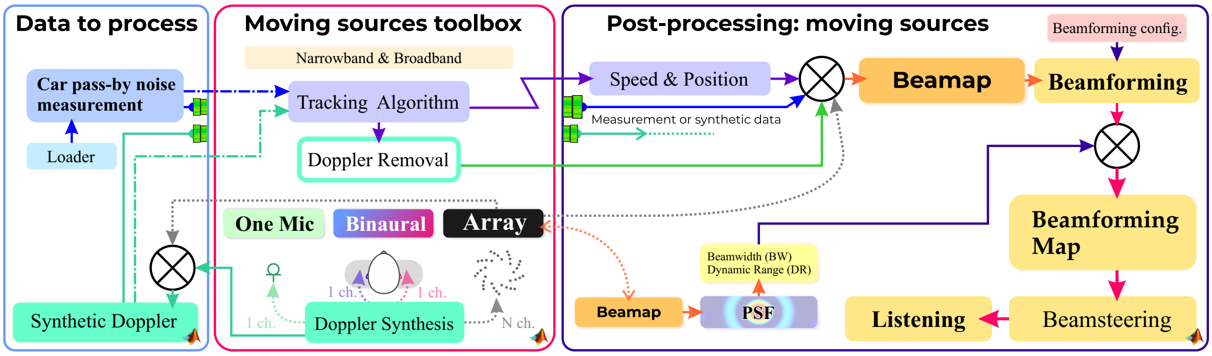
4.3 Airfoil and integration toolbox

In order to diversify the application field, the research group also needed a set of codes to integrate several tools, allowing for new possibilities. Unlike Beamap coded in Matlab, this endeavor is Python-oriented, although it also communicates with Matlab. The idea is to integrate powerful aspects of other toolboxes instead of recoding them. Therefore, this research by the student Michael Ackermann had two main goals: (a) to create a versatile toolbox for data communication among sets of toolboxes; and (b) to use the turbulence-airfoil interaction noise model, developed and coded by Hirono et al. [28], via Amiet Tools and bridged into Acoular [52].

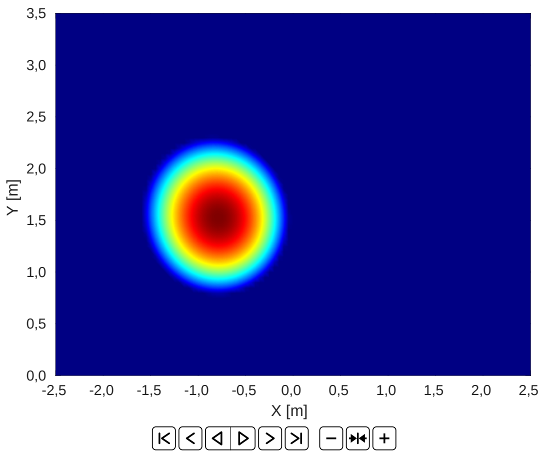
This new branch is named **Augen** (an acronym for "Amiet-Acoular Integration Module in Python") and is considered a Python part of Beamap toolbox. The current state of the project can be consulted in the GitHub repository[12].

As can be observed in Fig. 6, simulations of Conventional Beamforming (CB) are in accordance between Amiet Tools and Acoular (in this example case for a spiral array). This Python-Python connection is carried out by exchanging the Cross-Spectrum Matrix (CSM) and the Steering Vector. In the second row of Fig. 6 it is possible to observe results without the CSM's diagonal, as well as a case using DAMAS [7], options not yet present in Amiet Tools. Further discussion and details on codes are in Ackermann et al. [1].

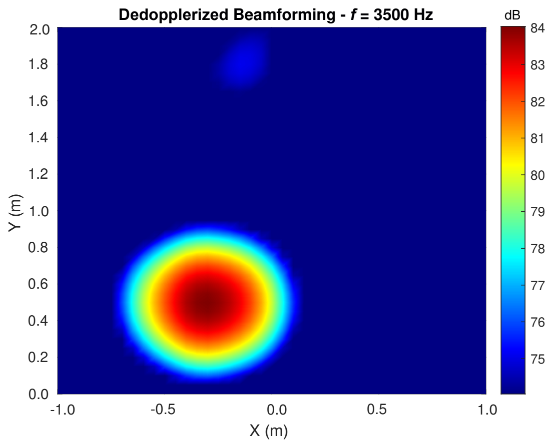
[12] Augen GitHub repository: https://github.com/eac-ufsm/augen.



(a) Software data flow.



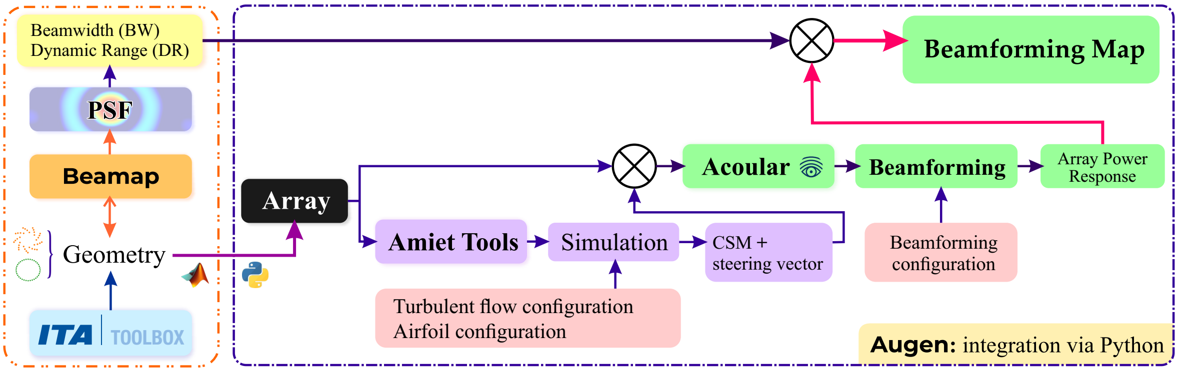
(b) Animation of a point source passing-by.



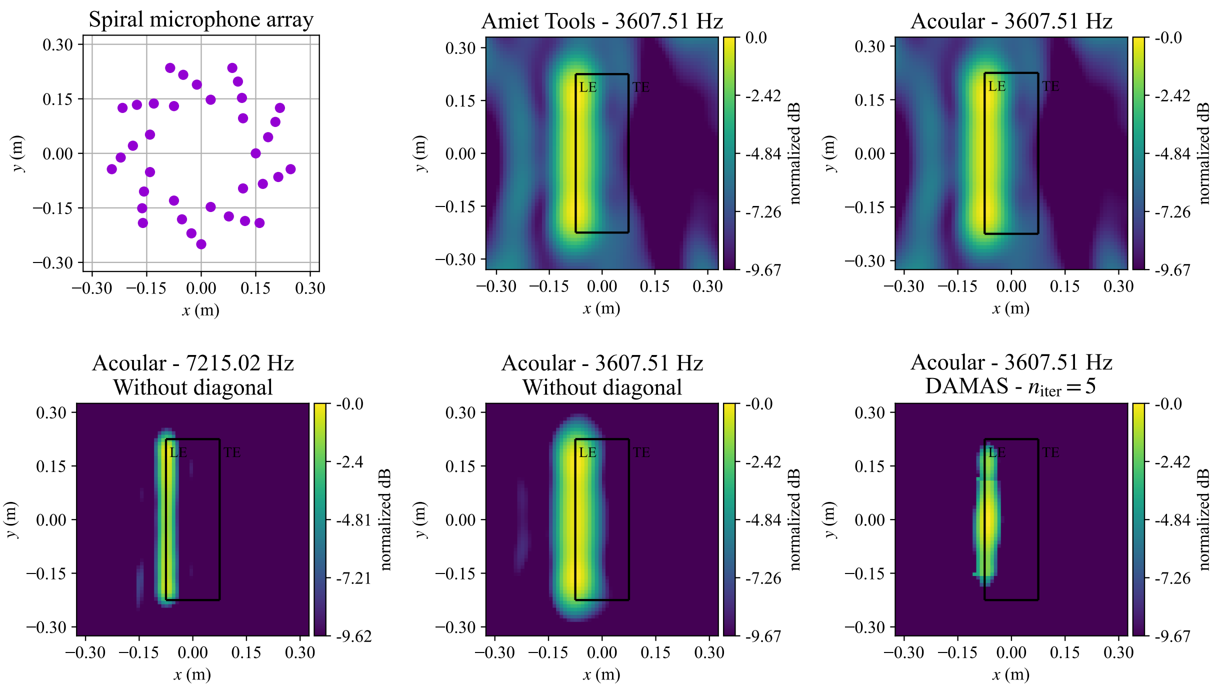
(c) Dedopplerized Beamforming ($f = 3.5$ kHz).

Figure 5: (a) Software data flow and (b) & (c) results of beamforming processing. (b) Animation of a point source passing-by (use the controls below the figure)[13]; and (c) Dedopplerized Beamforming ($f = 3.5$ kHz) using the toolbox developed.

[13] Use Acrobat or Foxit as PDF reader.



(a) Software data flow.



(b) Acoustic imaging: Amiet Tools and Acoular (Augen).

Figure 6: (a) Software data flow and (b) spiral microphone array simulation — beamforming results using Amiet Tools and Acoular (scanning plane 0.49 m distant and opening angle of 0.325 m × 0.325 m).

4.4 Beamforming with MEMS mics

Since the early 2000s, MEMS[14] microphones have been conquering space in the electronic device consumer market. In 2014, their selling numbers overcame those of the electret models, establishing MEMS microphones as the *de facto* acoustic transducer in gadgets such as smartphones, notebooks, and wearable devices [38]. The main reason for this is their low-cost, tiny size, and in some models, the presence of an integrated analog-to-digital converter. Concerning their acoustic characteristics, MEMS mics are very stable against climate changes (such as temperature and atmospheric pressure), having almost no sensitivity drift over time, and, finally, have an adequate frequency response and dynamic range. Furthermore, MEMS technology offers a high manufacturing standardization, meaning that a batch of microphones has a very tight phase, sensitivity, and frequency response (which is ideal for applications such as beamforming) [37, 59].

Recently, much interest has arisen in using MEMS microphones in acoustic arrays due to their aforementioned traits [59]. Following this trend, EAC also has ongoing research in this field. The main goal is to study possible hardware implementations using readily available boards (such as the Arduino-compatible Teensy microcontroller) and build scalable (and portable) arrays that could be used both as a didactic tool and a measurement device. For now, the choice of a microcontroller over an FPGA[15] is due to its greater simplicity and Teensy board's promising technical specifications (in addition to a solid audio processing library and an engaged open-source community). Applications with one (sound level meter) [39] and two microphones (binaural recorder) [21] have been already studied and published, while 4- and 8-microphone arrays are still in the testing and prototyping phases. Moreover, an educational tutorial on *how to set up a first MEMS acquisition* has been recently published [40].

5 BEAMFORMING IN THE GRADUATE PROGRAM

The focus of this article has been the undergraduate program. Likewise, a continuing path after finishing it is the graduate program (Master's and Doctorate). Therefore, it is worth briefly mentioning that developed projects have PBL effectively employed, culminating in both scientific articles and the thesis itself.

Developments with array-related topics (at the graduate level) had cooperation among Civil Engineering/Architecture and Mechanical Engineering (at UFSM), some of them are briefly cited ahead. One project explored spatial room impulse responses by using a spherical array combined with room acoustics techniques, beamsteering, and spherical harmonics [11]. The idea of directional impulse responses can aid in the field of absorption planning for auditoriums and rooms, for example. Another project studied the practical effects of a solid versus acoustically transparent planar array upon separating sources in space, the increased pressures (due to diffraction), and the capability to avoid front-back confusion when creating acoustic images.

When an EAC undergrad joins the graduate program and the field of research ends up being array techniques, the transition into the topic is smoother than compared with students who join without previous background on array topics. It is also common that graduate students receive

[14]Micro-Electrical-Mechanical.

[15]Field-Programmable-Gate-Arrays, a "programmable" hardware very capable of parallel processing and data acquisition, which is often used in array applications [16, 34, 49].

support from undergrads, given that they possibly are in the same research group. In this case, the cooperation is fruitful for both sides.

6 RESEARCH & DEVELOPMENT

Research, teaching, and extension are inseparable within the university. Accordingly, they always walk together and cooperate with each other. This means that research innovation, when possible, is promptly implemented in class contents.

Nowadays there are several parallel initiatives dealing with array signal processing. Some of them have been already cited throughout this text. For example, recently, a project started with the aim to apply beamforming approaches to map the sound radiation of acoustic guitars. In a different direction, sequential virtual array techniques are being studied for the extraction of impedance properties of acoustic devices and materials — as well as in the context of diffuse field estimation.

Other ongoing research includes the combination of beamforming and binaural techniques, beamforming on cost-effective devices, beamforming aiding speech-to-text transcription, and beamforming supported by the boundary element method (BEM). They all have working groups with professors, undergrad, and graduate students.

7 REFLECTIONS ON LEARNING AND PROGRESS

At first, some students may be a bit scared by the number of channels and signal processing involved. However, when they overcome that feeling they attain a sense of accomplishment by achieving an understanding of such a sophisticated (and beautiful) technique. Another point that they enjoy is the space filtering (via beamsteering). For example, when two loudspeakers, one playing a song and the other a noise, are measured at the same time, they point and listen (practically) to just one, they usually exclaim "— *Cool! How is that possible?*".

As stated by the third author (EAC final year student):

> "— *I learned a lot just by discussing the problems and projects with colleagues. It seems that there is a psychological effect involved, too, because with the professor (authority figure) explaining, the student usually accepts and moves on. Now, discussing topics with colleagues, there is no way to simply accept them and we end up building knowledge together*."

This is one example of the positive effect of active learning approaches. Moreover, since EAC has ran such techniques for (at least) 10 years, there is a *hands-on culture* inside the program. Learners expect to enter a given semester (or subject) so they can also do what students ahead in the program have told them.

Tales Storani, an EAC *alumnus* (2019) and currently NVH Application Engineer at Microflown Technologies (the Netherlands) states that

> "— *The contact with hands-on beamforming contributed to elucidating better the theory behind it. Moreover, it improved my knowledge and view of multi-channel acquisition and software programming related to it*."

This shows the idea of converting abstract to concrete knowledge. At the same time, although a proven advancement in learning, AL techniques may experience inconvenient situations when a learner rejects the PBL, preferring quick written tests instead of projects. This may happen because of diverse reasons. It is possible to cite student personal choices, or simply because PBL is different from their prior school experience. Nonetheless, an interesting metaphor, quoting[16] a well-known writer, may reflect the presented ideas

> "— *The task of the modern educator is not to cut down jungles, but to irrigate deserts*."
> C. S. Lewis

8 CONCLUSION

This article briefly introduced the Acoustical Engineering (EAC) undergraduate program at the Federal University of Santa Maria (UFSM), Brazil, along with the array-related themes developed there. Its focus has been on the Active Learning (AL) methodologies applied to beamforming, either in the context of subjects within the program or the Bachelor's Thesis and research carried out. It has shown the relative success of engaging PBL in hands-on abstract to concrete knowledge acquisition across the structured curriculum and research projects.

The interpretation of time-windowing to space-windowing is a process that works better when analogies with optics are produced, for example. Several aspects of array processing are not intuitive, at least at a first sight, demanding reading, and study. Since beamforming is a potentially intricate topic, the Problem/Project-Based Learning (PBL) approach, together with the increasing experience across the EAC's semesters, enables the *hands-on experience*, providing learners the opportunity to consolidate abstract knowledge into concrete. This is a key point when an educator is conducting a class on a given subject or a research project.

Thus, the authors believe that solely classical written tests do not promote the problem-solving skill that an engineer must use in their professional life, proving the important role of *practice by doing* combined with theory. As discussed in this article, beyond positive comments from learners, the positive feedback from companies hiring (or working with) EAC students captivates the educators in the sense that the employed strategies are educating engineers in the correct direction.

It is a continuing process, as a university is always evolving.

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[16] Excerpt from the book *The Abolition of Man, or, Reflections on Education with Special Reference to the Teaching of English in the Upper Forms of Schools*, originally published in 1943 [36].

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