MELUTA

MELUTA

NAVISP SMAM

Navigation Innovation Support Program
Sound Monitor for Autonomous Machines.

Satellite data and sound monitoring as enablers for autonomous mobile work machines

Funded by ESA NAVISP program, Element 2, activity NAVISP-EL2-055

MELUTA

CONTENTS

MELUTA

WE LEAD

Signal processing, software development and sensor technologies are Meluta's core competencies. We specialize in acoustic and vibroacoustic sensory systems.

Our daily business is to design, plan, and implement signal processing software, and algorithms for commercially available systems.

MELUTA

PROFILE

Founded in 2015 - Seven years of technology and product development

- Technology development and commercialization based on information in sounds and vibrations

Sound and vibration analysis

- Situational awareness for autonomous and remotely controlled machines
- Monitoring of industrial processes, public areas and ships
- Predicting of safety and productivity incidents on structures, machines and equipment

Combination of software and signal processing expertise

- Modular software for off-the-shelf hardware
- Time series data processing with signal processing, sensor fusion and machine learning
- Fully embedded systems to any kind of machinery or devices etc.

MELUTA

SMAM SCOPE

Better efficiency, environmental friendliness and safety are important trends driving the development of mobile work machines.

Satellite data is used in several applications to assist positioning of the machines. However, the next step is towards mobile work machines with more autonomy.

A higher autonomy requires reliable and robust situation awareness in the near field of mobile work machines in order to enable precise and safe autonomous operation.

The use of sound and machine learning applied to improve the situational awareness represents a novel approach. The aim is to demonstrate how the analysis of audio signals can complement existing satellite and sensor data to optimize operations and identify risky situations in the operation of mobile work machines.

The novel element is the development of a microphone array to identify *(i) the direction of the coming sound and (ii) to classify the source of the sound.*

MELUTA

CO-OPERATION

Meluta co-operated with Sandvik and a few other companies on mobile working machine sector to discover benefits of sound monitoring.

Ponsse, Patria and Novatron additionally provided ideas and feedback on the use-cases

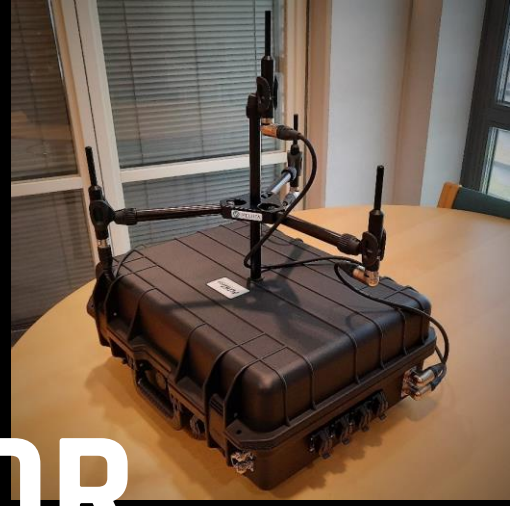
SANDVIK

PONSSE

Patria

NOVATRON
EARTHMOVING AUTOMATION

MELUTA

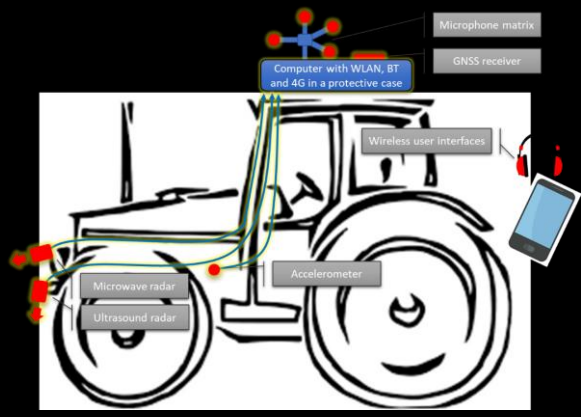


DEMONSTRATOR

Flexible demonstrator - MAX™ - Meluta Advanced eXecution platform - developed to be used to introduce and gain interest in sound and vibration sensing possibilities.

Reference self-sustaining hardware implementation with various sensor interfaces, connectivity, UI, utilizing sound monitoring and satellite data with software platform, advanced signal processing and machine learning techniques to demonstrate a few functionalities, which have been identified with partner companies to benefit safety and productivity for mobile working machine operations.

MELUTA



DEMONSTRATOR

The demonstrator system operates in standalone way. Effectively this means, that it does not need operating power from the host work machine and it does not connect to any wired or wireless data interfaces of the work machine.

Mechanically, the core of the demonstrator system is packed as a field operations suitable, compact and rugged unit using a IP65 classified tool suitcase, Flyht Pro WP Safe Box 5 (external dimensions 515x414x200 mm). The suitcase is then typically placed on the roof of the work machine cabin and the wired sensors are assembled to appropriate locations within the work machine.

MELUTA

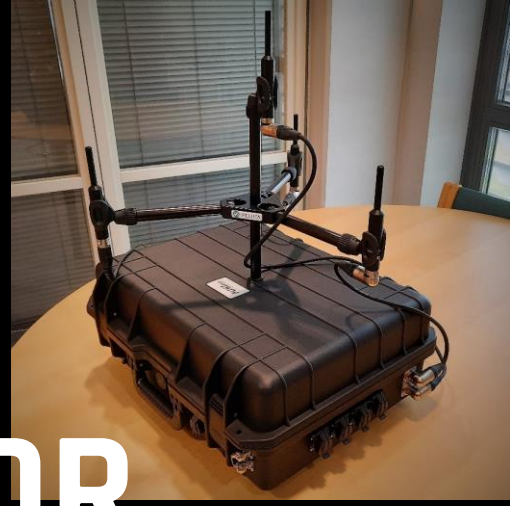
DEMONSTRATOR

The core of the demonstrator system is formed by an industrial/vehicle PC Tensor I20 with wired interfaces to all necessary sensors and wireless interfaces towards remote user interface and selected internet services.

Work machine environmental acoustic sounds are collected with a 4-microphone matrix enabling sophisticated direction finding and classification related digital signal processing algorithm usage.

The physical arrangement of microphones defines the overall performance of the microphone matrix.

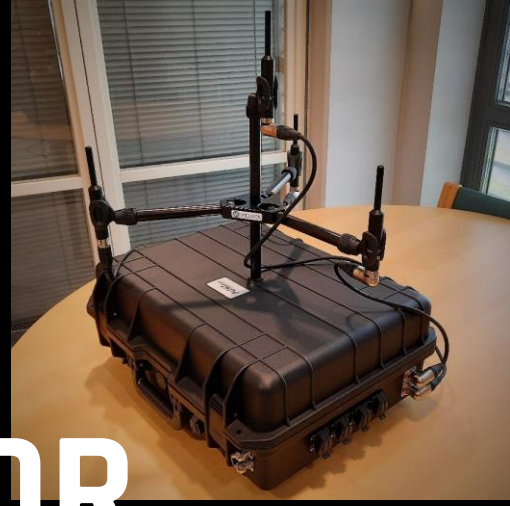
MELUTA



DEMONSTRATOR

Previous experience from Meluta projects involving sound source detection and direction finding have shown that a 4-microphone system arranged in “Y” shape with “leg” length of 20 to 40 cm is a good compromise between size, ruggedness, complexity and directional performance for human shouting and emergency vehicle siren type of sounds. Object direction finding accuracy is estimated to be in the region of +/-10 to 20 degrees in good signal-to-noise (S/N) conditions. It is important to note that when running digital signal processing algorithms involving beamforming the used microphones must be omnidirectional. We used 4 Beyerdynamic MM-4 omnidirectional microphones.

MELUTA



DEMONSTRATOR

Other key components include:

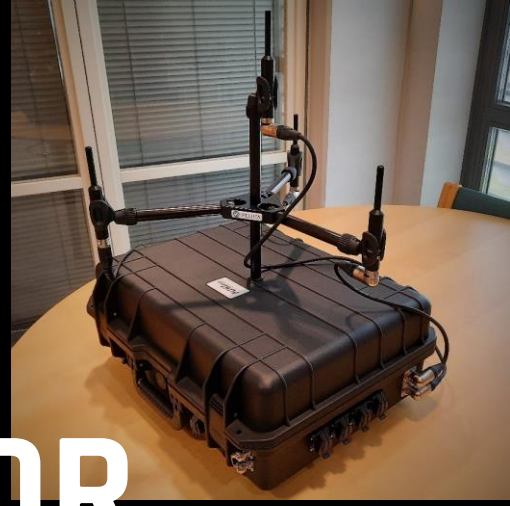
USB controlled audio interface Tascam US-4x4HR 192kHz/24-bit

MMF KS80D accelerometer and USB interface Roga Plug.n.DAQ Lite

GNSS Navilock NL-8200U Multi GNSS UDR receiver

Two types of obstacle detection sensors: Ultrasound HRUSB-MaxSonar-EZ4 series MaxBotix MB1443 and microwave radar Acconeer XE132 evaluation kits having XM132 modules and A1 system-in-package radar transceiver.

MELUTA

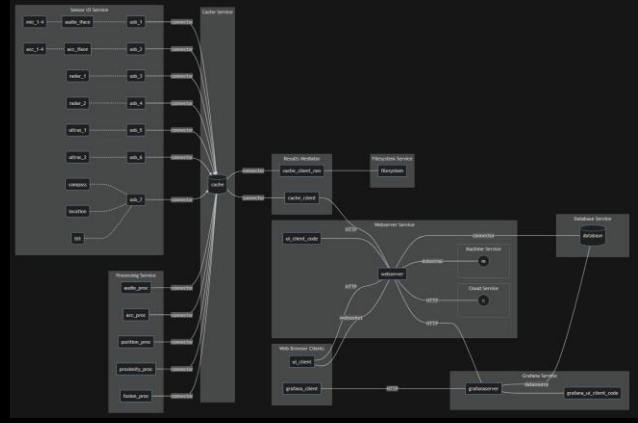


DEMONSTRATOR

Demonstrator is powered using 12V 20Ah TAB Li-Fe-Po battery and it is charged from 230V mains using a CTEK MXS 5.0 battery charger.

Operation time with one charge is a workday, on longer recording needs charger can work as a power supply for the system.

MELUTA



DEMONSTRATOR

Demonstrator software reads various sensors and perform signal processing and data analysis. Analysis results are stored for further use together with accurate timing and location information. Results are shown on user interface as positioned events on map and according needs result data can be also used to visualise how results are changing over time.

SW is implemented as loosely coupled micro services which are partitioned into several independent isolated entities (containers) communicating with each other using TCP based protocols.

MELUTA

DEMONSTRATOR

User interface has been implemented as web browser client.

Key elements

- Radar display (numerical multiradar displays)
- Red spot (work machine location)
- Circle around work machine (object area)
- Long pointer on circle (direction where emergency vehicle is detected)
- Arrowhead on circle (direction of work machine heading)

Arrowhead is used to show heading of work machine. In initial implementation north is always on top and heading arrow is shown on heading angle compared to north.

MELUTA

COMMERCIAL PLAN

For solutions identified with commercial potential a commercialization plan was be done for development of the system to fulfill physical and functional requirements of fixed installation.

In Meluta, we believe that autonomous vehicles need sound and vibration sensing to cope in the real-world environment. There are so many things happening and tasks to control that all senses are required for safe and productive operation.

MAX™ is used as a development platform, capability demonstrator, starting base for custom projects and marketing / sales / awareness creation for Meluta

MELUTA

COMMERCIAL PLAN

MAX™ is mainly marketed to the selected customer segments in the work machinery area. However, there is a possibility of a secondary market in the autonomous car segment. Therefore, Meluta is ready to create networks where the offering is made together with several providers.

Monetization is planned to be done mainly via licensing. However, equipment sales are not excluded if it fits the customer's needs or is preferred to purchase for the customer. Meluta also provides spare parts, training, and support to adapt MAX™ to customers' control systems.

MELUTA

COMMERCIAL PLAN

Meluta aims to help customers with a more refined business model. Direct commissions are not the optimal way to create control systems. It is not efficient to always start from scratch. With a product platform, the development costs are divided among several customers and projects. Software quality and maturity can be significantly improved with the continuous development of the platform.

Pricing is determined case-by-case. Meluta's sales must understand the customer value of the MAX™ in each case. Win-win licensing price is determined by typical pay-back times for the industry. Therefore, Meluta needs to have a solid understanding of the customers' business and their value proposition.

MAX™ BUSINESS CANVAS

Idea

Current sensor solutions cannot provide comprehensive situational awareness in work machinery in all conditions

Navigation systems fail during gaps of GNSS signal

Sound and vibration will be fused with other sensors to improve situational awareness and safety of the teleoperated or autonomous work machinery

Robust navigation systems can be created, with sound analysis, during gaps of GNSS signal

Market

Machinery market is several T€ / year. Navigation sensor systems is several B€ / year

Partners: Huld, Xortec, Treon, Radientum, TUNI, VTT

Competitors: Bosch, Volansys, Cerence, Sonoware, Reality analytics

Customer Segment

Customers are companies that are looking for competitive edge and/or are market leaders

- Mining & rock excavation
- Forest machinery
- Construction machinery
- Work machinery control system providers

Business Value

Sound analysis and signal processing are the core competencies of Meluta

Work machinery market is moving towards teleoperated and autonomous systems. MAX can be used to add sound sensing to these systems

System sales directly to customers:

- Software licensing
- Development support
- Support, training and maintenance
- Spare parts

MAX will evolve around the customer needs and different implementations. Licensing fees must cover development costs and support company growth

Features

Using sound and vibration sensing together with vision, radars, GNSS and other information sources, MAX can improve the situational awareness

Features:

- Connectivity
- Modularity
- Best fit algorithms
- Can be mass produced
- Remote support
- Adaptive (AI/ML)

Equipment fit well in the environment they are used

Systems are accompanied with maintenance guides based on Meluta's comprehensive know-how

Metrics

Success:
Market penetration in at least one target customer segment

Viability:

- Gross profit goal min. 70%
- Net profit goal 10%

Failure:

- Less than 3 customers
- Not viable

Evangelism

Meluta is a world class sound analysis, signal processing and software systems provider
Web-site provides value adding white papers and blogs for customer's decision making

Visual Identity

MAX™ – Meluta Advanced eXecution

Go To Market

Direct sales to selected customers. Social media is used to attract traffic to Meluta's web-site. Web-site provides valuable, educational and engaging material (papers, blog, video)

Key Resources

3rd party SW –licenses

Risks

Environmental protection of the microphones is difficult

Is MAX interesting for improving navigation robustness and safety?

Are Meluta's systems reliable enough?

MELUTA

SMAM USE CASES

Co-operators interest and feasibility focused set implemented:

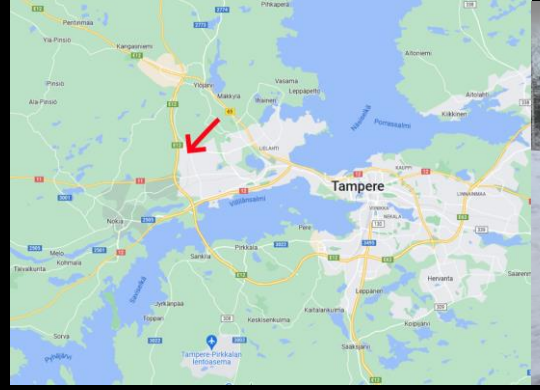
1. Detect emergency vehicle sound and the direction of arrival

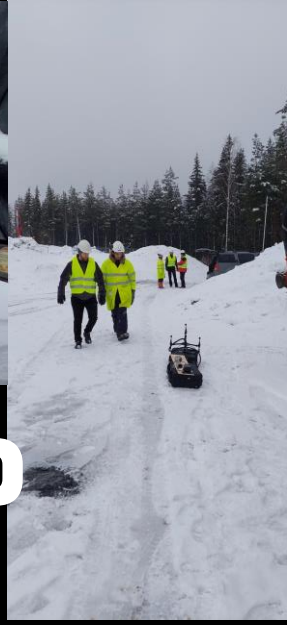
2. Help listening to environment using adaptive signal processing technology and provide enhanced external soundscape into cabin (and remote operation center.)

3. Enhance map / track matching with sound based information and combine detected audible issues with location and direction information

4. Near field obstacle detection

MELUTA





SMAM TEST CAMP

Tests performed at Sandvik surface drilling test site located about 1km north of Sandvik's main factory in Finland at Pirkkala 25th Feb. December is a typical winter month in Finland and the test site was covered with thick snow, temperature was 0°C, some light snow, relative humidity 95%, wind 4 m/s from the southwest.

Pantera DP1500i is a hydraulic, diesel-powered, self-propelled top-hammer drill rig used for production or pre-split drilling in large quarries or open-pit mines and construction sites. It drills holes with a diameter of 89 to 152 millimeters (3 ½ to 6 inches). The Pantera has a Caterpillar C-series engine, which has power between 350hp and 385hp depending on the model.

MELUTA

SMAM TEST CAMP

Before the test day we had the test readiness review 23rd Feb, and we executed the tests 25th Feb in Sandvik premises demonstrating the capabilities and collecting results, gain professional feedback from the Sandvik engineering research team.

During the Sandvik testing we recorded test results and additionally the sound and sensor data fully for further analysis. Additional quantitative tests were executed on the beginning of March to make sure we did not miss anything.

MAX™ system was installed on top of the cabin of the Pantera drilling rig, the test equipment had a non-obscured line of sight around the drilling rig.

MELUTA

SMAM TEST CAMP

All sub-systems were controlled via Android phone UI. The UI showed the geo-location of the rig, direction, and type of the detected “EVD” and the operator could switch on and off the adaptive noise filtering for the blue-tooth headsets as well as indications of radar detections.

The test system was working as intended, and we didn’t have any technical issues during the testing, system worked as planned right from the start.

MELUTA

SMAM EVDD

Emergency vehicle direction and detection (EVDD) system.

MELUTA

SMAM EVDD

Emergency vehicle direction and detection (EVDD) system.

Why?

- Audio can be heard sometimes multiple seconds before visual sight can be acquired (city streets).
- Emergency vehicle sirens give clear signal to the driver about surrounding situation and this information should be made available to autonomous vehicle decision making.

MELUTA

SMAM EVDD

Emergency vehicle direction and detection (EVDD) system.

How?

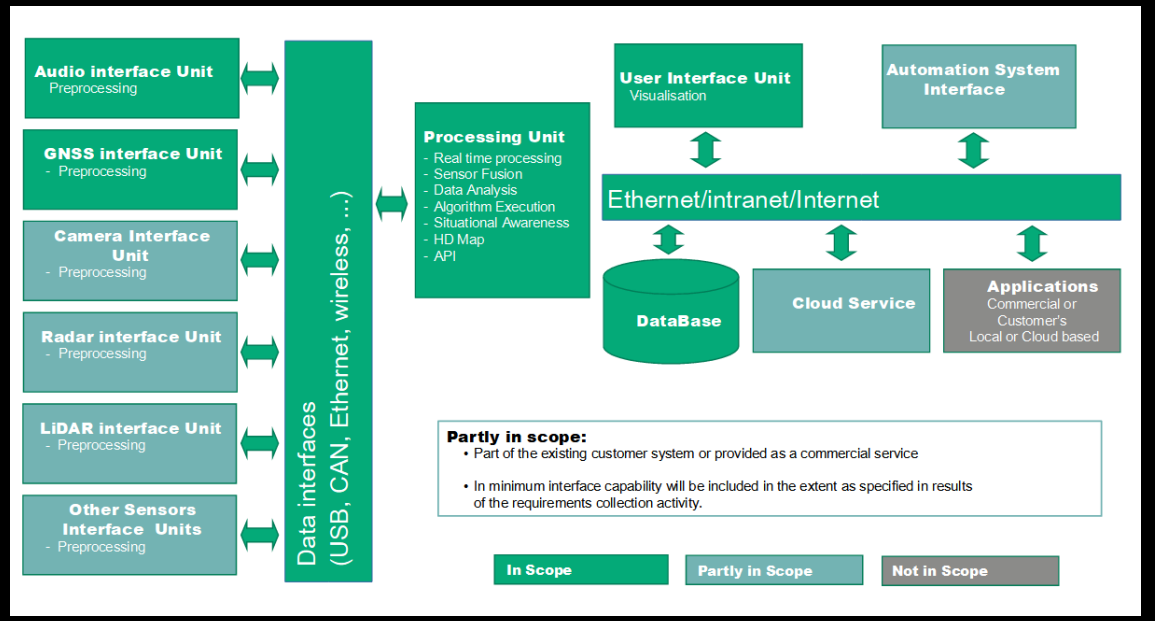
- Detect emergency vehicle audio and predict the direction of arrival for that sound.
- Use cutting edge technology by implementing latest research into MAX.
- Output information that can be delivered to easy-to-use UI on the MAX, autonomous vehicle decision layer or any other subscriber to the MAX interface.

MELUTA

EVDD DATAFLOW

Microphone input -> recording -> EVDD block ->output

=> subscribers to the EVDD block



MELUTA

EVDD DATA

Focus on working with low SNR.

No easy way to record real data with reliable ground truths.

Record clean samples and mix them with desired noise to create good training and testing data for both detection and direction.

MELUTA

EVDD DATA GATHERING

Initial recordings from collaboration with Tampere Police University College track with police cars with sirens on.

- Not accurate enough direction information as the test setup didn't allow it.

Another recording session on nearby empty airfield to get noise free recordings with precise ground truths for neural network training.

- Sirens played back from large speaker and recorded on the microphone array from different directions and volumes simulating different distances.
- Sirens from police car recordings and ambulance and fire truck ripped from Youtube videos with little to no background noise
- No sweeping sounds as the direction was changed only between recordings.

MELUTA

EVDD DIRECTION

Estimate the direction of incoming sound using phase difference between microphone pairs.

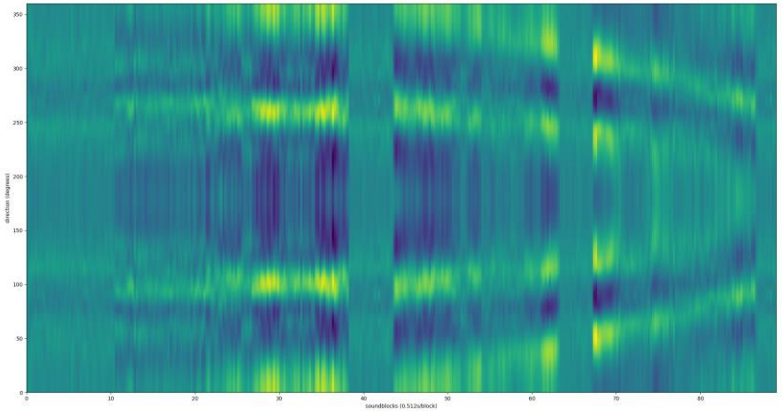
Each pair of microphones provides direction probability for each direction and frequency.

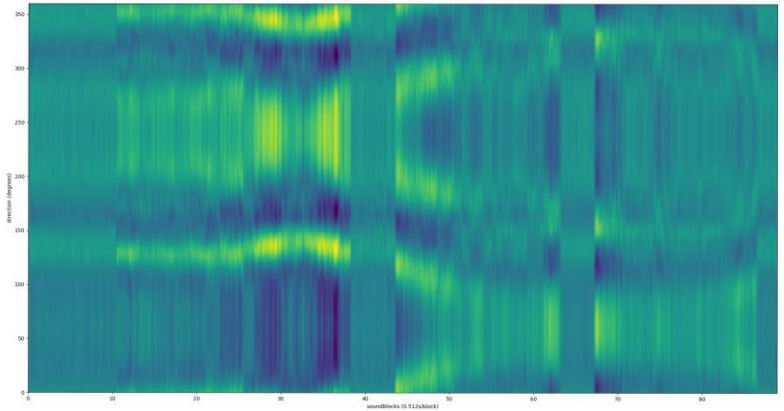
Combining multiple pairs of microphones for accurate direction probability.

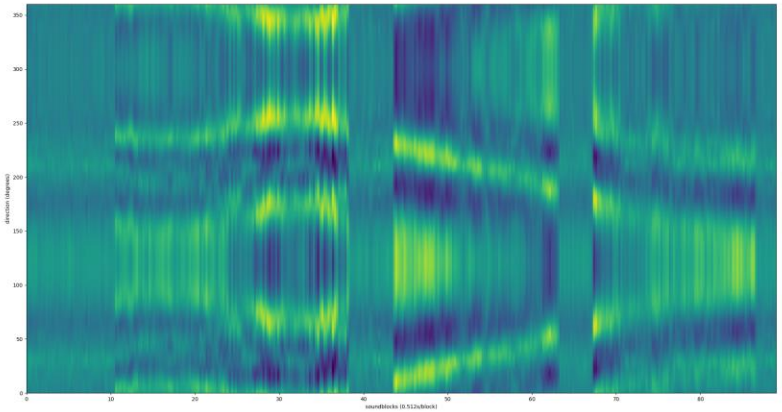
Array of 4 microphones forms total of 6 pairs.

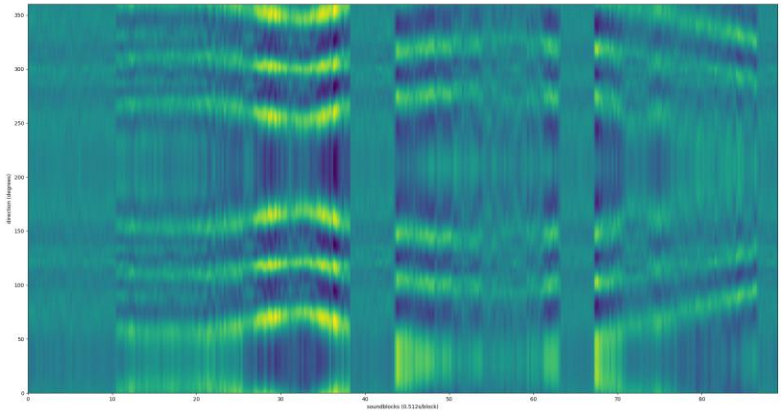
Generalizes to any number of microphones.

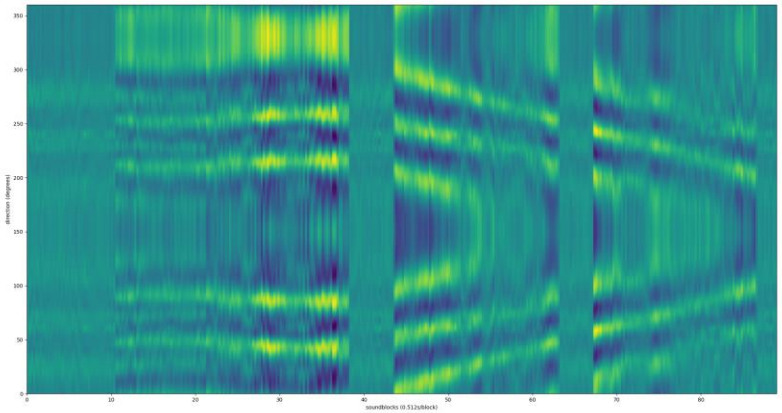
2D direction estimation. 3D direction estimation is already implemented and ready to be used.

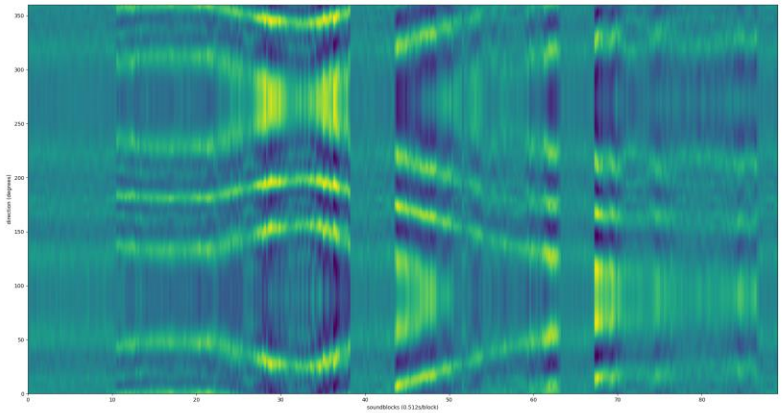

direction (degrees)
soundblocks (0.512s/block)

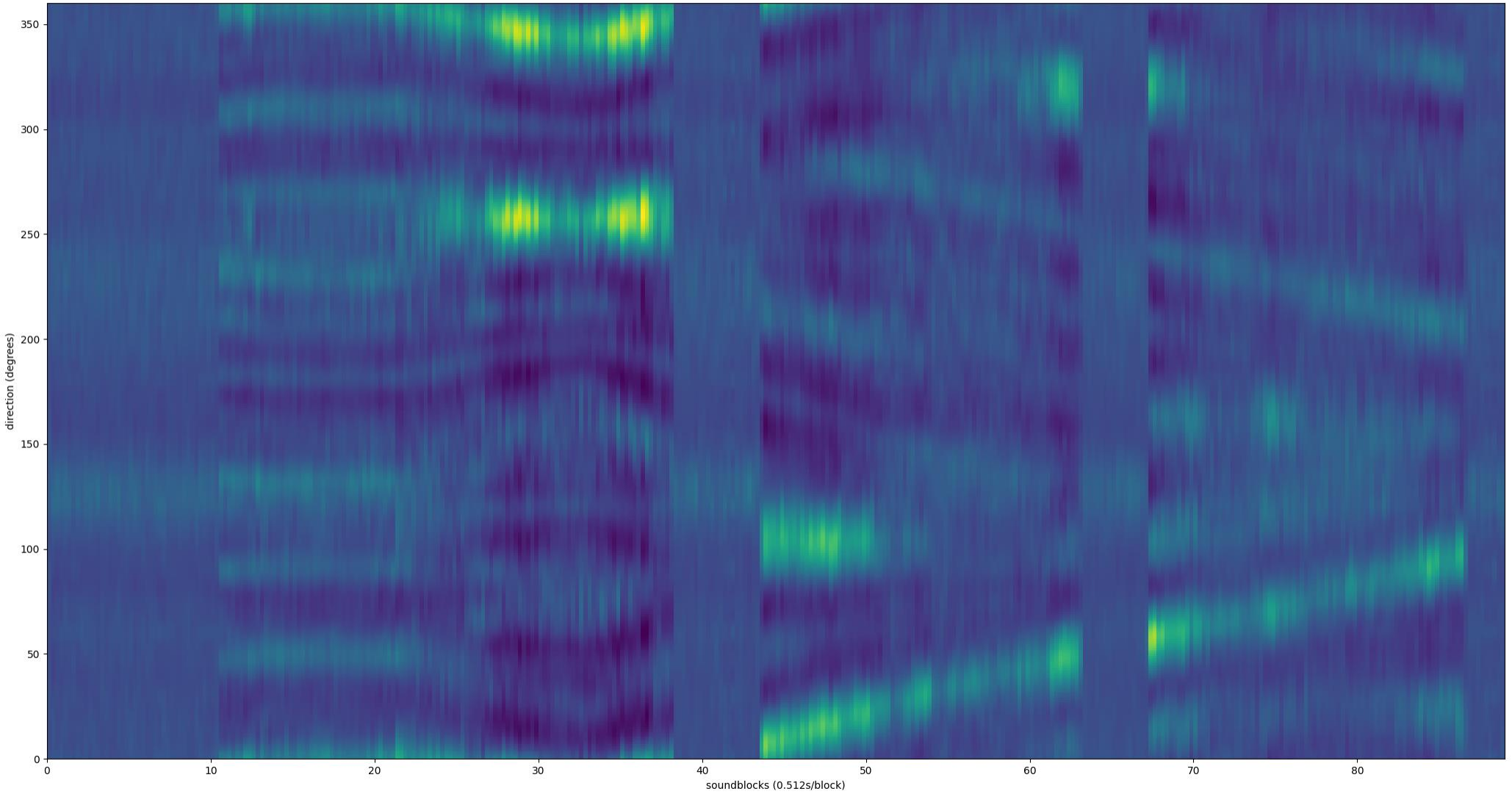

direction (degrees)
soundblocks (0.512s/block)


direction (degrees)
soundblocks (0.512s/block)


direction (degrees)
soundblocks (0.512s/block)


direction (degrees)
soundblocks (0.512s/block)


direction (degrees)
soundblocks (0.512s/block)

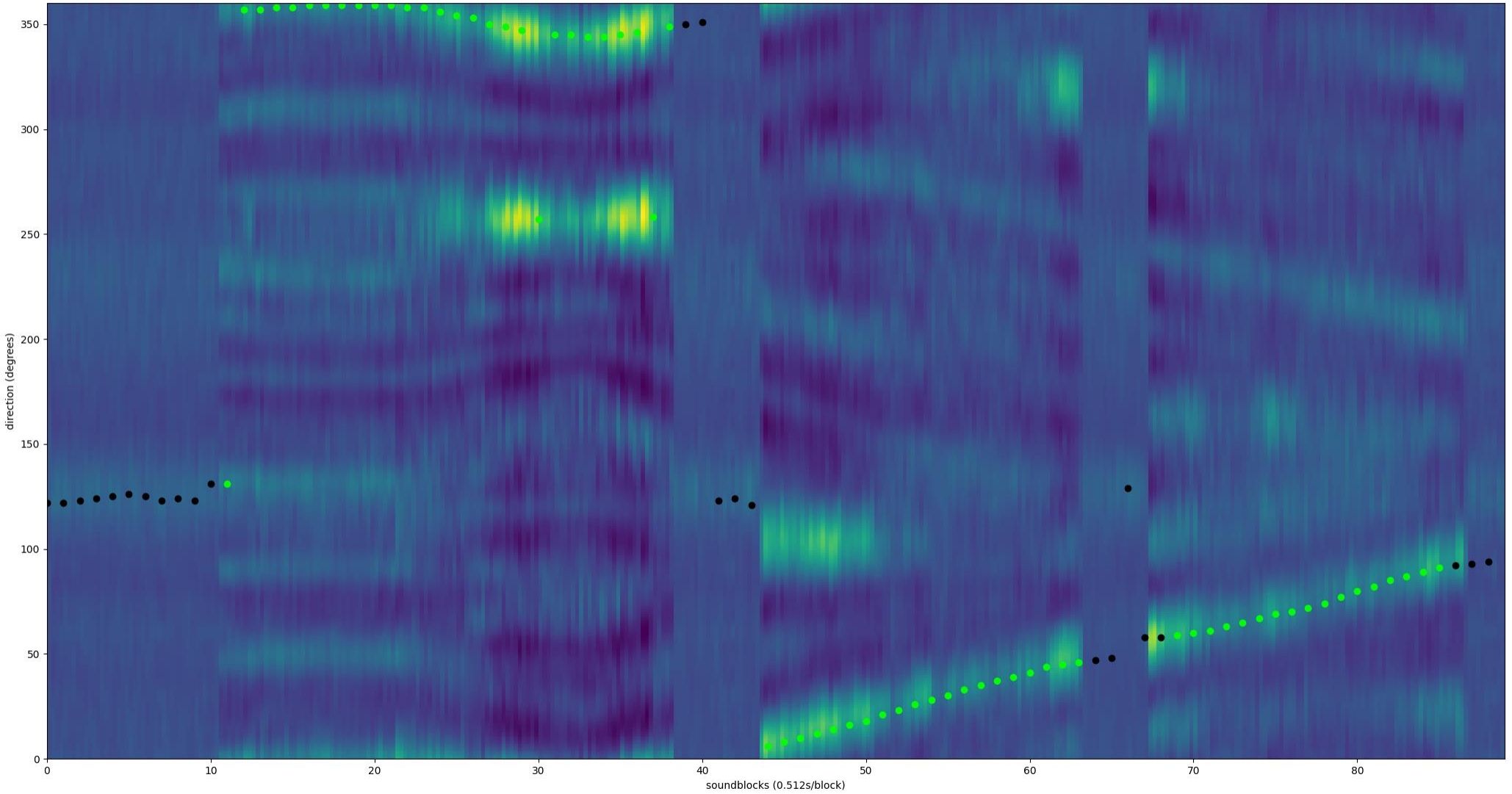

direction (degrees)
0
50
100
150
200
250
300
350
0
10
20
30
40
50
60
70
80
soundblocks (0.512s/block)

MELUTA

EVDD DIRECTION POST PROCESSING

Reduce the effect of reflections and other outliers.

Average for more reliable output vs time sensitivity.


direction (degrees)
0
50
100
150
200
250
300
350
0
10
20
30
40
50
60
70
80
soundblocks (0.512s/block)

MELUTA

EVDD DIRECTION CHALLENGES

Reflections.

Finding the direction of correct sound source in case of overlapping sounds in same frequency range.

Beamforming and filtering could be used to improve direction by reducing unwanted noise.

Microphone array dimension optimization.

More varied data.

MELUTA

EVDD DETECTION

Neural network approach based on the latest research papers on the subject.

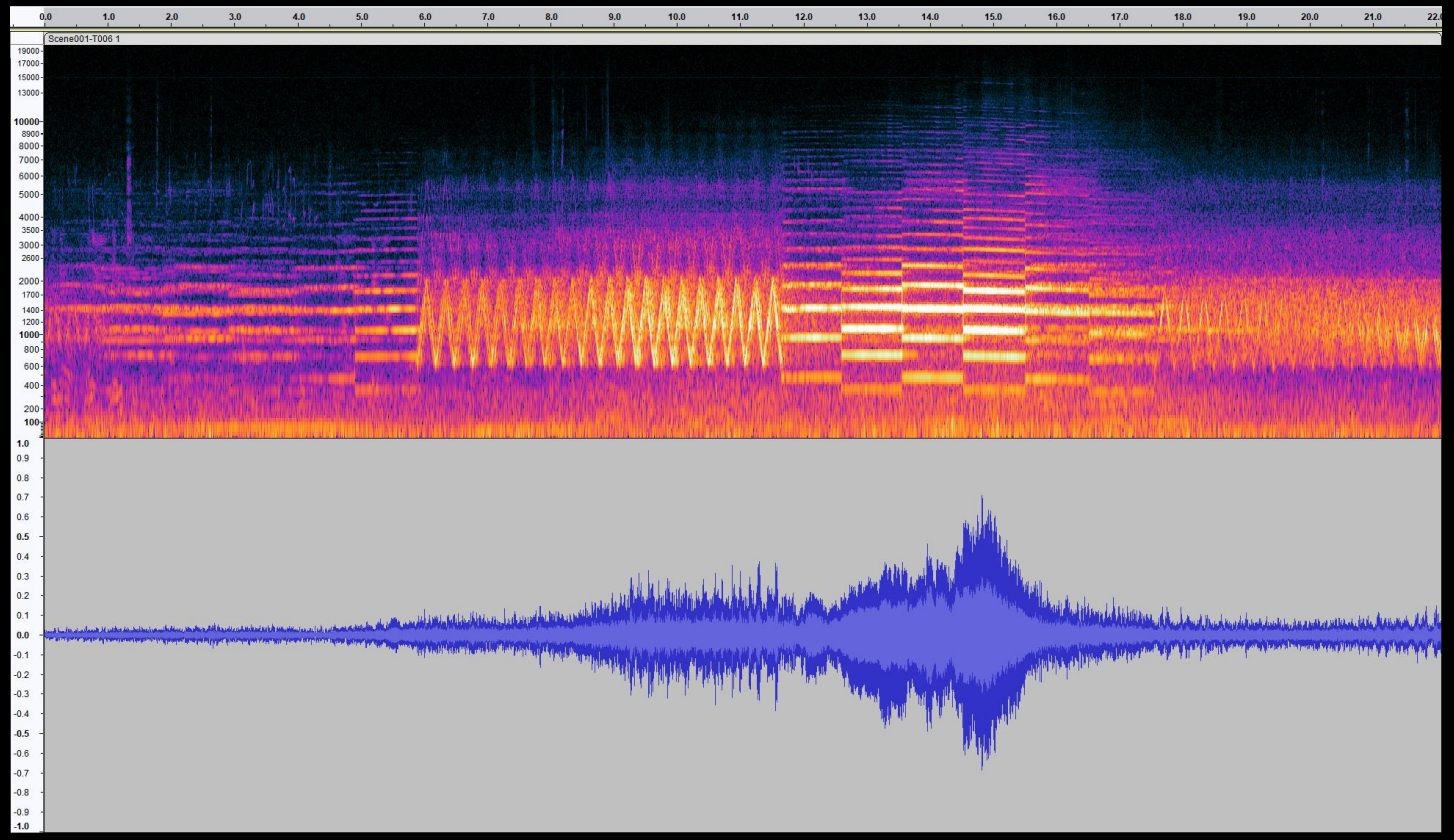
Base architecture from study by V. Tran and W. Tsai, "Acoustic-Based Emergency Vehicle Detection Using Convolutional Neural Networks", 2020.

Two different CRNN approaches, one for raw audio feature and one for STFT feature.

PyTorch machine learning framework with hyperoptimization using RayTune.

MELUTA

EVDD DETECTION FEATURES



MELUTA

EVDD RAW AUDIO NETWORK

Raw audio data as input.

1D convolution layers extract information that is passed to 2D convolutions.

GRU units extract temporal information and fully connected layers do the prediction.

Small and efficient network.

MELUTA

EVDD STFT AUDIO NETWORK

Short Time Fourier Transform (STFT) data as input.

2D convolutions to extract information out of spectrogram.

GRU units extract temporal information and fully connected layers do the prediction.

Larger and more accurate network.

MELUTA

EVDD DETECTION FUSION POST PROCESSING

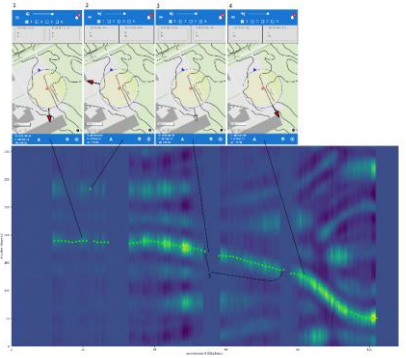
Spectral feature proved to be more accurate overall, but in some specific cases the raw audio network performed better.

Join network outputs with additional information from latest direction changes for better accuracy.

Infinitely tuneable fusion block.

Easy to modify sensitivity and accuracy vs delay trade-off.

MELUTA



EVDD RESULTS

EVDD performed according to expectations and even exceeded those expectations by being able to estimate directions and detect siren noise from simulated range of over 200 meters quite easily and even with the engine providing noise.

Sound reflections caused occasional wrong direction estimation, improvement through echo cancellation and adaptive filtering to suppress environment noises identified.

MELUTA

EVDD JOINT NETWORK

One network for both detection and direction.

Relatively hot research topic.

Need for more complex data that is fully annotated.

MELUTA

SMAM RESULTS

Help listening to environment using adaptive signal processing technology and provide enhanced external soundscape into cabin (and remote operation center.)

Real time speech was evaluated by listening the environment through Bluetooth headphones and evaluated by six (6) test listeners.

MELUTA

SMAM RESULTS

For the soundscape enhancing both Normalized Least Mean Square filter and Wiener filter were tested and for the last implementation the Wiener filter was chosen.

The Wiener filter is an adaptive filter, which dampens the engine noise and enhances the speech. It is good for this solution, since the engine noise is stationary.

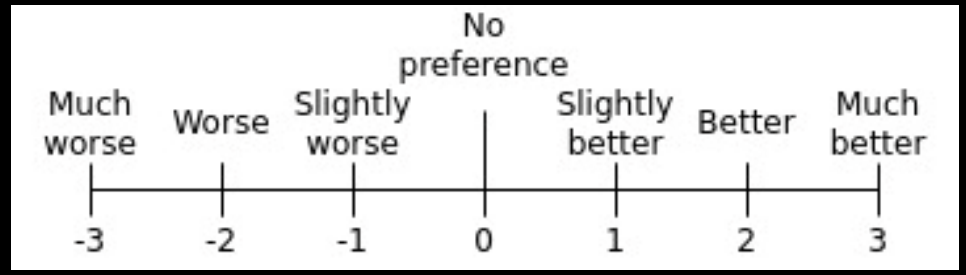
The filtered soundscape was brought to the listener through the Bluetooth headphones. The filtering and the Bluetooth connection combined caused a delay of few milliseconds, which is considered reasonable.

MELUTA

SMAM RESULTS

In the subjective test the test subject sat inside the vehicle with the Bluetooth headphones on. The test voices were played from the loudspeaker simulating the distances defined in the test plan.

The test subject was told to compare the effect the filtering had to the soundscape and fill the even grade scale for comparison tests, which was based on ITU-R BS.1284-2 standard



MELUTA

SMAM RESULTS

Test ID	Input	Expected output	Actual output	Acceptance criteria	Test status
UC4_T1	Human shouting at 5m distance when engine is running,	Clear improvement in readability, subjective assessment result 2 or better	subjective assessment result 3	Subjective assessment result 1 or better	Output better than expected
UC4_T2	Human shouting at 10m distance, others as UC4_T1	Subjective assessment result 2 or better	subjective assessment result 2	Subjective assessment result 1 or better	Expected output received
UC4_T3	Human shouting at 20m distance otherwise as UC4_T1	Subjective assessment result 2 or better	subjective assessment result 2	Subjective assessment result 1 or better	Expected output received
UC4_T4	Simulated ambulance siren at 50m distance, otherwise as UC4_T1	Subjective assessment result 2 or better	subjective assessment result 2	Subjective assessment result 1 or better	Expected output received
UC4_T5	Simulated ambulance siren at 100m distance, otherwise as UC4_T1	Subjective assessment result 2 or better	subjective assessment result 2	Subjective assessment result 1 or better	Expected output received
UC4_T6	Silent environment, engine not running	Experienced soundscape does not get worse	subjective assessment result 0	Subjective assessment result 0 or better	Expected output received
UC4_T7	Silent environment, engine running at operating RPM	Experienced soundscape does not get worse	subjective assessment result 2	Subjective assessment result 0 or better	Output better than expected

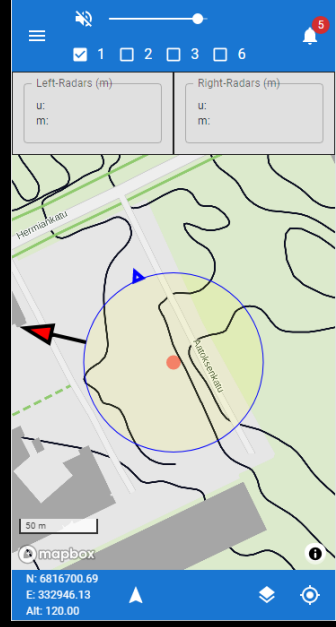
MELUTA

SMAM RESULTS

This system showed clear improvement for the machine operator to hear and detect humans talking near the machine. The filtering also significantly reduced the engine noise coming from the drill rig. The difference was remarkable and there were hardly any dispersion in the results, so they were considered reliable.

MELUTA

SMAM RESULTS



Enhance map / track matching with sound based information and combine detected audible issues with location and direction information

Target was met to create object map of detected sound or other objects with observation time, location, and direction information.

Object map can be in future also shared with remote operation centre. The operation centre utilises mainly video feed for the operator, which is prone to effects of adverse weather, harsh and dusty conditions that block visibility of the optical camera sensors. Typically, the remote operator oversees many autonomous working machines, from 5 upwards, and potential improvement for the remote operator is to bring those video feeds to the operator's attention that have sound-based events.

MELUTA

SMAM RESULTS

Near field obstacle detection

Ultrasound radar testing showed good performance on <2m distances, but lack of fast detection limits usable speeds to prevent collision to <5km/h.

Microwave radar testing showed good performance on <5m distances and detection speed less than 200ms. Makes it more suitable for avoiding collision to <15km/h.

MAX™ can be utilized to detect objects on the way of tires / tracks or pinch points before moving the machine improving the safety especially with large visibility limited machines.

MELUTA

SMAM CONCLUSIONS

Sound direction and EVD detection proved to be able to work 180 degrees directly and indirectly up to 65m in very noisy environment and up to 200m in more quiet area. MAX™ can avoid accidents with emergency vehicles.

Surrounding sounds were enhanced so that it sounded better or much better with the filter on than without the filter. The difference was remarkable. MAX™ can help in critical communication situations to avoid harm to people.

MELUTA

SMAM CONCLUSIONS

MAX™ provides availability of situational awareness through sound and obstacle detection, extending the application range of PNT technologies.

In current phase MAX™ is not trying to enhance PNT accuracy or overcome gaps in PNT positioning. Instead, focus is in providing additional information of nearby environment potentially needing separate attention within autonomous or remote controlled operations.

MELUTA

FUTURE

MAX™ is a flexible demonstration platform used to introduce and gain interest in sound and vibration sensing possibilities. We firmly believe that it can open good business opportunities for Meluta.

During the SMAM project, we have studied the markets, competition, opportunities, and challenges that we face.

Market potential and timing are excellent. Most of the work machinery companies are developing some autonomy or teleoperation to their products. There is some competition in this area, but our opinion is that it is better to have many companies working in this new field to spread the knowledge of sound sensing opportunities.

MELUTA

FUTURE

It is pretty challenging to create a system installed into a work machine operated in harsh conditions. However, we believe that the task can be solved.

MAX™ is still a very immature system, and we are at the beginning of its development. New sensors and new algorithms will be added onto this platform that is designed to be evolved.

Also, new applications can be created as the capabilities of the system are expanded. For example, we are looking into autonomous cars, ships, and other vehicles for new opportunities in addition to the work machinery.

MELUTA

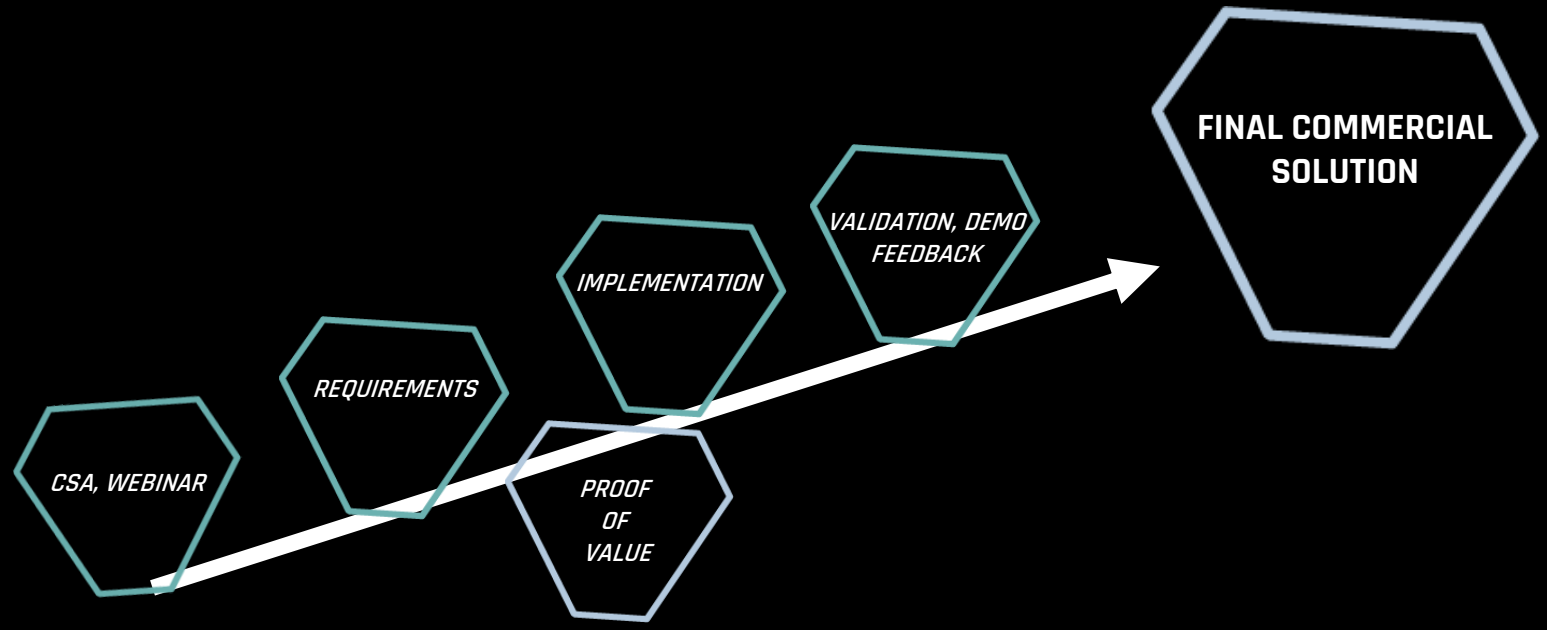
FUTURE

For a startup company like Meluta, we need to succeed well in one narrow niche in this field to be able to transform from a startup to a growth-up company.

I want to thank everybody at ESA and our co-operation companies for providing world class support and insights for Meluta future direction!

MELUTA

PHASES



MELUTA

HEAR, DON'T GUESS

Markku Salmela
+358 50 524 7438
markku.salmela@meluta.fi

Meluta Oy Ltd
BID-2683932-2
Address: Hermiankatu 12 C 1,
FI-33720 Tampere, FINLAND

www.meluta.fi

MELUTA