Pros and cons of mobile sensors

Fabio Bonsignorio
Professor, ERA CHAIR in AI for Robotics,
Head AI for Robotics Lab

CEO and Founder Heron Robots

University of Zagreb
Faculty of Electrical Engineering and Computing
Laboratory for Autonomous Systems and Mobile Robotics

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No. 952275

www.heronrobots.com

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

G2NET

CA17137 Working group 2

Machine Learning for low-frequency seismic measurement

WG 2: Machine learning for low-frequency seismic measurement

Led by Velimir Ilić velimir.ilic@gmail.com
and Fabio Bonsignorio fabio.bonsignorio@gmail.com

Abstract

The performance of Earth-based GW detectors is largely influenced by the ability of combating the low-frequency ambient seismic noise and other seismic influences. These tasks require multidisciplinary research in the fields of seismic sensing, signal processing, robotics, machine learning and mathematical modeling.

The working group 2, deals with acquisition, processing and interpretation of seismic data, with the goal of combating the seismic influences at GW detector site, using the multidisciplinary research, with a focus on advanced techniques available from state-of-the-art machine learning algorithms.

WG 2 Tasks

WG 2 is actively working on the following tasks

1. Nonstationary signal analysis
2. Deep learning for seismic time series
3. Newtonian noise detection and seismic sensor arrays
4. Probabilistic robotics for seismology and GW detection

More info: https://www.g2net.eu/wgs/WG 2-machine-learning-for-low-frequency-seismic-measurement

Mailing list: wg2-g2net@ego-gw.it

CA17137 MoU - WG2's main tasks

1. To assess the influence of seismic signals on GW records.

2.To learn current approaches to the issue of seismic noise and adapt appropriate methods from the wide spectrum of seismological tools.

3. To participate in creating ML procedures to automate data processing.

4.To design a solution for the application of robots and seismic sensors to monitor seismic noise around GW detectors and help in the Newtonian Noise suppression.

5. To investigate possible ML methods in seismological problems.

Human resources management

WG2 challenges: Network growing and knowledge sharing

- Strengthening of the internal WG2 research networks in order to support the project for adaptive robots for seismic noise monitoring and to further advance the projects for ML techniques for the noise analysis of gravitational wave detectors.
- Step 1: Better reallocation of tasks between and within working groups relying on wide set of multidisciplinary expertise that we have.
- Step 2: Inclusion of new young researchers in our network which would be allocated to the critical tasks. STSM missions and training programs we are continuously working on could represent an important motivation for new young members and solid base for achieving of this objective
- <u>News: a PhD from the newly constituted AIFORS Lab will join in the coming weeks, more people may join in the future</u>

WG2 activities: challenges

WG2 networking

- Zoom meetings (8 in the previous year), seminars (3 in the previous year), (1 in this year). Regular 1 to 1 contact within WG2.

Document management

- Templates: scheduling the meetings, agenda/minutes…
- Minutes mostly available at Asana

Repository development

- Improvement of the repositories for datasets from members to be used for tasks and experimentation.
- Improvement of the library of literature: state of the art research papers, tutorial and textbooks on GW physics, geophysics, computer science and robotics.

Nonstationary signal analysis

- Extraction of Useful Information from Noisy Signals
- GW and seismic signal denoising
- Time-Frequency vs. Vertex-Frequency analysis
- Signal Decomposition in Dispersive Channels

6 publications,
several in progress

Contact:
Jonatan Lerga (RiTeh, Croatia)
jlerga@riteh.hr

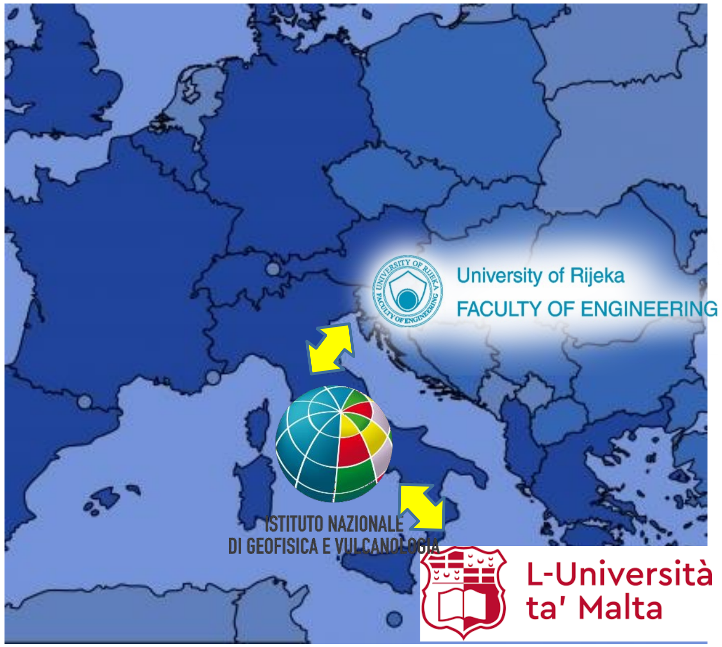
In collaboration with: Nikoleta Saulig, Elena Cuoco, Miloš Daković, Isidora Stanković, Eftim Zdravevski...

Collaboration with WG1

WG2 Overview

Machine learning for seismic time series

- Rapid prediction of earthquake ground shaking intensity for VIRGO using ML
- Time-Frequency Representations of seismic data: earthquake detection using ML
- Intra-domain and cross-domain transfer learning for time series
- Learning to Invert Pseudo-Spectral Data for Seismic Waveform Inversion



Contacts:

1. Ivan Štajduhar (RiTeh, Croatia)
   istajduh@riteh.hr
2. Dario Jozinović (INGV, Itally)
   djozinovi@gmail.com
3. Christopher Zerafa (University of Malta)
   christopher.zerafa.08@um.edu.mt

In collaboration with Anthony Lomax, Alberto Michelini, Carlo Giunchi…

3 STSM-s accomplished
2 publications, several in progress

NN detection and seismic sensor arrays

- Analysis of seismic data from the Virgo network
- Seismic networks at the ET candidate site in Sardinia
- Seismic networks for machine learning
- Advanced equipment (mobile seismic sensors, infrasound microphone…)

Potential industrial application!

Contact:
Tomek Builk (University of Warsaw, Poland)
tb@astrouw.edu.pl

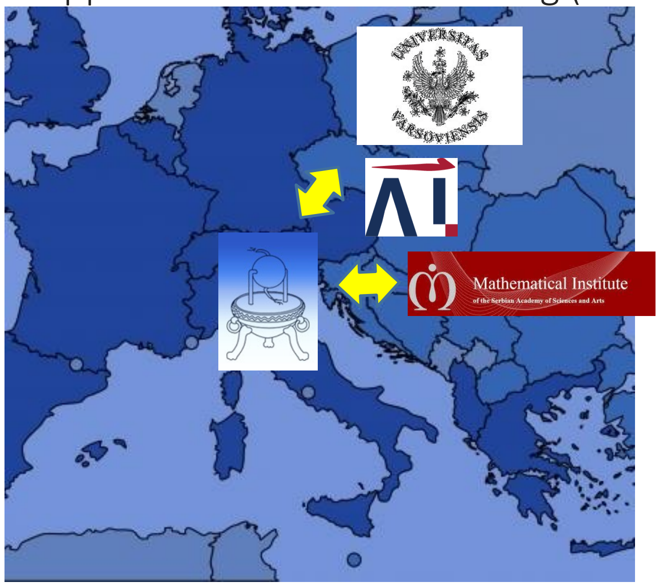
In collaboration with Fabio Bonsignorio and Ian Harms

Collaboration with WG3

WG2 Overview

Probabilistic robotics for seismology and GW detection

- Gaussian and non-Gaussian processes for the characterization of Newtonian, seismic and other kinds of noises
- Advanced information theoretic methods for multi-sensory fusion to drive the information gathering and motion planning (information theoretic measures, probabilistic graphical models, causal networks, dynamic programming…)
- Simultaneous Localization and Geographical Fields Mapping by means of network or swarms of autonomous mobile robots.
- Applications to seismic sensing (initial Roomba tests). Possible industrial application!



Contact:
Fabio Bonsignorio (Heron Robots, Italy and FER, University of Zagreb)
fabio.bonsignorio@heronrobots.com
In collaboration with Tomek Builk, Velimir Ilić, open to others

Possible cooperation with WG1 and WG3 (EGO and GSSI)

WG2 Overview

Reproducing Kernel Hilbert Spaces and Applications: Signal Theory, Machine Learning, Robotics, and AI (NEW!)

•Try to address adaptive filtering of complex signals by using complex reproducing kernels
•Profits from complex analysis methods developed elsewhere (e.g. within quantization theory for physical systems whose classical phase space is a complex manifold, cf. E. Barletta & S. Dragomir & F. Esposito, and involving weighted complex kernels, to deal with problems in signal and learning (regression and classification9 theories
•In particular, we shall be interested in biologically inspired signal processing (cf. K. Li & J.C. Principe, [LiPr]) by following the philosophy proposed by F.P. Bonsignorio (cf. F.Bonsignorio) and seeking to transpose real kernel methods to the complex domain.
•The link of RKHS with ReLu, and then to the modeling of (deep) neural networks and learning systems in general, and to band-limited complex analysis representation of non-linear physical systems with limited bandwidth and energy, as typically mechanical, electrical and biological systems, suggests that a new modeling framework for natural and artificial systems processing information could be achieved on the basis of the novel theoretical mathematical methods developed
•The new methods could provide substantial progress in the understanding of information processing in biological systems, for example in the human immune system, and the design of radically new kind of embodied/nactive AI based robots, much closer to 'animal' inntelligence than current more advanced prototypes.

Contact:
Sorin Dragomir (UNIBAS, Italy)
sorin.dragomir@unibas.it
Fabio Bonsignorio (Heron Robots, Italy and FER, University of Zagreb)
fabio.bonsignorio@heronrobots.com

Possible cooperation with WG1 and WG3 (EGO and GSSI)

WG2 activities: Dissemination

Various worskop/ seminar presentations, Lecture Material on Robotics in GW and Geophysics (Online 2021),a couple of papers in preparation

EGU General Assembly 2020

EGU2020-22165, updated on 09 Mar 2020
EGU General Assembly 2020

Ambient seismic noise suppression in COST action G2Net

Velimir Ilić[1], Alessandro Bertolini[2], Fabio Bonsignorio[3], Dario Jozinović[4], Tomasz Bulik[5], Ivan Štajduhar[6,8], Iulian Secrieru[7], and Soumen Koley[2]
[1]Mathematical Institute of the Serbian Academy of Sciences and Arts, Serbia
[2]National Institute for Subatomic Physics, Netherlands
[3]Heron Robots, Italy
[4]Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy
[5]Astronomical Observatory, University of Warsaw, Poland
[6]University of Rijeka, Faculty of Engineering, Croatia
[7]Institute of Mathematics and Computer Science, Moldova
[8]University of Rijeka, Center for Artificial Intelligence and Cybersecurity, Croatia

WG2 activities: The second CA17137 training school

This school was a result of the initiative taken by WG2 co-leader Christopher Zerafa, a Ph.D. student in the Department of Geosciences. The training school included modules in signal processing, time series analysis, machine learning, deep learning, gravitational waves and geophysics.

Webpage: Learning https://indico.ego-gw.it/event/46/

Possible ws: Machine learning, artificial intelligence, robotics and complex physical systems

High profile open to all theoretical foundations and mathematics oriented workshop

Venue: TBD (Belgrad?)

DD/MM/2023 - DD/MM/2023 (2 days)

WG2 Overview

Regional to global development

WG2 challenges: Network growing and knowledge sharing

- Active collaborating countries: Croatia, Italy, Poland, Malta, Montenegro, North Macedonia, France – mostly ITC countries!

- Goal: Extension of collaboration network from southern-easter to northern-western (developed) countries

Gender balance

- Goal: Increase the number of female collaborators in WG2, with the help of diversity agent and external experts

WG2 Overview

Cooperation activities

A few STSM virtual and in person for mobile robots system (sw and hw) development

Strategic goal: Grant applications

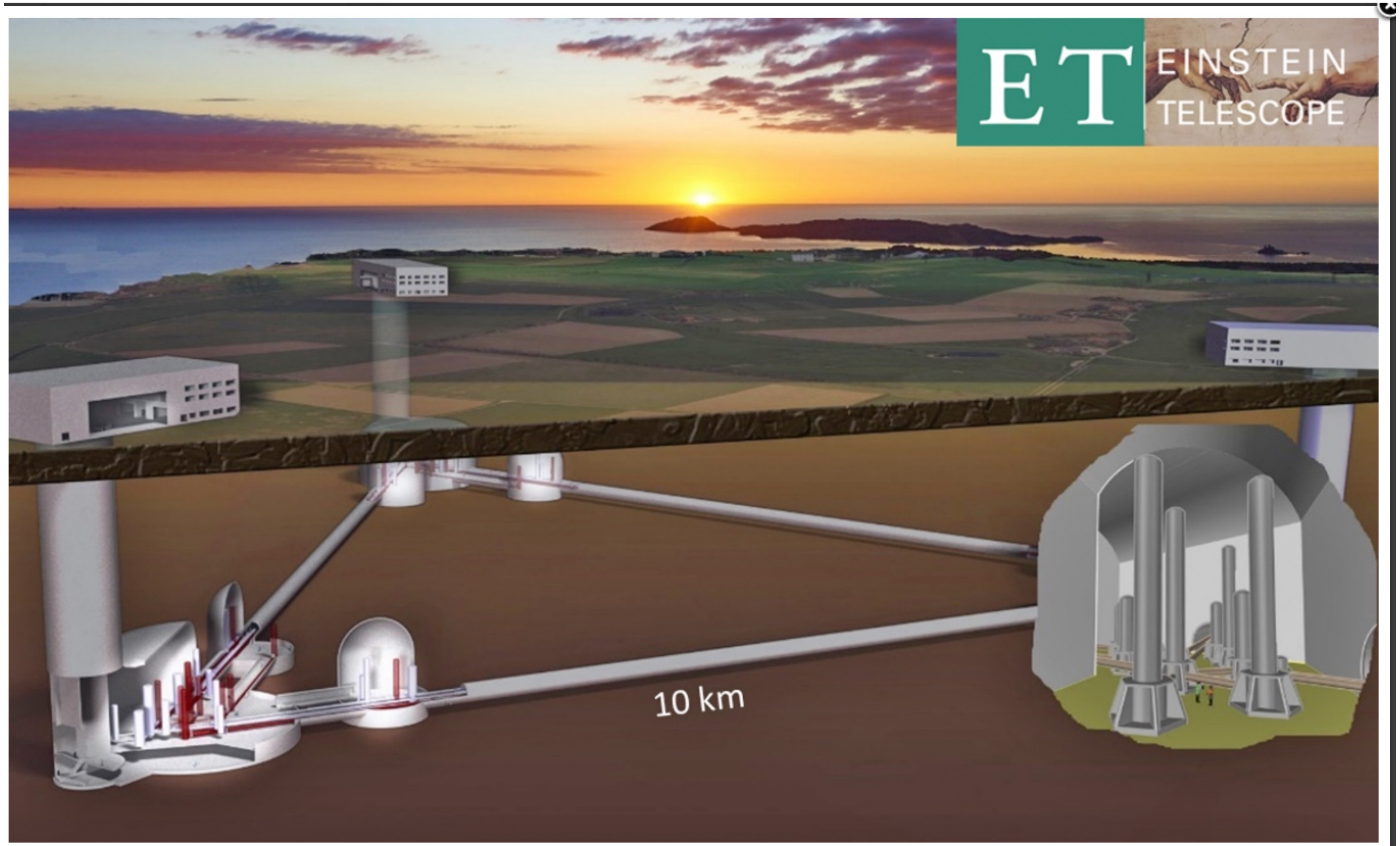
- Horizon Europe
- National, regional and other possibilities

WG 2 is still growing! Contact us!

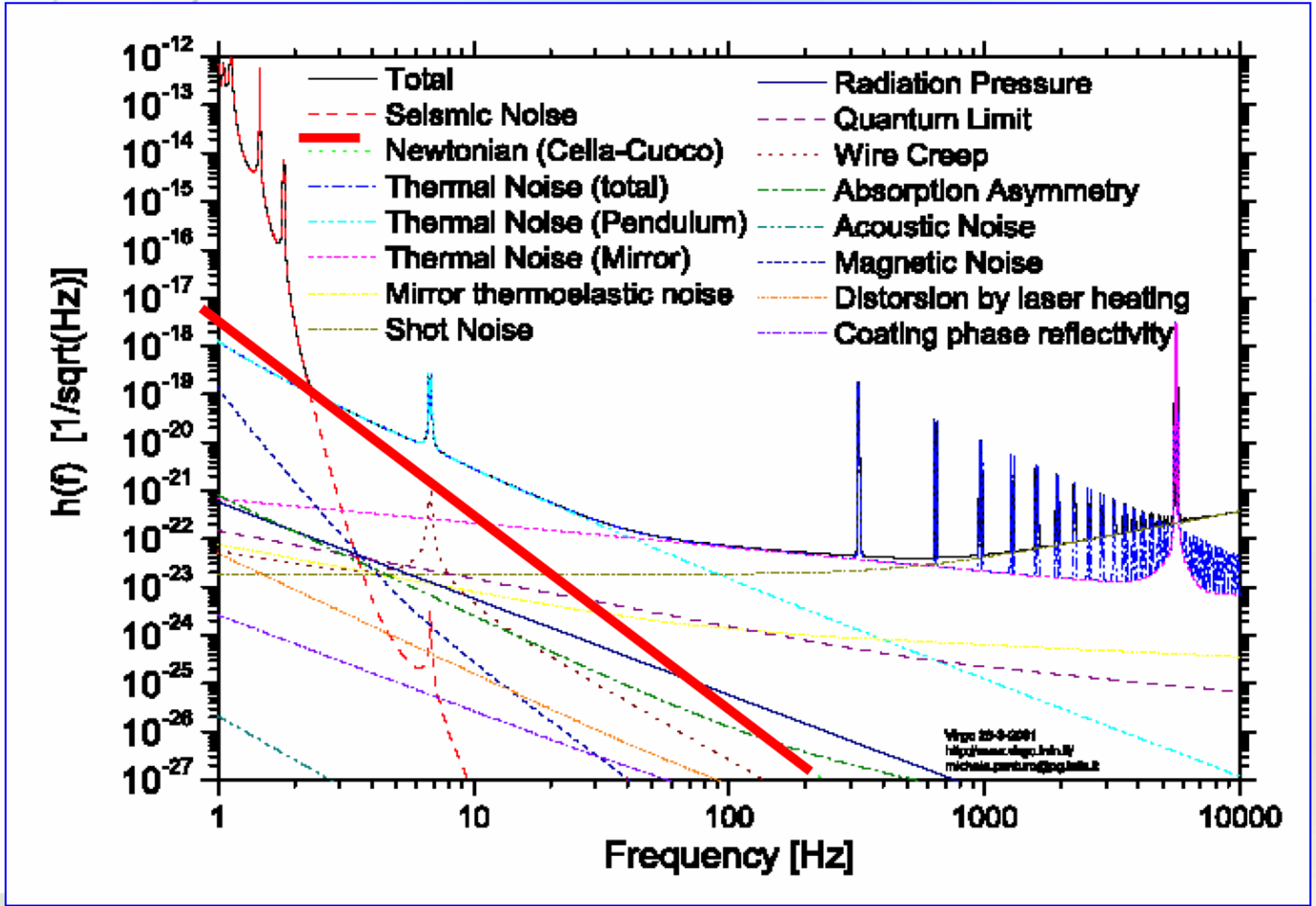
Contacts:

Jonatan Lerga: jlerga@riteh.hr
Christopher Zerafa: christopher.zerafa.08@um.edu.mt
Ivan Štajduhar: istajduh@riteh.hr
Dario Jozinović: djozinovi@gmail.com
Tomek Bulik: tb@astrouw.edu.pl
Fabio Bonsignorio: fabio.bonsignorio@gmail.com
Velimir Ilić: velimir.ilic@gmail.com

ET



Seismic NN: elastic models



Giancarlo Cella
INFN sez. Pisa

3rd ILIAS Annual meeting
Gran Sasso INFN National Lab
February 28-March 3, 2006

Netwonian Noise

A naïve view

Main Issue: Rayleigh waves (and lacking knowledge of underground mass distribution)

Problem: model underground and surface mass distribution and land motion (same issue with the atmosphere) to characterize and predict Rayleigh waves

Other sources of noise:

'Environmental'

i.e.

- Acoustic
- EM
- Others...

Multisensory Data Fusion in Robotics

Multisensor data fusion is the process of combining observations from a number of different sensors to provide a robust and complete description of an *environment* or process of interest.

Data fusion finds wide application in many areas of robotics such as object recognition, *environment mapping*, and localisation.

From: H. Durrant-Whyte, T. C. Henderson,
Multisensor Data Fusion,
Part C, Chapter 25, in B.Siciliano, O. Khatib (eds.) Springer Handbook of Robotics, 2008

Multisensory Data Fusion in Robotics

Principles

It's essentially an application of Bayes' rule:

$$P(\boldsymbol{x} \mid z) = \frac{P(z \mid \boldsymbol{x}) P(\boldsymbol{x})}{P(z)} .$$

assuming conditional independence:

$$P(z_1, \cdots, z_n \mid \boldsymbol{x}) = P(z_1 \mid \boldsymbol{x}) \cdots P(z_n \mid \boldsymbol{x}) = \prod_{i=1}^{n} P(z_i \mid \boldsymbol{x}) .$$

We get the multisensory expression:

$$P(\boldsymbol{x} \mid \mathbf{Z}^n) = C P(\boldsymbol{x}) \prod_{i=1}^{n} P(z_i \mid \boldsymbol{x}) ,$$

and its recursive form:

$$P(\boldsymbol{x} \mid \mathbf{Z}^k) = \frac{P(z_k \mid \boldsymbol{x}) P(\boldsymbol{x} \mid \mathbf{Z}^{k-1})}{P\left(z_k \mid \mathbf{Z}^{k-1}\right)} .$$

Multisensory Data Fusion in Robotics

Methods

- Bayes’ Rule
- *Probabilistic Grids*
- The Kalman Filter (plus Extended Kalman Filters, Information Filters, etc.)
- Sequential Monte Carlo Methods
- Alternatives to Probability

NN mitigation

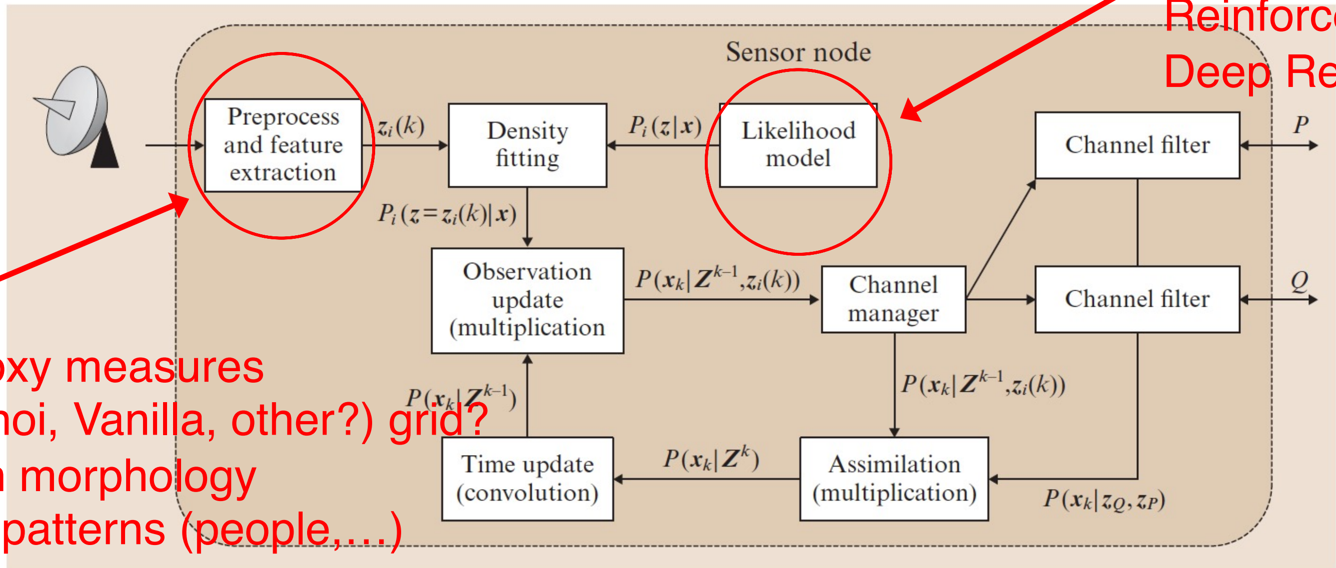
Preliminary ideas

- (adaptive) Modeling of the area (emi) sphere of r ≈ 10 m to 5 km by a network of robots equipped at least with onboard seismometers which change adaptively their positions

- Dynamic optimization of sensor positions (for example doubling those already installed?)

Decentralised Data Fusion like AnserII but with two main changes

Semi-supervised,
Reinforcement Learning?
Deep Reinforcement Learning



Density proxy measures
on a (Voronoi, Vanilla, other?) grid?
Also terrain morphology
and usage patterns (people,....)

Mathematical structure of a decentralized data fusion node

Multisensory Data Fusion in Robotics
Example: ANSER II: Decentralised Data Fusion

Quantum by INNOSEIS (a spin-out from the National Institute for Subatomic Physics in the Netherlands) is an ultra-light weight (< 1kg) wireless seismic sensor network that dramatically reduces deployment costs, while scaling up to 1 million nodes for onshore exploration. It has be designed for static Wireless, sensor networks. However, a daisy-chain small network is operating in Cascina already and no major issues prevent to mount them on mobile platforms.

…outcome from g2Net-wg2 cooperation between Heron Robots and Astrocent (T. Bulik and team)

Network of Mobile seismic sensor to be used in inaccessible areas, possibility of characterizing seismic fields with a small number of sensors, **adjustable sensor array layout, prototype ready**

Ros on Raspberry PI: SW stack can fit to any similar robot (including 'Roomba/Create') with minimum changes'

Infrasound microphone

ROS

T. Bulik and team's geophone

CONFIDENTIAL

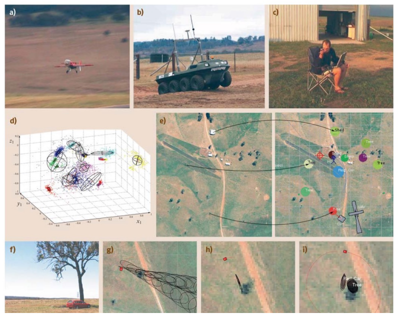
Infrasound microphone

Needed to characterize the infrasound field, **Low cost, Sensitivity in the range of 1-30Hz, lots of uses: geophysics, volcanology etc**, Potential industrial applications (unfortunately ☺), **Prototype ready**

…outcome from wg2 cooperation between Heron Robots and Astrocent (T. Bulik and team)

CONFIDENTIAL

Multisensory Data Fusion in Robotics
Example: ANSER II: Decentralised Data Fusion



A synopsis of the ANSER II autonomous network and its operation.
(a–c) Main system components;
(a) air vehicle,
(b) ground vehicle,
(c) human operative.

(d–e) The perception process;
(d) top three dimensions of features discovered from
ground-based visual sensor data along with the derived mixture model describing these feature properties
(e) sector of the overall
picture obtained from fusing air vehicle (UAV), ground vehicle (GV) and human operator (HO) information. Each set of ellipses
corresponds to a particular feature and the labels represent the identity state with highest probability.

(f–i) Sequential fusion
process for two close landmarks: (f) a tree and a red car, (g) bearing-only visual observations of these landmarks are successively
fused, (h) to determine location and identity (i).

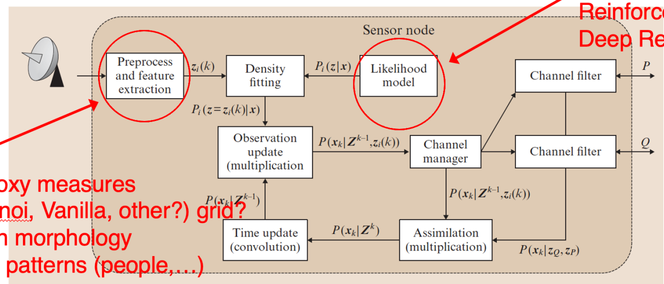
Note the Gaussian mixture model for the bearing measurement likelihood

H. Durrant-Whyte, T. C. Henderson,
Multisensor Data Fusion,
Part C, Chapter 25, in B.Siciliano, O. Khatib (eds.) Springer Handbook of Robotics, 2008

Infrasound microphone

Decentralised Data Fusion like AnserII but with two main changes

Semi-supervised,
Reinforcement Learning?
Deep Reinforcement Learning



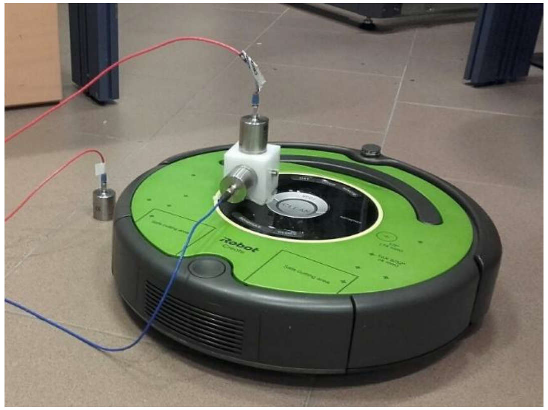
Density proxy measures
on a (Voronoi, Vanilla, other?) grid?
Also terrain morphology
and usage patterns (people,…)

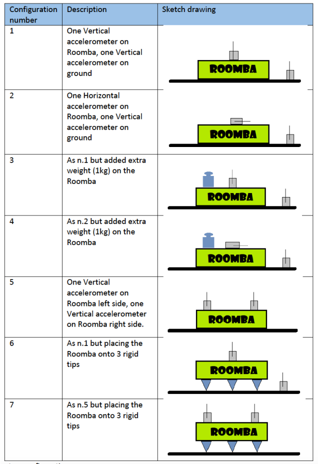
Mathematical structure of a decentralized data fusion node

A Multisensory Multiagent platform for GW detection and Geophysics applications: Testing Platform

Seismometers and accelerometers behaviours: https://tds.virgo-gw.eu/?content=3&r=15998

We used three Meggit mod. 731-207, sensitivity 10V/g, range 0.2-1300 Hz (-3dB) spectral noise 0.09 μg/sqrt(Hz) at 10Hz and one ONO-SOKKI spectrum analyser CF-3600A.





Configuration number	Description	Sketch drawing
1	One Vertical accelerometer on Roomba, one Vertical accelerometer on ground	ROOMBA
2	One Horizontal accelerometer on Roomba, one Vertical accelerometer on ground	ROOMBA
3	As n.1 but added extra weight (1kg) on the Roomba	ROOMBA
4	As n.2 but added extra weight (1kg) on the Roomba	ROOMBA
5	One Vertical accelerometer on Roomba left side, one Vertical accelerometer on Roomba right side.	ROOMBA
6	As n.1 but placing the Roomba onto 3 rigid tips	ROOMBA
7	As n.5 but placing the Roomba onto 3 rigid tips	ROOMBA

A Multisensory Multiagent platform for GW detection and Geophysics applications: Testing Platform: some limits

This won't affect 'our' robot (HeronRobots+Astrocent): different mechanics

Seismometers and accelerometers behaviours: https://tds.virgo-gw.eu/?content=3&r=15998

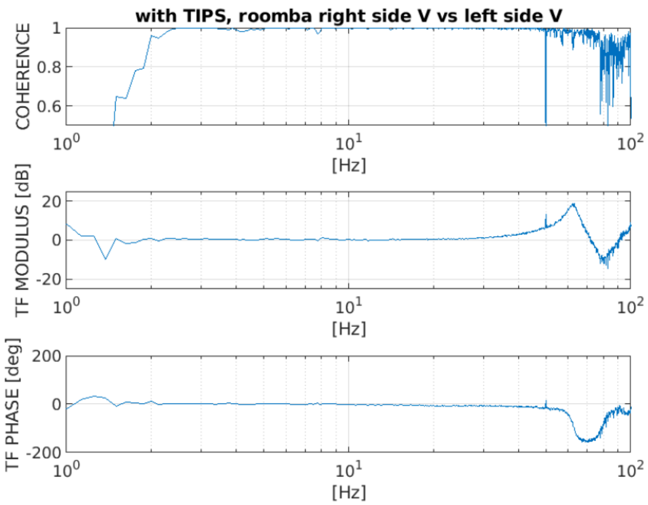


Figure 10. Two accelerometers in configuration n.7, (top) real part of coherence, (middle) modulus of the transfer function, (bottom) phase of the transfer function.

Methods

Signal modeling by GP regression (+ LAMOR, FER-UNIZG)

Information Gain

Multi-robot coordination and task allocation (+ LAMOR, FER-UNIZG)

Discussion

1) spatially distributed stochastic sources of noises (e.g. newtonian noise, but not only)

2) the spatial distribution of noise sources changes over time

3) network sensor optimization should change over time (no way to obtain trustable distributions under ergodic assumptions) EKF and similar needed?

Discussion

1) mass density distribution originates newtonian tensor of noise according to classical gravity on the detector interference ‘points’, not really continuous field, not stationary, true for many relevant noises

2) Earth is a dynamical geophysical system, a chaotic one

Discussion

→ Sensors (for example seismic sensors, but not only) must be moved over time. Geology is (most of the times) slow so human intervention is an option

Humans are slower, more mechanically noisy and the human generated noise is more difficult to model

Discussion

Mobile sensor networks like those considered here will generate huge flows of data to be interpreted in quasi-real time.

That will need massive utilization of data science, ML/DL and in general AI methods.

Discussion

Together, Robotics and AI/ML/DL can enable a giant leap in GW detector technologies and geoscience alike

Thank you!

fabio.bonsignorio@fer.hr
fabio.bonsignorio@gmail.com
fabio.bonsignorio@heronrobots.com

www.shanghailectures.org