A robotized environmental sensor array for gravitational wave observatory sites

Mario Graziaplena, Giulio Ballardin, Luca Francescon, Federico Paoletti, Emmanouil Sotiropoulos, Dimitrios Spyropoulos, Maria Concetta Tringali, Francesca Badaracco, Matteo Di Giovanni, Irene Fiori, Jan Harms, Paolo Bastia

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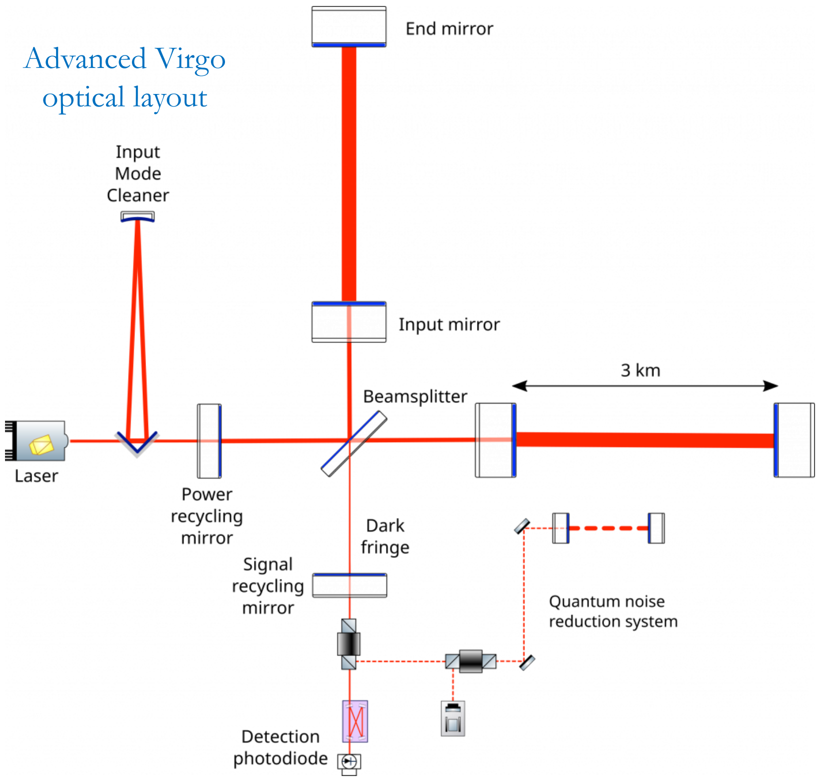
Outline

- Virgo interferometer
- Newtonian noise
- Flexible Grid Mapping Tool
  - Mobile Unit Board
  - Data Unit Board
  - Control Unit
- Conclusions

Virgo interferometer

Virgo interferometer

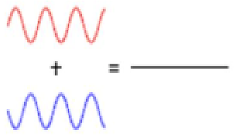
Advanced Virgo optical layout



- The Virgo gravitational wave (GW) detector is a Michelson laser interferometer with two perpendicular, 3 km-long arms.
- A beam splitter divides the incident laser beam into two equal components sent into the two arms of the interferometer.

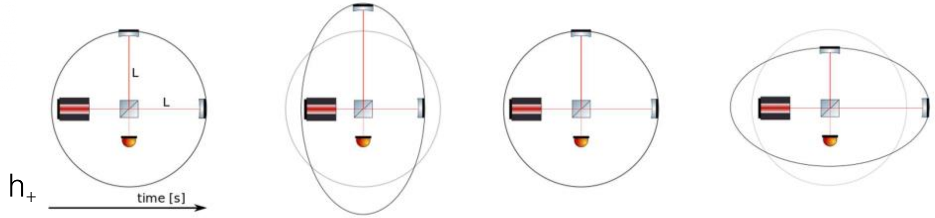
DISTRUCTIVE INTERFERENCE

- The two recombining beams interfere destructively on photodiode→**dark fringe condition.**



No signal on photodiode

- When a GW passes through the interferometer it produces an infinitesimal variation (10^{-18} m) in the length of the two arms (one arm lengthens while the other shrinks).



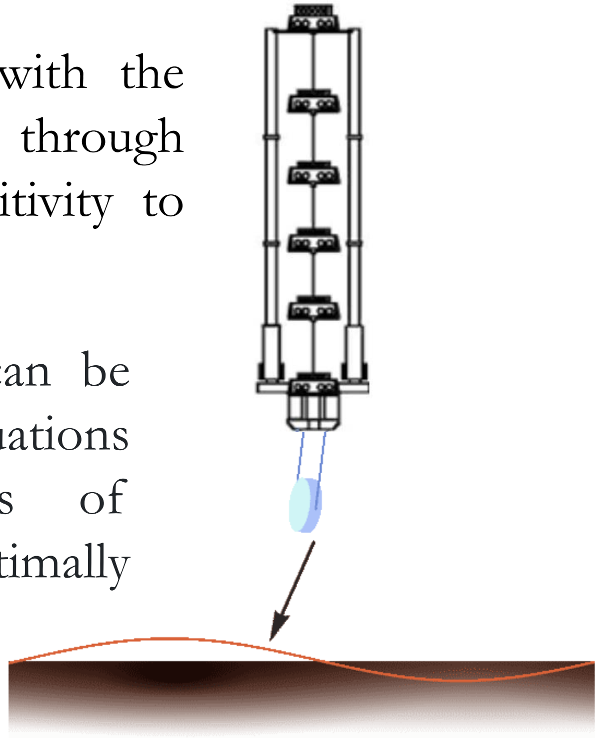
COSTRUCTIVE INTERFERENCE

- A network of GW detectors, LIGO-Virgo-KAGRA, operates as a single experiment worldwide detecting GW signals from astrophysical sources and pinpointing the source sky location→ in the last three observing runs, 90 GW events have been detected.

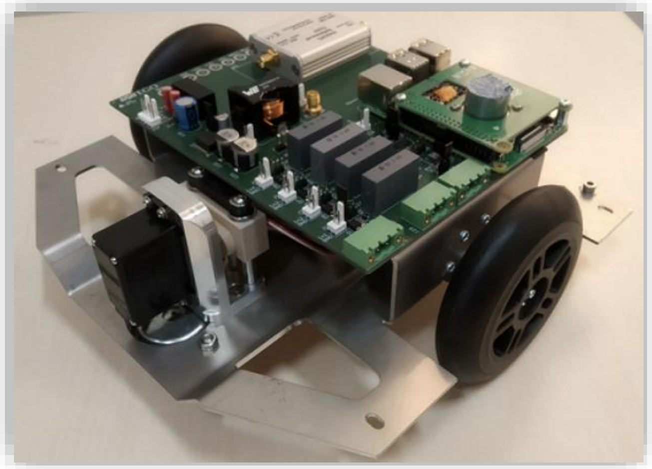
Newtonian noise

Virgo experimental hall

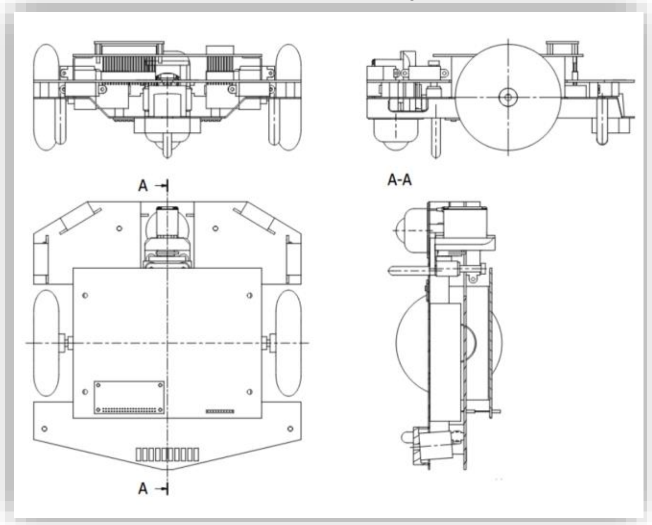
- Among the variety of the noise sources, due to different physical processes, the Newtonian Noise (NN) is one possible noise source that affects a GW interferometer.
- The NN can be generated by atmospheric density fluctuations and seismic displacements.
- Mass-density fluctuations can interact directly with the mirror test masses, suspended by superattenuator, through gravitational forces impacting the detector sensitivity to GWs.
- This kind of noise can not be shielded but can be reconstructed by monitoring mass/density fluctuations near the mirror test masses by means of seismic/microphones sensors and then use optimally tuned filters to cancel it.



Flexible Grid Mapping Tool

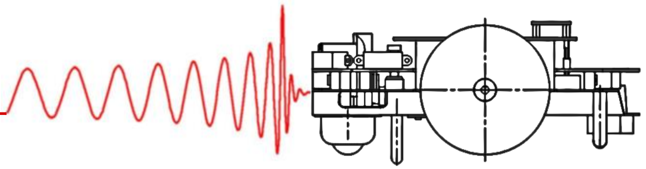


Robot unit layout

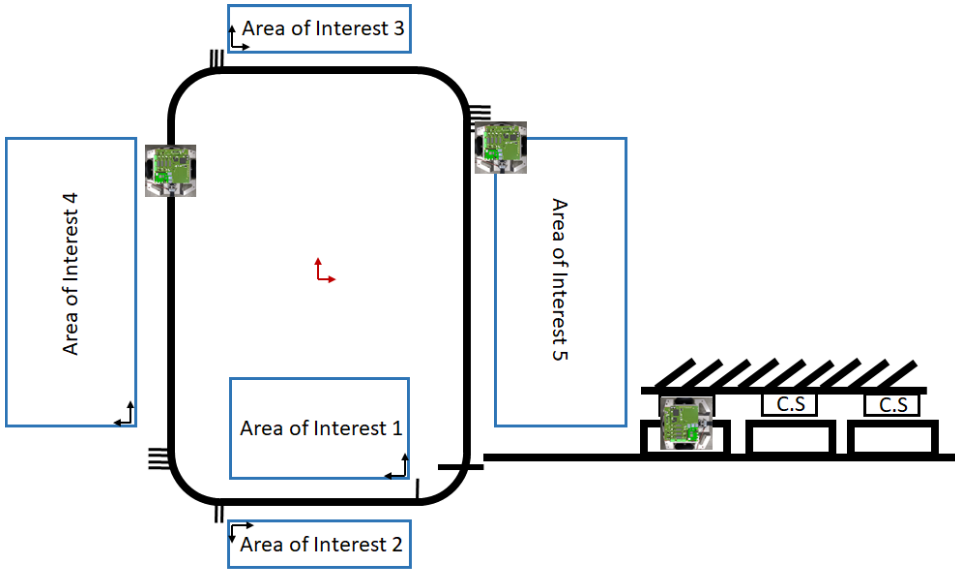


- **Optimizing the positions of the sensors is paramount to maximize the performance of the NN cancellation.**
- The NN changes with time → new sensor positioning is required.
- Alternative approach: array of mobile seismic sensors that can autonomously move to the optimal positions.
- The **Flexible Grid Mapping Tool** (FGMT) is part of the European research project AHEAD-2020. The objectives are:
  - construction of three robot units (proof of concept);
  - navigation inside Virgo experimental areas;
  - deployment of the seismic sensor and data acquisition;
  - transfers the data wirelessly to the control software;
  - seismic data from all robotic units synchronized among themselves and with the Virgo data system, and be accessible by the control software through an on-line server.
- FGMT is being carried out at the Virgo interferometer site with the collaboration of the EGO and the Gran Sasso Science Institute.

Robot navigation in a nutshell



- The robotic units aim to move in Virgo experimental halls in presence of mostly fixed obstacles.



Main path marked by white adhesive PVC stripes with a black 2 cm wide line in the middle.

Area of interest marked by stripes and identified by black and white stripes resembling a bar-code perpendicular to the main track stripe.

Charging station identified by unique bar-code pattern.

Movement inside the area of interest

- combination of going straight and making on-spot turns.

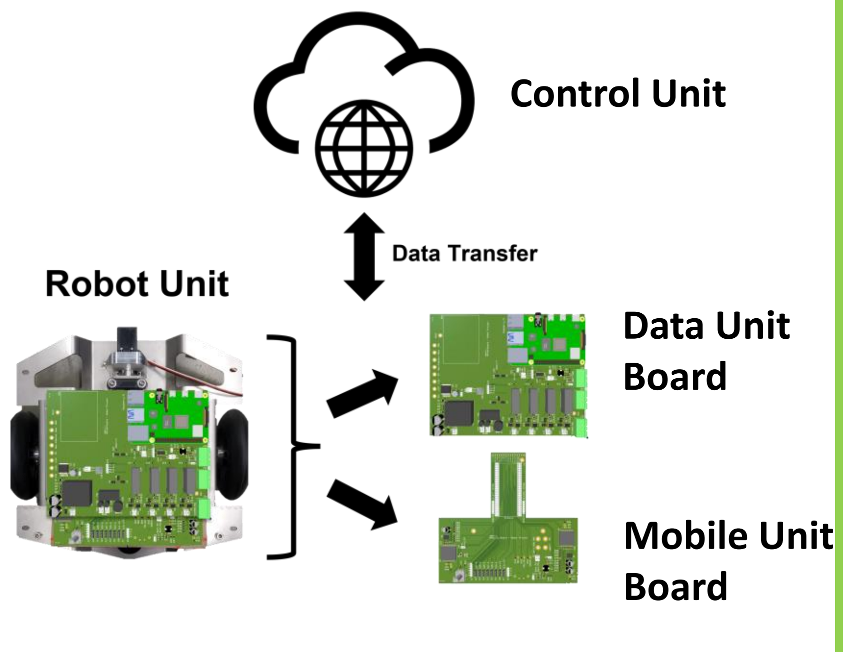
Line following cruise

- Use of the IR array sensors installed on the bottom.

Recognition of the area of interest

- The control software sends to robot (ID, X, Y):
  - ID bar-code of the area of interest;
  - (X,Y) are the coordinates of the desired location in the local system of the area of interest.
- Match between the read bar-code pattern and the hard coded pattern of the ID→ the robot enters in the area.

FGMT system architecture

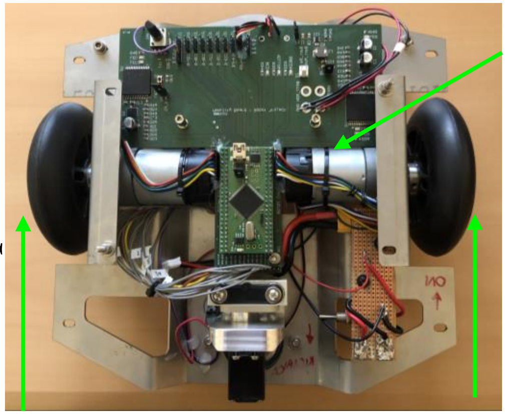


FGMT system architecture

- The FGMT system architecture is composed of three subsystems:
  - **Control Unit (CU)** is a cloud-based system that collects the data from the sensors installed on the robots and periodically processes the data to produce new optimized positions for the placement of the robots.
  - **Mobile Unit Board (MUB)** is in charge of the entire navigation system of each Robot Unit.
  - **Data Unit Board (DUB)** is in charge of reading and digitizing the seismic sensor signals and of the wireless transmission of the data to and from the MUB and the CU.

Robot Unit

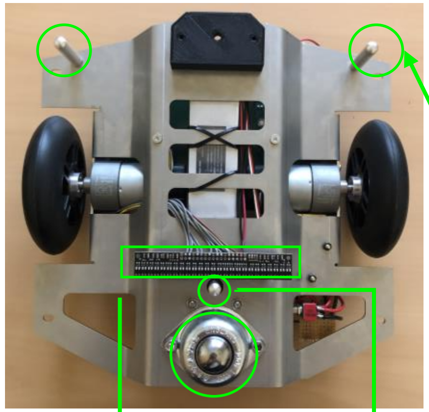
Top side



Motor

2 rubber wheels (D=10 cm)

Bottom side



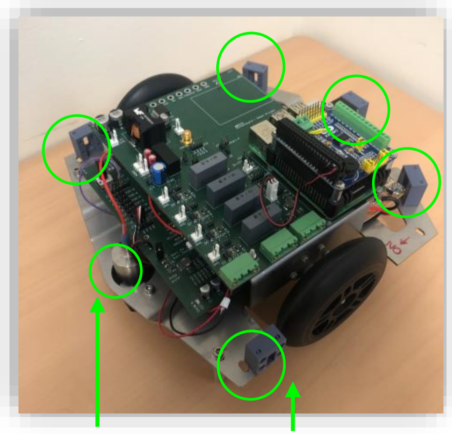
Point contact

IR sensors

omni-directional spherical wheel

leg

- The frame was designed in order to achieve maximum rigidity and compactness:
  - compromise between material and mechanical rigidity/weight →steel frame of 1.5 mm thick.
- The robot size 25×25×12 cm, weight ~3 kg (~17% frame).
- Battery is 4 cell Lion, 2Ah capacity:
  - position chosen to guarantee good stability during seismic measurements;
- Seismic measurement:
  - a three-point contact with the floor by means of two fixed and one retractable pivot (leg) to guarantee a reliable seismic noise measurements of the ground.
  - accelerometer installed on the frame (Wilkoxon model 731-207).

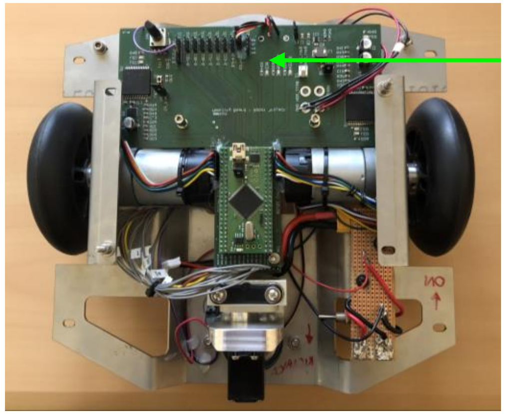


Top side

accelerometer

IR sensors

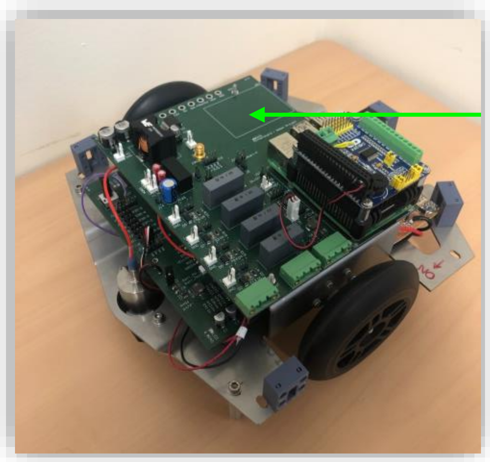
MUB and DUB



Mobile Unit Board (MUB)

Mobile Unit Board

- ATmega2560 microcontroller;
- code for the robot navigation;
- power supply;
- communication with wheel motors;
- connectors for the IR sensors.



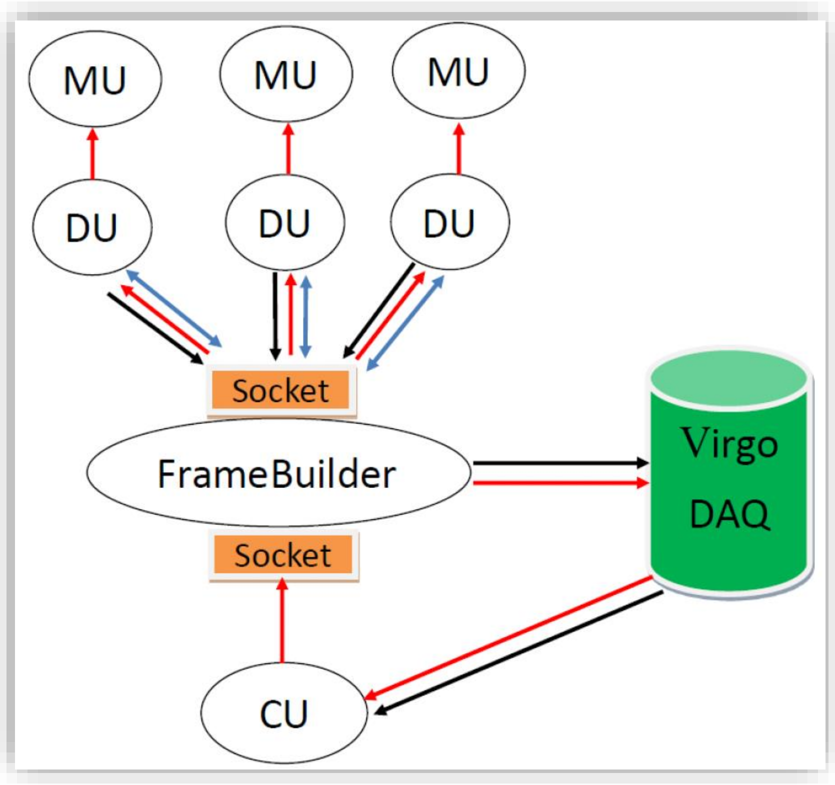
Data Unit Board (DUB)

Data Unit Board

- Raspberry Pi 4 model B microprocessor manages the data acquisition and data transfer;
- high precision external AD/DA extension board used to digitize the seismic sensor analog signal (sampling rate 1 kHz);
- a GPS disciplined oscillator (GPSDO) module is used to provide a stable clock synchronized with the Virgo detector signals.

Control Unit

FGMT data flow scheme



position coordinates data flow
sensor data flow
timing synchronization
Virgo data acquisition

Data Unit Board functionalities consist in:

- data acquisition of sensors and their synchronization with Virgo data acquisition (DAQ) system;
- wireless communication with MUB and CU in order to transfer sensors data and position coordinates.

Control Unit functionalities consist in:

- reading the seismic data from the DAQ and analysis;
  - the scope is to produce new optimized robot positions for noise cancellation purposes (Badaracco et al. 2020);
  - the CU processes 1 hour long data segments every three hours (computation time).
- After the optimization process is done, the CU sends the positions to the DUB and starts a new optimization.

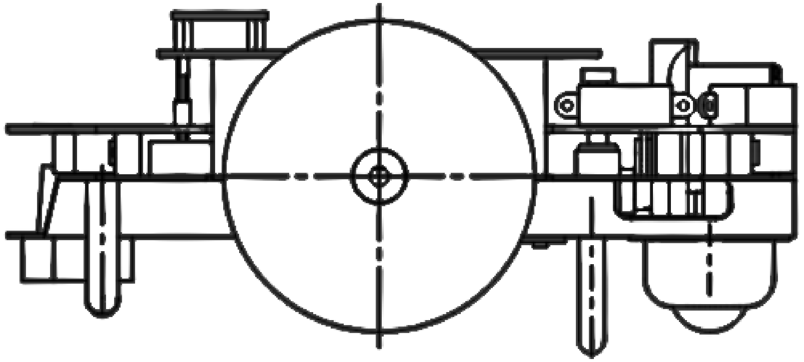
Conclusions

Next steps

- Communication between the different Units
- Managing the conflicts among robot units along the line path.
- Battery charging → when needed drive to the charging station and connect to charging dock.
- Test and finalization of the code for the sensor positioning optimization.

Future applications

- The environmental noise mapping in underground GW detectors sites, like the Einstein Telescope:
    - different navigation techniques can be considered (e.g., LIDAR technique).



Thank you for your attention!