ANNEX I

Evaluation study of *Roomba iRobot* as possible platform for movable seismic array

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Abstract

The *Roomba Create 2 iRobot* is considered as a first easy off-the-shelf solution to serve as preliminary test movable platform for seismic sensors to monitor seismic ground motion. One basic requirement is that this platform should be rigid, that is free from mechanical modes, and well connected to ground in the frequency band of interest of seismic measurements. We report about measurements of mechanical transfer functions of this platform and characterization of its first mechanical modes. We comment on its use as seismic platform and suggest mechanical features for a more performant platform that could be designed ad-hoc . There are hints that a platform able to work properly in a frequency band up to 50 Hz, i.e in the Newtonian Noise frequency window could be developed with limited improvements over the simple platform that we have used for our study. Previous tests suggest that the same platform could actually be used as-it-is for micro seismic measurements in the 1-10 Hz frequency band.

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Introduction

As first easy and straight approach the *[Roomba iRobot "Create 2" ("Roomba" in the followings)]* programmable robot is considered as mechanical platform for a robotized movable seismometer to measure ground motion. One possible application could be in seismic arrays for Newtonian Noise cancellation, where the position of the sensors could be optimized by machine learning based optimization algorithms. Another possible application is for low-frequency (1-10Hz) seismology with a network of sensors installed on mobile robot platforms.

A suitable platform needs to be "well connected" to ground in the frequency region of interest.
In particular, to set a reasonable reference, for the purpose of seismometers of NNC seismic array the usable band is between 5Hz to 50Hz. This means that ideally the platform to soil mechanical transfer function should be flat (free of internal modes) between 5Hz and 50Hz and dropping by at most 3dB at 5Hz and 50Hz.
We used a pair of accelerometers to measure this transfer function and characterize the modal response of the Roomba.

The accelerometers used are three Meggit mod. 731-207, sensitivity 10V/g, range 0.2-1300 Hz (-3dB) spectral noise 0.09 µg/sqrt(Hz) at 10Hz. The readout is done with ONO-SOKKI spectrum analyser CF-3600A in the EGO electronics laboratory.

A picture of the setup:

Measurements

This table lists the measured configurations:

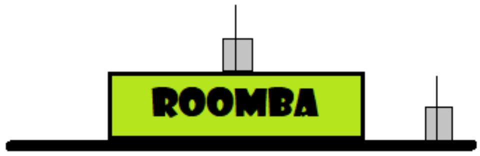
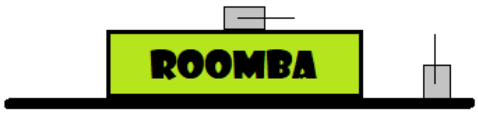
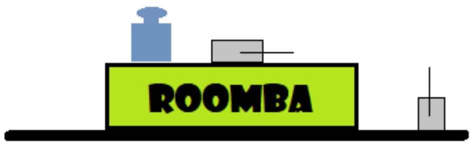
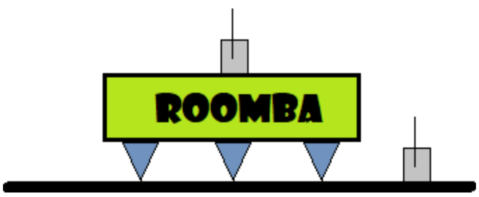
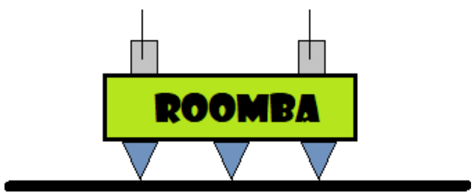
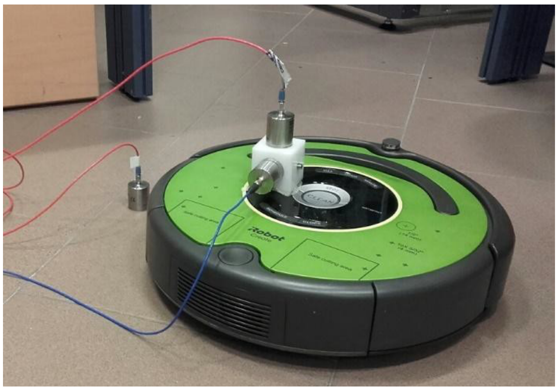
Configuration number	Description	Sketch drawing
1	One Vertical accelerometer on Roomba, one Vertical accelerometer on ground	
2	One Horizontal accelerometer on Roomba, one Vertical accelerometer on ground	
3	As n.1 but added extra weight (1kg) on the Roomba	
4	As n.2 but added extra weight (1kg) on the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

Table 1. Test setup configurations.



Left: accelerometers setup. Right: roomba bottom with 3 Trillium tips attached.

We used double side tape, which assures good contact of the accelerometer to the surface. To orient the accelerometer horizontally we used a solid *Teflon* (PTFE) cube (see above picture).
A Huddle test (accelerometer pair measuring nearby) proved that the accelerometer pair had transfer function (TF) consistent with 1 in the band 1Hz to 200Hz.
We find that jumping on the floor nearby is a best practical way to excite the system and perform TF measurements, at least for the purpose of this preliminary test.

A first set of measurements is done with the Roomba "as it is" just resting on the floor and accelerometers in different configurations: n.1 to n.5 in Table 1 and Figures 1 to 5.

The first two measurements (n.1 and n.2) are with one accelerometer on Roomba top (vertical or horizontal) and one on the ground nearby. We repeated them (n.3 and n.4) adding a weight (1kg approximately) onto the Roomba. We then performed one measurement (n.5) with the two accelerometers on the sides.

Subsequently, we took three conical steel tips from one Trillium C20 seismometer and attached them with double side tape to the Roomba bottom. We repeated two of the previous measurements (n.1 and n.5) with this layout. These were measurements n.6 and n.7.

Results

The Roomba "as it is" has a sort of flat TF from 2Hz to 10Hz, the coherence however is not so good denoting a bad contact with soil. Note that below 2Hz the measurement is likely not reliable because of the limited performance of the accelerometers that we have used for this test. At 25Hz it appears the first resonance of the Roomba, and correspondently a loss of coherence (Figure 1). The same 25Hz is present also in the horizontal direction, where a 15Hz mode also appears (Figure 2).
Adding the weight does not improve significantly the coherence, although it moves the 25Hz frequency slightly down (24Hz) as expected (Figures 3 and 4).
When putting the two accelerometers on the sides of the Roomba body we find a very clean 25Hz (Figure 5) which disappears when putting the accelerometers close to the centre (not shown). This identifies the 25Hz as a roll mode of the structure around the axis passing through the two wheels (see the picture above).

When the Roomba sits on the 3 tips (arranged in 120deg configuration) the TF improves a lot: both because a larger coherence and because it is now flat between 1Hz and 30Hz (Figure 6). The first mechanical mode is now at 60Hz, and as we verified but do not show it is a vertical mode of the body.

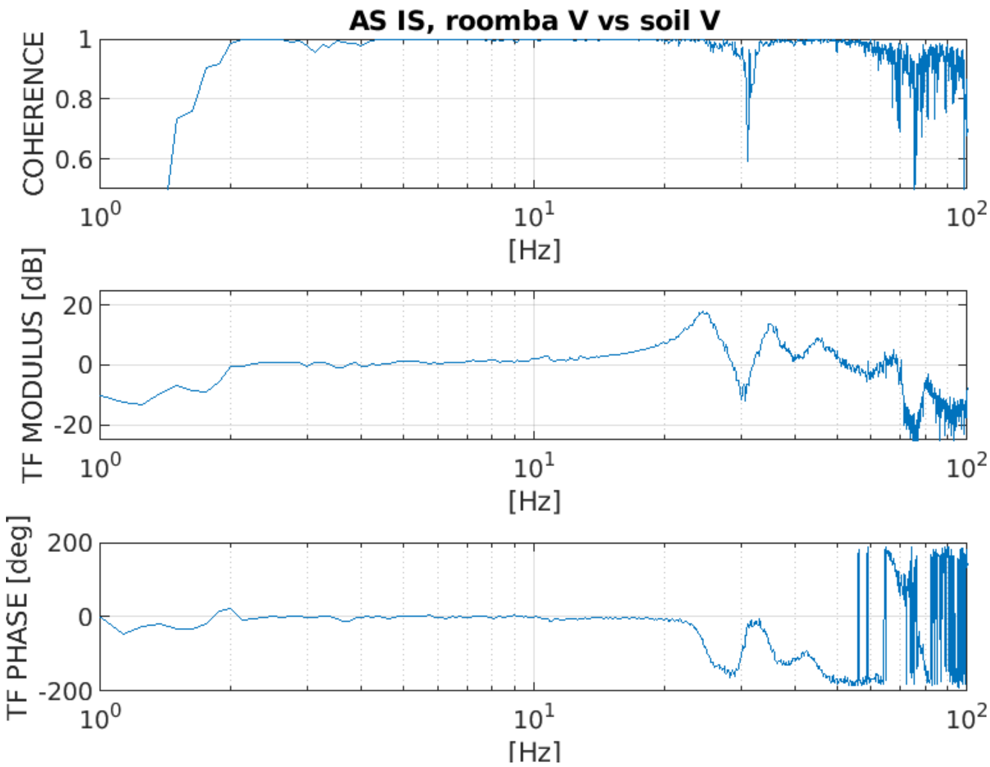


Figure 1.

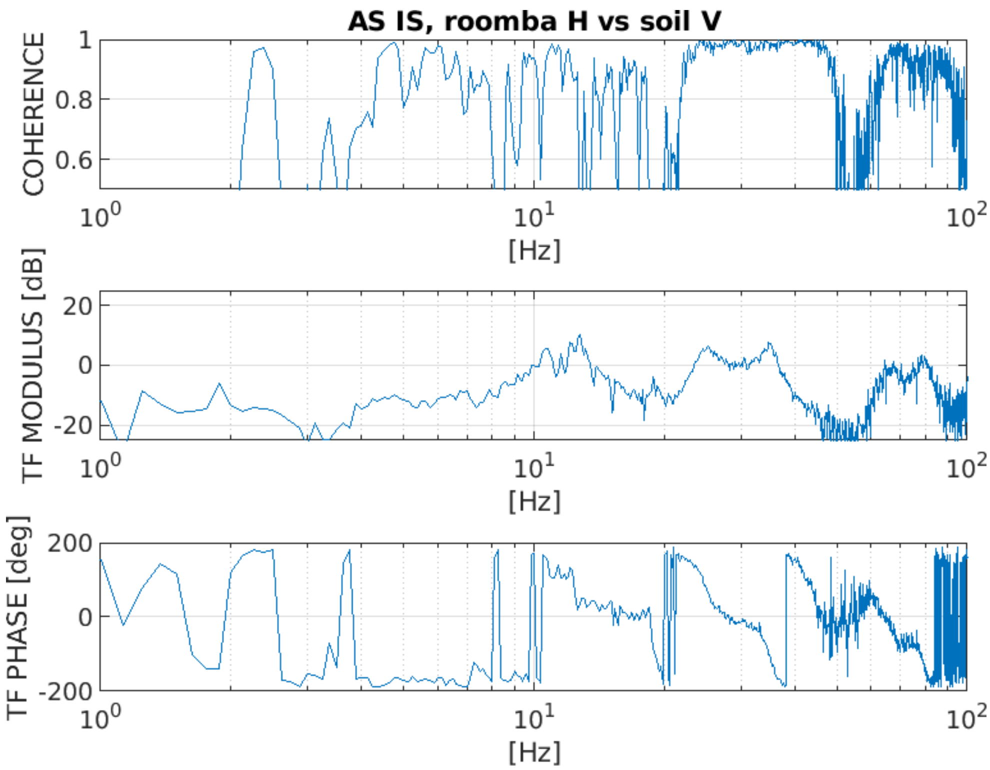


Figure 2.

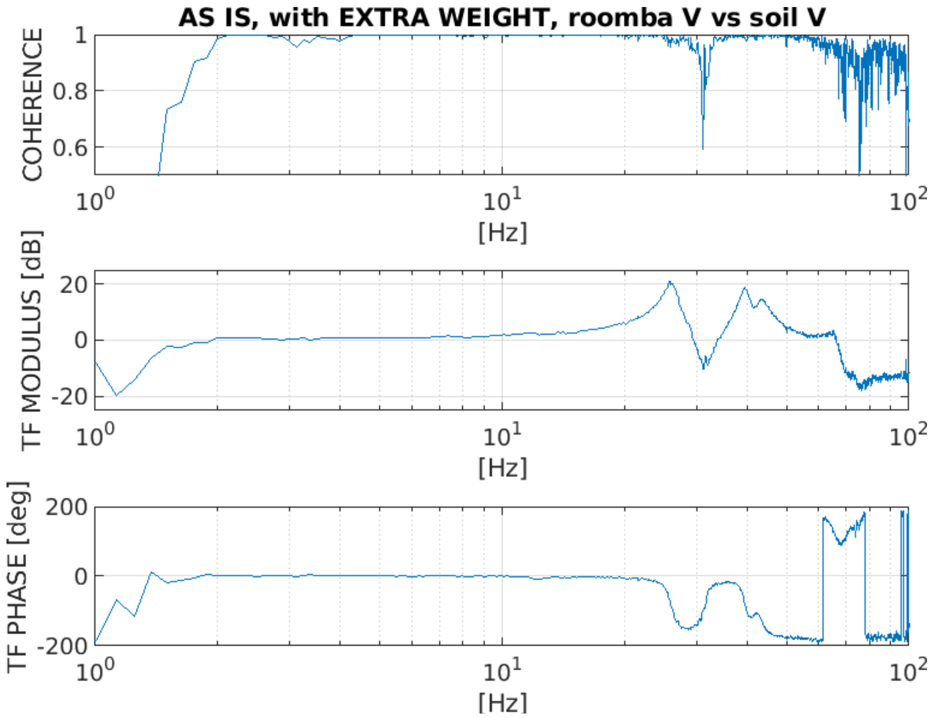


Figure 3.

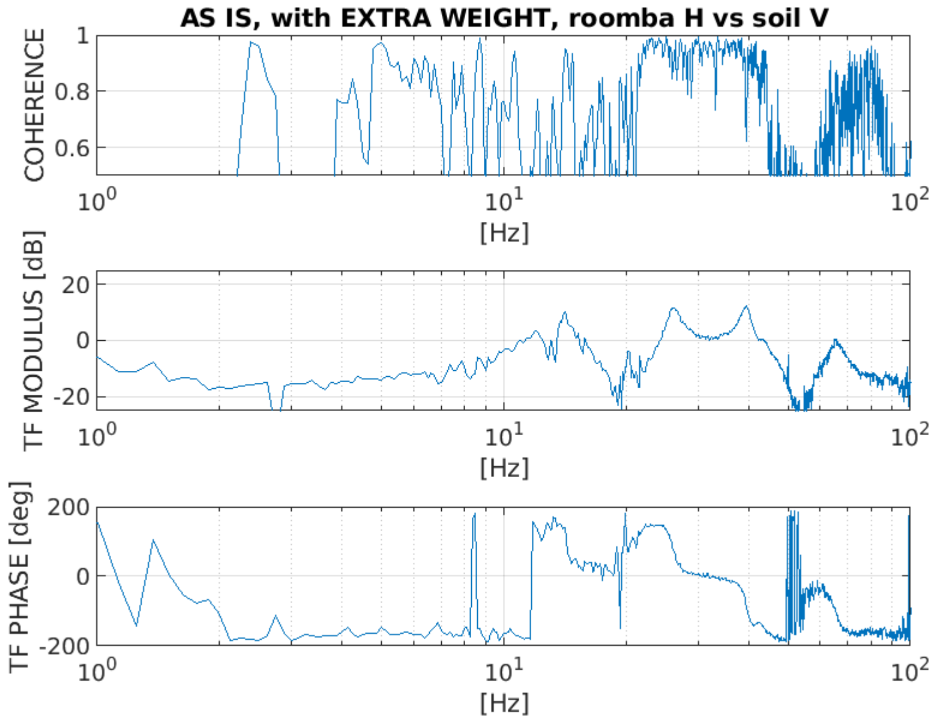


Figure 4.

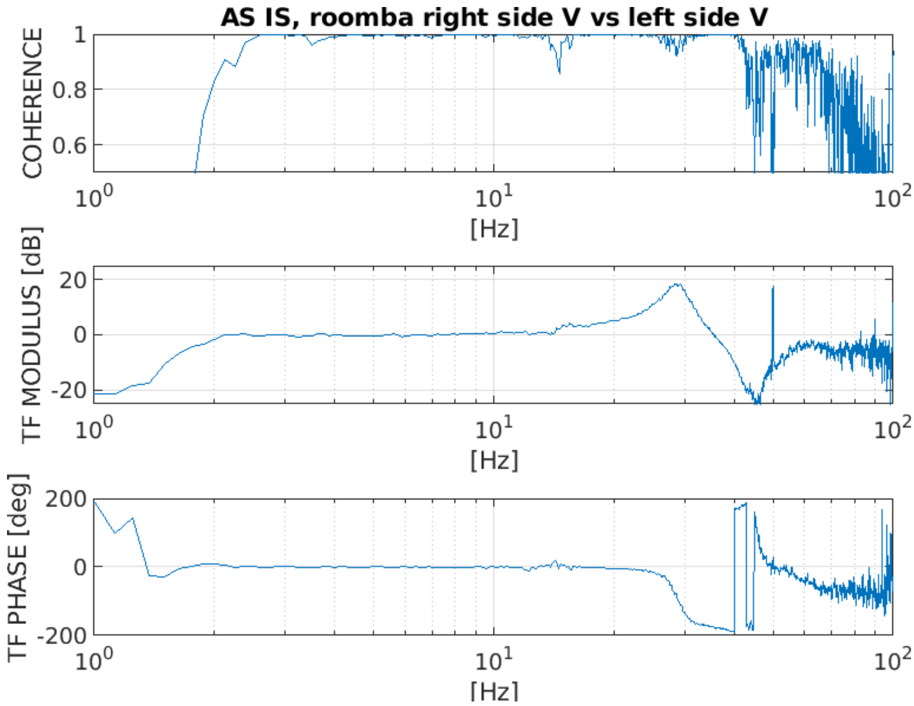


Figure 5.

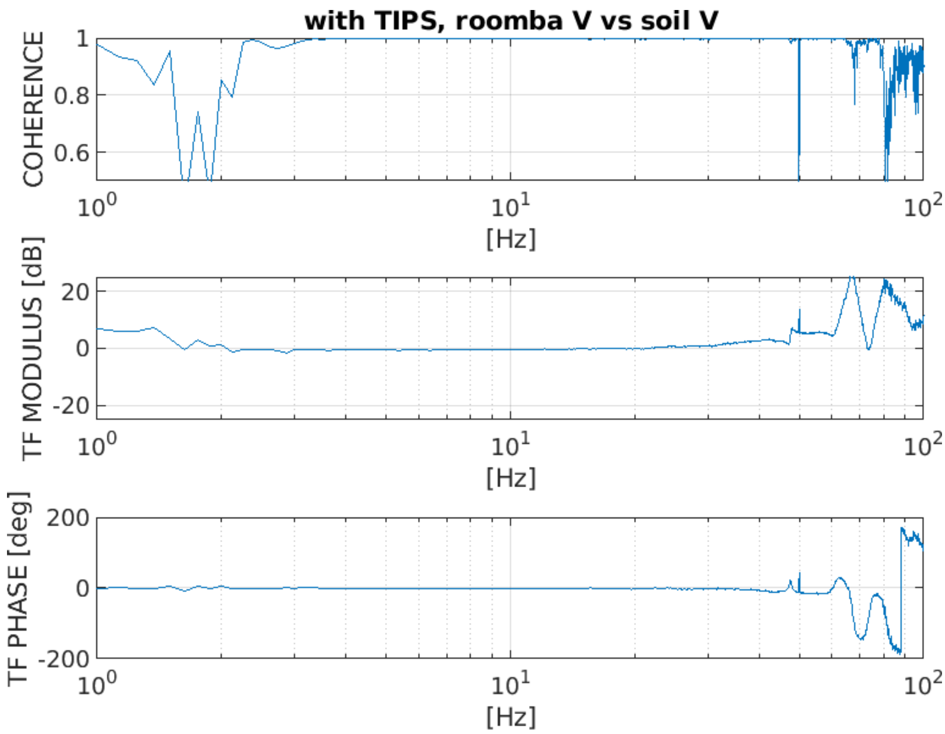


Figure 6.

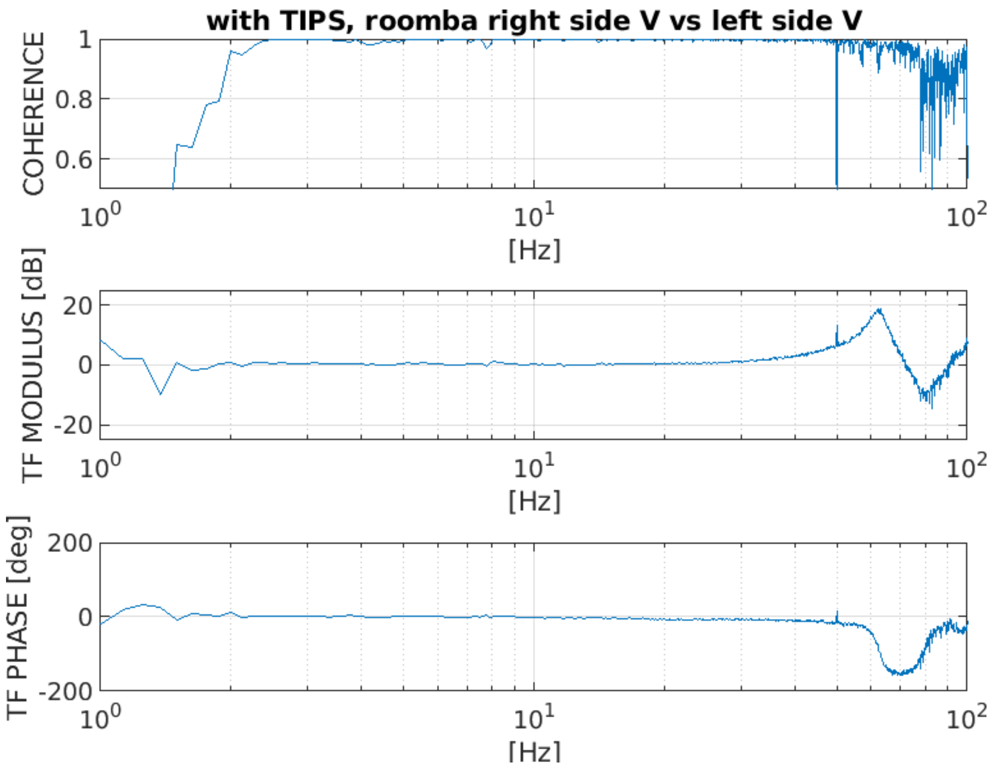


Figure 7.

Conclusions

If we target Newtonian Noise cancellation, the Roomba "as it is" does not offer a good enough mechanical contact to the soil, as proven by the poor coherence and because of the presence of a first roll mode (25Hz) falling in the in the target frequency band for Newtonian Noise. Also, the simple action of adding extra weight (but not such to prevent the Roomba to lift up and move around) does not improve the contact with soil.

A simple way to realize a good contact is to make the support platform to rest on 3 tips. One possible solution is to realize a simple platform made of a rigid slab of Aluminum endowed with 3 steel tips (similar to the Trillium tips). A movable robotized wheeled cart would carry this platform and with its movable and retractile sort-of-arms gently deposit the platform on the soil when requested. This will be object of future studies.