MAS513-Advanced Robotics project:

Online health status detection of a motor

PROBLEM: Is it possible to determine the health status of the motor continuously using non-contact sensors and non-destructive testing?

Gianluca Salata, 27/10/2021

UiA University of Agder

State of art (summary):

KEY CONCEPT: Each fault is related to a precise harmonic in the spectrum

1) MCSA(motor current signature analysis)

This method require to measure the variation of the absorbed current from the motor.
From the current spectra is able to identify motor's fault thanks to a specific relationship.
For example, the frequency related to an air gap(eccentricity):

$$f_{\mathrm{ecc}} = \left\{ (R \pm n_d) \left(\frac{1-s}{p} \right) \pm n_{\omega s} \right\} f_0$$

2) Vibration analysis

Usually It is based on 3-axis MEMS accelerometers that measure the vibration of the shaft. Also in this case is possible to find fault analysing the spectrum of the displacement of the shaft.

An outer race bearing defect is related a to the characteristic frequency:

$$f_{\mathrm{oD}} = \frac{n}{2} f_{rm} \left(1 - \frac{\mathrm{BD}}{\mathrm{PD}} \cos \phi \right)$$

State of art:

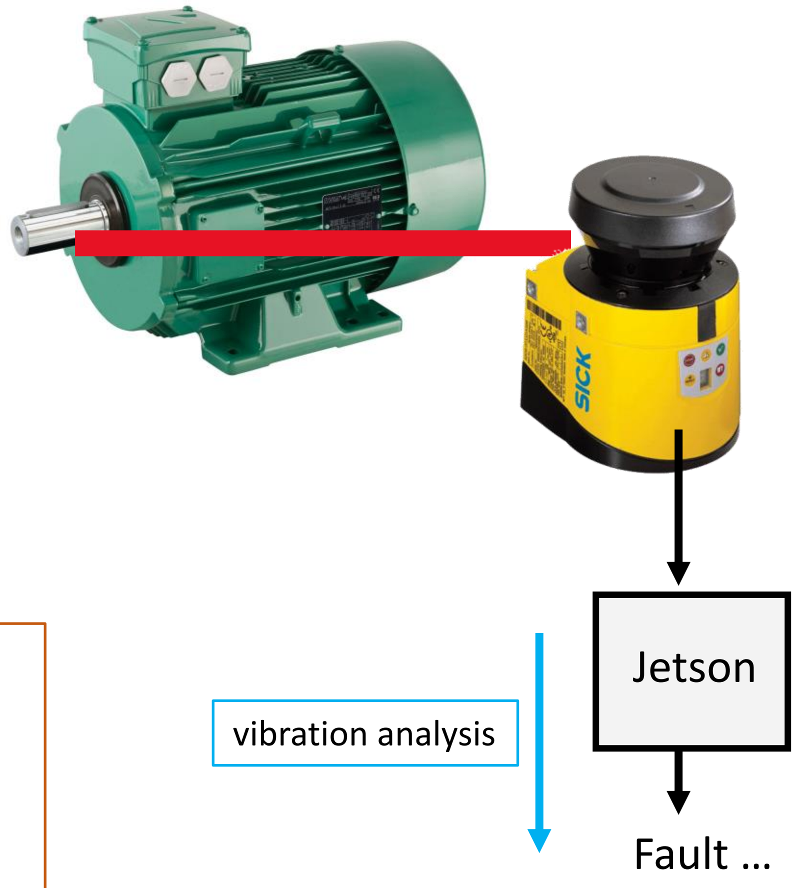
MCSA	*Vibration analysis*	*Vibration analysis with Lidar*
non-invasive	independent of the type of motor power supply	independent of the type of motor power supply
Easy to implement	low power consumption	High reliability
low signal-to-noise ratio	Low realiability	Non contact-sencors
contact-sensors	contact-sensors	High cost

Project’s aim

The aim is to determine the continous health status of the motor developing the vibration analysis with a Lidar

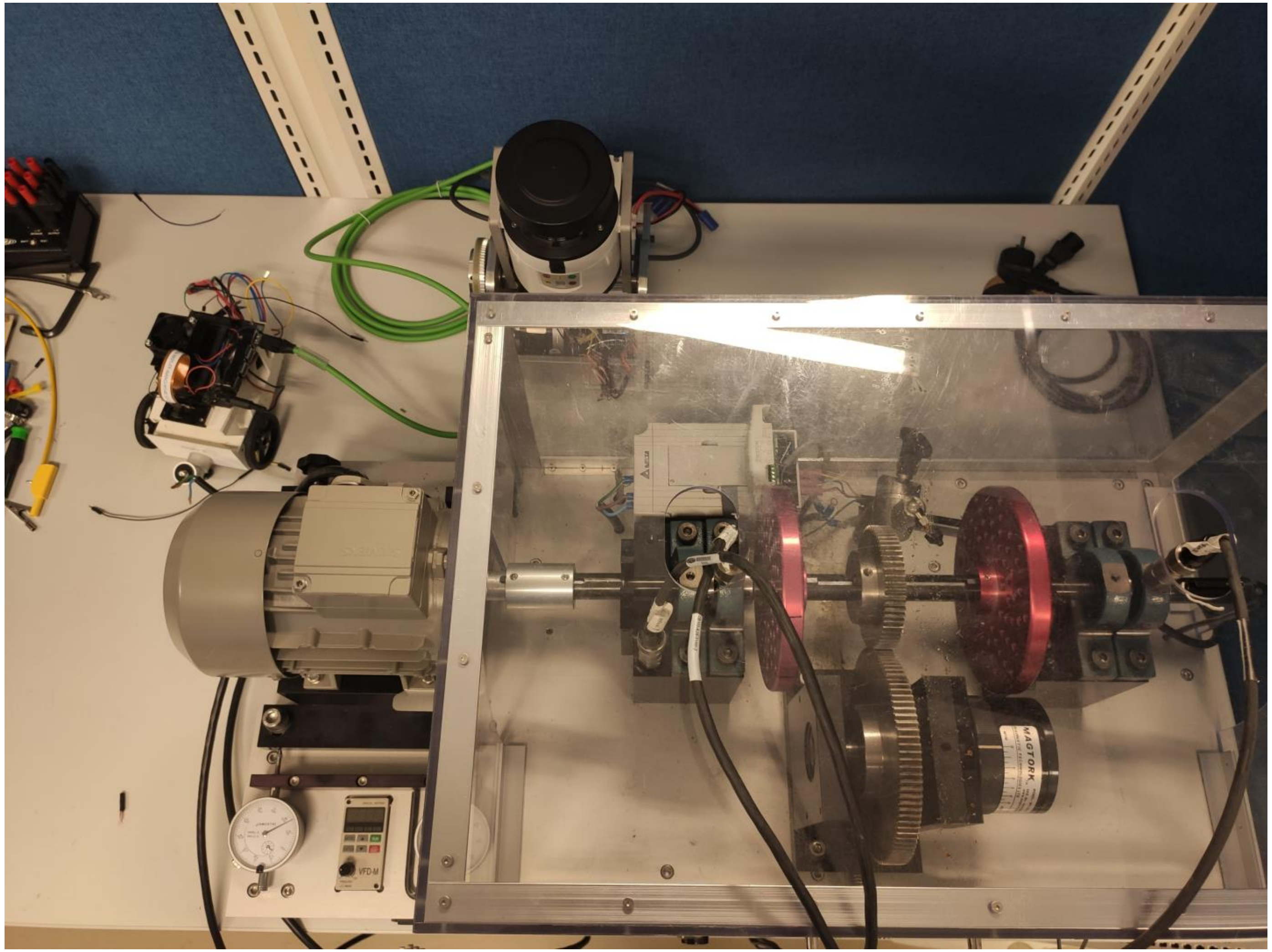
The project want to define how to connect a Lidar and how to acquire data that fits properly the vibration analysis.

Makeover of the sensing part of the most used technique

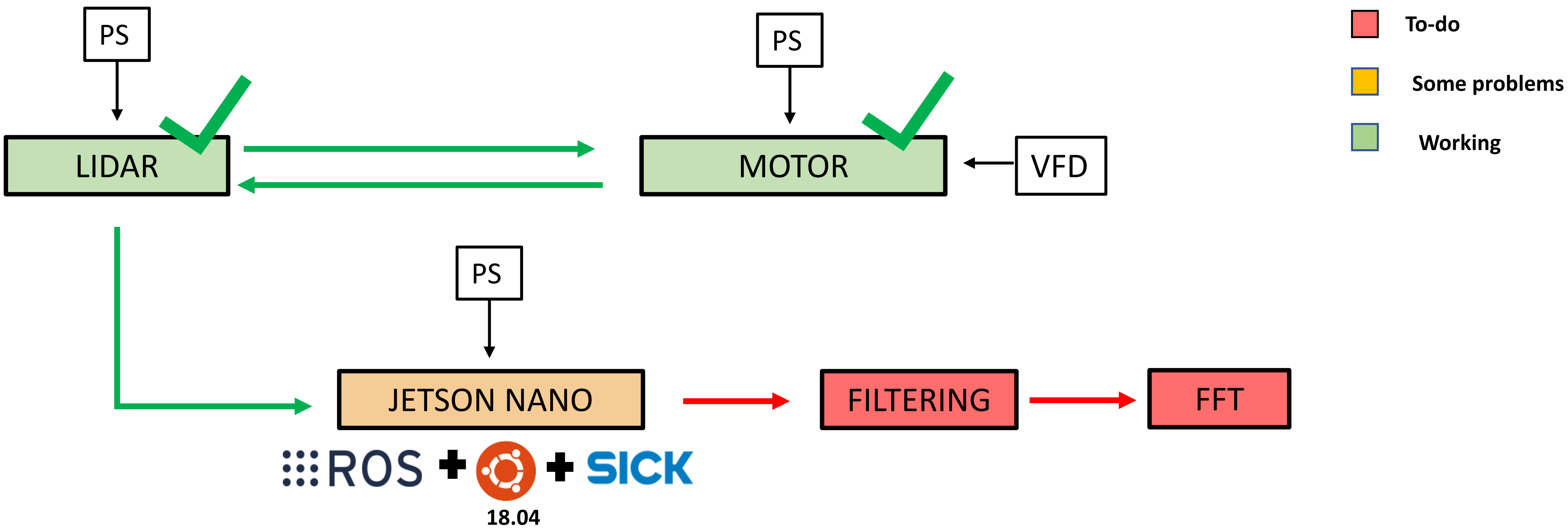


Assumptions:
1) Only one fault can occur for each run (NO multiple-fault diagnosis)
2) Only air between the Lidar and the target
3) Consider only one direction vibration

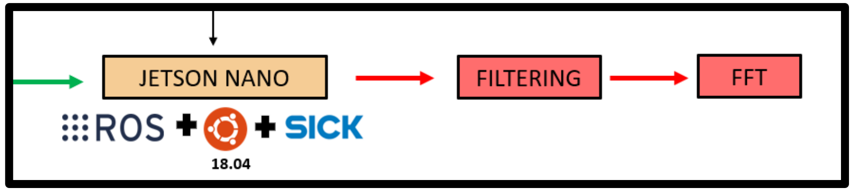
Experimental setup:



Actual progress:



Future steps:



1. Set the communication between ROS and the lidar.
2. Set the Lidar in order to acquire depth of only 1 point.
3. Process the data (converting from binary to decimal,filtering, FFT).

HOW

1. Solve previous problem and setting a reasonable comunication frequency.
2. Modify ROS node parameters and filtering the point.
3. Create a ROS node with manufatcurer's code for translation and python code base on scipy.fft for FFT.

Thanks for the attention!

UiA University of Agder Norway

Motor bearing damage detection using Lidar

Gianluca Salata

***Abstract*—This paper addresses the application of a non contact sensor for the detection of rolling-element bearing damage in induction machines; in particular using a Lidar to detect vibration of motor's shaft. Vibration monitoring of mechanical bearing frequencies is currently used to detect the presence of a fault condition. Since these mechanical vibrations are associated with damage in the inner race defects of the bearings, the outer race defects is modulated and ball defects are generated at predictable frequencies related to bearings geometry and operating speed. This paper takes the initial step of analysing the actual technique for bearing fault detection, MCSA and vibration analysis, by correlating the relationship between vibration and incipient bearing failures. It will define the mandatory setup of the lidar to acquire the vibration signal and all the procedures to connect properly the lidar to jetson nano properly. The aim of the paper is to define how to set the communication between a lidar and a laptop and acquire vibration data of a rotating motor's shaft, This helps to improve the classical vibration analysis using a non contact sensor.**

I. Introduction

NOWADAYS, timely maintenance of electric motors is vital to keep up the complex processes of industrial production. One of the most common cause of motor failures is bearing faults. Early detection of this faults allows replacement of the components, rather than replacement of the motor.Determine the continuous health of a motor can be useful to predict a failure and to enable some procedures to put the motor into safety condition. This can also help the engineer to be aware of the type of the failure that occur. Analysing the behaviour of a motor is possible to discover an incoming fault in it. There is a strong relationship between the type of fault and some variable parameters of the motor, such as the input current or the shaft vibration. Modern technique exploit this relation to detect the fault, each of them with advantages and disadvantages but all of them rely on contact sensors. Motors are usually placed in hostile environments, in particular induction motors, so the sensor need to be rugged and designed to survive for a long period of time at critic condition. With this paper, the aim is to overcome the problem to place a sensor in contact with the motor when it is located in hostile or not very accessible environments. A lidar is potentially able to detect a vibration of a motor from distance, for example from a more accessible and safer place instead being in the same area of the motor; this could improve the lifespan of the sensor and the maintainability of the sensing system. This paper demonstrate how to acquire data from a non contact sensor such a lidar in order to use them in the vibration analysis for detection of two different bearing fault: inner and outer race bearing's defect fault.

G. Salata was with the faculty of Engineering and Science Universitetet i Agder, Grimstad, 4078 NOR

Ajit Jha are with University of Agder .

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II. State of art

Different methods were being proposed in order to overcome the problem with the most common technique and to improve the reliability of the system; Paulo and Daniel, in [1] proposed to detect fault through sound and vibration signals; in fact the sound is a physical phenomenon that provides information about the behaviour of a system and can be used as a parameter for determining the condition thereof. The acoustic sound waves contain information about the health status of the machine because sound is produced by mechanical vibrations. The electric motor is not an exception, and the vibrations generated by defects in bearings, mechanical unbalances and broken rotor bars produce sounds with characteristic frequencies associated with each fault. However the downside of sound signal analysis is its sensitivity to external noise , which should be avoided whenever possible; this limits enormously the application of this technique. The diagnosis through the analysis of acoustic sound signal is a first non-invasive method using non-contact sensor, a microphone in this case, to check the motor's status. The most popular and used technique for the detection of faults in induction motors with contact sensors are: the MCSA (motor current signature analysis) and the analysis of vibration signals. Both methods are based on the same concept: each fault is related to a precise harmonic component. It means that from a Fourier transform of a signal is possible to determine the which fault occur inside the motor. They differ in the signal they analyse: MCSA use the supplying current signal while vibration analysis is based on the displacement of motor's shaft.

A. MCSA

This technique involves the analysis of stator current signals collected with a current clamp or an ammeter. It is based on the recognition that an electric motor (ac or dc) driving a mechanical load acts as an efficient and permanently available transducer by sensing mechanical load variations and converting them into variations in the induced current generated in the motor windings.These motor current variations are carried by the electrical cables processes as desired. Motor current signatures, obtained in both time and over time to provide early indication of degradation. As described in [2], to diagnose motor faults, MCSA uses the current spectra, which contains potential information of motor faults. Therefore, it is important that abnormal harmonic frequencies are independent of the types of drive-systems or control techniques. [3] and [4] relate each bearing fault to a precise harmonic in the current spectra, using the geometry of the bearing; for example a bearing failure cause the variation of air-gap length when a rotor turns and it generates and harmonic at the frequency:

$$f_{bearing} = f_0 \pm n_b f_{i,0} \tag{1}$$

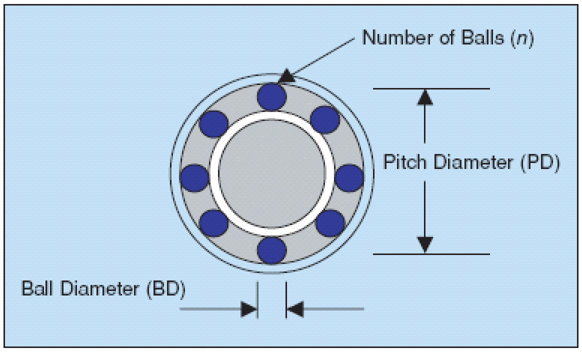


Fig. 1. Bearings parameters [5]

$$f_{i,O} = \frac{n}{2}(1-s)\,f_0\left\{1 \pm \frac{\mathrm{BD}}{\mathrm{PD}}\cos\beta\right\} \tag{2}$$

Where n_b is the number of balls, PD is the bearing-pitch diameter, BD is the ball diameter, β is the contact angle of crack on races, and n is the positive integer, f_0 is the electrical supply frequency, s is the per-unit slip respectively. In MCSA, the equation to determine the harmonic's frequency of bearing fault are almost similar to the equation in the vibration analysis; to obtain the frequency in MCSA is necessary to add the supply frequency of the motor to the equation of vibration analysis. The MCSA technique has the advantages of being non-invasive, easy and cheap to implement, providing good results in fault diagnosis; however, under certain conditions its application is not sensitive enough because it has a low signal-to-noise ratio.

B. Vibration analysis

It is based on the signal coming from accelerometer/vibrometers positioned on the crankshaft; 3-axis MEMS accelerometers are frequently used due to its ability to measure vibration at very low frequency, around 0Hz. The bearing fault related vibration frequencies are easily calculated with known bearing geometry and rotor speed as explained in [5]. The equation to determine the frequency for each type of bearing's defect are:

$$f_{\mathrm{oD}} = \frac{n}{2} f_{rm}\left(1 - \frac{\mathrm{BD}}{\mathrm{PD}}\cos\phi\right) \tag{3}$$

$$f_{\mathrm{ID}} = \frac{n}{2} f_{rm}\left(1 + \frac{\mathrm{BD}}{\mathrm{PD}}\cos\phi\right) \tag{4}$$

$$f_{\mathrm{BD}} = \frac{\mathrm{PD}}{2\mathrm{BD}} f_{rm}\left(1 - \left(\frac{\mathrm{BD}}{\mathrm{PD}}\right)^2\cos^2\phi\right) \tag{5}$$

$$f_{\mathrm{CD}} = \frac{1}{2} f_{rm}\left(1 - \frac{\mathrm{BD}}{\mathrm{PD}}\cos\phi\right) \tag{6}$$

where f_{rm} is the rotor speed in revolutions per minute; others parameters are relate to the geometry of ball bearing and is shown in figure 1: Vibration analysis has the advantage that its results are independent of the type of motor power supply, high reliability, low power consumption, low cost and yields good results, but its implementation requires using accelerometers as the basic sensors that must be placed near or on the motor; the sensor is exposed to a possible bad environments, this reduce the lifespan of the sensor and its reliability.

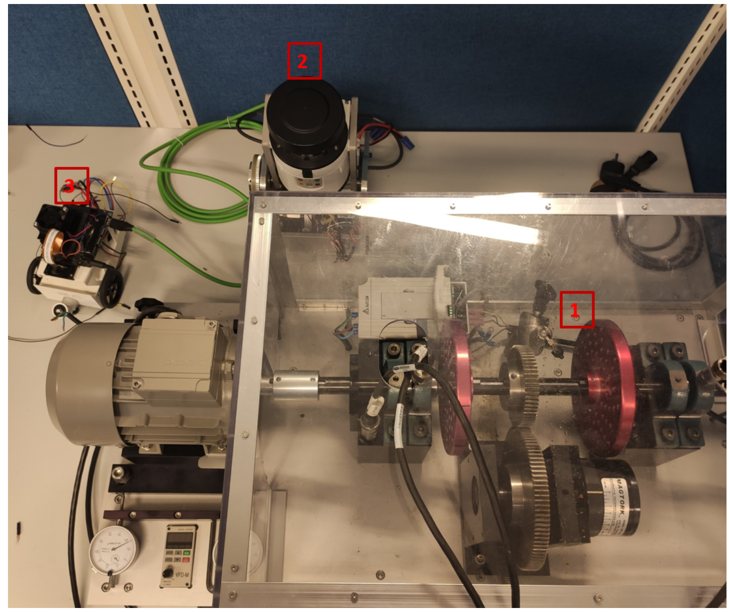
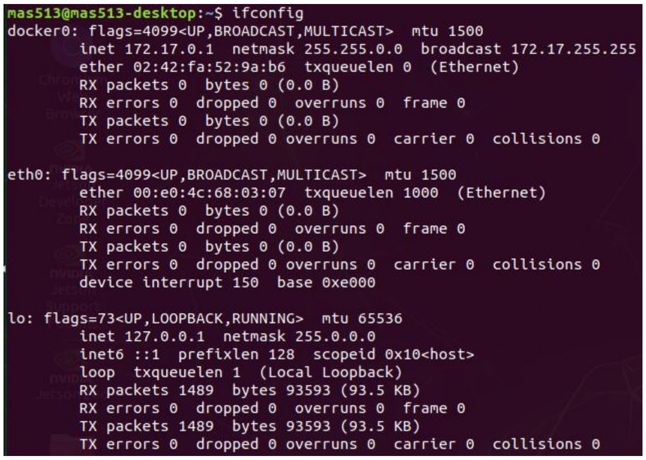


Fig. 2. Experimental setup with the vibration simulator(1), SICK lidar(2) connected through Ethernet to a jetson (3).

III. METHODOLOGY

The project use an experimental setup composed by a vibration simulator (Dylab mvs 510), a SICK LMS133 lidar and a Nvidia jetson in order to process data. As shown in figure 2, the vibration simulator, is composed by an induction motor that drive a shaft connected to a load through a reduction gearbox. The motor speed can be easily controlled change the supplying frequency thanks to the VFD-M AC motor drive and the load is simulated through a magnetic rotor which transform kinetic energy into heat, generating a variable load torque. In order to simulate the vibration the system is equipped with defected bearings that support the main shaft; the defect on the bearings is known: one has a 1mm inner race hole, the second bearing has a 1mm outer race hole. This complex system can simulated different working condition with healthy or defected bearings. To detect the shaft's vibration a 2D lidar is used and it is positioned perpendicular to the shaft (number 2 in figure 2), otherwise a misalignment in the Lidar cause a mis-reading of the shaft's displacement. The position's data produced by the lidar are sent to a computer unit, in this project a Nvidia Jetson Nano, through a Ethernet cable (number 3 in figure 2).

The choice of the jetson nano is due to the necessity of more computational power than a raspberrypi, because the aim is to process data in almost real time with complex algorithms. On the board is installed Ubuntu 18.04 with ROS 1 melodic version, this is the only ROS version suitable for this type of Ubuntu. The Lidar used in this project is the LMS133, made by SICK, it has an aperture angle of 270° horizontal with a frequency of 50/25 [Hz], and a very large range of detection (20 [m]), as default. It comunicates with the board



```
mas513@mas513-desktop:~$ ifconfig
docker0: flags=4099<UP,BROADCAST,MULTICAST>  mtu 1500
        inet 172.17.0.1  netmask 255.255.0.0  broadcast 172.17.255.255
        ether 02:42:fa:52:9a:b6  txqueuelen 0  (Ethernet)
        RX packets 0  bytes 0 (0.0 B)
        RX errors 0  dropped 0  overruns 0  frame 0
        TX packets 0  bytes 0 (0.0 B)
        TX errors 0  dropped 0 overruns 0  carrier 0  collisions 0

eth0: flags=4099<UP,BROADCAST,MULTICAST>  mtu 1500
        ether 00:e0:4c:68:03:07  txqueuelen 1000  (Ethernet)
        RX packets 0  bytes 0 (0.0 B)
        RX errors 0  dropped 0  overruns 0  frame 0
        TX packets 0  bytes 0 (0.0 B)
        TX errors 0  dropped 0 overruns 0  carrier 0  collisions 0
        device interrupt 150  base 0xe000

lo: flags=73<UP,LOOPBACK,RUNNING>  mtu 65536
        inet 127.0.0.1  netmask 255.0.0.0
        inet6 ::1  prefixlen 128  scopeid 0x10<host>
        loop  txqueuelen 1  (Local Loopback)
        RX packets 1489  bytes 93593 (93.5 KB)
        RX errors 0  dropped 0  overruns 0  frame 0
        TX packets 1489  bytes 93593 (93.5 KB)
        TX errors 0  dropped 0 overruns 0  carrier 0  collisions 0
```

Fig. 3. Active interfaces

through a Ethernet cable, so its necessary to set properly the ip-addresses of the board and the Lidar. The ip of the lidar must have the same value of the board ip for every number that is covered by the subnet-mask but they have to differ in the other numbers; in this case the Lidar's ip is 192.168.0.1 (it's the default value), so the board's ip must be 192.168.0.x (because the subnet-mask is 255.255.255.0) where x could be every integer number different from 1. To set properly the IPs is possible to change the Lidar's ip through the manufacturer's proprietary software, SOPAS Engineering Tool (available only for Windows OS), or to change the board's ip from the settings. Once connected the Ethernet cable to the board in order to set up the communication is necessary to remove the *docker0* interface that is pre-installed in OS such as Ubuntu for jetson; to do that must be run the command: *sudo ip link delete docker0*. This interface is a virtual bridge created by Docker; it randomly chooses an address and subnet from a private defined range and it assigned to the device, to guarantee a better safety of the board. It's possible to check the presence of *docker0* using the command *ipconfig*, which shows all active interfaces on the board (as shown in figure 3).

Whereupon, through the manufacturer github repository, is necessary to download and install the open-source project to support the laser scanner for ROS 1, that is called *sick scan*. This stack provides a ROS driver for multiple SICK lidar and radar sensors. Following the guided procedure for the download, recommended from source, adding also the development branch for more update support for all the Sick lidar. Summarising the mandatory commands:

1) *source /opt/ros/melodic/setup.bash*
2) *mkdir -p /ros_catkin_ws/src/*
3) *git clone git://github.com/SICKAG/sick_scan.git*
4) *cd ..*
5) *catkin_make install*
6) *source /ros_catkin_ws/install/setup.bash*

Then all the steps must be repeated to install the development branch but at step 3 the command is : *git clone -b devel –single-branch git://github.com/SICKAG/sick_scan.git*. The command at step 6 must be run every time is necessary to open a new terminal and working with lidar commands/data. To change Lidars's parameters like for example: maximum and minimum angle of scanning, type of data, intensity etc is necessary to modify the launch file before the start of the ROS node. The launch file, of the specific lidar that we are going to use, is contained in the source folder (*src*) of the local ROS repository folder (usually called "*catkin-ws*"). After setting all the parameters the ROS node is launched to start acquire data from the lidar which are published on the topic *pointcloud2* through the command *roslaunch sick_scan sick_lms_1xx*.

IV. Conclusion and Discussion

All the described steps guarantee a reliable and fast connection between the Lidar and the Jetson Nano. They also provide basic ROS nodes and useful program to control and set the Lidar parameter and for data acquisition. This procedure is made specifically for the experimental setup described in the previous section but the main logical process is applicable to different instrumentation. For a better understanding of the process, few ROS's acquaintance and experience with Linux software are required. In the end the experimental setup is almost ready to exchange data between the sensing part (lidar) and the computer unit and is possible to start processing that data. The aim of this paper is to improve the vibration analysis method using a non contact sensor like a Lidar, because it can solve some problems related to the accelerometers such as reduced lifespan caused by hostile environments, etc. The outcome of this project is to propose a variation of the vibration analysis; this could be still improved and it could raise new academic challenges. The data's processing phase of this project can be developed using a better noise filtration or a better Lidar in order to obtain a more accurate fault detection. But also determinate the continuous health status of a motor can helps to develop different type of predictive maintenance. For example, is possible to determine if some components inside of the motor are going to fault and schedule a maintenance before the broke; this helps reducing drastically the downtime of a machine.

At this point of development of the project multiple problem occur during the communication set up; this paper suggest to use Ubuntu 18.04 with ROS 1 "melodic" because is the most used version and more help can be found on internet. Therefore the choice of the Jetson Nano, instead of a more common raspberry pi, was forced by the absence of the right desktop version of Ubuntu for the raspberry. The desktop version requires more computational power but simplify the setting and debug process. Moreover the ip lidar can be changed only trough the manufacturer's software available for Windows OS and requires a password: the password set by default is *"client"* but, if the lidar was already used and someone has changed it, is possible to set to the default settings re-writing the EEPROM memory; this process cannot be done often because the writing process degrades the lidar memory permanently. The set up process can still encounter some errors during the boot of the ROS node. A possible error like, *"maybe*

Sopas mode is wrong, wait for 2000ms" is caused by the security settings of the board because the board needs more time to check if the device is safe. In order to solve his problem the connection with the lidar must be set as *local-link only* in Ubuntu settings. However this error can be neglected, the system continue to work. The process described above has still some problems: during the boot, while the ROS node and the lidar exchange data to communicate its parameters and the working method an error occur: *" Error Sopas answer mismatch Error unexpected ...*". This error could be caused by a mismatch between the parameters set in the launch file on the board and the parameters sets on the lidar trough the SOPAS engineering tool; therefore the easiest solution could be to restore factory data of the lidar and change the parameters on the board's launch file according the default lidar's setting. The latest problem which cause the death of the *SickScanServices's* ROS node, described by the error code *-11* should be related to the problem described previously; so after solving this 2 problem the board could acquire properly the lidar's data. The next step for the project are to translate the pointcloud generated by the lidar into a depth data of a single point, because the designated application of lidar requires an accurate measurement of a single point. At the end, the depth data should be processed by a new ROS node, with filters, to make proper FFT of the signal. After done that all the next steps in order to detect bearing's fault are the same described in the vibration analysis technique, [5].

APPENDIX A
GITHUB REPOSITORIES

- Project repository: https://github.com/gianlucasalata-unipd/MAS513-Continuous_motors_health_monitoring.
- Lidar repository: https://github.com/SICKAG/sick_scan

REFERENCES

[1] Paulo Antonio Delgado-Arredondo, Daniel Morinigo-Sotelo, Roque Alfredo Osornio-Rios, Juan Gabriel Avina-Cervantes, Horacio Rostro-Gonzalez, Rene de Jesus Romero-Troncoso, Methodology for fault detection in induction motors via sound and vibration signals, Mechanical Systems and Signal Processing, Volume 83,2017,Pages 568-589,ISSN 0888-3270,

[2] J. Jung, J. Lee and B. Kwon, "Online Diagnosis of Induction Motors Using MCSA," in IEEE Transactions on Industrial Electronics, vol. 53, no. 6, pp. 1842-1852, Dec. 2006, doi: 10.1109/TIE.2006.885131.

[3] R. R. Schoen, T. G. Habetler, F. Kamran and R. G. Bartfield, "Motor bearing damage detection using stator current monitoring," in IEEE Transactions on Industry Applications, vol. 31, no. 6, pp. 1274-1279, Nov.-Dec. 1995, doi: 10.1109/28.475697

[4] W. T. Thomson and M. Fenger, "Current signature analysis to detect induction motor faults," in IEEE Industry Applications Magazine, vol. 7, no. 4, pp. 26-34, July-Aug. 2001, doi: 10.1109/2943.930988.

[5] M. J. Devaney and L. Eren, "Detecting motor bearing faults," in IEEE Instrumentation & Measurement Magazine, vol. 7, no. 4, pp. 30-50, Dec. 2004, doi: 10.1109/MIM.2004.1383462.