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Integrating sensors for robots operating on offshore oil and gas platforms

(Integration of sensors required on robots to be able to perform operators' tasks on offshore oil and gas platforms)

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Abstract

This thesis presents a solution to integrate sensors and instruments on a robot to be used instead of operators on unmanned oil and gas offshore platforms. Operators have various tasks from inspection to maintenance in the platforms. Because of high costs of having operators in offshore platforms, there has been always an ambitious to design a fully unmanned automated platform to decrease the costs and increase human safety in oil and gas industry. These days Robotics is quite mature to be utilized in different industries. There are few manufacturers that produce robots in order that robots perform some activities in industrial environment. But the Robot usage in offshore platforms has higher risks and they have not been used before as a rigid solution, because of inaccessibility to platforms at all conditions (such as bad weather). In this thesis, I have collected the operator tasks which are possible to be done by robots, provided main requirements to use the robots in oil and gas offshore platforms and found the sensors and instruments to be suitable to mount on the robot to measure, collect and analyze required data. Finally, the proper way for data processing and analysis was done in MATLAB Simulink to present the result of measurements and data collection.

The topic of this thesis was inspired from oil and gas offshore industry and robots are going to be used in one of the largest oil and gas offshore projects in North Sea (Yggdrasil) which will be started to operate from 2027. This EPC project (Engineering Procurement Construction) has been started from 2021 and currently is ongoing in detail engineering. The information regarding operators' tasks and required specifications for sensors and instruments were provided based on this project requirements. The report of this thesis can be used in future for the sensors and their integration on robots. It was not possible to test or prototype on existing robots within master thesis schedule because of different schedule of the master thesis and this oil and gas project. Only simulation was carried on showing the results of this thesis.

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1 Introduction

Nowadays the offshore oil and gas industry is going to be more and more automated, and the goal is to replace operators' actions and tasks as much as possible with robots to decrease OPEX (operational expenditure), hazards to human (operators) and CO2 emissions. This has been an ambition in oil and gas offshore industry as its OPEX is huge amount. Offshore platforms are also considered as a hazardous environment because of hydrocarbon existence. In addition, manpower transportation to/from offshore causes CO2 emission. In existing oil and gas offshore projects, Robotics application is being investigated to be used to mitigate the above issues. This thesis is about integrating sensors on a robot to use it instead of operators on the offshore platform. Robots have not been used before in Offshore environment and based on Norsok standards (Norwegian petroleum industry standards), there are some challenges to integrate sensors with existing robots and the way to design them to be suitable to use in offshore platforms.

In last years, some research has been done to evaluate different aspects of robotics usage in oil and gas industry. For instance, a lecture "Design considerations for mobile offshore Oil & Gas inspection robots" by Sindre Sætre Hammerlund from NTNU Department of design was discussed about operations which are possible to be automated. Moreover, present robots were investigated to check if they meet the requirements. The actual mechanisms were asked to be researched and developed in future. [1]

The tasks which the robots should perform in offshore platform has been collected from operation and maintenance teams in oil and gas industry and the robot was developed with some add-on sensors to be able to do some checking and reports based on the measured data. That is, a pre-condition for partly unmanned operations is to have robotics that can do check and report activities. There are some industrial robots in the market to use for this project. The shortlisted robot suppliers are Taurob [2], Anybotics [3] and Exrobotics [4]. The photo and type of robots which can be selected are shown below. The body of the robots is ready to use with some capabilities but not all requirements. These capabilities are Stair climbing up to 45º, 360º turning, Movable arm and All terrain capability such as gravel, floor gratings and mud for Taurob robot. Also, they are ATEX rated (suitable for hydrocarbon environment). The limited number of different instruments and sensors can also be added based on client request, adaptability with robot design and availability in the market. They can be camera, gas finding thermal camera, directional microphone, and multi-gas sensor. So, the sensors and instruments need to be selected to make the robots suitable for using as operators for inspection tasks.

Taurob Robot (Inspector model)

Anybotics Robot (ANYmal model)

Exrobotics Robot (ExR-2 model)

Usage of mobile robots has not been started yet in offshore oil and gas industry because of severe offshore environment and strict regulations and standards in this industry. With technology progress, more automated operations are feasible to implement to achieve the unmanned platforms. Robots' technology is also more mature than before, and it can be developed to be used in offshore environment. The requirement has been listed to check whether they can be fulfilled with existing robotic technologies. The various sensors are required to be integrated on the robots to perform the tasks. In addition, data processing and analysis can be outlined for the instruments' measurement. Machine learning is also necessary for some parts of data processing and resulted commands which is not worked deeply in this thesis. But it will be referred in the relevant sections.

There are few main requirements which need to be taken into account for design:

- Sensors and instruments shall be certified for zone 1 hazardous area and selected based on Norsok standards to be able to use in offshore environment.
- Robots can carry the limited amount of load, so the weight of sensors and instruments shall be considered during their selection. (for example up to 15 kg for Anybotics robot)

1.1 Objective

As mentioned, the idea of this thesis was taken from an oil and gas project in North Sea. There are some challenges to find suitable sensors and instruments according to project requirements, to implement them on robots in order that they can do check and reports activities. The main challenges are to find proper sensors with ATEX certification, high accuracy, and reliability. In this thesis, below sections were decided to be done as they are more relevant to the field of studies:

- Investigate and list the tasks which operators are doing in offshore oil and gas platforms (check and report tasks)
- Define the acceptance / performance criteria for the instrumentation/detection.
- Find suitable sensors and instruments for offshore oil and gas environment to be used to perform above tasks
- Integrate the sensors on the body of robots which are available in market and proper for this application
- Data processing, analysis of the sensor's measurements and result reporting

The robots need to be designed to do some maintenance activities as well. For this kind of activities, the manipulator arm is required. In this thesis, these required activities are not considered as they are more relevant to Robotics field of studies. In addition, Communication infrastructure to transfer data and/or results to onshore central control room has not been considered in my work although they are crucial part in this project. All in all, the main points are estimated to be necessary for this project are shown in Figure 1.4.

Simplified illustration of the overall robotics check & report concept

1.2 Method

The first part of this thesis is related to the definition of robot's requirements on the oil and gas offshore platforms. Based on these requirements, the proper sensors and instruments are selected, and the design of each sensor is explained theoretically to figure out their methods of operation in this application. Some of these sensors require data processing to read their measurement, convert them to understandable data for analysis and making the appropriate result to transfer to onshore for monitoring or maintenance purposes. The data processing for these sensors were simulated in MATLAB to present the possible designs and results in this application. Of course, there can be different ways to perform data analysis, but the way was taken in this thesis as per research on different ways of data analysis for each sensor and selecting the simple enough method to reach desired result in different conditions. The complexity of data analysis was tried to be reduced to make the code more robust and prevent the system bugs and malfunctioning.

1.3 Structure

Chapter 2: In the first part, the overall design review is outlined to show the project requirements and select the proper sensors accordingly. At first, the operators' check and report tasks were collected. Then the principles of hazardous areas and ATEX certification requirements are described to clarify its crucial requirement on overall design. Finally, the specification of required sensors and instruments is explained, and the suitable model is selected for each one.

Chapter 3: This chapter includes the brief table of sensors and instruments integration on a robot. In this thesis, a microcontroller is assumed to be the core of robot to process the measured data and react as per analysis outcomes, but it has not been evaluated in detail if that can be the most suitable option. However, the required circuitry boards are proposed in case of microcontroller usage as robot's brain.

Chapter 4: In this chapter, first, the concepts of image processing, sound processing and Vibration analysis are introduced. The proper methods to process the measured data are selected as per project constraints and MATLAB simulation is also carried out to present the selected methods of data processing for sensors and instruments.

Chapter 5: The works and assumptions done in this thesis are discussed in this chapter. Furthermore, the parts which are not possible to be done in the master thesis were explained as future work.

Chapter 6: This chapter is the conclusion and gives an overview of the thesis.

2 Overall design review

2.1 Robots' tasks

Operation is the most important role in oil and gas industry after production start. It needs critical actions on different process sectors. It varies from monitoring, control to maintenance. Operators are instructed to follow certain actions on different situation. Since existence of operators on offshore oil and gas platforms costs a huge amount of money permanently, the authorities are willing to find the ways to reduce these expenses. It's worth to mention that there can be environmental and safety risks to have operators on offshore platforms. Operators can be replaced with robots for some simple daily actions. In Yggdrasil project, the target is 2 weeks unmanned and 4 weeks manned platform at start. Therefore, the daily activities which shall be done by operators are investigated and listed to be performed by robots. As the thesis subject is to integrate sensors and instruments on robots, only the check and report activities are mentioned in below list and other type of activities such as manipulation are not taken into account.

- Gas leakage is an important safety issue that may cause catastrophic accidents in oil and gas platforms. That is why fixed located infrared hydrocarbon gas detectors are used on different locations of the platform where the chance of gas leakage is foreseen. In addition, while operators need to do maintenance works which may cause hazardous issues, they should take a mobile handheld gas detector to make sure that maintenance location is safe to work. This mobile type of gas detectors can measure the hydrocarbon gas range. The gas leakage may happen in compressor bundle, export compressor cooler and cooling medium expansion tank area as examples. Figure 2.1 shows a sample of these mobile gas detectors.[5] The combustible gases such as Methane (CH_4) is necessary to be measured on the platforms. The common type of these gas detectors is NDIR (Non-Dispersive Infra-Red) in this application. This instrument can measure 0-100% LEL (Lower Explosive Limit) of a gas which is the lowest concentration of a gas that might be explosive. The LEL can vary for different types of gas. For methane, it is 5% of its volume. So, a NDIR gas sensor needs to be added on the robot in order to check the volume of gas concentration on a location where a maintenance work shall be done. The detail of this type of sensors are described in section 2.3.1.

Figure 2.1 A sample of mobile handheld gas detector

- Liquid leakage is another issue which is needed to be checked regularly for different equipment such as pumps, vessels, and separators. Liquid leakage can happen because of several reasons like corrosion or leakage on pipe flanges or connections. This task is done by operators visually as the liquid is detectable by eye. In order to detect the liquid leakage as well as gas leakage by robots, a thermal IR camera can be used. The photos from the camera shall be processed to detect the leakages. In sections 2.3.2 and 4.1 the details are explained.
- Motors are widely used for different applications such as pumps, compressors etc. Sound of the drive motor can show if its operation is normal, so operators check the sound of drive motors without load and under load. This is a task mentioned on operation manual for Miscellaneous pumps package. The experienced operators know the normal and malfunction sound of motors and they can detect the differences by listening to the sound for a short time. This task can be implemented on robots by adding microphones and sounds processing. More details will be explained in sections 2.3.3 and 4.2.
- Vibration is also checked on pumps under load. That is another factor to show if the pump is working well. Operators check the vibration of pumps as another regular task based on operation manual. Each component of a pump produces a distinct vibration

pattern or characteristic. It can be predicted when a machine will break and schedule maintenance in a cost-effective way by trending various vibration signatures over time. Normally operators have handheld vibration detectors for small motors which do not have permanent vibration sensors on them. The example of these handheld vibration detector is shown in figure 2.2.[6] This mobile vibration detector can measure the acceleration and frequency of vibration; the detector is used by operators to check if equipment acceleration is in acceptable range. This can be done by having vibration sensor on robot arm to be attached on the motor bearing enclosure and measure its vibration. The data from vibration sensor needs to be analyzed to check if the motor operation is healthy. Sections 2.3.4 and 4.3 are describing the vibration sensor selection criteria and its data analysis respectively.

Figure 2.2 A sample of mobile handheld vibration detector

- Last but not least is visual inspection. Operators are instructed to inspect pipes, equipment, instrument gauges etc. This task can vary from checking the painted surfaces for damages to the surface protection to reading the tank level from level gauges. There is usually a checklist of places to inspect, and operators shall provide input of their inspection on the checklist. In some cases, such as reading gauges, the measured figure shall be recorded in the checklist. In this thesis, a digital camera is added to take pictures from the desired locations and transfer the pictures to onshore central control room to be processed and analyzed there.

2.2 Philosophy for sensors' installation in hazardous areas

2.2.1 Hazardous areas

An explosive atmosphere is a mixture of air, under atmospheric conditions, of flammable substances in the form of gas, vapor, or combustible dust, fibers, after ignition, permits self-sustained propagation.

To protect people, environment, and the installation from the dangers of explosion, certain rules and guidelines are required to be complied.

Hazardous areas should be classified into zones according to the likelihood of an explosive atmospheres being present. It is important that all electrical equipment and hot surfaces are protected in such a way that no ignition of the explosive atmosphere can occur. This kind of equipment is called Ex equipment.

Area, where there is a risk of an explosion, are generally classified into four types of areas, depending on what causes the danger. They are Gas, Dust, Explosives and Oxygen-enriched atmosphere.

2.2.2 Fire triangle

For a substance to be able to burn, three factors must be present: This can be presented by the fire triangle. If one of the sides in the triangle is not present, a fire will not be able to start or sustain, and an explosion cannot occur because an explosion is just a rapid fire (high flame propagation).

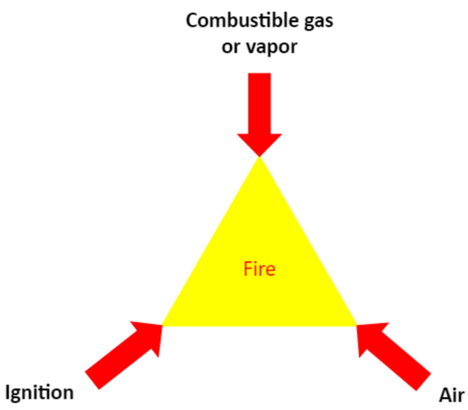


Figure 2.3 Fire triangle

2.2.3 Classification of areas

The principles for classification of hazardous areas with gases and vapors are described in NEK EN 60079-10-1. [7] There are several factors which shall be taken into consideration when developing a classification area for a platform. There are three different zones based upon the frequency of the presence and duration of an explosive atmosphere during normal operation. Outside the classified area is non-hazardous area. Also, area in which an explosive atmosphere is not expected to be present in quantities such as to require special precautions is called non-hazardous area or unclassified area.

- **Zone 0:** an area in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas or vapor is present continuously or for long periods or frequently.
- **Zone 1:** an area in which an explosive atmosphere consisting of a mixture of air of flammable substances in the form of gas or vapors is likely to occur in normal operation occasionally.
- **Zone 2:** an area in which an explosive atmosphere consisting of a mixture of air of flammable substances in the form of gas or vapors is not likely to occur in normal operation but, if it does occur, will persist for a short period only.

The classification documents show what kind of gas groups is expected in the area and the temperature class to deal with when selecting the equipment.

2.2.4 ATEX certification

ATEX equipment directive sets the requirements for electrical and non-electrical equipment which can be a potential ignition source in itself, and intended for use in hazardous areas, must undergo a procedure to ensure that the equipment meets the requirements for basic safety.

2.2.4.1 Type of Ex protection

The basic principles shall be followed for Ex protection to avoid ignition of flammable atmosphere or prevent the spread of such an ignition. These principles rely first and foremost on avoiding all the parts in the fire triangle occurring at the same time.

Below the types of Ex protection which are relevant to this thesis are explained:

Equipment protection by increased safety Ex 'e': [8] It is based on the basic principle "Avoid ignition sources" which means it prevents ignition sources from occurring by increasing design requirements for the equipment and gives requirements for control of surface temperature. An Ex 'e' enclosure should never contain sparking or hot components (temperatures above temperature class). It is also a requirement that the enclosure should be protected against harmful ingress of water and dust. Ex 'e' is often used as enclosure for control panels, equipment cabinets, junction boxes and motors.

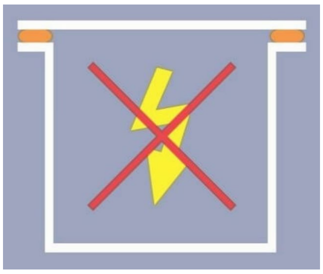


Figure 2.4 Ex 'e' equipment protection

Equipment protection by flameproof enclosure Ex 'd': [9] It is based on the basic principle "Containment" which means the enclosure prevents explosions inside the enclosure from transmitting to the surrounding explosive atmosphere. Flameproof equipment can often be recognized by its bulky and solid appearance and is often used when sparking or hot components have to be placed in hazardous areas. It is often costly in purchase and requires in many cases comprehensive maintenance to maintain the strict requirements for flameproof joints. Ex 'd' equipment is available as control panels, equipment casing, motors, switches and instruments.

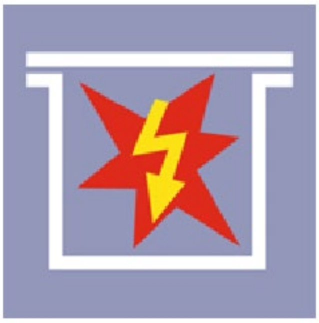


Figure 2.5 Ex 'd' equipment protection

Equipment protection by pressurized enclosure Ex 'p': [10] (also can be marked Ex 'px', 'py' or 'pz') It is based on the basic principle exclusion which means to prevent the explosive atmospheres to come in contact with ignition sources inside the enclosure by filling the enclosure with a pressure of air or inert gas. According to NEK EN 60079-2 [????] there should be an automatic device that isolate the electrical circuit when the pressure drops below a pre-prescribed minimum value (0.5 mbar for 'px' or 'py' and 0.25 mbar for 'pz'). Ex 'p' equipment is often used when sparking or hot components must be placed in potentially hazardous areas. Control rooms, analysis rooms and containers can also be protected by pressurization.

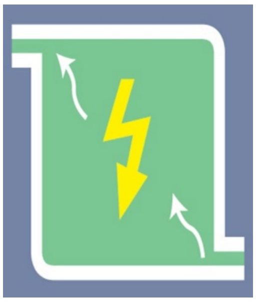


Figure 2.6 Ex 'p' equipment protection

Intrinsically safe electrical systems Ex 'i': [11] It is based on the basic principle "Energy Limitation" which means the energy in the sparks and temperatures that may occur are limited, so that these do not ignite the explosive atmosphere. Intrinsically safe electrical systems are a low energy technique that first and foremost is suitable for measurement and control signals. A big advantage is the ability to troubleshoot and adjust during operation without the risk of ignition of explosive atmospheres. Equipment with protection by intrinsically safety can be grouped into two categories of equipment. Intrinsically safe apparatus (Field equipment), and associated apparatus. Intrinsically safe field equipment connected to electrical equipment in non-hazardous areas, must be protected by an associated apparatus.

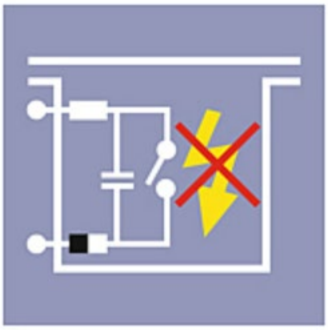


Figure 2.7 Ex 'i' electrical system

The important aspects of the design of intrinsically safe equipment are:

- The equipment is designed with voltage and current-limiting components

- The equipment is designed with limitation of stored energy in capacitance and inductance
- When combining intrinsically safe circuits and non-intrinsically safe circuits in the same equipment, the equipment is designed with sufficient separation to prevent transfer of energy to the intrinsically safe circuits. This must be done via an associated apparatus which contributes to limit the energy in the circuit.

Typical examples of associated apparatus are Zener barriers and galvanic isolation barriers. Associated apparatus must be placed in non-hazardous area.

2.2.4.2 Ex certified instruments used in different zones

Offshore oil and gas platforms contain different zones from non-hazardous areas to zone 1. Fixed Instruments and sensors which are required to be used in each zone shall be Ex certified for the usage in that specific zone. But the robots are designed to move around on the platform, and they might be needed to go in zone 1 areas for inspection or maintenance purposes. Therefore, they shall be Ex certified for zone 1 as zone 1 is the most critical zone on the platform. Below sensors and instruments are allowed to be used in zone 1:

- Intrinsically safe Ex ‘ia’ and Ex ‘ib’
- Ex ‘e’ and Ex ‘de’ enclosures
- Pressurization Ex ‘p’, ‘px’, ‘py’, ‘pxb’ and ‘pyb’

Robots proposed to be used on oil and gas platforms have Ex ‘p’ certification, so there would be a pressurized enclosure to install all electrical parts inside that. The sensors and instruments which are going to be selected in this project and installed on the robots, are intrinsically safe in order that they can be used safely in hazardous areas especially zone 1. But they shall be connected to the microcontroller of the robot which is inside the pressurized enclosure. Inside the pressurized enclosure is considered as safe area, so the associated apparatus such as galvanic isolation barrier shall be installed between the intrinsically safe sensor and microcontroller. This associated apparatus is also required to be located in safe area (pressurized enclosure).

2.3 Required sensors and instruments on robots

As per defined tasks for robots in section 2.1, some instruments and sensors are required to be integrated on the robot to make it able to perform the tasks. They are selected based on oil and gas offshore requirements and standards as well as availability in the market. Below the list of sensor and instruments required in this thesis are provided.

- **IR Thermal camera**: They are quite common to use for liquid and gas leakage and wherever the temperature can assist to show the proper operation of equipment. Further information and their design are explained in next section.
- **IR Gas sensor**: For some specific type of gas, it is possible to have a dedicated gas sensor on robot. That is required as a primary check before start to work on the hazardous areas. In oil and gas platforms, methane gas is one of major hazard gases which is required to be checked.
- **Directional microphone**: To check the sound of motors, a microphone is required. The directional microphone is considered as it can be used to find the direction of sound source to some extent as well as check the sound. More details are provided in related part.
- **Vibration sensor**: This sensor is used to check the vibration of pumps. It requires to be installed on the robot arm to make it possible to attach the bearing housing of the pump's motor and detect its vibration.
- **Camera**: To inspect the different equipment and instruments visually, camera is required. With the help of image processing, the damages to the surface protection and reading the gauges is possible.

In next sections, each sensor or instrument is explained with their design details.

2.3.1 IR Gas sensor

Gas sensors are commonly used to detect toxic or explosive gasses and measure gas concentration. Infrared (IR) sensors use the absorption of infrared light at a particular wavelength or range of wavelengths to determine the amount of gas present. Flexible bonds that are capable of three-dimensional vibration keep molecules together. Each molecule has a set of preset vibrational modes that it may operate in. Each mode indicates a certain frequency of vibrational motion. After receiving energy from infrared light, a chemical bond continues to vibrate at the same frequency but with increased amplitude. The frequency must coincide with the frequency of the mode of vibration in order for infrared radiation to be absorbed.

Only infrared wavelengths that fit with the vibration modes of the chemical bonds in the gas molecules are absorbed when infrared light passes through a sensor chamber containing a measurable gas. The remainder of the light passes through the chamber without obstruction. The device counts the quantity of light that the molecules in the sensor chamber absorb. The quantity of light that reaches the active detector as compared to the reference signal decreases according to the concentration of detectable gas.

In the molecules being analyzed, the chemical bonds are what cause the infrared light to be absorbed. Larger molecules provide more chances for infrared light absorption because they have more chemical bonds linking the atoms in the molecule together. The bigger flammable gas molecules such as hexane, octane, and nonane are hence more sensitive to NDIR (Non-Dispersive Infra-Red) sensors.

Methane and propane are two frequently encountered flammable gases that may be easily detected by IR sensors. However, in order for IR sensors to detect a gas, the molecules' bonds must absorb IR at the wavelengths used for measurement.

2.3.1.1 Analog and Digital gas sensors

A continuous voltage or amperage proportionate to the gas level is sent out by analog gas sensors. A computer or a microprocessor can read the character strings that digital gas sensors send and receive.

The benefit of an analog gas sensor is that, typically, as the gas level rises, the sensor's electrical output, measured in amps or voltage, similarly rises. After the sensor has been calibrated, the signal can be utilized to power an ammeter or voltmeter that displays the quantity of gas present on a dial gauge.

Internally analog gas sensors are used in non-dispersive infrared (NDIR) gas sensors. The infrared absorption of gas molecules in a particular spectrum, as detected by a specialized photo sensor, is known as NDIR. An amplifier circuit is used to increase the amount of detected infrared light once it has been measured as either milliamperes (mA) or microvolts (mV). An analog-to-digital (ADC) converter is incorporated into the sensor's circuitry in order to interpret this analog signal.

To put it another way, every gas sensor is analog. A digital gas sensor can be created by including an on-board analog-to-digital converter.

A sensor's analog voltage or current is converted by an analog to digital converter to a digital output that indicates the gas level. Fast response time on gas sensor applications may be made thanks to the ADC chip near proximity to the analog gas sensor.

RS-232, the industry standard for serial data input and output, is one of the common digital signal outputs. Positive and negative voltages are sent over two wires using RS-232 and transformed to binary. To send and receive a digital signal from a sensor, just the transmit data and receive data wires (Tx and Rx) and a ground wire are required. Wherever a short-range, point-to-point, low-speed wired data connection is appropriate, RS-232 is frequently utilized.

2.3.1.2 Cons and Pros

The fact that IR sensors use less power than catalytic sensors is one of their main advantages. Another advantage is that IR sensors may be utilized in oxygen-deficient or inert atmospheres since they do not require oxygen to detect gas. In addition, IR sensors lack catalysts and other components that may be harmed by silicones or other catalytic sensor poisons.

The fact that numerous non-flammable gases and vapors, such as carbon dioxide and water vapor, can absorb IR light is a significant drawback of this method. The analyzer must use very specific IR light wavelengths tuned to the substances of interest (and/or wavelengths tuned specifically to the substances of non-interest, as a compensating reference signal for the wavelengths captured by both the substances of interest and the substances of non-interest) in order to successfully reject these non-flammable materials.

2.3.1.3 IR gas sensor model

IR gas sensor selected for this application is industrial grade NDIR CH_4 Sensor-SJH [12]. This sensor has been chosen because of its miniature size and suitability of usage in zone 1 hazardous area. The NDIR CH_4 sensor SJH can detect methane (CH_4) concentration of 0 to 100% and is based on NDIR technology, which is superior than thermal catalysis and heat conduction technology. It benefits from easy use, precise measurement, convenient operation, simultaneous voltage and serial port output, and dual beam design. It is often used in gas detection and analysis in the petrochemical, chemical, coal, medical, laboratory, and other areas in order to fulfill the various needs of industrial field and laboratory measurement. Below there are some features of this sensor:

- NDIR technology, with long life and full measurement range
- Explosion-proof grade Ex ia IIC T4 Ga
- Internal full range temperature compensation
- Diffusion sampling, stable performance
- High precision, high resolution 0.01%
- Small size and fast response
- Easy to install and reduce maintenance
- Compatible with digital and analog voltage signal output

Figure 2.8 NDIR CH4 Sensor-SJH

As mentioned in the specification of this product [13], molecules like CO_2 and CH_4 have infrared absorption spectra and are made up of many atom kinds. Intensity of absorption follows

Lambert-Beer's Law. When a light wave, that corresponds to a particular gas with an absorption spectrum, travels through the gas being measured, its intensity is dramatically reduced. The observed gas concentration and the intensity attenuation are correlated. This relationship is according to Lambert-Beer's Law. The NDIR sensor's fundamental operating theory is as follows:

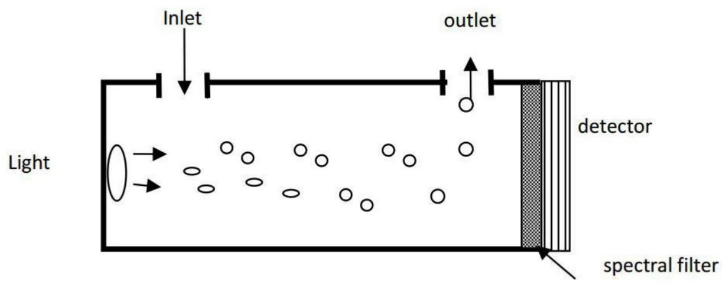


Figure 2.9 Simplified illustration of NDIR sensor

Basic mathematical model: The majority of polyatomic gases, both organic and inorganic, absorb light at a certain wavelength in the infrared area. The Lambert-Beer Law may be used to indicate how transparent this gas molecule is to a certain wavelength of infrared light:

Light transmissivity, I is formulated:

$$I = I_0 e^{-kpl} \qquad (2.1)$$

Light absorption intensity, i is:

$$i = I_0 - I = I_0(1 - e^{-kpl}) \qquad (2.2)$$

I_0: incident light intensity

l: thickness of gaseous medium

p: gas concentration

k: absorption coefficient

Sensor Pin D (Vout) output signal is 0-2.5V DC voltage, where 0.4-2.0V corresponding to 0-100% of methane gas. Also Pin T (TX) and R (RX) are used for RS232 serial communication and can be connected to microcontroller to read the measurement as well as perform sensor calibration and configuration. As the output communication level is 2.5 V, sensor needs to transform the voltage when connecting with 5V devices such as an Arduino microcontroller. The interface circuit is as follow:

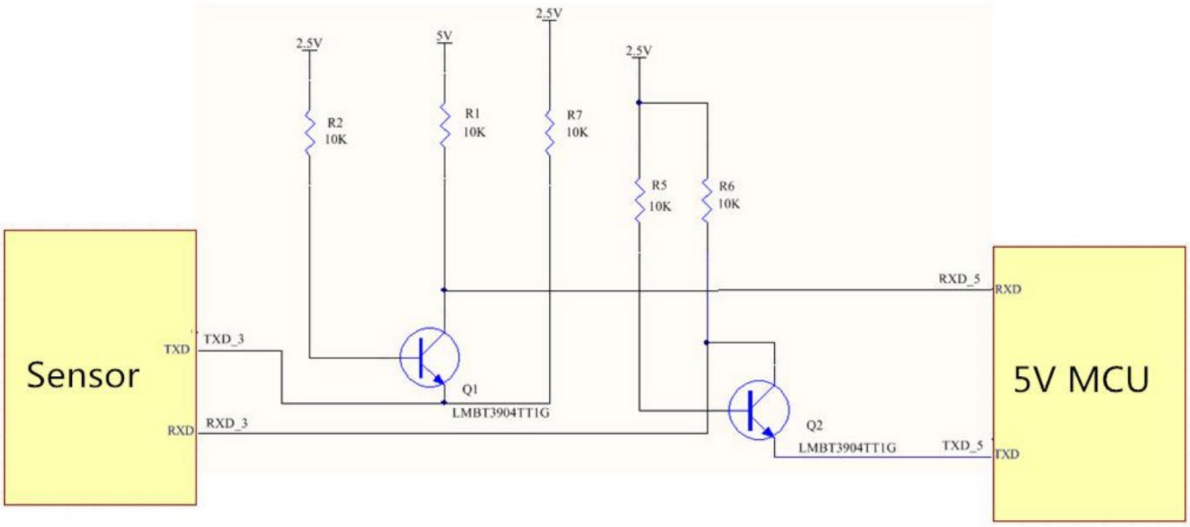


Figure 2.10 2.5V Communication Level Converted to 5V Communication Level Circuit

2.3.2 IR Thermal camera

Infrared radiation is emitted by every item, sometimes referred to as a heat signature. An infrared camera, called a thermal imager, detects, and quantifies an object's infrared radiation. The infrared data is transformed by the camera into an electronic picture that displays the target object's apparent surface temperature.

A unique detector chip (sensor array), that houses thousands of detector pixels organized in a grid, serves as the target for infrared radiation which is focused by an optical system within an infrared camera.

An infrared camera's primary components are made to process infrared radiation since the device is intended to capture heat energy from its surroundings. Infrared radiation must travel via a lens and sensors in order to reach its destination. The infrared radiation concentrated on each sensor pixel causes it to respond, creating an electrical signal. The camera processor uses each pixel's data to do a mathematical computation and build a color map of the object's perceived temperature. A separate color is allocated to each temperature value. The resultant color matrix is sent to memory and shown on the camera's screen as a thermal image—a representation of the object's temperature. Red, orange, and yellow are often the brighter colors and represent warmer temperatures since they release heat and infrared radiation. As a result of less heat and infrared radiation being released, the colors purple, dark blue, and black indicate lower temperatures.

Many infrared cameras also have a visible light camera that takes a regular digital image every time the trigger is pulled. It is simpler to connect problem regions in your infrared image with the real equipment or location you are evaluating by mixing these photos.

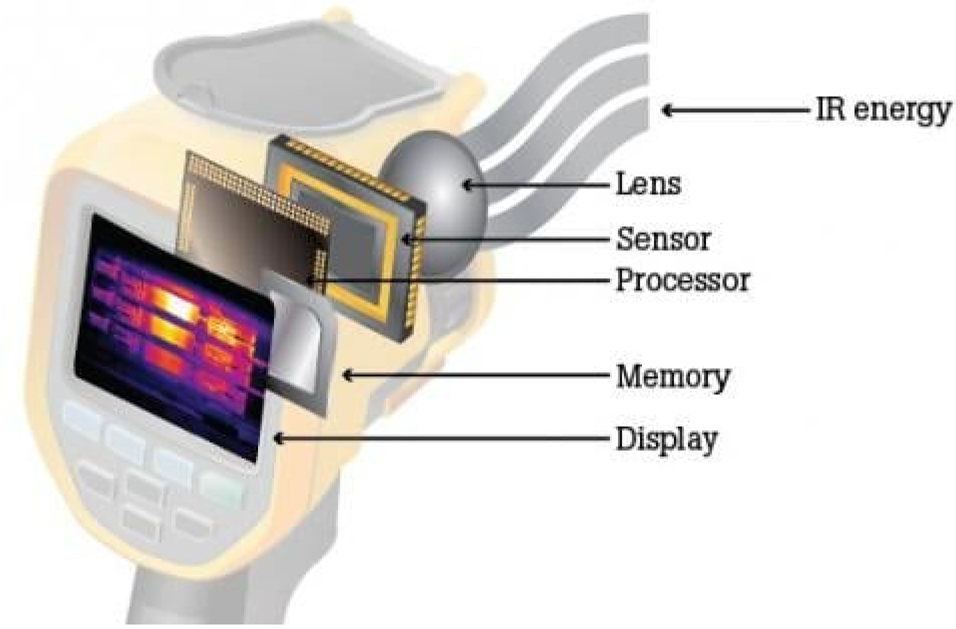


Figure 2.11 Simplified illustration of IR Thermal camera

The factors are required to be considered in selection of IR camera for this project is the camera resolution, temperature range that camera can detect, ability to save images in a memory card, battery type and lifetime and the compatibility to work in hazardous area subject to explosive gasses.

The naked eye cannot see many industrial gases and chemical substances. Methane and other volatile organic compound (VOC) gas leaks can now be rapidly and readily located using an infrared (IR) camera. It has the ability to scan a larger area more quickly and in places that are challenging to access with contact measuring tools. A leak is visible as a vapor plume in an infrared picture. Industries employ infrared imaging to detect leaks, broken pipelines, ruptured seals or valves, and other emissions. [14]

IR thermal camera is a suitable instrument to detect gas and liquid leakage. The detection method is described in section 4.1 in detail.

2.3.2.1 Cons and Pros.

One benefit of a thermal camera is that it can take pictures of objects at their actual temperatures without the aid of an external light source since it can detect infrared radiation that is emitted by the item itself and linked to its own temperature.

Compared to a visible light camera, they can see through smoke, fog, haze, and other atmospheric obscurants better.

For enhanced precision, each pixel contains one microbolometer. The microbolometer is an element that absorbs radiation and raises temperature as a result. Because of this, thermal cameras have a lower resolution than a typical camera.

2.3.2.2 IR thermal camera model

For this project, the CorDEX TOUGHPIX DIGIHERM pocket-sized digital and thermal imaging camera was chosen since it is a go-anywhere camera with the strength and durability to get the job done [15].

The following are some of its standout features:

- Certified by both ATEX and IECEx (EX II 2G / Ex ib op is IIC T4 Gb)
- Adaptive thermal blending
- 5 Mega Pixel digital camera with motorized, automated focus. capture photos at a high resolution
- Extremely powerful LED flash for photographing in low light
- TOUGHPIX DIGITHERM weighs less than 400 grams and is made of strong, lightweight aviation grade aluminum.
- Removable, rechargeable battery

- The capacity to measure with an accuracy of up to 2% or 2 degrees between -10C and +380C.
- Removable Memory Card
- 80x60 Pixel Array thermal photo

The CorDEX TOUGHPIX DIGIHERM camera is used for taking thermal images. The images are accessible via WIFI. So, the microcontroller can be communicated with the camera to read images and process them for gas and liquid leakage. There is a specific model of Arduino microcontroller board (ARDUINO UNO WiFi REV2) [16] which has the capability to connect to WIFI network. The camera is working with Lithium-ion battery, which is able to work four hours, the working time duration is acceptable for robot task rounds. And it is possible to be recharged when the robot goes back to its dedicated station.

Another important usage of thermal camera is to check the temperature. For electrical motors, temperature is a crucial factor that shows the convenient operation of motor. The photo of motor can be taken by thermal camera and its maximum temperature of its surface can be checked in microcontroller.

Figure 2.12 CorDEX TOUGHPIX DIGIHERM camera

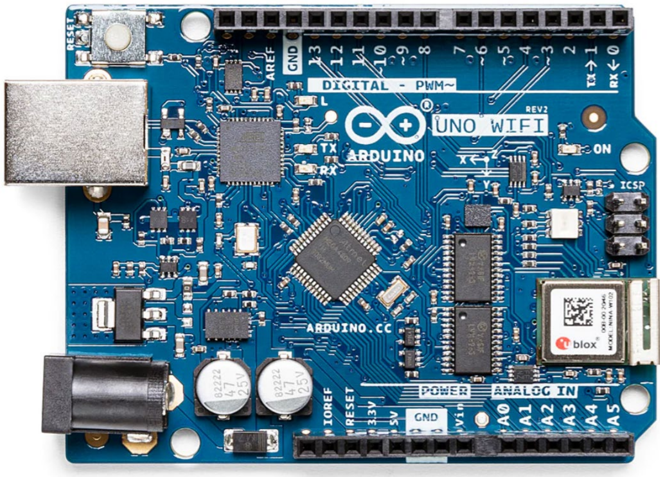


Figure 2.13 ARDUINO UNO WiFi REV2

2.3.3 Microphone

Sound source localization is one of complex majors in robotic. It allows a robot to find the location of a sound source only with the sound signal. There are various techniques for sound source localization which depends on different factors. It will be explained briefly in section 4.2.1 in order to make the correct selection for sound processing in this thesis.

One of the issues which needs to be considered for sound source localization in industrial areas and specifically on oil and gas offshore platform is that the amount of noise, high-level sounds are more than other applications and there can be different sound sources at the same time so it is not rational to rely on sound processing for fault detections if other solutions can be found. Of course, sound processing can be efficient in some applications like checking the motor drive's sound.

The number of microphones required for this application will be specified in section 4.2.2 based on the selected sound processing method. Here the criteria for selection of the microphone model are explained.

For accurate measurements, selecting the correct measuring microphone is crucial. The many kinds of microphones are made for various kinds of sound fields. Appropriate microphone can be selected to prevent any measurement mistakes by being aware of the variations between the microphones. It is crucial to comprehend the link between the microphone and the acoustic surroundings since the sound field is often complicated. It might be difficult to analyze a sound field with plenty of standing waves and reflections. A sensible selection of the measuring microphone, whether it is free-field, diffuse-field, or something in between, greatly simplifies post-processing and data interpretation. It's essential to know the type of sound field to select the appropriate microphone for the measurement and obtain accurate findings. The following is a description of the three various ideal sound fields:

Pressure field: It is the field that is uniform in phase and amplitude over a surface or a tiny, closed chamber.

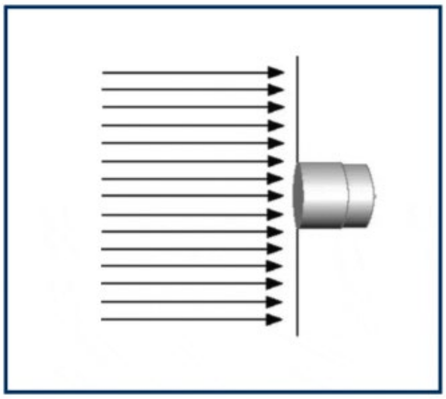


Figure 2.14 Pressure field

Free field: It is a field that is devoid of any reflective objects. Therefore, the straight sound without any reflections is the only sound that may reach a microphone or listener in this sound field. The sound field may be compared to simple plane waves radiating in a certain direction, supposing a single monopole sound source. In a constrained frequency range given by the size of the chamber, a loudspeaker in an anechoic chamber can be thought of as a free-field scenario.

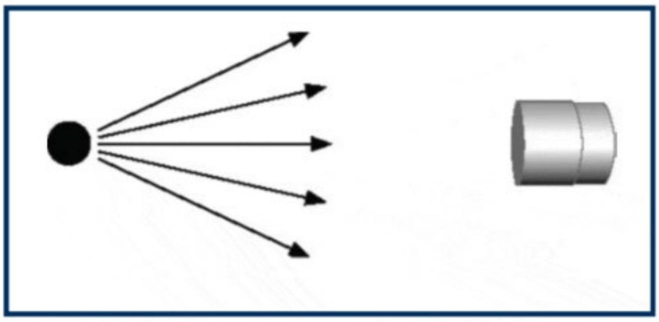


Figure 2.15 Free Field

Diffuse field: Also known as a random incidence field, it has sound entering with an equal probability and level from any direction. As an example, diffuse fields are attempted to be replicated within a constrained frequency range by reverberant chamber used for acoustic testing.

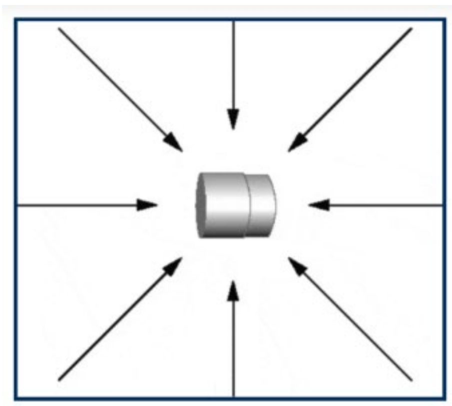


Figure 2.16 Diffuse field

Despite the three sound fields indicated above, there are three primary categories of measuring microphones in the market:

Pressure microphone: It is made to find the real sound pressure applied to the microphone's diaphragm surface. This implies that the microphone will measure any diffraction effects it may be causing to the sound field, and the measurement findings may be altered. Pressure microphones are often installed on a boundary (such as a wall). As a result, it measures the sound pressure at the border.

Free-field microphones: Inserting an item into a sound field will result in some localized disruption of the sound field. Free-field microphones are made to compensate for their presence in the sound field and measure the sound pressure as if they were not there. In order to account for the disruptions, the microphone causes to the sound field, free-field microphones are made to measure the sound pressure as it was prior to the microphone being added to the sound field. Ideally, the measurement shouldn't be impacted by the microphone's existence. The diffraction effect causes the acoustical pressure in front of the diaphragm to grow while the sensitivity of the free-field microphone drops proportionally. This is accomplished by increasing the microphone cartridge's internal acoustical dampening. The outcome is a microphone output that is proportionate to the sound pressure as it was prior to the microphone's entry into the sound field.

The fact that this adjustment only functions in a free field setting with a 0 degree incidence from a sound source must be taken into account. Even when we are not working in a perfect free-field environment, free-field microphones have become the industry standard for acoustic measurements in many applications.

Random-incidence microphones: Known also as diffuse-field microphones, it should be utilized in an environment with a random incidence sound field, where sound is present in all directions at equal volume. This may happen in a room with plenty of reflecting surfaces or a reverberation chamber.

2.3.3.1 Microphone model

There might be different conditions in locations where robots need to inspect on offshore oil and gas platforms. Some are indoor areas which are considered as diffuse field, some are open space outdoor areas which are considered as free field and some others are outdoor areas surrounded with equipment which is between diffuse and free field. Therefore, free-field microphone was selected as it is common to use in industry and it was the only type suitable for hazardous areas. Usage of free field microphone in diffuse field can result underestimation on the sound pressure level. That will be further discussed in sound processing section.

The Hazardous area approved microphone & preamplifier PCB® Model EX378B02 is a pre-polarized condenser microphone system that is suitable for the industry. It can be used safely in gaseous hazardous situations where ordinary microphones may generate a spark and fire since it complies with the Hazardous Areas & Explosive Atmospheres standard. The EX378B02 is outfitted with a Free-field microphone cartridge, conforms with Intrinsic Safety Protection requirements for all above-ground applications worldwide, and complies with under-ground Mine Safety protection requirements for all mining areas outside of North America. [17]

Figure 2.17 Hazardous area approved microphone & preamplifier PCB® Model EX378B02

This design makes use of the most widely used microphone cartridge, a 12" Free field pre-polarized microphone that complies with IEC 61094-4 working class standards. The world's first test and measurement grade condenser microphone and preamplifier set intended for hazardous locations is created when this 0V microphone is enclosed in a spark-resistant box that conforms with ATEX standards.

Some features of EX378B02 microphone are mentioned below:

- ATEX, IECEx, and ETL c/us approvals
- Class 1, Zone 0, AEx ia/Ex ia IIC T4 Ga
- Prepolarized (0V) design
- 15.5 dBA to 137 dB capability
- High sensitivity, 50 mV/Pa
- Uses cost effective coaxial cables

After selection of microphone, the hardware needs to be chosen to collect data from microphones. The quality of acquisition hardware affects the data quality read from microphones.

There are various types of sound acquisition modules. Here one model is selected, NI PCI-4462 [18], 4-input sound module which is compatible with microphone working range to acquire sound signal. This device provides dynamic signal acquisition in sound applications with ability to sample 4 sound signals simultaneously and interface with microcontroller through PCI Bus. As the microcontroller is not capable to read PCI Bus, a converter shall be designed to convert the PCI bus to an acceptable protocol for microcontroller such as UART. This converter design is not considered in the thesis, but it needs to be designed for integration of sensors on the robot.

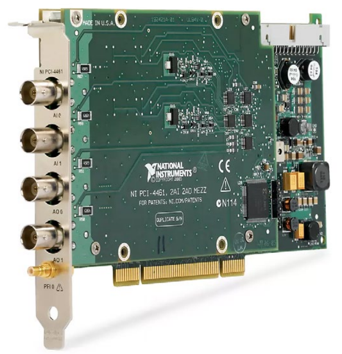


Figure 2.18 NI PCI-4462 sound acquisition module

2.3.4 Vibration Sensor/ Accelerometer

Accelerometers measure an object's acceleration or vibration. They are applied to a variety of tasks, such as calculating an item's change in velocity or calculating the angle of tilt of an object by measuring the acceleration of gravity. Accelerometers are used for monitoring a variety of machinery, including motors, pumps, fans, compressors, and mainly rotating and reciprocating devices in industry since they are simple to use and function across a wide range of frequencies.

An accelerometer is an electromechanical instrument to measure an object's acceleration as well as the various forces acting on it. Accelerometers are capable of measuring both static and moving forces. Gravity and friction are examples of static forces, which maintain an object's consistent direction and position without changing them.

Dynamic forces, in contrast, are unpredictable and actually alter an object's direction or location. As they can detect changes in acceleration and translate them into vibration data, accelerometers are incredibly helpful. Accelerometers (also known as acceleration sensors) use electrical impulses to monitor vibration, providing information about the health of a machine.

An accelerometer measures dynamic or static acceleration using a sensor that outputs an electrical signal. How the accelerometer responds to acceleration depends on the kind of sensor it contains.

A piezoelectric accelerometer, for instance, stresses the inside of the sensor's crystal when measuring acceleration. The sensor then produces an electrical charge in response to stress that is proportionate to the forces pushing upon the item. Accelerometers detect any movement in an item, measure the forces acting on it, and then provide an electrical signal that is proportionate to the acceleration detected.

Accelerometers track acceleration and translate it into voltage to quantify vibration. They are often put on equipment to detect vibration in machinery running at a high frequency. An accelerometer integrated to velocity is often used to detect any anomalies on machines operating at low frequencies. The integrated velocity signal has a higher signal-to-noise ratio than a pure acceleration signal in a machine running at low frequencies. A piezoelectric accelerometer is probably the best option for utilizing an accelerometer to monitor vibration, especially in industry. High impedance accelerometers and low impedance accelerometers are the two main types of piezoelectric accelerometers.

An impedance converter transforms the distinctive charge output of high impedance piezoelectric accelerometers into electrical electricity. The electrical charge is directly connected to the measuring devices in this type of accelerometer. High impedance accelerometers are able to be applied in high-temperature conditions, in contrast to low impedance accelerometers.

Low impedance varieties of accelerometers have a lower integrated charge-to-voltage converter but employ the same piezoelectric sensors as high impedance ones. When compared to high impedance accelerometers, they feature a wide frequency range and low output noise. Low impedance accelerometers are increasingly often used in industrial settings to detect vibration problems in rotating and reciprocating machinery as a result.

Monitoring vibrations is one method of avoiding equipment failure. Unexpected machine problems or failures can be quite costly. Machine vibration can be monitored, and any unusual patterns can be used to predict when a machine will fail or suffer significant damage. For big and medium-sized machines, vibration monitoring system are available for this offshore project, but not for small size machines. Therefore, the robots need to use accelerometers to measure vibration on small motors.

2.3.4.1 Vibration sensor model

EX640B01 Intrinsically safe vibration sensor has 4 to 20 mA output, 0 to 1 in/sec pk, 3 to 1k Hz, top exit, 2-pin connector. The 640B Series Industrial 4-20mA Sensors combine the capabilities of a piezoelectric vibration sensor and a 4-20mA vibration transmitter. The sensor outputs a 4-20mA signal that is proportional to the overall velocity or acceleration of the machinery. Ideal for monitoring the vibration of equipment such as motors and pumps, the output of the sensor can be used for predictive maintenance.

General Features are mentioned as follow:

- Imbedded Piezoelectric Accelerometer for improved accuracy and frequency response.
- Vibration range can be in Acceleration or Velocity.
- Allows for continuous vibration monitoring of critical applications.
- Reduces sophisticated vibration analysis requirements.
- RV (Raw Vibration) option for conducting frequency analysis and machinery diagnostics.
- RVVO (Raw Vibration Velocity Output) option for conducting freq. analysis and machinery diagnosis.
- Rugged stainless-steel construction for applications in harsh environments.
- Flexible design allows for various custom requirements

Figure 2.19 EX640B01 Intrinsically safe vibration sensor

The 640B Series operates from a standard 2-Wire, 4-20mA loop. If utilizing a loop-powered device, connect Pin A of the sensor to the positive (+) input from the power source and Pin B of the sensor to the negative (-) input from the power supply. To read 4-20 mA signal with a microcontroller, below configuration is recommended in installation and operating manual of the instrument. In this case, the sensor is powered and a load resistor in line with the output is used.

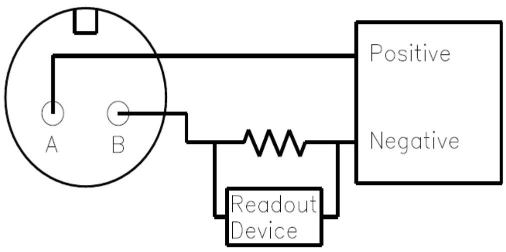


Figure 2.20 Vibration sensor wiring

The resistor generates a DC voltage that is proportional to current by:

$V = IR$ (2.3)

If $R = 250\Omega$ and $I = 6\,mA$, then $V = 1.5\,VDC$. Resistor value shall be less than $(V_{supply} - 12)\ 50$.

Therefore, the redundant device shown on figure 2.20 can be the connection to an AI (Analog Input) of the microcontroller.

For RV (Raw Vibration) option to conduct vibration analysis, another signal output can be added on the 3rd wire connection which is shown in figure 2.21. The RV option includes a 100 mV/g ± 20 % additional output. The accelerometer frequency range is 1 Hz-1 kHz, maximum amplitude of 15 g-pk.

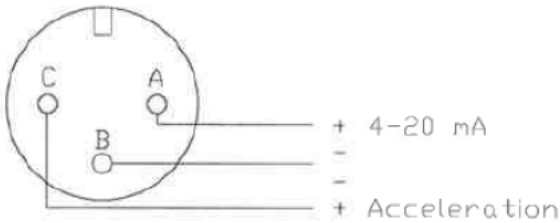


Figure 2.21 Vibration sensor connection with RV (Raw Vibration) option

As this vibration sensor is intrinsically safe, its connection to microcontroller shall be through associated apparatus like galvanic isolation barrier or Zener barrier. Its wiring and the isolation barrier model are recommended in installation and operating manual of the sensor as below:

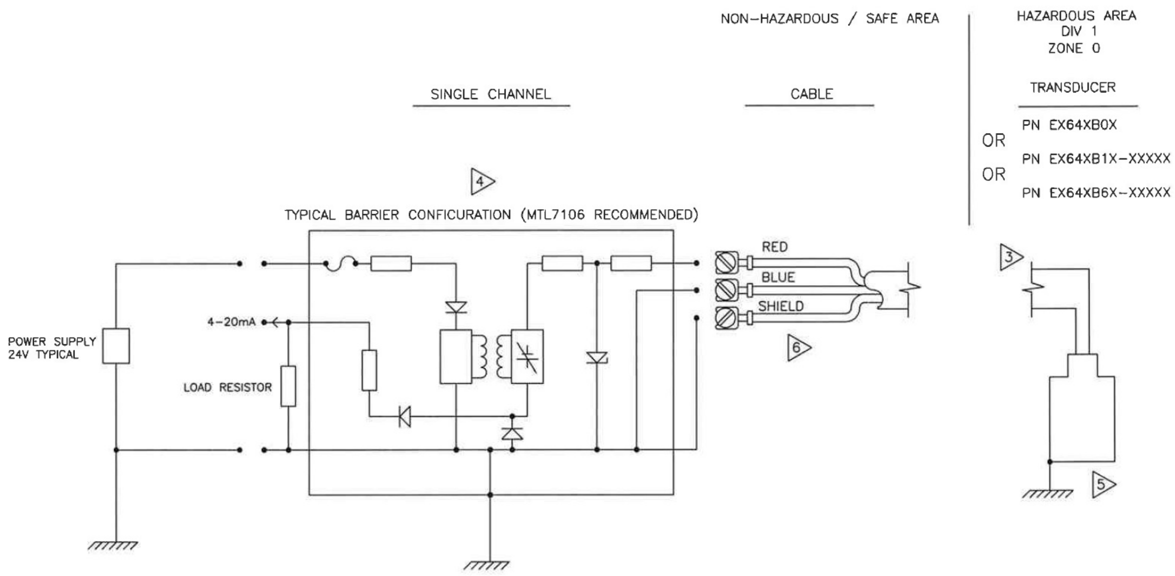


Figure 2.22 Vibration sensor connection to safe area

This sensor needs to be attached to the enclosure of motor bearing. There are different types of connection such as screw type and magnet type. Magnetic installation makes it simple to take measurements for mobile devices and is frequently used for industrial monitoring. For accurate measurements, especially at high frequencies, the right magnet selection and a well-prepared mounting surface are essential.

3 Integration of sensor and instruments

The sensors and instruments are required to be integrated to analyze the measured or captured data. The integration can be implemented by a microcontroller or a FPGA on the robot. In this thesis a microcontroller is assumed to integrate all sensors and instruments. The type of connection was explained for each sensor or instrument where the required sensors and instruments on robots are provided in section 2.3. All data collected in the microcontroller can be analyzed, checked, and compared with the samples and set points for normal conditions. If any discrepancy is found, the result will be reported as an alarm to onshore central control room.

Here a table is provided to gather all required data for integration of sensors and instruments. The microcontroller design is not worked on this thesis as it can be integrated with microcontroller of the robot body.

Table 3-1 - Table of required data for integration of sensors and instruments

NO.	SENSOR/ INSTRUMENT	INSTRUMENT OUTPUT TYPE	BOARD/ CIRCUIT REQUIRED FOR THE CONNECTION TO MICROCONTROLLER
1	IR Gas sensor	RS232 Serial communication	Circuit based on figure 2.10
2	IR Thermal camera	WIFI	ARDUINO UNO WiFi, figure 2.13
3	Microphone	Sound data, 10-14 VDC with frequency from 7-10,000 Hz	Sound Acquisition module, figure 2.18 A PCI to UART converter board
4	Vibration sensor	- 4-20 mA - ±1.5 mV AC	Galvanic Isolation Barrier, figure 2.22

Figures 3.1 and 3.2 are shown an overall schematic of sensors and instruments integration on a robot and illustration of sensors and instruments installation on a robot, respectively.

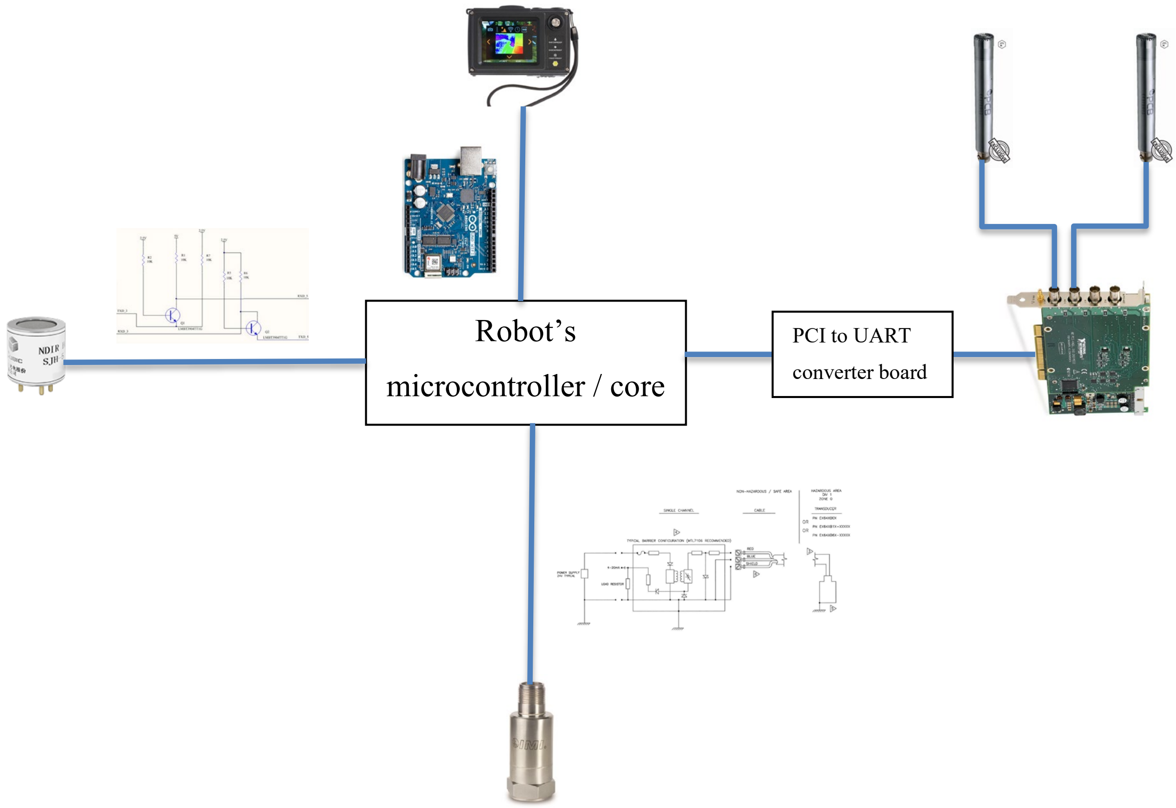


Figure 3.1 An overall schematic of sensors and instruments integration on a robot

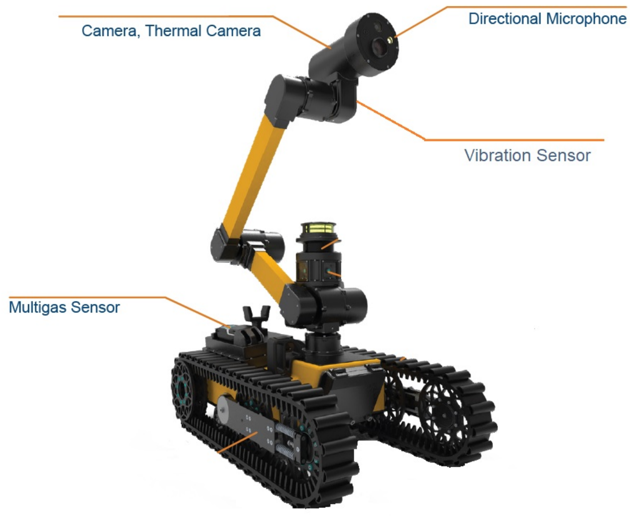


Figure 3.2 Illustration of sensors and instruments installation on a robot

4 Simulation

4.1 Digital Image processing

The use of a digital computer to run an algorithm on digital photographs is known as "digital image processing." Digital image processing offers significant benefits over analog image processing as a subfield or area of digital signal processing. It permits the application of a considerably larger variety of algorithms to the input data and can prevent issues like the accumulating noise and distortion during processing. Digital image processing may be treated as a multidimensional system since pictures are specified across two dimensions. [19]

The widespread deployment of MOS (Metal Oxide Semiconductor) technology in the 1970s transformed electronic signal processing. The first single-chip microprocessors and microcontrollers were built using MOS integrated circuit technology in the early 1970s, followed by the first single-chip DSP (Digital Signal Processor) chips in the late 1970s. Since then, DSP chips have been utilized extensively in digital image processing.

As a result, digital image processing may provide both more sophisticated performance on straightforward jobs and the execution of techniques that would be unachievable with analog technology.

In this thesis, the pictures taken from thermal IR camera are required be to processed in order to find the liquid and gas leakages and also the abnormal temperatures on some equipment like motors can be exctarcted and reported for more investigation. These activities are possible to be implemented on robots with the help of digital image processing. There are some techniques to perform digital image processing which are explained in following sections.

4.1.1 Feature extraction

Feature extraction is a process used in machine learning and image processing that starts with a set of measured data and creates derived values (features) meant to be informative and not repetitive. This process speeds up the learning and generalization processes and, in some cases, improves human interpretations. Dimensionality reduction is the result of feature extraction. [20]

A reduced collection of features, also known as a feature vector, can be created from input data that is too vast to analyse and is considered to be redundant (for example, the same measurement in both feet and meters or the repetition of pictures provided as pixels). The process of selecting a portion of the first characteristics is known as feature selection. [21] It is anticipated that the chosen characteristics will include the pertinent information from the input data, allowing the required job to be carried out using this condensed representation rather than the entire starting data.

Thermal images saved in wifi network link contain a colorbar which shows the spectrum of colors. Each color is presenting the temperature of the surface on that pixel. So the extraction of color bar from an image is one of the applications of feature extraction. The colorbar extraction can be used as a sample to interpret the image colors and find the image matrix with showing the temperature on each pixel.

4.1.2 Pattern recognition

The automatic detection of patterns and regularities in data is known as pattern recognition. It has uses in machine learning, image analysis, and signal processing. Pattern recognition has its roots in engineering and statistics, and some contemporary methods for doing so make use of machine learning, thanks to the greater accessibility of massive data and the wealth of computing power. In addition to considering acquisition and signal processing, pattern recognition places additional emphasis on the signal. [22]

Pattern recognition in machine learning is the process of giving a label to a certain input value. Classification is a type of pattern recognition that tries to categorize each input value into one of a set of classes (for instance, determining the temperature of a photo's pixels). Other sorts of output are included in the more broad problem of pattern recognition.

The fundamental goal of pattern recognition algorithms is to conduct the best matching of the inputs, taking into account their statistical fluctuation, and to offer a fair response for each and every conceivable input. In contrast, pattern matching algorithms seek out perfect matches between the input and already-existing patterns.

Pattern recognition as it is used now is:

In the discipline of pattern recognition, regularities are automatically found in data using computer algorithms, and then these regularities are used to perform tasks like categorizing the data into distinct groups. [23]

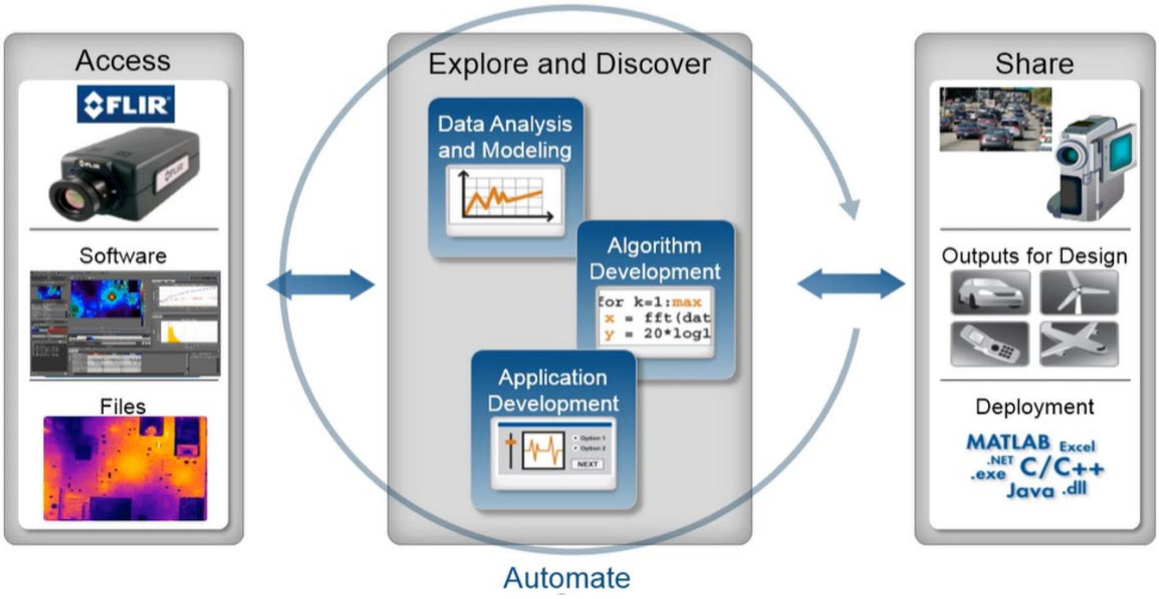


Figure 4.1 MATLAB Simulink- Thermal image processing

4.1.3 MATLAB code for reading thermal images

The images captured from CorDEX TOUGHPIX DIGIHERM camera are RGB thermal images which need to be converted to temperature images with the help of embedded colorbar. In this part, the code for this conversion is provided with a sample of thermal image from the selected camera. As a colorbar is shown on all images, the first task is to separate the colorbar and RGB thermal image. The position of colorbar is fixed in all images from the camera and the tempearture range which is measurable by camera is known. The colorbar is used for mapping of RGB colors to measurable temperature range. Then the temperatures are determined from the colors of each pixel in the photo and the temperature image is made. In the Matlab simulink code provided in Appendix A, the thermal image with the size of 80 x 60 pixels is converted to the temperature image. A 80 x 60 frame/ matrix size is provided from each thermal image and each cell of the frame is showing the temperature of the specific pixel. This frame taken from each image will be used in next sections in order to process images to detect the gas or liquid leakage or high temperature of the devices.

The below image is a sample of thermal image taken from Cordex IR camera, the color spectrum on the right side is the colorbar for this image which is used for color mapping.

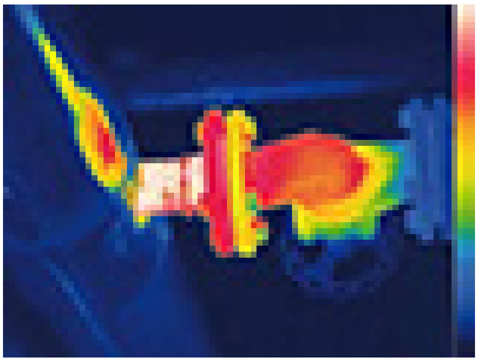


Figure 4.2 Thermal image sample

Below the result of MATLAB simulation code is shown. First the RGB image and colorbar are cropped and shown separately in figures 4.3. Then RGB image is converted to an indexed image with associated colormap, shown in figure 4.4. The thermal image is also presented as grayscale image with corresponding colorbar in figure 4.5. In this image, the poiner can show its position on the matrix as well as the cell's temperature while moving around. Finally, the histogram of thermal image is provided in figure 4.6 to show the overall temperature view of the thermal image as thermal image can be used to find the highest and lowest temperature of the image as well as the percentage of different temperatures on the photo.

As one of robot tasks on the platform is to check the temperature of critical equipments such as motors, the thermal image taken from IR camera is checked to find the maximum temperaure, and compared it with the reference temperatre for the respective equipment. In the matlab simulink, the maximum temperature is taken and checked with the reference temperature. The alarm is provided if the maximum temperature is more than reference temperature.

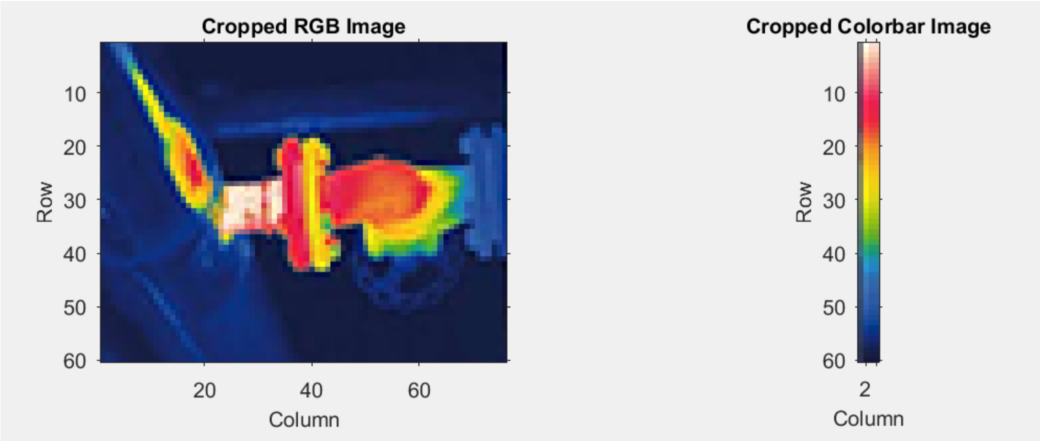


Figure 4.3 Cropped RGB Image and Cropped Colorbar image

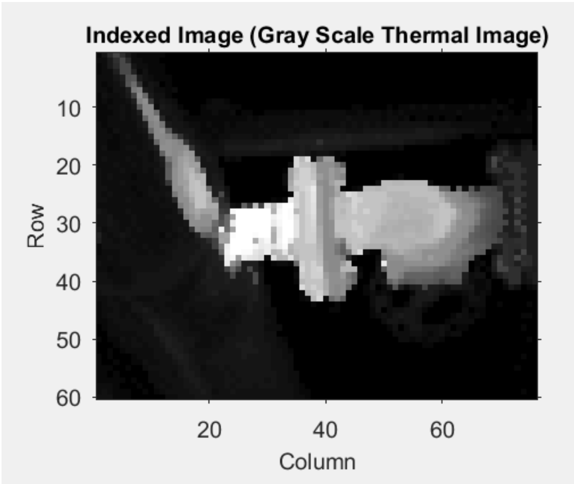


Figure 4.4 Indexed image

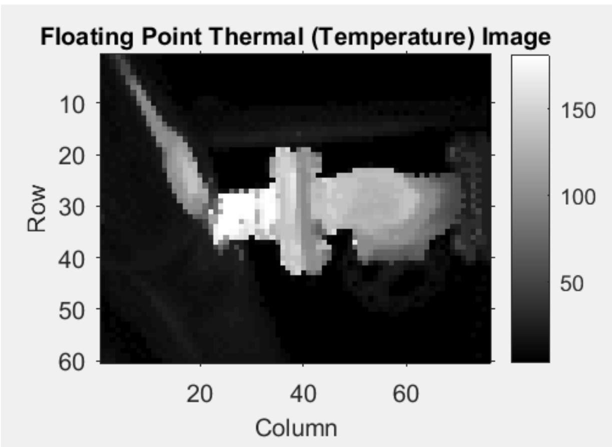


Figure 4.5 Thermal image as grayscale image with corresponding colorbar

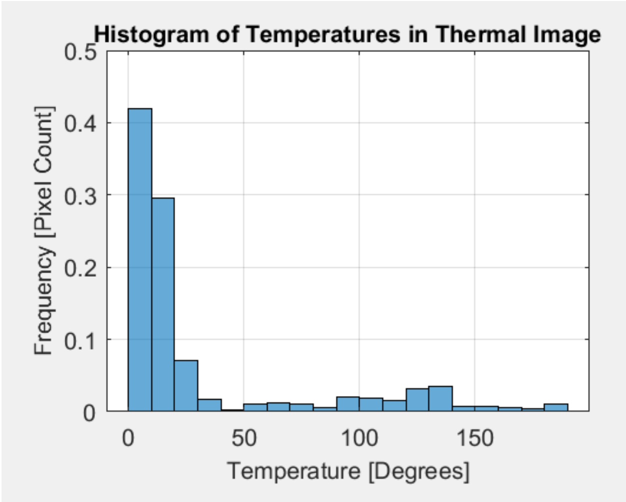


Figure 4.6 Histogram of thermal image

4.1.4 Liquid and gas Leakage detection with IR thermal camera

Different methods are used to detect liquid and gas on equipment and pipelines with IR thermal camera. After evaluation of different methods, below method was selected based on the application in this thesis. This technique subtracts subsequent frames (pictures). The suggested approach for leakage detection has a good detection time and high accuracy. [24]

The majority of the leakage detection techniques now in use are based on the physical characteristics of the liquid in the pipes. A mathematical model for leakage is created using measurement metrics such as the density of the liquid inside the pipes, process variables like pressure, velocity, and temperature, and pipe size and form. Precision will be significantly impacted by sensor data synchronization issues since these approaches frequently employ various sensors at various locations on the pipes. In addition, leakage detection techniques that are quick and precise are needed, particularly when minor leaks are present. Artificial intelligence (AI) and machine vision algorithms can offer a framework for understanding the circumstances on an oil and gas platform, identifying its various operations, and making choices.

The key contribution inspired from the lecture [24] is to offer an automated visual leakage inspection technique that is not dependent on human inspection or ability. A testbed with a demonstration platform and an infrared (IR) camera was employed to achieve this goal. The demonstrator platform's images were utilized to create an intelligent leakage detection solution based on machine vision methods. The testbed results obtained demonstrate that the suggested technique can detect the leakage with high accuracy.

In order to prevent direct human exposure and inspection inside the platform, the first crucial need is to offer safe leakage inspection. An automatic leakage inspection system that is independent of operator involvement is an important component of automatic check and report by robots. The suggested method's accuracy, which can guarantee reliability, particularly in a dangerous circumstance, is the next crucial criterion for a leakage-detection device. As a result, the suggested approach must likewise be resistant to noise. The identification of microscopic leaking droplets is another difficulty in leakage inspection. Small leaks are not well defined in the this thesis as there is not the Atex certified thermal camera with high resolution in the market. A small leak often refers to a scenario where the pressure variations caused by the leakage are minimal compared to the measurement noise levels and the entire pressure range. A small leakage is defined as the fewest pixels necessary to create a leaking drop in a picture at this thesis.

As explained, IR camera is used as exterior vision-inspection system for monitoring the equipment and pipelines. In this method, few images are taken with constant delay between them from a specific equipment or pipeline. After that, the frame/ matrix of thermal image which contains the temperature of each pixel is provided as x_f for each image (f is the number of images from the specific equipment). While there is liquid or gas leakage on an equipment or pipeline, the gas or liquid is visible on the IR camera because of the different temperature of liquid or gas and environment. In addition, the leakage is growing over time and the consecutive photos may change if there is a leakage with the pace more than the speed of taking pictures. The subsequent images are subtarcted.

$$X_f = |x_f - x_{f-1}| \quad (4.1)$$

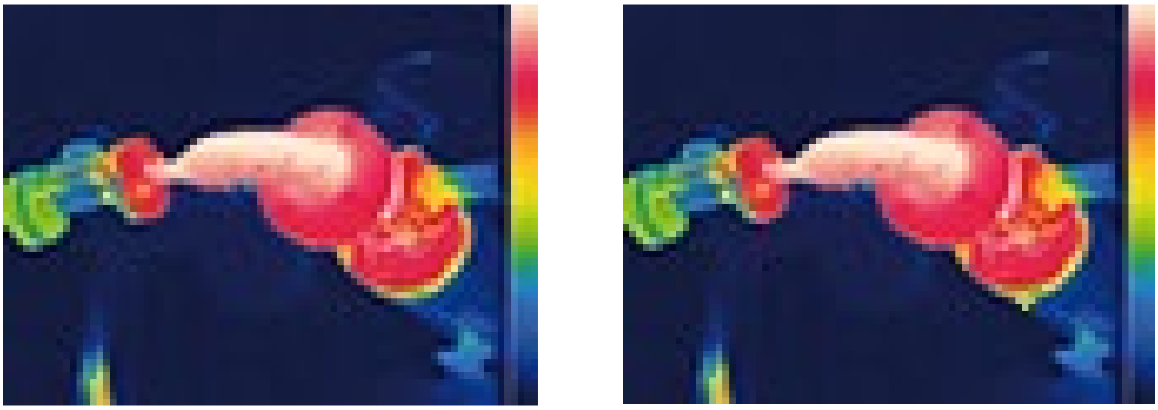
where x_f and x_{f-1} are the f_{th} and $(f-1)_{th}$ frame of thermal images, respectively; X_f is the subtracted frame; the index f is $f = 1, \dots .4$ for checking each equipment. After the frames are subtracted, a noise removal is implemented to X_f (the subtracted frame).

The subtracted frames are subjected to background noise reduction in the first stage, where pixels with values below a predetermined threshold, (δ = 3.6 ̊C, it is calculated based on accuracy of thermal IR camera which is 2% of the temperature range), are set to zero. One further noise filter step is used once the background noise has been eliminated: single-pixel noise reduction. The fundamental premise behind this noise-removal process is that a leaking drop does not consist of just one pixel, but rather several nearby pixels. Some pixels in the subtracted frames contain non-zero values, whereas all of their nearby pixels have zero values. Since these single pixels typically have large values and cannot be removed as background noise, they will have an impact on the final images after image processing. Therfore, the relevant pixel should be set to zero if all of its neighbors have values of zero. The most important pixels (identifying leakages) and their impact will be preserved through feature extraction while other pixels can be removed.

After these steps, if the resulted frame has any non-zero cell, it is considered as anomalous image and if all cells are zero, it is a normal image. This process is repeated for all consecutive photos taken from an equipment or pipeline (3 subtracted frames are made for each equipment). The photos shall be exact same images from the same location to be able to compare in this method. If the result is showing the analmalous images for two of three subtracted images, it will be reported as alarm for more investigation.

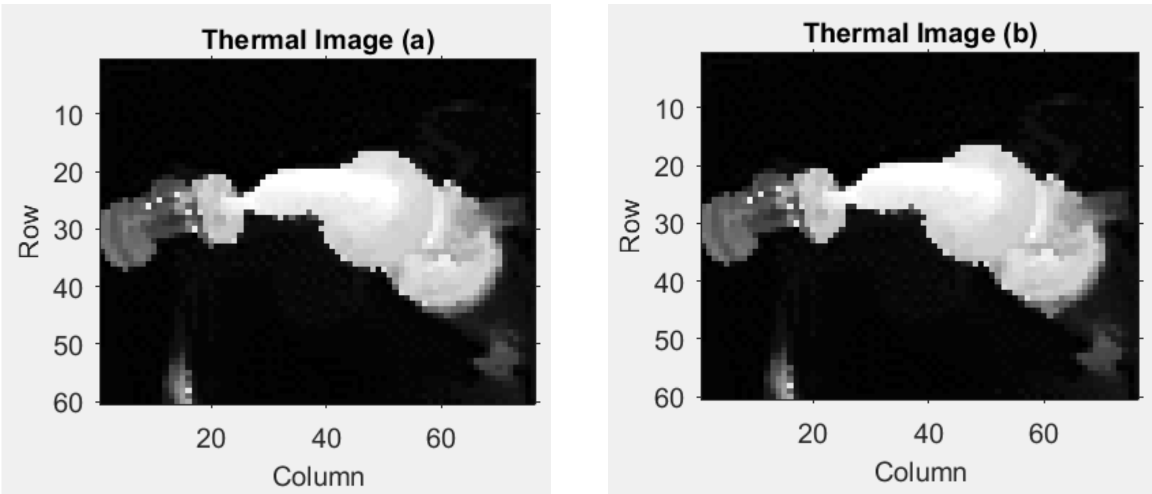
4.1.5 MATLAB code for image processing (liquid and gas detection)

In this section, the image processing stages to detect liquid or gas leakage are illustrated with MATLAB Simulink. As the real data is not available for this thesis, only two images are considered to be taken sequentially from IR camera and the whole process is shown on these two images. In real image processing, the number of images can be more to make the higher accuracy and reliability of the robot. The images, shown in figure 4.7 (a) and (b), are transformed to thermal images, shown in figure 4.8 (a) and (b) with the matrices showing the temperature of each pixel. The matrices of thermal images are x_1 and x_2. After having the two thermal image frames, subtracted thermal image frame (X_2) is provided in figure 4.9. The next step is the background noise reduction and single pixel noise removal which the result is shown in figure 4.10. It is visible that there are some leakage points in the image after noise removal (red circles). In last step, the subtracted thermal image after noise removal is checked whether it contains any non-zero pixel. This process needs to be checked with more photos and if non-zero pixels are found in other subtracted thermal images, the alarm shall be reported to onshore central control room for more investigation.



(a) *(b)*

Figure 4.7 sequential images from IR thermal camera



(a) *(b)*

Figure 4.8 Thermal/ Grayscale images

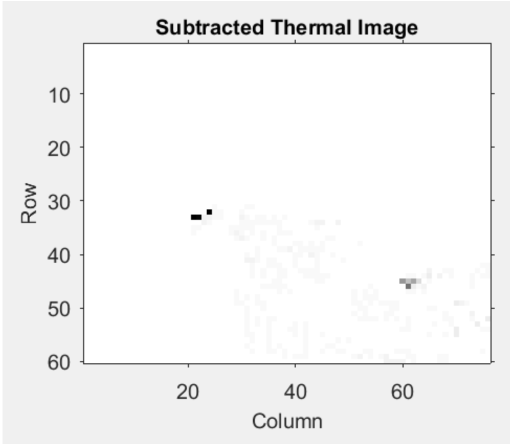


Figure 4.9 Subtracted thermal image

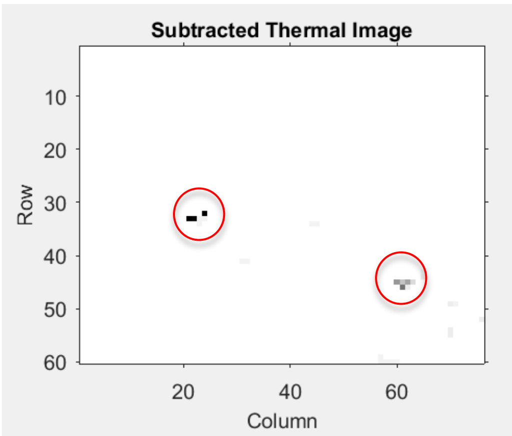


Figure 4.10 Subtracted thermal image after noise removal

4.2 Sound processing

There can be various tasks to be performed by microphones installed on robots. One of the ambitions is to find and localize the source of sound which is a critical task on the open platform with some equipment surround the robot and different sound sources. Another important task would be the sound level from some equipment such as motors. In next sections, the methods to carry out the tasks are discussed and illustrated in MALAB Simulink.

4.2.1 Review of Sound Source Localization methods

This review's major goal is to comprehensively map the state of the Sound Source Localization (SSL) area and to provide a place to start SSL in robotics. This part includes a thorough analysis and categorization of SSL approaches as well as widely used tracking strategies, and a number of obstacles and research goals. [25]

Automatically estimating the location of sound sources is the aim of sound source localization. In polar coordinates, SSL may be used to estimate the following two aspects of a source position:

- Estimating the direction of arrival (this can be done in one or two dimensions).
- Distance calculation.

SSL shall consider the possibility of several sound sources being active in the environment in real-world circumstances. Estimating the location of many simultaneous sound sources is so required. Furthermore, since both the robot and the sound source may be moving, it's critical to monitor its location over time.

Traditional methods like single direction-of-arrival (DOA) estimates, learning-based methods (such neural networks and manifold learning), and beamforming-based methods have all seen significant advancements because to SSL. Several aspects of SSL in robots have become apparent while implementing these techniques on robotics platforms, including: type and number of microphones, number of sources and their and mobility, noise and reverberation robustness, array geometry type to be used, robotic platforms type, etc.

The problem of locating a source only from audio data is addressed by sound source localization (SSL). Typically, there are several stages of data processing involved in this. Since the data is obtained directly from the microphones and offers SSL estimation, an end-to-end methodology is taken into consideration. The input signals are initially processed to extract the features. The feature-to-location mapping process that follows often makes use of a sound propagation model. The description of each approach makes specific mention of these three phases. An overview of these three phases is provided as below:

4.2.1.1 Propagation models

The user may be very close to or far from the microphone array depending on the robotic application, the positioning of the microphones because there may be an object between them, and the room characteristics because they determine how sound is reflected from the environment. Additionally, the kind of features to be used is typically determined by the propagation model.

The free-field/ far-field model, which is the most often used propagation model, has the following assumptions:

Free field: Each microphone receives the sound from each source in a single, straight line. This indicates that there aren't any obstructions between the sources and the microphones or inside the microphones themselves. Additionally, it is assumed that there are no reverberations or reflections from the surroundings.

Far field: The sound wave may be thought of as being planar because of the relationship between the inter-microphone distance and the distance of the sound source from the microphone array.

The second assumption substantially streamlines the process of mapping a feature to a place. There are more propagation model types that apply to SSL in robotics. The near-field model [26] makes the assumption that the user may be close to the microphone array, necessitating the assumption that the sound wave is circular. There are also situations where the propagation model is taught, such as neural network-based methods [27] and manifold learning [28].

4.2.1.2 Sound Characteristics

The approaches that were studied employ a variety of acoustic properties. An overview of the most well-known ones is given in this section:

Time difference of arrival (TDOA):

It is the difference in time between two signals that were collected. This property is often referred to as the inter-aural time difference (ITD) in binaural 2-microphone arrays that employ external pinnae. There are numerous approaches to figure it out, including timing the intervals between the signals' moments of zero-level crossings [29] or between the onset timings deduced from each signal [30]. However, cross-correlation techniques are the most widely used method of TDOA calculation [31].

Inter-microphone intensity difference (IID):

It is the energy differential between two signals at a specific moment. The source location of a two-microphone array may be identified using this characteristic, which can be derived from time-domain data. A multi-microphone array is required [32] or a learning-based mapping approach can be utilized [33] to give higher resolution.

Spectral notches:

The microphone signals are somewhat asymmetric when employing external pinnae. As a consequence, depending on the direction of a sound source, the result of their subtraction offers a decrease or amplification in some frequencies. Through experimentation, these notches can be mapped against the direction of the sound source [34]. However, it is advised to use learning-based mapping when using these features because trivial changes to the external pinnae could impair the findings from these observations [35].

Binaural/spectral cues:

It is a common phrase used to describe the feature set made up of the inter-microphone level difference (ILD) and the inter-microphone phase difference (IPD) together. With learning-based mapping, this feature set is frequently utilized. To lessen the impact of reverberation, they are frequently removed on the onset. However, their use is restricted to particular end-to-end methodologies.

4.2.1.3 Mapping methods

A given extracted feature is intended to be mapped to a location by a mapping technique for SSL. Applying a propagation model directly, like the free-field/far-field model, is a typical way to do this. However, some features necessitate an exploration or optimization of the SSL solution space, particularly those used for multiple-source-location estimation. An approach that is frequently used is to conduct a grid search, in which a mapping function is applied throughout the SSL space and the output is recorded for each location of a sound source that is being tested. A solution spectrum is the result, and peaks (or local maximums) are thought to represent SSL solutions. The most popular mapping technique for multiple-source-location estimates is this one.

Other mapping techniques exist besides grid-search. They are primarily concerned with developing the mapping function using recorded data from sources with known locations. As a result, the propagation model is indirectly encoded in the mapping function that was learnt.

4.2.1.4 Sound source localization end-to-end methodologies

As previously indicated, the direction of arrival (DOA) of a sound source and its proximity to the microphone array are often taken into account when determining the position of a sound source. The origin is typically thought to be at the center of the array of microphones. The elevation plane is orthogonal to the azimuth plane, which is parallel to the horizon of the physical universe.

This section presents a taxonomy of end-to-end SSL techniques. A form of divide-and-conquer SSL concept has gained popularity as a result of the two components that make up a sound source location: the assessment of the DOA and the distance are done individually. Additionally, the only aspect of the location that is typically reported is the DOA. However, significant progress has been made in distance estimation, which justifies their own branch.

The taxonomy presented is provided as below:

1-dimensional single DOA estimation: The methods which estimate the DOA in the azimuth plane with a single source are provided in this type.

2-dimensional single DOA estimation: The methods which estimate the DOA in both the azimuth and the elevation plane with a single source are provided in this type.

Multiple direction-of-arrival estimation: The methods which estimate the DOA of multiple sources are provided in this type. They are in the azimuth plane most of the time, but their generalization way to both planes is provided too. There are three subcategories for this type:

- **Beamforming-based:** spatial filtering for different DOA candidates can be performed.
- **Subspace methods:** The differences between noise and signal subspaces are taken into account.
- **Source clustering through time:** Single DOA over various time frames is estimated and a multiple-DOA solution by clustering the outputs is provided.
- **Distance estimation:** Methods which the distance of the sound source to the microphone array is estimated are provided.

4.2.2 Selected Sound Source Localization method

As mentioned in previous section, sound source localization is the process of using sounds to pinpoint a source's location and distance. Accurate localization of a sound source is made possible by these two factors, which is essential for a few applications. However, since the robot can move and estimate the distance of the sound source by moving, getting the distance is not necessary for this project. The robot can move in the estimated direction and recheck the sound source if the direction and sound level are approximated. It may be inferred that the robot is moving toward the sound source as long as the sound source is pointed in the same direction and the sound level is rising as the robot moves, and that is adequate for this application. This makes it possible to create less complicated systems without sacrificing performance.

This project focuses on a straightforward method for determining a source's direction using two microphones. The approach is given and put to the test to determine its reliability. MATLAB is used to program the system to process the sound signals. The method for sound source localization in this section has been inspired from a master thesis, Direction of arrival estimation– A two microphones approach. [36]

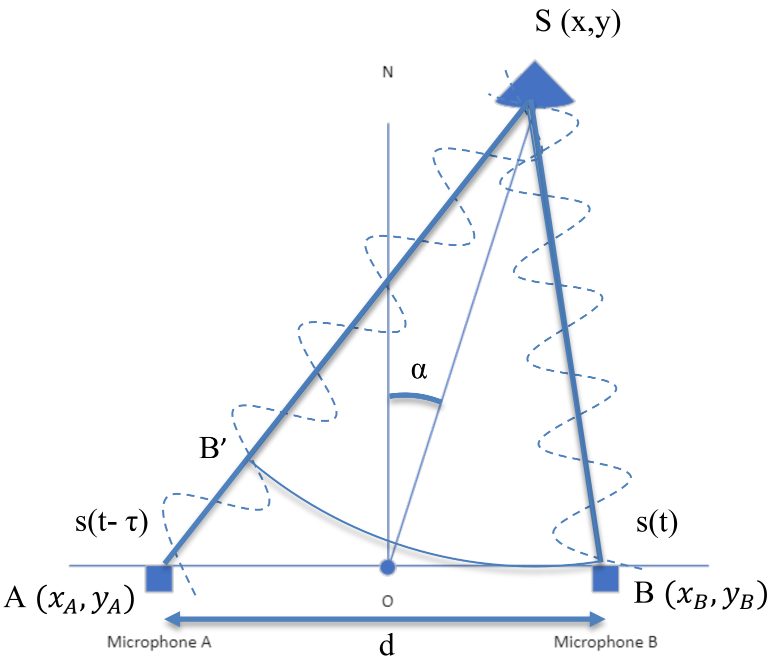


Figure 4.11 Illustration of the time difference of arrival at two microphones receiving a sound wave

Figure 4.11, which depicts the simplified system, displays the delay in a sound wave's arrival at two microphones. The system's output is an as-accurate-as-possible estimation of the angle. The goal is to identify the direction in which sounds from a source (S) in front of two microphones arrive. It is necessary to take into account an origin (O) from which the measurements are taken. The robot's microphones are set in place and spaced at a specific distance (d) apart. The origin is then placed in the center of the microphones. The angle for the direction or angle of the sound source is defined by considering the orthogonal line to the microphone axis at the origin (ON).

The sound moving through the air to the microphones first reaches microphone B and then microphone A because the sound source is closer to microphone B than microphone A. These two moments' time difference is indicated by τ. An analog signal, s(t), represents the sound signal. The signals recorded by both microphones should theoretically have almost similar amplitudes and only be slightly delayed. It follows that the signal recorded by microphone A would be s(t- τ), given that the signal recorded by microphone B is s(t).

According to figure 4.12, the sound source in this system can be on the front semi-circle of the microphones. These can be in any position between -90° and +90°.

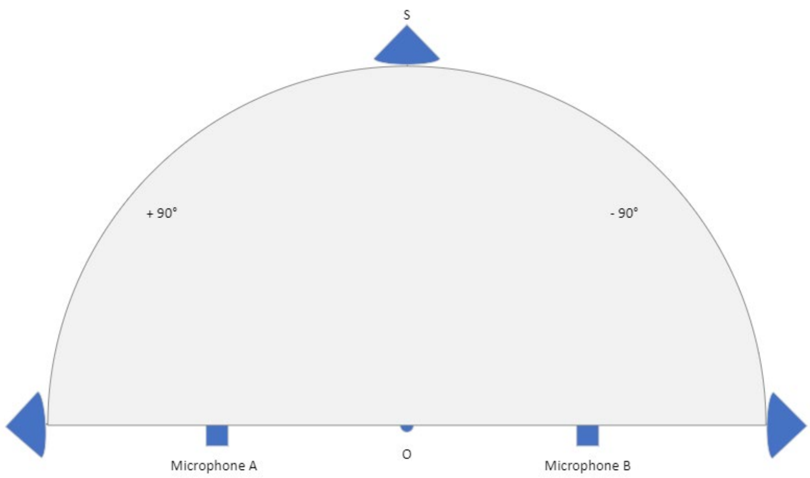


Figure 4.12 Sound source location

Once both signals are captured, they are processed to estimate the time delay. The first step is to convert the analog signal to digital signal for processing. Analog to digital conversion is performed by sampling from the analog signal. Signals are changed from continuous-time domain to discrete-time domain during the sampling process. The sampling frequency f_s is the primary variable. An analog signal called s(t) is used to represent the voice. The two microphones' signals were separated in time, and this was indicated by τ. The delay would reflect the amount of time needed to travel the differential distances (distance from sound source to microphone A minus distance from sound source to microphone B, AB') when a movement at the speed of sound (c = 343 m/s) is taken into account. Thus, the signals recorded by microphones B and A are $s_1(t)$ and $s_2(t)$, respectively. The time is expressed in samples after the microphones have sampled the signals.

$$s_2(t) = s_1(t - \tau) \qquad (4.2)$$

To determine the time difference on microphone A and B received sound signals τ, cross-correlation is used in this thesis as it is one of the common methods for Sound Source Localization.

$\tau = argmax \sum_{t=t_1}^{t_2} s_1(t).s_2(t)$ (4.3)

Generalized cross-correlation (GCC) function is provided in MATLAB and its output is the time difference, τ, of receive sound signals on microphone A and B. As sound speed is known, the differential distance, AB', can be calculated.

$AB' = \tau . c$ (4.4)

In order to have higher accuracy, it is better to select high sampling frequency. Minimum sampling frequency shall be double of signal frequency to prevent temporal aliasing, but it is efficient to have higher sampling frequency as much as possible. Another important point is to have the delay on received signal in microphone A and B less than the half of wavelength of the sound signal in order to prevent spatial aliasing. As the wavelength of sound signal is considered λ, the delay is better to be AB' $< \frac{\lambda}{2}$. When the microphones are far apart, issues start to occur. In this scenario, the delay may rise until it exceeds λ/2. If that happens, either the delay can be falsely detected, or maybe it isn't detected at all. In case of false estimation of delay, the microphone A is detected to be closer than microphone B to sound source.

The maximum differential distance (AB') can be equal to the microphones' distance (d) while the sound source is on -90° or +90° positions, therefore d $< \frac{\lambda}{2}$.

$\lambda_{min} = \frac{c}{f_{max}}$ (4.5)

As there is a wide range of sound frequency in industrial environment, the maximum frequency (10 kHz) is considered to calculate the minimum wavelength. Therefore,

$d < \frac{343\ m/s}{2\ x\ 10{,}000\ Hz} = 1.7\ cm$ (4.6)

Calculated distance between the microphones is too small and affect the accuracy of the direction estimation. Therefore, longer distance 17 cm is considered which causes to read the sound signals less than 1 kHz without any issue. But for the high frequency sound, there might be some issues such as spatial aliasing. It needs to be noted that the most of large equipment on offshore platforms has low frequency sound. In case of high frequency sound, since the sound source localization is processed while the robot is moving, the false reading can be recognized if the robot is moving towards the wrong location. So, the sound direction is not maintained the same as before while moving towards the sound source and robot can change the movement toward the new direction to check its validity. It is worth to be mentioned that the robots are not moving only based on the sound source localization data as they have camera and GPS to proceed the way forward. But the sound source direction is also important to be estimated to complete the abilities of the robots.

After calculation of AB', the sound source angle, α, needs to be calculated. Based on the assumptions, $y_A = y_B = 0$ and $x_A = -x_B = \frac{d}{2}$. Also, it can be seen from the figure 4.11 that AB'=AS - SB' and SB'=SB.

After several calculations, the position of sound source can be estimated as below:

$$y = \pm\sqrt{\frac{\text{AB}'^2}{4} - \frac{d^2}{4} + x^2(\frac{d^2}{\text{AB}'^2} - 1)} \qquad (4.7)$$

$$\alpha = \tan^{-1}(\frac{dy(x)}{dx}) \qquad (4.8)$$

To estimate the position of sound source, a wide range of x is considered and the y is calculated based on the equation 4.8. Then the sound source angle, α, is calculated based on the slope of (x, y) estimated samples.

4.2.3 MATLAB code for Sound Source Localization

In order to simulate the sound processing, a sound file (.wav) sample from an industrial environment related to a fire engine pump is used. The sound signal is considered to be received on microphone B and it is delayed 0.2 ms to be received on microphone A. Figure 4.13 shows the sound signals received on microphone A and B.

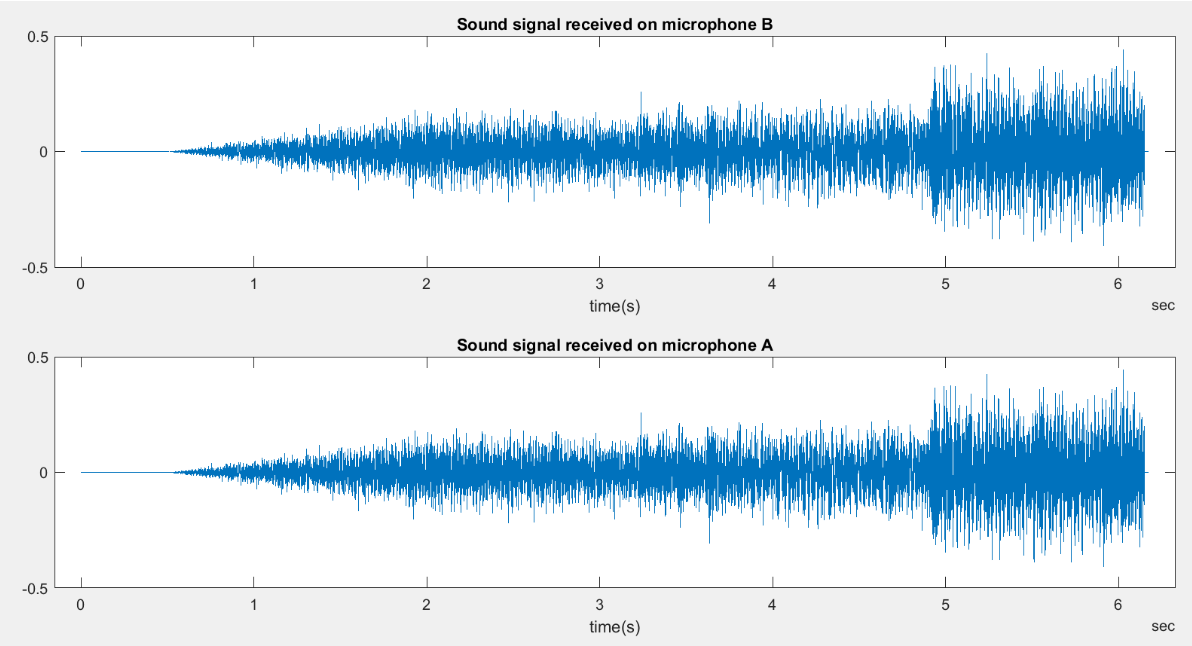


Figure 4.13 Sound signal received on microphone A and B

The delay is not visible on figure 4.13, but it can be seen on figure 4.14 as zoomed in and a sample point in tagged.

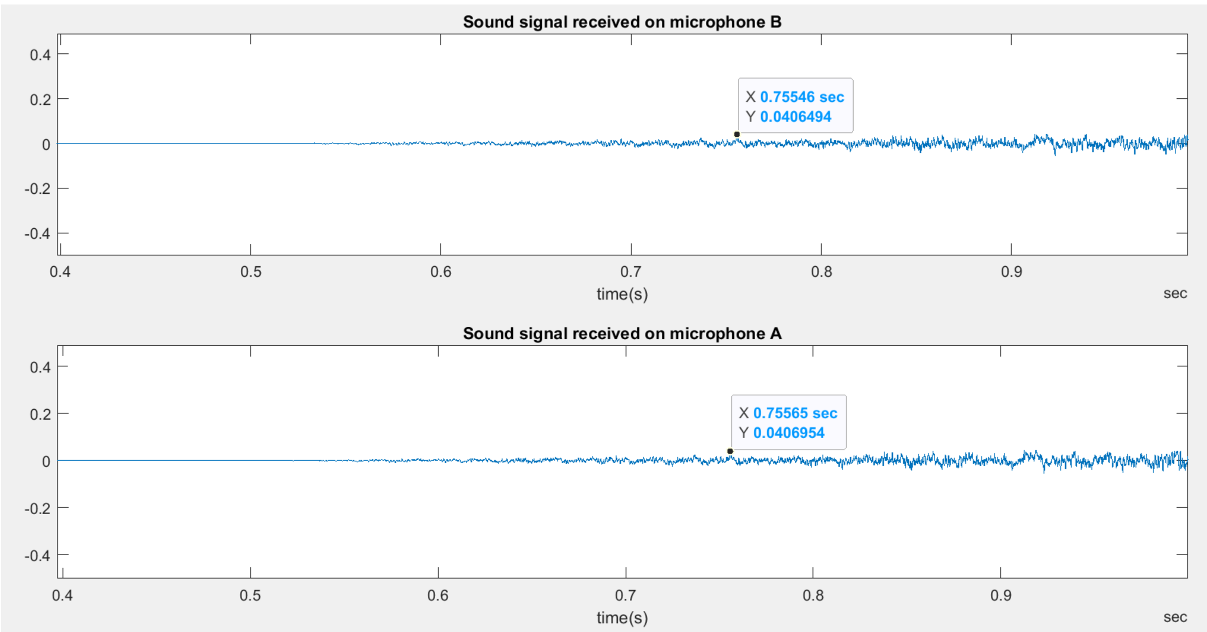


Figure 4.14 Zoomed Sound signal received on microphone A and B

Figure 4.15 presents the estimated sound source positions in the range of x from -20 to +20 meters. As mentioned, the direction of sound source can be found based on the slope of the estimated line.

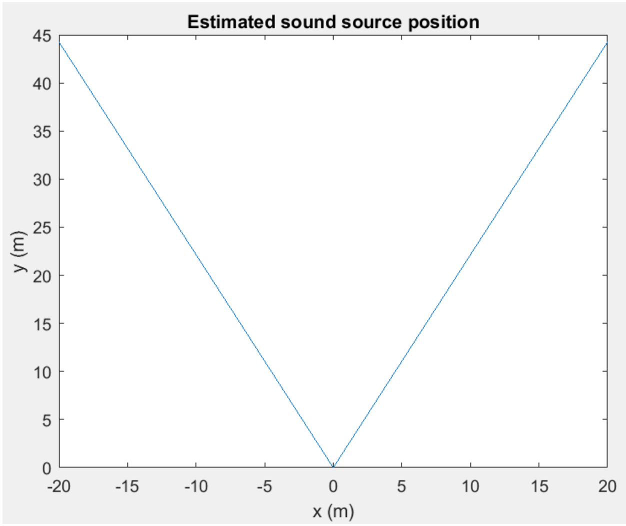


Figure 4.15 Estimated sound source position

The sound processing design is valid as long as the calculated AB' is less than or equal to the distance between microphones, d, which shows the sound source is on front semicircle of the microphones. Otherwise, the robot needs to use the other features like its camera or GPS to move closer to targeted equipment. To illustrate the estimated sound source and its angle, the valid range of delays were checked in MATLAB. As per equation (4.4) and above limitation for AB', it can be concluded that time difference between microphone A and B shall be less than 0.49 ms ($\tau = \frac{\text{AB'}}{c} = \frac{0.17\ m}{343\ m/s} = 0.49\ ms$) in order to have the valid estimation. Therefore, the time difference from - 0.5 ms to + 0.5 ms is taken to estimate the sound source position and its angle. The result is shown on figure 4.16.

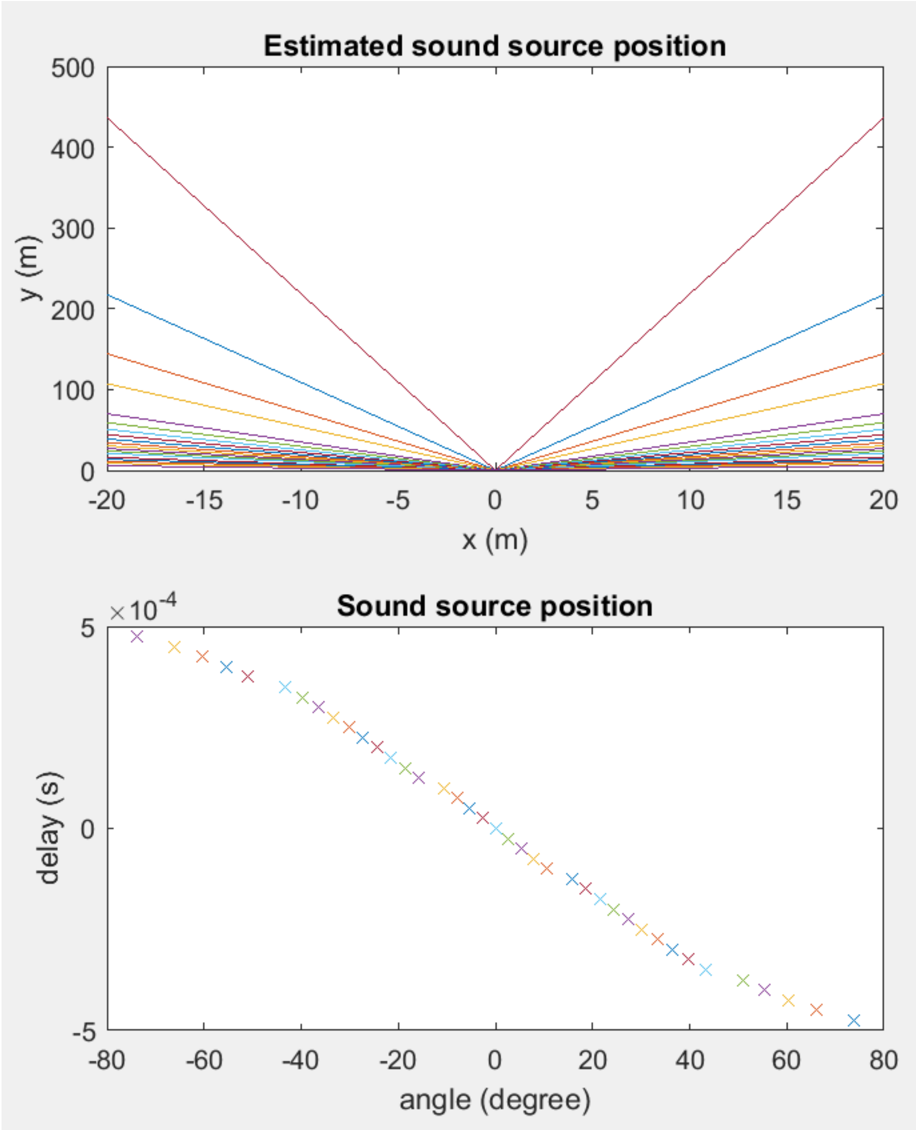


Figure 4.16 Sound source position and its angle for time difference (delay) from -0.5 ms to +0.5 ms

4.2.4 MATLAB code to calculate Sound Pressure Level

Sound pressure level in dB is required to be checked as it is a way to make sure of the proper operation of equipment. For example, the sound pressure level on the pump can present its operation. For different equipment, the reference sound level is required to be set in microcontroller of the robot. After calculation of sound level, it is compared with reference, and it can report the alarm in case of higher sound pressure level than the reference.

In Appendix C, the MATLAB code to calculate the sound pressure level in dB is provided. The content of sound file (.wav) is proportional to the output voltage range of the microphone. While the sound file (.wav) is read, the content can be converted to the voltage of the microphone. And as per the equation (4.9), the sound pressure level can be found. This equation is provided in installation and operation manual of selected microphone. [17]

$$SPL = \left(20 \log\left(\frac{V_{rms}}{S\,P_{ref}}\right)\right)\ dB \qquad (4.9)$$

S is the sensitivity of the microphone which is 50 $^{mv}/_{Pa}$ and P_{ref} is the reference pressure in air that is $20x10^{-6}\ Pa$. The maximum output voltage for selected microphone is ±7 V. So, the content of audio file (.wav) which is between -1 and +1, can be multiplied to the maximum output voltage in order to provide the audio voltage signal. The voltage signal is shown on figure 4.17.

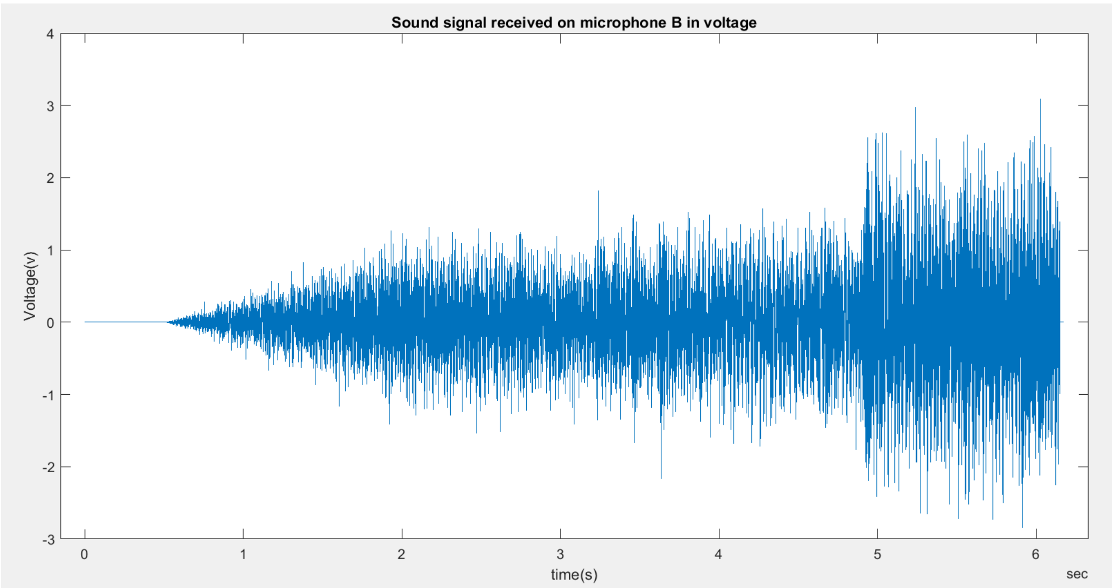


Figure 4.17 Sound signal read from microphone B in voltage

The sound pressure level for each period of 0.23 second is calculated and checked with the sound pressure level reference of the equipment. Figure 4.18 shows the sound pressure level in dB for each period over the time.

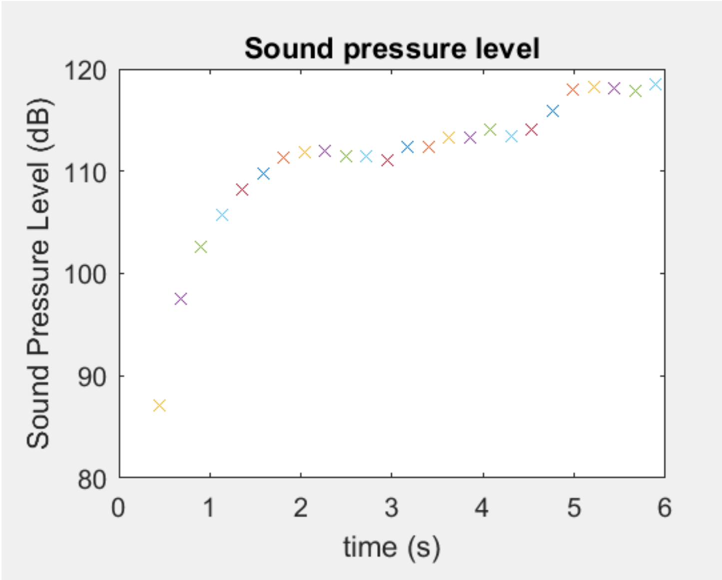


Figure 4.18 Sound pressure level in each period

4.3 Vibration Analysis [37, 38]

Since vibration is an oscillating motion around equilibrium, most vibration analysis focuses on figuring out how fast the oscillation is happening or how much the frequency varies with the stiffness of the system. The vibration frequency might be established for basic sine waves by examining the waveform in the time domain, but when more frequency components and noise are introduced, spectrum analysis is required to obtain a more precise understanding of the vibration frequency.

The practice of monitoring the vibration levels and frequencies of machinery and utilizing that data to assess the state of health of the machine and its components is known as vibration analysis. The first step in this procedure is to measure vibration with an accelerometer. The quantity of vibration and frequency the machine is creating, often how many times per second or minute the vibration happens, are represented by a voltage signal produced by an accelerometer attached to the machine.

The accelerometer's data was utilized to record the signal as either an amplitude vs. time (time waveform) or an amplitude vs. frequency (fast Fourier transform) waveform. All of this data is analyzed by using computer program algorithms to assess the machine's health and spot potential issues like looseness, unbalance, misalignment, lubrication problems, bearing failures, critical speeds, and more.

4.3.1 Vibration Analysis Methodology

Each of the several concepts of vibration analysis provides precise details on the characteristics and operational circumstances of the vibrating parts.

Time domain: The waveform of a vibration signal generated by a vibration sensor is in mv AC. The time domain encompasses this signal. Plotting amplitude in g (9.81 $m^2/_s$) against time can be used to translate the time domain to amplitude. Spectrum analysis is used to find most machine vibration problems, however others can be seen more clearly in waveforms. A few characteristics are discernible in assessing the severity of a vibration profile when studying vibration data in the time domain (amplitude plotted against time): amplitude, peak-to-peak value, and RMS. For shock occurrences, the peak or amplitude is useful, but it ignores the duration and subsequently the energy of the event. Peak-to-peak has the same advantages as peak-to-peak with the additional benefit of displaying the wave's highest excursion, which is helpful for examining displacement data, particularly clearances. Because it directly correlates with the energy content of the vibration profile and, consequently, the vibration's capacity for causing damage, the RMS (root mean square) value is often the most helpful. RMS also considers the waveform's time history.

Frequency domain: The outcome of spectrum analysis on the waveform outlined previously is a representation of frequency vs. amplitude known as a spectrum. Spectrum analysis or frequency domain analysis are used to conduct the majority of in-depth analyses of machinery vibration.

Numerous types of analysis, computations, and algorithms are employed to identify other elements of vibration analysis outside of these fundamental concepts. These consist of:

- **Time waveform:** A time waveform is an acceleration versus time graph. Time waveforms display a brief time sample of unprocessed vibration, offering hints about the state of equipment that aren't necessarily obvious from the frequency spectrum.

Figure 4.19 shows an example of vibration sensor signal in time domain. FFT is a technique for utilizing time waveform vibration signals as a tool for vibration analysis.

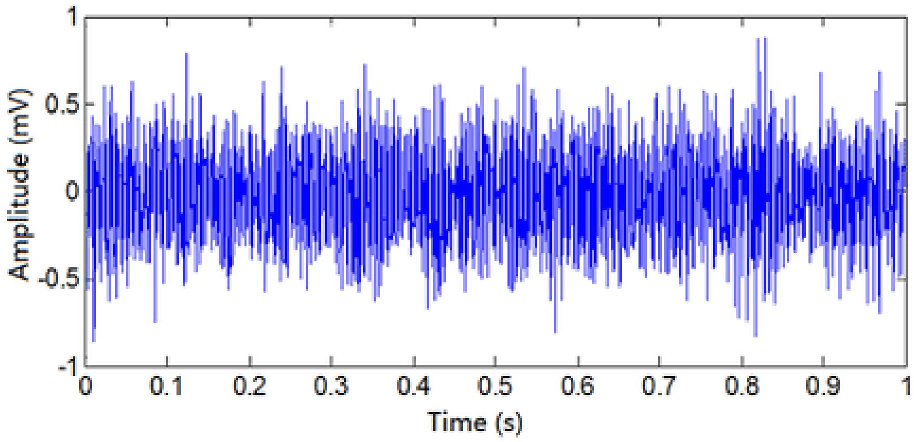


Figure 4.19 Vibration sensor signal in time domain

- **Fast Fourier Transform (FFT):** In reality, every periodic waveform is merely the accumulation of a number of straightforward sinusoids with varying frequencies, amplitudes, and phases. A signal may be broken down into its constituent sine wave components using Fourier analysis or spectrum analysis. A Fourier series is the sum of sine waves. The outcome is acceleration/vibration amplitude as a function of frequency, which enables study in the frequency domain (or spectrum) to comprehend the vibration profile more thoroughly. The majority of vibration analysis is normally carried out in the frequency range. A spectrum may be generated from a time waveform using the FFT technique. To put it another way, it is a computation used to separate a signal into all of its frequencies. A signal is transformed using FFT from the time domain to the frequency domain. The fast Fourier transform is most frequently used to find alignment or balance issues with machines. Figure 4.20 presents a vibration sensor signal in frequency domain with applying FFT to its time domain waveform.

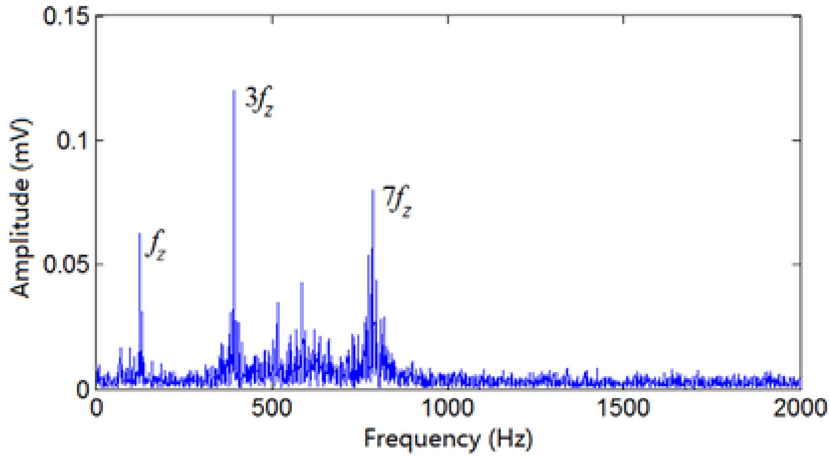


Figure 4.20 Vibration sensor signal in frequency domain

- **Phase measurement:** In the context of vibration analysis, phase refers to the relative timing difference between two signals, which is expressed in angle- rather than time-based units. The two signals being compared must be of the same frequency for it to function. FFT is used with phase measurement to identify machine problems such loose components, misalignment, and imbalance. Figure 4.21 shows an example of amplitude and phase signals on frequency domain.

Figure 4.21 Amplitude and phase signals in frequency domain

- **Order analysis:** It is a type of FFT analysis that is typically used to measure the vibrations produced by machinery with a range of RPMs. In order analysis, the frequency axis of the spectrum is shown in orders of RPM rather than hertz. The word "orders" describes a frequency that is a multiple of a reference rotational speed. The order is two, for instance, if a vibration signal is equal to twice the frequency of the motor's rotation.

4.3.2 Measurement Parameters for Vibration Analysis

Three key characteristics are identified by each of these vibration analysis methods: acceleration, velocity (RMS or peak), and displacement. Each of these characteristics highlights specific frequency ranges in a different way, and they may be used to detect problems. Let's examine each parameter one by one.

- **Acceleration:** High frequencies are more important in acceleration. However, an acceleration signal is not exclusive. It is possible to transform the acceleration signal to displacement or velocity.
- **Displacement:** Similar to how acceleration emphasizes high frequencies more than low frequencies, displacement focuses on low frequencies. Displacement measurements are often only employed when analyzing mechanical vibrations in their entirety. Displacement may be used to identify imbalance in a rotating component that results from a sizable quantity of displacement at the machine's shaft's rotational frequencies.
- **Velocity:** The most crucial metric is velocity since it is connected to the destructive power of vibration. Both high frequencies and low frequencies are given equal weight. Typically, the best indicator of the intensity of vibration is the RMS value of velocity, which is measured between 10 and 10,000 Hz. Peak amplitude is multiplied by 0.707 to determine RMS.

To assist in identifying specific failure frequencies for the components such as bearings, databases would be preloaded with hundreds of fault frequencies for that specific equipment.

4.3.3 MATLAB code for vibration analysis

The selected vibration sensor has a 4-20mA output signal which is equivalent to 0-1 in/s peak of velocity signal. With proposed connection in figure 2.20 this signal can be connected to microcontroller to read peak velocity measurement. This output signal can be compared with a peak velocity reference and triggered the alarm if peak velocity is going higher than its reference. As the resistor holds 1-5 VDC voltage proportional to 4-20mA current signal from vibration sensor, the 0-1 in/s peak velocity is equivalent to 1-5 VDC voltage on microcontroller.

So, if the output current from vibration sensor is 6mA, the voltage on microcontroller AI (analog input) is 1.5 VDC which is equal to 0.125 in/s peak velocity. This analog input is always checked and if it goes higher than peak velocity (e.g., 0.5 in/s equivalent to 3 VDC on AI), the alarm is shown the high vibration peak velocity.

There is also additional RV (Raw Vibration) output from selected vibration sensor which can present acceleration waveform with amplitude of 15 g peak. This signal is provided with sensitivity of 100 mv/g; therefore, the output voltage signal will be mV AC from -1500 to +1500 mV. The signal shall be recorded for few seconds and then transformed to frequency domain by FFT (Fast Fourier transform). Then, amplitude of acceleration is calculated to check it on frequency domain. For each equipment, there can be different faulty conditions which are detectable on frequency domain. First the vibration data for healthy equipment shall be captured to have a reference for the checking. Then any measured vibration data can be compared with the reference to recognize the failures on the equipment. In this thesis, an electric motor's vibration data is used to check its condition. Three datasets are checked, one without load and with half speed, the other with load and half speed and the last dataset with imbalance problem and half speed. The MATLAB code for vibration analysis is provided in Appendix D.

Raw vibration data (acceleration) and its RMS are shown in time domain in figure 4.22 and 4.23, respectively. These signals are related to the raw vibration data of electric motor without load and with half speed.

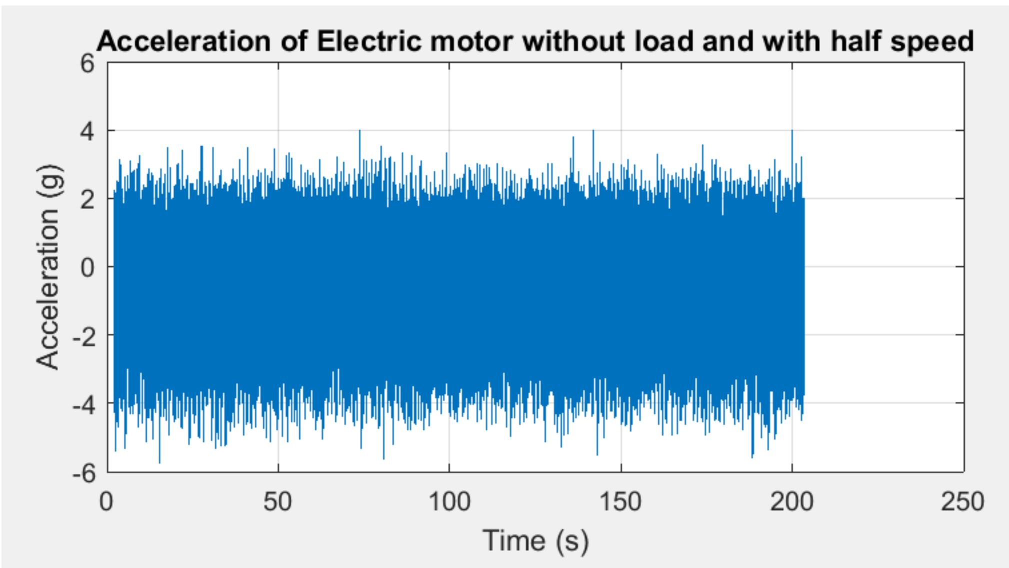


Figure 4.22 Raw Vibration data of electric motor without load and with half speed- Acceleration in time domain

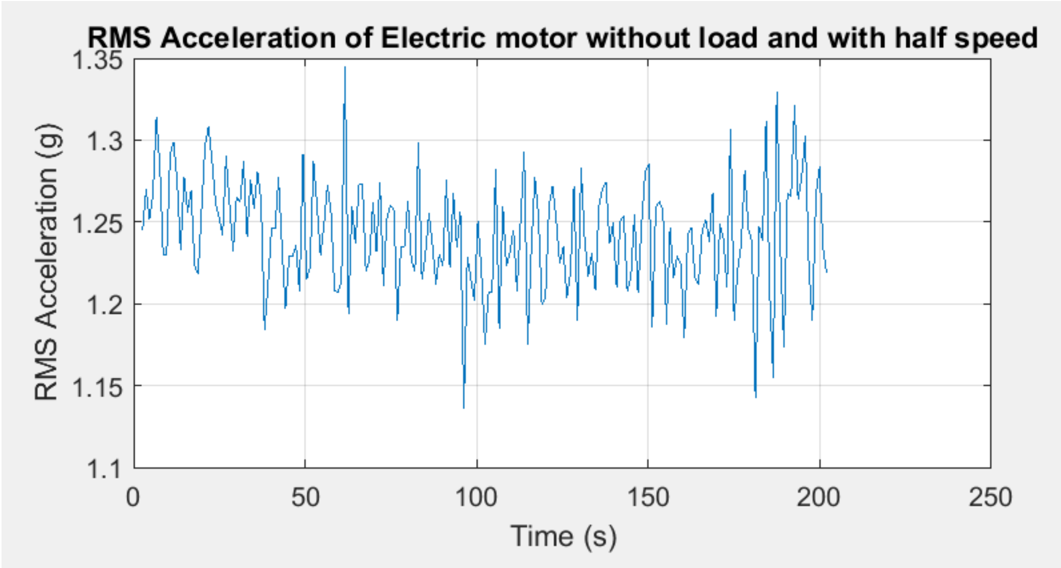


Figure 4.23 Raw Vibration data of electric motor without load and with half speed - RMS Acceleration in time domain

As mentioned before, FFT of acceleration signal converts the acceleration waveform from time domain to frequency domain. The amplitude of these acceleration waveforms on different frequencies is plotted in figure 4.24. This signal has important role to diagnose the equipment. The amplitude of acceleration can have a limit on some specific frequencies such as the frequency of motor or its revolutions per minute. Also, the highest vibration (amplitude of acceleration) can be occurred on this frequency. In figure 4.24, the highest acceleration amplitude is seen at 23 Hz which is equivalent to motor speed, around 1,400 rpm. Lower acceleration amplitudes can be made because of different reasons such as harmonics and noises.

The other vibration dataset for electric motor with load and half speed is transformed to frequency domain to be analyzed and compared with the first vibration dataset. Figure 4.24 is shown its amplitude of acceleration in frequency domain. As it can be seen, the high values of acceleration amplitude are in the same frequencies and only their amplitude is higher with load in compared with motor without load.

As per these two plots, it can be concluded that high amplitude of acceleration shall be on motor speed with a specific limit which is on full load. If the highest acceleration amplitude occurs on different frequency, the equipment might be faulty. The possible faults can be figured out by robot and its alarm can be sent out to control room to be analyzed in more details.

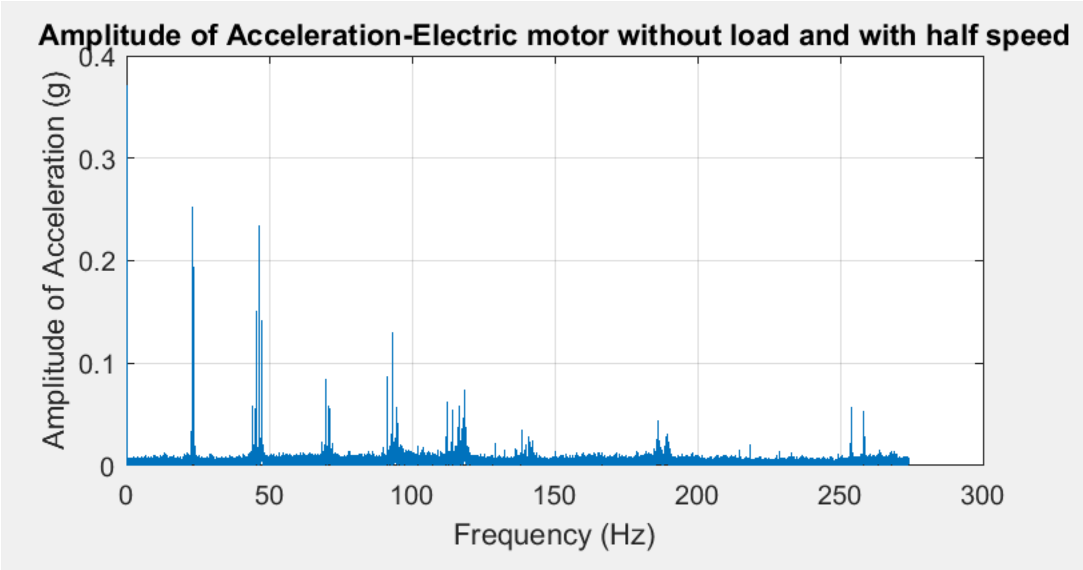


Figure 4.24 Amplitude of Acceleration in frequency domain for electric motor without load and with half speed

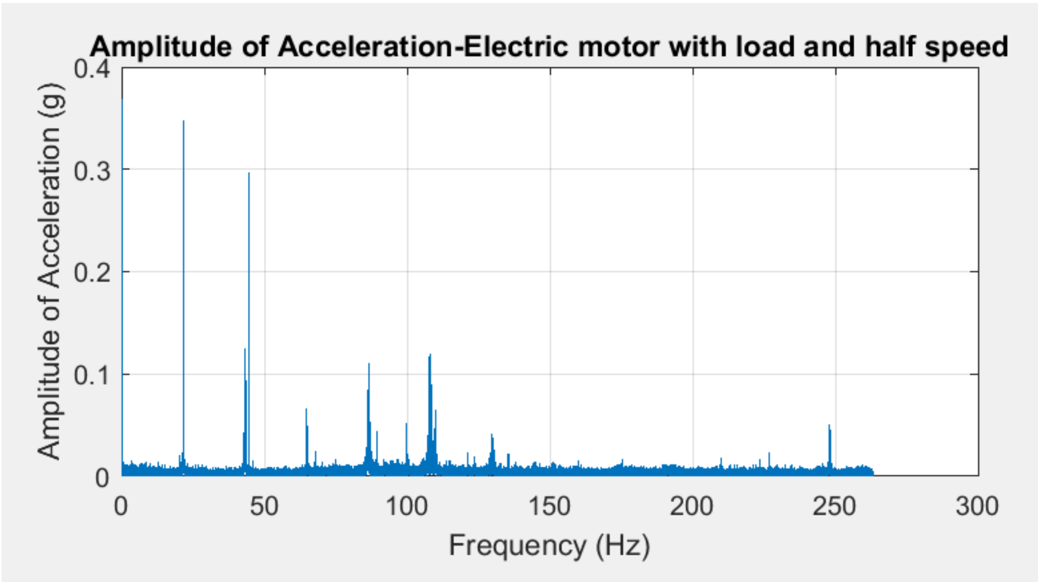


Figure 4.25 Amplitude of Acceleration in frequency domain for electric motor with load and half speed

The last vibration dataset is related to electric motor with half speed and mechanically imbalance fault. Figure 4.26 and 4.27 present raw vibration data (acceleration) and its RMS in time domain. It is obvious that acceleration values are higher than values with first dataset for healthy motor. That is to say, it is possible to detect the faulty motor with its RMS or peak acceleration values.

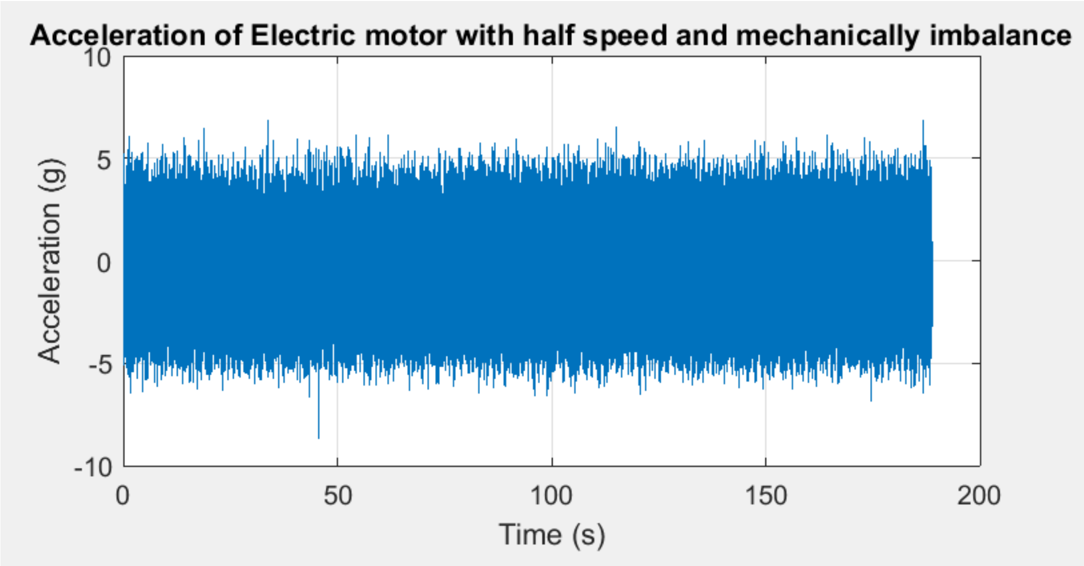


Figure 4.26 Raw Vibration data of electric motor with half speed and mechanically imbalance- Acceleration in time domain

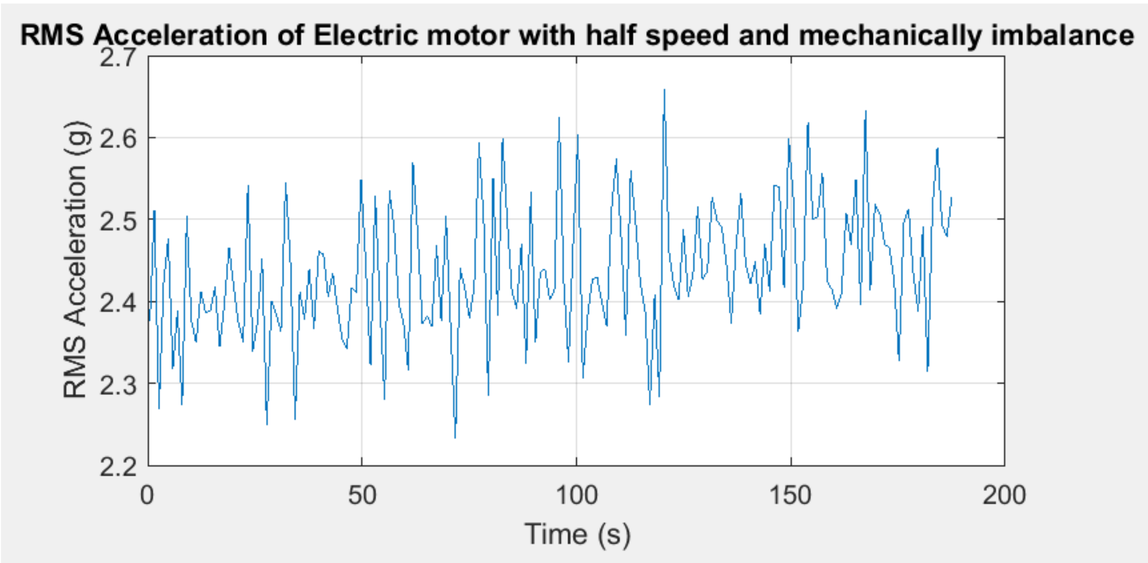


Figure 4.27 Raw Vibration data of electric motor with half speed and mechanically imbalance- RMS Acceleration in time domain

Figure 4.28 is accordingly the amplitude of acceleration waveforms in frequency domain which is produced from FFT of acceleration signal in time domain. It can be seen that the highest acceleration amplitude is not on 23 Hz frequency (same as figure 4.24 and 4.25). While the highest amplitude of acceleration is on 100 Hz frequency. This considerable difference from reference dataset can be detected by robot and recorded as alarm to send to CCR (central control room) for more investigation.

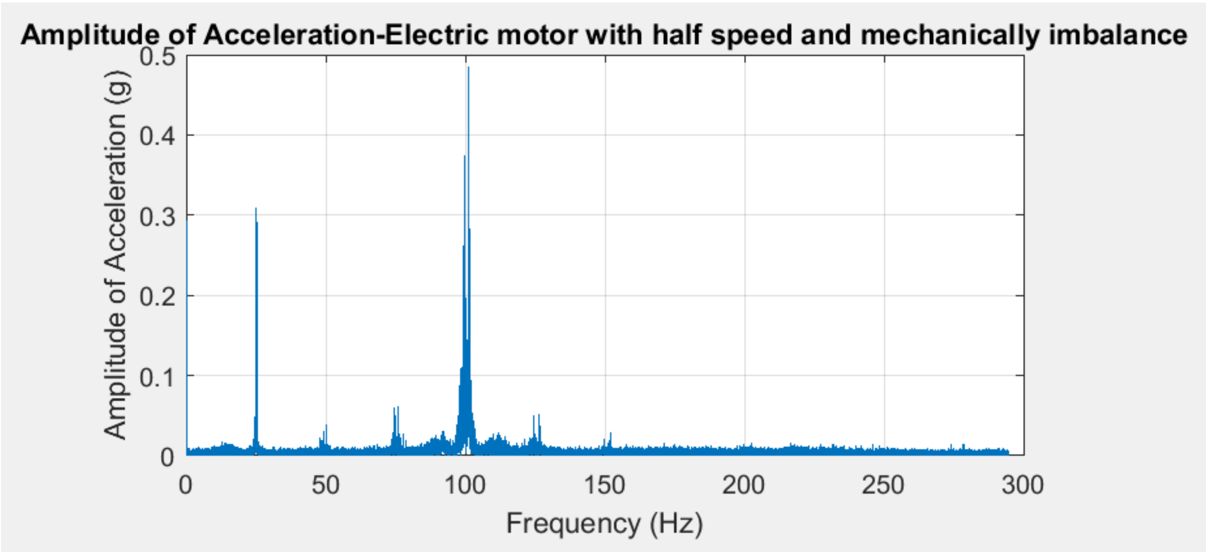


Figure 4.28 Amplitude of Acceleration in frequency domain for electric motor with half speed and mechanically imbalance

5 Discussion and future work

This thesis was about integrating sensors and instruments on robots which have crucial role on oil platforms in Yggdrasil project. The intention of robots' usage is to have unmanned offshore platforms and decrease the human resources available 24/7 on offshore platforms. To achieve this target, robots are required to carry out different tasks from check and report to maintenance. Only the check and report tasks were taken into account on this thesis. There are many stages from front-end design of the robots to manufacture and test them in different conditions. Therefore, it was not possible to perform all these stages in the time frame of this thesis. The goal of this thesis was to design the required sensors and instruments for check and report tasks as well as proposing the suitable methods to analyze measured and captured data in order to report the hazards, faults, and malfunctions of equipment.

Check and report tasks done by operators were collected to make the list of instrument and sensors with which the robots need to collect the information (inspection data). The sensors and instruments were selected based on project requirements and NORSOK standards. Some of these instruments are not accurate enough to be used in offshore oil and gas environment. For example, the resolution and accuracy of thermal IR camera is an important factor to make the robot more reliable on gas and liquid leakage detection. Currently, there is no ATEX certified IR thermal camera with high resolution. There are some ongoing works to achieve ATEX certification for some models of IR thermal camera. With higher resolution, the thermal images can be more accurate and small leakages are also recognizable. After instrument selections, the processing and analysis of measured data were investigated, and a suitable method was proposed to check the data and report the failures. These process and analysis were simulated in MATLAB to make sure of their functionality. The result of MATLAB codes was presented in chapter 4.

Necessary hardware to integrate these instruments were not studied in detail since it can be embedded with the robot microcontroller used for some other tasks. Just a microcontroller was proposed as a solution to integrate the sensors. And design of the microcontroller board with all required features such as WiFi and 4-20mA reading ability (listed in chapter 3) is needed to be done for sensors integration on robot. That is, what was shown in chapter 2 about selection of microcontroller boards is an example in order to present a way to implement the proposed design. Therefore, its reliability and operability need to be evaluated as future work. In addition, the proposed sensors and instruments are required to be procured and integrated on a robot to make a prototype. Afterwards, the prototype shall be tested in different conditions to get approval of ready to use on offshore platforms. The physical design of robots and instruments installation on them are remained as future work. But it is worth mentioning that manufacturer and model of instruments and sensors were selected and ready to be utilized for physical assembly.

Some other parts of robot design to complete the check and report tasks such as data transfer to central control room was not discussed in this thesis as it needs to be checked as per offshore facilities and network availability. The robots' activities for equipment inspection are not continuous streaming of everything, only data is captured or measured while it is required to be checked and reported. So, the data processing can be used as a function whenever it is applicable. The robot should be designed to have a data storage to save the measured data and upload the reference data to be employed for data analysis so that it can check while it is running and report (alarm) if there is a significant deviation. In addition, it shall have the possibility of transfer or download the data to a local PC when the robot has finished the inspection round.

6 Conclusion

This thesis aimed to identify effective strategies for integration of sensors and instruments on a robot in order that the robot can carry out operators' tasks on offshore oil and gas platforms. Based on study of acceptable instruments on offshore oil and gas platforms and project requirements as per standards, it can be concluded that ATEX certification and reliability of the sensors and instruments are important factors to consider when designing the whole system. In addition, the suitable data processing methods were selected to present the way to analyze the measured data from sensors and instruments. The results indicate that sensors can be found as per requirements and the data processing is implementable to find the hazards and failures of the equipment on oil and gas platforms.

This research clearly illustrates the sensors and instruments model which are taken into account to capture or measure the required data for check and report purposes by robots. Moreover, the integration of these instruments was demonstrated with the help of a microcontroller and solutions were proposed how to read different types of instruments' outputs such as WiFi and 4-20mA analog output in the microcontroller, but it also raises the question of functionality and speed of microcontroller in this application since it has not been evaluated thoroughly.

To better understand the implications of these results, future studies could address the most suitable robots' brain which might be a microcontroller as proposed in this thesis or a FPGA. The robust design would be completed with building a robot prototype and test it for all check and report tasks to make sure of reliability and accuracy of the proposed solutions in this research.

This thesis simulation results in MATLAB have shown that chosen sensors and instruments which are a NDIR (Non-Dispersive Infra-Red) gas sensor, a thermal IR (Infra-Red) camera, two microphones and a vibration sensor are in line with selected methodologies for image processing, sound processing, and vibration analysis, respectively, to check and report the platforms problems before the serious dangers can occur. Gas and liquid leakage, abnormal sounds and high vibrations from equipment are the dangers and malfunctions which have been simulated in MATLAB to prove that they are detectable with this research outcome.

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Appendix A

Matlab simulink code for conversion of the image taken from IR camera to the thermal image:

```
>> File = 'thermal_image.png';
>> folder = pwd;
>> FileName = fullfile (folder, File);
>> RGBImage = imread (FileName);
>> [rows, columns, NumberOfColors] = size (RGBImage);
>> imshow (RGBImage, []);
>> figure.WindowState = 'maximized';
>> axis on;
>> fontSize = 10;
>> refTemperature = 200;
>> Title = "RGB Image";
>> title (Title, 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> drawnow;
>> grayImage = min (RGBImage, [], 3);
>> roiPosition= [1, 1, columns, rows];
>> ImagePosition = [roiPosition(1), roiPosition(2), roiPosition(3)-4, roiPosition(4)-1];
>> hold on;
>> rectangle ('Position', ImagePosition, 'EdgeColor', 'r', 'LineWidth', 2);
>> rgbImage = RGBImage (1 : 60, 1 : 76, :);
>> colorBar = RGBImage (1 : 60, 77 : 80, :);
>> [cbr, cbg, cbb] = imsplit (colorBar);
>> blackMask = (cbr == 0) & (cbg == 0) & (cbb == 0);
>> allBlackRows = all (blackMask, 2);
>> allBlackColumns = all (blackMask, 1);
>> colorBar (:, allBlackColumns, :) = [];
>> colorBar (allBlackRows, :, :) = [];
>> [cbr, cbg, cbb] = imsplit (colorBar);
>> meanR = mean (cbr, 2);
>> meanG = mean (cbg, 2);
>> meanB = mean (cbb, 2);
>> end1String = 'top';
>> end2String = 'bottom';
>> ColorMap = [meanR(:), meanG(:), meanB(:)] / 255;
>> ColorMap = flipud (ColorMap);
>> highTemp = 181.1;
>> lowTemp = 3.2;
>> subplot (2, 3, 1);
>> imshow (RGBImage, []);
>> figure.WindowState = 'maximized';
>> axis on;
>> Title = "RGB Image";
>> title (Title, 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> drawnow;
```

```
>> rectangleColorBar = [77, 1, 3, 59];
>> hold on;
>> rectangle ('Position', ImagePosition, 'EdgeColor', 'r', 'LineWidth', 2);
>> rectangle ('Position', rectangleColorBar, 'EdgeColor', 'r', 'LineWidth', 2);
>> subplot(2, 3, 2);
>> imshow (rgbImage, []);
>> axis on;
>> Title = "Cropped RGB Image";
>> title (Title, 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> drawnow;
>> subplot (2, 3, 3);
>> imshow (colorBar, []);
>> axis on;
>> impixelinfo;
>> Title = "Cropped Colorbar Image";
>> title(Title, 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> drawnow;
>> indexedImage = rgb2ind (rgbImage, ColorMap);
>> subplot(2, 3, 4);
>> imshow(indexedImage, []);
>> impixelinfo;
>> axis on;
>> Title = "Indexed Image (Gray Scale Thermal Image)";
>> title (Title, 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> drawnow;
>> thermalImage = lowTemp + (highTemp - lowTemp) * mat2gray(indexedImage);
>> subplot(2, 3, 5);
>> imshow(thermalImage, []);
>> axis on;
>> colorbar;
>> title ('Floating Point Thermal (Temperature) Image', 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> hp = impixelinfo();
>> hp.Units = 'normalized';
>> hp.Position = [0.45, 0.03, 0.25, 0.02];
>> subplot(2, 3, 6);
>> histogram(thermalImage, 'Normalization', 'probability');
>> axis on;
>> grid on;
>> Title = "Histogram of Temperatures in Thermal Image";
>> title (Title, 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Temperature [Degrees]', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Frequency [Pixel Count]', 'FontSize', fontSize, 'Interpreter', 'None');
>> maxTemperature = max (thermalImage(:));
>> fprintf('The maximum temperature in the image is %.2f\n', maxTemperature);
>> if (maxTemperature > refTemperature)
    fprintf('The maximum temperature in the image is higher than the reference temperature');
end
```

Appendix B

Matlab simulink code for image processing to detect liquid or gas leakage:

```
>> File1 = 'thermal_image11.png';
>> File2 = 'thermal_image15.png';
>> folder = pwd;
>> FileName = fullfile (folder, File1);
>> RGBImage1 = imread (FileName);
>> FileName = fullfile (folder, File2);
>> RGBImage2 = imread (FileName);
>> [rows1, columns1, NumberOfColors1] = size (RGBImage1);
>> [rows2, columns2, NumberOfColors2] = size (RGBImage2);
>> fontSize = 10;
>> grayImage1 = min (RGBImage1, [], 3);
>> grayImage2 = min (RGBImage2, [], 3);
>> rgbImage1 = RGBImage1 (1 : 60, 1 : 76, :);
>> rgbImage2 = RGBImage2 (1 : 60, 1 : 76, :);
>> colorBar = RGBImage1 (1 : 60, 79 : 80, :);
>> [cbr, cbg, cbb] = imsplit (colorBar);
>> meanR = mean (cbr, 2);
>> meanG = mean (cbg, 2);
>> meanB = mean (cbb, 2);
>> ColorMap = [meanR(:), meanG(:), meanB(:)] / 255;
>> ColorMap = flipud (ColorMap);
>> highTemp = 181.1;
>> lowTemp = 3.2;
>> indexedImage1 = rgb2ind (rgbImage1, ColorMap);
>> indexedImage2 = rgb2ind (rgbImage2, ColorMap);
>> thermalImage1 = lowTemp + (highTemp - lowTemp) * mat2gray(indexedImage1);
>> thermalImage2 = lowTemp + (highTemp - lowTemp) * mat2gray(indexedImage2);
>> subplot(2, 3, 1);
>> imshow (rgbImage1, []);
>> axis on;
>> Title = "Cropped RGB Image (a)";
>> title (Title, 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> drawnow;
>> subplot(2, 3, 2);
>> imshow (rgbImage2, []);
>> axis on;
>> Title = "Cropped RGB Image (b)";
>> title (Title, 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> drawnow;
>> subplot(2, 3, 4);
>> imshow(thermalImage1, []);
>> axis on;
>> colorbar;
```

```
>> title ('Thermal Image (a)', 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> impixelinfo;
>> subplot(2, 3, 5);
>> imshow(thermalImage2, []);
>> axis on;
>> colorbar;
>> title ('Thermal Image (b)', 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> impixelinfo;
>> thermalImage = abs (abs (thermalImage2 - thermalImage1) - highTemp);
>> subplot(2, 3, 3);
>> imshow(thermalImage, []);
>> impixelinfo;
>> axis on;
>> title ('Subtracted Thermal Image', 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> for j = 1 : 76
    for i = 1 : 60
    if (181.1 - thermalImage (i,j)) <= 3.62
    thermalImage (i,j) = 181.1;
end
end
end
>> for j = 2 : 75
    for i = 2 : 59
    if (thermalImage (i,j) ~= 181.1)
    if (thermalImage (i-1,j) == 181.1) & (thermalImage (i+1,j) == 181.1) & (thermalImage (i,j-1) ==
181.1) & (thermalImage (i,j+1) == 181.1)
    thermalImage (i,j) = 181.1;
end
end
end
end
>> subplot(2, 3, 6);
>> imshow(thermalImage, []);
>> impixelinfo;
>> axis on;
>> title ('Subtracted Thermal Image after noise removal', 'FontSize', fontSize, 'Interpreter', 'None');
>> xlabel ('Column', 'FontSize', fontSize, 'Interpreter', 'None');
>> ylabel ('Row', 'FontSize', fontSize, 'Interpreter', 'None');
>> for j = 1 : 76
    for i = 1 : 60
    if (181.1 - thermalImage (i,j) ~= 0)
    break
end
end
end
>>  fprintf('Leakage is found on this equipment or pipeline');
```

Appendix C

Matlab simulink code for sound source localization:

```
>> c=343;
>> d=0.17;
>> SPL_ref = 120;
>> [soundsig1,Fs]=audioread('pump_sound3.wav');
>> sound(soundsig1,Fs)
>> soundsig1_vol = 7 * soundsig1;
>> info=audioinfo('pump_sound2.wav');
>> t=0:seconds(1/Fs):seconds(info.Duration);
>> t=t(1:end-1);
>> subplot(2,3,1);
>> plot(t,soundsig1);
>> title('Sound signal received on microphone B');
>> xlabel('time(s)');
>> subplot(2,3,3);
>> plot(t,soundsig1_vol);
>> title('Sound signal received on microphone B in voltage');
>> xlabel('time(s)');
>> ylabel('Voltage(v)');
for delay = -5e-4 : 25e-6 : 5e-4
>> soundsig2= delayseq(soundsig1,delay,Fs);      %20e-5,Fs);
>> subplot(2,3,2);
>> plot(t,soundsig2);
>> title('Sound signal received on microphone A');
>> xlabel('time(s)');
>> tau = gccphat(soundsig2, soundsig1, Fs);
>> AB_extra = tau*c;
>> if (AB_extra < d) & (AB_extra > -d)
   x_est=-20:0.1:20;
   x_coef=2*ones(1,length(x_est));
   y_est = sqrt((AB_extra)^2/4-(d/2)^2+(4*(d/2)^2/(AB_extra)^2-1)*x_est.^x_coef);
   subplot(2,3,4);
   plot(x_est,y_est);
   title('Estimated sound source position');
   xlabel('x (m)');
   ylabel('y (m)');
   hold on
   x_est1=round(length(x_est)/4);x_est2=round(length(x_est)/8);
   slope=(y_est(x_est1)-y_est(x_est2))/(0.1*(x_est1-x_est2));
   if tau>0
   Alfa_rad=atan(slope);
   Alfa_degree=Alfa_rad*180/pi;
   angle=-90-Alfa_degree;
   subplot(2,3,5);
   plot(angle,delay,'x');
   title('Sound source position');
   xlabel('angle (degree)');
   ylabel('delay (s)');
```

```
  hold on
  elseif tau<0
  Alfa_rad=atan(-slope);
  Alfa_degree=Alfa_rad*180/pi;
  angle=90-Alfa_degree;
  subplot(2,3,5);
  plot(angle,delay,'x');
  title('Sound source position');
  xlabel('angle (degree)');
  ylabel('delay (s)');
  hold on
  else
  angle=0;
  subplot(2,3,5);
  plot(angle,delay,'x');
  title('Sound source position');
  xlabel('angle (degree)');
  ylabel('delay (s)');
  hold on
end
  elseif AB_extra == d
  angle=-90;
  subplot(2,3,5);
  plot(angle,delay,'x');
  title('Sound source position');
  xlabel('angle (degree)');
  ylabel('delay (s)');
  hold on
  elseif AB_extra == -d
  angle=90;
  subplot(2,3,5);
  plot(angle,delay,'x');
  title('Sound source position');
  xlabel('angle (degree)');
  ylabel('delay (s)');
  hold on
  elseif (AB_extra < -d) | (AB_extra > d)
  fprintf('Differential distance is not valid, Robot move towards the equipment and check the sound
again');
end
end
>> for i=1:10000:270000
  soundsig1_check = soundsig1_vol(i:i+9999);
  V_rms=rms(soundsig1_check);
  SPL=20*log10(V_rms*1e6);
  subplot(2,3,6);
  t1=i/Fs;
  plot(t1,SPL,'x');
  title('Sound pressure level');
  xlabel('time (s)');
  ylabel('Sound Pressure Level (dB)');
  hold on
  if SPL>SPL_ref
  fprintf('High sound pressure level, check the equipment');
  else
```

```
   fprintf('Equipment SPL= %d dB.\n',SPL);
end
end
```

Appendix D

Matlab simulink code for vibration analysis:

```
>> close all
>> clear all
>> freq_motor = 50;
>> Vib_data = csvread('Vibration_Data_electric_motor_mechanically_imbalanced_half_speed.csv');
>> [N,m] = size(Vib_data);
>> time = Vib_data(:,1);
>> Vib = Vib_data(:,2);
>> Fs = 1/(time(2)-time(1));
>> subplot(2,2,1)
>> plot(time,Vib)
>> xlabel('Time (s)');
>> ylabel('Acceleration (g)');
>> title('Acceleration of Electric motor with half speed and mechanically imbalance');
>> grid on;
>> width = floor(Fs);
>> steps = floor(N/width);
>> t_RMS = zeros(steps,1);
>> x_RMS = zeros(steps,1);
>> for i=1:steps
   range = ((i-1)*width+1):(i*width);
   t_RMS(i) = mean(time(range));
   x_RMS(i) = sqrt(mean(Vib(range).^2));
end
>> subplot(2,2,2)
>> plot(t_RMS,x_RMS)
>> xlabel('Time (s)');
>> ylabel('RMS Acceleration (g)');
>> title('RMS Acceleration of Electric motor with half speed and mechanically imbalance');
>> grid on;
>> freq = 0:Fs/length(Vib):Fs/2;
>> Vib_fft = fft(Vib);
>> Vib_fft = 1/length(Vib).*Vib_fft;
>> Vib_fft(2:end-1) = 2*Vib_fft(2:end-1);
>> subplot(2,2,3)
>> plot(freq,abs(Vib_fft(1:floor(N/2)+1)))
>> xlabel('Frequency (Hz)');
>> ylabel('Amplitude of Acceleration (g)');
>> title('Amplitude of Acceleration-Electric motor with half speed and mechanically imbalance');
>> grid on;
>> subplot(2,2,4)
>> Vib_fft(abs(Vib_fft) < 0.02)=0;
>> plot(freq,angle(Vib_fft(1:floor(N/2)+1))*180/pi)
>> xlabel('Frequency (Hz)');
>> ylabel('Phase of Acceleration (degree)');
>> title('Phase of Acceleration-Electric motor with half speed and mechanically imbalance');
>> grid on;
>> [maxval,idx]=max(abs(Vib_fft));
```

```
>> if freq(idx) > freq_motor
   fprintf('High vibration %2.6f g on frequency %4.4f Hz, check the equipment \n',maxval , freq(idx));
end
```